Modular Design in Triboelectric Sensors

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Triboelectric nanogenerators (TENGs) have garnered considerable interest as a promising technology for energy harvesting and stimulus sensing. While TENGs facilitate the generation of electricity from micro-motions, the modular design of TENG-based modular sensing systems (TMSs) also offers significant potential for powering biosensors and other medical devices, thus reducing dependence on external power sources and enabling biological processes to be monitored in real time. Moreover, TENGs can be customised and personalized to address individual patient needs while ensuring biocompatibility and safety, ultimately enhancing the efficiency and security of diagnosis and treatment.

modular design | real-time diagnosis | triboelectric sensor | self-powered system

1. Introduction

Since its invention in 2012, triboelectric nanogenerators (TENGs) has gained considerable attention for its potential to harvest energy and serve as an active sensor in diverse fields, such as green energy, molecular detection, and healthcare [1]. TENGs can convert mechanical energy into electrical energy, making them a promising technology for energy-harvesting applications. Moreover, their ability to generate electrical signals in response to various stimuli, such as mechanical pressure, vibration, temperature changes, and position, makes TENGs potential sensors for multiple applications [2][3].

Meanwhile, as the Internet of Things (IoT) continues to evolve rapidly, TENG-based energy-harvesting and environment-sensing technologies have garnered further interest due to the unique advantages of self-power supply and miniaturisation [4][5][6]. This makes growing innovation in personalised diagnosis possible, which is especially attractive if supported by information technologies such as wireless connectivity, cloud services, and data storage [7]. TENG-based modular sensing systems (TMSs) can seamlessly integrate with IoT devices, facilitating real-time data collection, processing, and sharing for remote monitoring and analysis. This integration can significantly improve the accuracy and efficiency of medical diagnosis and treatment, ultimately leading to better patient outcomes.

Theoretically, the critical advantage of TENG technology is its compatibility with a wide range of raw materials, which has led to the development of TENG-based biosensors with significant potential for real-time diagnosis in clinical applications due to the wide selection in triboelectric polarity, biocompatibility, and mechanical and other fascinating properties [8][9]. For instance, TENGs can be used to measure various clinical parameters, such as glucose levels, blood pressure, heart rate, and respiratory rate [10][11]. These biosensors can be conveniently worn as a patch or integrated into wearable devices, allowing the continuous monitoring and analysis of physiological signals to be achieved [12].

Modular design in TMSs offers numerous advantages for clinical applications. Firstly, processing using a sensor module, TENGs demonstrate excellent sensitivity, allowing the subtle changes in physical and chemical signals to be detected [13]. Secondly, selecting highly biocompatible modules makes them safe for long-term implantation in the human body. Thirdly, the TENG power generation module can harvest energy from the body, enabling them to operate continuously without the need for external power sources [14]. Lastly, this modular design can be customised to specific patient needs, providing accurate and reliable real-time diagnosis and treatment [15]. These benefits underscore the enormous potential of modular design in TMSs for clinical applications in real-time diagnosis, making them ideal candidates for healthcare applications [16][17][18].

2. Biological Energy Collection

2.1. Working Principle of TENGs

TENGs utilise the triboelectric effect and electrostatic induction coupling to convert biomechanical energy into electrical energy [19][20]. When two materials with different degrees of electronegativity come into contact, electrons flow between them [21][22]. When they are separated, electrostatic induction causes electrons to flow to the external load, generating alternating currents by repeating the contact–separation cycles [23][24].

Working modes of TENGs: TENGs can be categorized into four working modes: vertical contact–separation mode, lateral sliding mode, single-electrode mode, and independent triboelectric layer mode.

Vertical contact–separation (CS) mode: Electrons are exchanged at the contact surface when two objects with different degrees of electronegativity are in vertical contact. The separation of the two objects causes electrostatic induction, leading to a potential difference between the electrodes attached to them, generating electric current. With the repetition of contact–separation cycles, alternating current is output [25].

Lateral sliding (LS) mode: Similar to the vertical contact–separation mode, the principle of lateral sliding involves the horizontal displacement of the two objects. An alternating current is generated by repeated removal in the horizontal direction [26].

Single-electrode (SE) mode: This mode uses the Earth as an electrode to generate a potential difference between the metal electrode and the Earth with electrostatic induction, producing current [27].

Freestanding triboelectric layer (FT) mode: The FT mode involves placing a charged object between two electrodes attached to the dielectric layer. The movement of the charged object between the two electrodes changes the potential difference between them, generating current [28].

TENGs can be designed according to the personalized needs of patients, utilizing a variety of friction layer materials and electrode materials. With the ability to generate high-power output, TENG-based devices have the potential to support complex functional modules, making them suitable for a wide range of medical applications.

2.2. Motion-Based TENGs

Motion-based TENGs represent cutting-edge development in the field of TENG technology. By converting mechanical energy into electrical energy, these innovative devices are particularly suited for wearable and self-powered sensing applications. Modularity is vital in motion-based TENGs, as it facilitates customisation and adaptability for various use cases and environments. This feature dramatically enhances the devices' efficiency and versatility [29].

2.3. Implantable TENGs

Implantable TENGs capitalise on innovative technology to develop versatile, self-powered medical devices seamlessly implanted within the human body. These devices are specifically designed to target various health conditions, fostering healing and promoting tissue maturation.

In one study, Zhao et al. developed an advanced, self-powered implantable electrical stimulator utilising a TENG to address damaged myocardium [30]. This innovative device generates an electric field on interdigitated electrodes, thereby facilitating the maturation of neonatal rat cardiomyocytes by enhancing the expression of specific proteins. Furthermore, it improves sarcomere organisation, fracture formation, and intracellular calcium levels. Driven by physiological movement, the TENG functions as an implantable medical electronic device for electrically promoting cardiomyocyte maturation, offering invaluable technical support for treating myocardial defects and restoring cardiac tissue function.

3. Modular Design in Respiratory and Cardiovascular Systems

3.1. Respiratory System

3.1.1. TMSs for Gas Diagnosis

The TENG-based gas diagnostic modular system represents a groundbreaking approach of TENG-based biosensors to the real-time diagnosis of respiratory gases in humans [31][32]. As a critical aspect of this system, modularity enables customisation and adaptability to be achieved, thereby enhancing the performance and usability of TMSs across a range of diagnostic applications.

In complementary development research, Zhang and his team designed a self-powered sensing system that employs a TENG to detect exhaled gas and diagnose diseases [33]. What sets this system apart is the TENG's ability to be driven by respiration, functioning as both a power source and a sensor. The TENG comprises a

Ti_3C_2Tx MXene/NH_2-MWCNT composite, and both the friction layer and electrode. The system's modular design encompasses the TENG, the MXene/NH_2-MWCNT composite, and the support vector machine model for respiratory type identification. Consequently, the device boasts excellent gas sensing response, a low detection limit, and a rapid response/recovery time. The TENG also holds potential application value in diagnosing diseases related to exhaled gas and can differentiate various respiratory types using a support vector machine model.

The TENG modular gas diagnostic system epitomises a state-of-the-art solution for real-time respiratory gas analysis, leveraging sophisticated materials and modularity to augment functionality and cater to a wide range of clinical applications. The advancements made by Wang et al. and Zhang's team emphasize the promising potential of TENG technology for developing highly efficient and adaptable diagnostic systems for various respiratory conditions.

3.1.2. TMSs for Hypoventilation Syndrome and Asthma Diagnosis

Peng et al. have made significant strides in this field by designing a modular electronic skin (e-skin) utilising TENG technology for real-time respiratory monitoring and obstructive sleep apnoea–hypopnoea syndrome (OSAHS) diagnosis [34]. Comprising 66 multilayer polyacrylonitrile and polyamide nanofibers as the contact pairs and deposited gold electrodes, the e-skin offers energy autonomy and accurate real-time respiratory monitoring. With its high-pressure sensitivity, good air permeability, and excellent working stability, the e-skin is a foundation for a self-powered diagnostic system that enables the real-time detection and severity evaluation of OSAHS to be achieved, ultimately improving sleep quality. Developed with a facile and low-cost electrospinning strategy, the e-skin possesses numerous micro-to-nano hierarchical porous structures that enhance contact electrification and facilitate thermal-moisture transfer. This allows the e-skin to achieve peak power density capable of powering hundreds of LEDs and charging various commercial capacitors under specific loading frequencies and applied force. With its immense potential for wearable medical electronics and personal healthcare monitoring, the e-skin emerges as a promising device for clinical applications.

3.1.3. TMSs for Intelligent Mask Design

Lu et al.'s work exemplifies the value of modularity in the development of an intelligent facemask with a novel, structured respiratory sensing triboelectric nanogenerator (RSTENG) for respiratory monitoring [35]. The RSTENG comprises four distinct modules: a copper electrode layer, a polytetrafluoroethylene (PTFE) film layer, an aluminium foil layer, and a sponge layer. By integrating these modules, the facemask can monitor the breathing status and diagnose respiratory diseases, such as those caused by the COVID-19 pandemic. The modular design enhances the development of respiratory monitoring devices and their potential clinical applications. It achieves the integration of a breath-driven human–machine interface (HMI) system and an apnoea alarm system. These additional features empower users with disabilities to control small household appliances with breathing and provide timely alarms when breathing ceases, respectively.

3.2. Cardiovascular System

3.2.1. TMSs for Cardiac Real-Time Diagnosis

TENG cardiac real-time diagnosis represents a groundbreaking approach to heart activity monitoring, utilising TENGs for sensing and analysing various aspects of cardiovascular function [36][37][38][39]. This innovative method harnesses the power of modularity to develop compact, flexible, and biocompatible devices that boast enhanced functionality and seamless integration, revolutionising the field of cardiac monitoring and treatment.

One remarkable example of modularity in TENG cardiac real-time diagnosis is the self-powered endocardial pressure sensor (SEPS) designed by Liu et al. Comprising four layers, this modular structure protects blood and moisture while enabling the real-time monitoring of endocardial pressure to be conducted [40]. The SEPS can be miniaturised, flexible, and integrated with a surgical catheter for minimally invasive implantation. Its excellent linearity and sensitivity allow cardiac arrhythmias such as ventricular fibrillation and ventricular premature contraction to be detected. By offering valuable information for heart failure patients, the SEPS holds significant clinical applications and potential for implantable healthcare monitoring, providing safe pressure sensing, diagnosis, and the monitoring of cardiovascular disease.

3.2.2. TMSs for Pulse Real-Time Diagnosis

Pulse real-time diagnosis is an innovative approach in healthcare that utilises TENG technology to continuously monitor and evaluate cardiovascular health. TENGs can convert mechanical energy, such as the pulsatile motion of blood vessels, into electrical signals, which can then be analysed for various health indicators. By measuring these electrical signals in real time, healthcare professionals can obtain valuable insights into a patient's heart rate, blood flow, and overall cardiovascular function, potentially allowing the early detection of anomalies and timely intervention for improved patient outcomes to be conducted [41][42][43][44][45][46].

4. Modular Design in Musculoskeletal Systems

4.1. Bone System

4.1.1. TMSs for Bone Morphology Diagnosis

Real-time bone morphology diagnosis is a cutting-edge method involving the continuous observation and evaluation of bone structures and joint health [47]. This approach enables the prompt identification and diagnosis of issues to be achieved, including wear debris, joint and spinal motion, head movement during sleep, and bone healing processes. By embodying a modular design, real-time bone morphology diagnosis systems can be tailored to specific applications or user requirements. This flexibility allows various components to be integrated, such as imaging devices, sensors, data processing units, and user interfaces, which can be easily combined or interchanged to create a customised diagnostic solution. Modularisation also facilitates seamless integration with other healthcare technologies and systems, enhancing the overall functionality and efficiency of the diagnostic process.

4.1.2. TENGs for Bone Repair

TENG bone repair, a groundbreaking method for promoting bone regeneration, employs TENGs to convert human body movement into electrical stimulation. This process activates cellular mechanisms crucial to bone healing. By harnessing TENG technology in bone repair, this non-invasive, self-powered, and energy-efficient approach presents a promising alternative to conventional bone healing techniques. It can potentially provide more effective and tailored treatment strategies in orthopaedics and regenerative medicine [48].

4.2. Neuromuscular System

4.2.1. TMSs for Motion System

The TENG-based sensing system for motion detection refers to an advanced technology that employs TENGs to monitor and analyse movement-related parameters [49]. TENGs can convert mechanical energy, such as vibrations or displacements, into electrical signals that can be analysed to provide valuable insights into motion patterns [50]. By embodying a modular design, we can produce systems with higher sensitivity and stability for motion diagnosis, such as combining the original TENG module with a wireless communication module filter module, which can create a customised motion detection solution. It enhances the overall functionality and efficiency of the motion detection process.

4.2.2. TMSs for Parkinson's Diagnosis

One such example is the modular system designed by Kim et al. [51]. It combines a highly stretchable and self-healable TENG for energy harvesting and tremor sensing with two distinct modules: a catechol–chitosan–diatom hydrogel (CCDHG) electrode module and an M-shaped Kapton film module. The biocompatible and eco-friendly CCDHG electrode module offers high stretchability, self-healing ability, and conductivity. In contrast, the M-shaped Kapton film module enhances the contact area and sensitivity of the TENG, acting as a tremor sensor to detect low-frequency vibrations from the human body. This self-powered tremor sensor can diagnose Parkinson's disease by measuring the low-frequency vibrational motion of patients and has potential applications in biomedical health monitoring, intelligent e-skins, soft robotics, and wearable bioelectronics.

5. Modular Design in Bacteria Diagnosis and Sterilization

5.1. TMSs for Gram-Positive Bacterial Diagnosis

In clinical application settings, the real-time diagnosis of Gram-positive bacteria is crucial to determining the appropriate treatment for patients suffering from bacterial infections [52]. The early and accurate identification of these pathogens helps medical professionals make informed decisions regarding antibiotic selection, reducing the risk of complications and improving patient outcomes [53]. Additionally, real-time diagnosis assists in preventing and controlling nosocomial infections, ensuring a safer healthcare environment [54].

5.2. TENGs for Gram-Positive Bacterial Sterilization

The real-time sterilisation of Gram-positive bacteria exemplifies a pioneering approach for rapidly and proficiently eliminating detrimental microbes [55]. This avant-garde method plays a vital role in numerous industries and public health endeavours, as it aids in upholding hygiene, curbing the transmission of infections, and guaranteeing product safety. The foremost merit of real-time sterilisation technology lies in its modularity, which enables distinct yet interrelated components to be amalgamated to establish a cohesive, self-powered system. By incorporating specialised modules, these sterilisation systems can attain unparalleled levels of efficiency while mitigating environmental impact. For instance, one application might pair a piezoelectric energy-harvesting module with an advanced sterilisation module, working together to eliminate pathogenic bacteria. Zhang et al. have presented a modular device consisting of two key components: a TENG and a nanowire electrode array (NEA) [56]. The TENG module generates electricity to power the NEA module, sterilising urine by irreversibly electroporating pathogens using high-voltage pulsed electric fields. The resulting TENG-driven NEA (T-NEA) system demonstrates exceptional sterilisation efficiency, over 99.9999%, in synthetic urine contaminated with various bacterial strains. Moreover, the T-NEA system effectively degrades organic components in urine using radical oxygen species generated during its operation. This modular design creates a self-powered, eco-friendly system capable of eliminating harmful bacteria and pollutants from urine while preventing the production of toxic by-products.

6. Conclusions and Prospect

6.1. TENGs in Energy Collection

6.1.1. Power Output

To advance the power output and conversion efficiency of TENG devices, it is crucial to optimise material properties, device geometry, and electrode design, ensuring that the harvested energy is adequate for the target application. Material selection plays a vital role in enhancing the performance of TENG devices, with a focus on selecting materials that possess high triboelectric properties and mechanical solid characteristics. Additionally, researchers should investigate new materials or material combinations to further improve charge generation and transfer efficiency, potentially leading to groundbreaking innovations in the field. Regarding device structure and design, it is essential to optimise these aspects to maximise the contact area and relative motion between the triboelectric layers.

6.1.2. Durability and Reliability

Selecting reliable raw materials is vital to improving stability and durability, ensuring devices can withstand various operating conditions while maintaining their performance. Therefore, researchers can focus on materials with high frictional electrical and solid mechanical properties to provide stronger elasticity and longevity to TENG equipment. Enhancing TENG stability in harsh environments is another essential consideration.

6.1.3. Multifunctionality

Researchers can choose to broaden the functionality of TENGs as a primary focus in the future. For example, integrating TENGs with other energy collection technologies, such as solar cells or thermoelectric generators, could give rise to hybrid systems capable of tapping into multiple energy sources, thereby enhancing overall energy output. This synergistic approach would maximize the benefits of each technology, potentially revolutionising the energy-harvesting landscape and contributing to a more sustainable future.

6.2. TENGs in Sensing Systems

6.2.1. Sensitivity and Signal Quality

In the pursuit of enhanced medical diagnostics, future research should concentrate on discovering innovative materials and designs to augment the sensitivity of TENG-based sensors. This entails directing research efforts toward synthesizing stable and sensitive new materials for creating sensors capable of detecting the most subtle changes in pressure, strain, or motion across various medical applications. Equally significant is the reduction in noise, which can be achieved by designing effective filter circuits to optimize signal quality.

6.2.2. Biocompatibility and Comfort

As the demand for non-invasive and comfortable diagnostic tools increases, researchers must investigate novel non-toxic and safe materials for direct skin contact or implantation. This can be accomplished by selecting biocompatible raw materials for TENG fabrication.

6.2.3. Wireless Communication

Incorporating wireless communication capabilities into TENG devices is crucial to achieving real-time data transmission and remote monitoring. This advancement could expedite diagnostics and empower healthcare providers to make more informed decisions. Alongside wireless communication, developing advanced algorithms for processing and analysing collected data is critical. These algorithms could facilitate extracting meaningful information and identifying potential abnormalities or patterns associated with various disorders or diseases, ultimately enhancing the accuracy of medical diagnoses.

6.2.4. Wearability and Durability

The effectiveness of TENG devices as continuous monitoring tools hinges on their wearability and durability. Researchers should focus on designing forms or novel materials that can withstand extended wear and tear while maintaining wearing comfort. Moreover, it is vital to investigate materials and fabrication technologies that can endure daily wear and environmental factors such as sweat, moisture, and temperature fluctuations. This could improve the stability of TENG devices in harsh environments.

6.3. TENGs in Bacterial Clinical Diagnosis and Sterilization

6.3.1. Sensitivity and Selectivity

To improve the sensitivity and selectivity of TENG-based devices, researchers should focus on optimizing the surface functionalisation process. This can be achieved by utilising specific recognition elements, such as antibodies, aptamers, or molecularly imprinted polymers, which target particular bacterial strains or biomarkers. By doing so, TENG devices could detect the presence of specific substances or pathogens with greater accuracy and precision. This enhanced sensitivity and selectivity could ultimately lead to more reliable and accurate diagnostic tools that can aid healthcare professionals in making better-informed treatment decisions.

6.3.2. Scalability and Integration

A crucial aspect of advancing TENG-based devices is the development of scalable fabrication processes. This would enable the large-scale production of TENG devices to be achieved, making them more accessible and cost-effective. Additionally, researchers should work towards ensuring that these devices can be easily integrated with existing diagnostic and sterilization systems, streamlining their implementation within healthcare facilities. TENG devices can become a mainstream solution for various diagnostic and sterilization applications by focusing on scalability and integration, contributing to a more efficient and effective healthcare system.

6.3.3. Power Output and Efficiency

The power output and conversion efficiency of TENGs play a pivotal role in their overall performance. Researchers should concentrate on optimizing the material, structure, and design of TENG devices to enhance their power output and conversion efficiency. By achieving this, TENG devices can generate sufficient power to effectively operate diagnostic and sterilization equipment without compromising performance. Increased power output and efficiency could not only improve the functionality of TENG devices but also contribute to the development of more energy-efficient and sustainable healthcare solutions.

6.3.4. Biocompatibility and Safety

In clinical settings, it is of utmost importance that TENG devices are made using biocompatible and non-toxic materials. This ensures the safety of patients and healthcare professionals, mainly when TENG devices come into direct contact with biological samples or are used on patients. Researchers should prioritize the selection of biocompatible materials and continuously assess the safety of these devices throughout their development process. By doing so, TENG devices can be confidently utilized in various healthcare applications, providing safe and effective solutions for diagnostics and sterilization.

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