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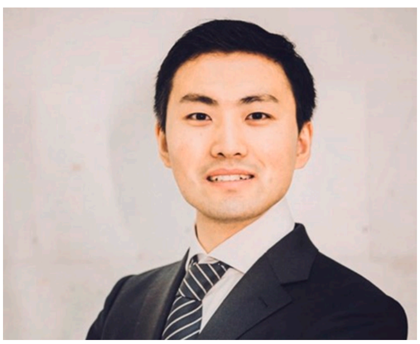
Voices

Nanogenerators for self-powered wearable devices

Over the past few decades, researchers have developed a diverse array of nanogenerators capable of converting ambient mechanical energy—such as breezes, body movements, or even subtle breathing—into electrical power. This technology not only reduces reliance on conventional batteries but also enables the development of lightweight, flexible, and eco-friendly wearable devices. In this Voices article, we gather insights from a global panel of experts to explore the latest breakthroughs and remaining challenges in this rapidly evolving field.



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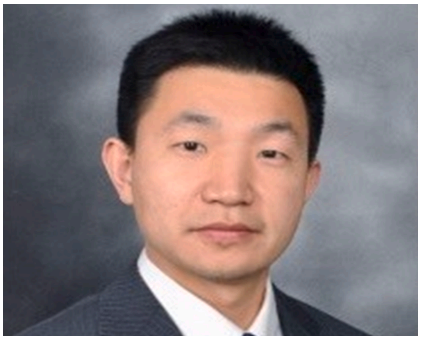
Triboelectric nanogenerators for wearable bioelectronics

Triboelectric nanogenerators (TENGs) have emerged as a groundbreaking technology for biomechanical-to-electrical energy conversion (http://hdl.handle.net/1853/54956). By harnessing a surface-charging effect between dissimilar materials, TENGs offer a unique combination of softness, lightweight design, biocompatibility, and wearability—even enabling implantable applications—driving revolutionary advancements in soft bioelectronics for personalized healthcare (https://doi.org/10.1016/j.matt.2021.01.006). TENGs efficiently convert low-frequency biomechanical motions into high-voltage, low-current electrical signals through contact electrification and electrostatic induction. They have successfully generated high-fidelity electrical signals from diverse biomechanical activities, including walking, arm movement, breathing, heartbeats, pulse waves, vocal vibrations, blood flow, vascular pressure, and stomach peristalsis, among others.

The unique working principle of TENGs provides multiple advantages, such as structural simplicity, cost effectiveness, and compatibility with various soft materials. Electrical signals produced from human body movements and physiological activities can serve as reliable power sources for biomedical devices, active sensors for biomonitoring, and electrical stimulation for sustainable therapeutic applications. By integrating TENGs with various functionalities, an autonomous body-area network can be developed for continuous, closed-loop biomonitoring and treatment, eliminating reliance on external power sources. With the rise of the Internet of Things and 6G wireless networks, TENG-enabled autonomous body-area networks have the potential to transform healthcare, shifting from a reactive, disease-centered model to a proactive approach focused on disease prevention and health promotion.

TENGs for wearable bioelectronics seem very promising. However, their operational stability is dependent on key factors. Firstly, material wear can lead to abrasion, gradually degrading performance and long-term reliability. Additionally, the effectiveness of TENGs depends on surface nanopatterning, which enhances output performance but suffers from limited mechanical resilience, potentially compromising electrical stability. Thus, further research is needed to optimize material performance and develop robust functionalization strategies.

Furthermore, humidity from the human body and ambient environment could further challenge the operational stability of TENGs. Another critical concern is the vulnerability to motion artifacts. As wearable bioelectronics, TENGs are exposed to unintended body movements that could generate interfering signals (https://doi.org/10.1038/s44222-024-00175-4), thus reducing sensing accuracy. Enhancing the motion artifact management capabilities of TENGs remains a complex yet active area of research.



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Beyond energy harvesting: Reimagining human-machine symbiosis

Wearable devices' reliance on batteries inherently sustains the industrial-era paradigm of one-way energy supply—humans provide electrical energy to devices, which in turn deliver data services, forming a clear energy-function exchange chain. The revolutionary potential of nanogenerators lies in their ability to transform the human body into a "bioenergy router." Utilizing diverse energy-harvesting technologies such as TENG, piezoelectric nanogenerator, and thermoelectric generator devices can now autonomously extract energy from human movement, metabolism, and even respiration, bringing the concept of a human energy microgrid closer to reality. Free from battery-life constraints, product designers can transcend size limitations, integrating more advanced sensors and functional modules. For example, health watches could incorporate precise biochemical detection chips to enable long-term monitoring of metrics like blood glucose and lactate levels; smart clothing might embed thermal management units for real-time temperature regulation, enhancing user comfort.

This technological leap not only promises to address the challenge of battery life but also triggers a profound paradigm shift in the human-machine relationship. From the user behavior perspective, when the electrical energy generated by physical activity can be quantified as device operational time (e.g., jogging for 10 min equates to 1 h of headphone playback), the flow of energy acquires a symbolic significance that incentivizes behavior. Companies may introduce energy-output exchange services, allowing users to trade exercise-generated electricity for data plans, membership benefits, and more. This bioenergy visualization reshapes the psychological contract between users and devices, transforming the energy flow generated by human activities into a perceivable, interactive interface. As a result, maintaining device operation evolves from a burdensome task into an engaging, embodied experience. In the healthcare sector, self-powered health-monitoring patches can continuously collect bodily data, supporting disease prevention and personalized medicine; in athletic contexts, wearable devices can dynamically adjust functional intensity based on the energy produced by the user, facilitating efficient energy utilization.

Perhaps the true value of nanogenerators does not lie in replacing batteries but in pioneering a new paradigm wherein energy equals interaction. Devices can intelligently adapt to user states by sensing energy output: when a user's energy output is low, the device could automatically reduce screen brightness or disable non-essential features. Conversely, when energy levels are adequate, it could activate advanced monitoring and analytical functions. Users unconsciously participate in the energy cycle through their physical activities. This vision of a symbiotic energy system could mark a critical step for wearables, evolving them from mere auxiliary tools into authentic extensions of the human body. As we explore this frontier, the answers to these questions will shape not only the future of wearable technology but also our understanding of human-machine symbiosis in the digital age.

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Triboelectric smart textiles for self-powered wearable devices

Wearable biosensors embedded into smart textiles have the potential to revolutionize healthcare by enabling continuous, real-time monitoring of vital signs. However, a major obstacle that stands in the way is the power supply. Current batteries are typically bulky, rigid, and require frequent charging, limiting the practicality of fully integrated wearables. To overcome this, energy-harvesting solutions that can transform everyday movements into usable electricity are needed.

TENGs offer a promising solution by converting mechanical energy from rubbing or friction into electrical energy, making them highly adaptable to harvesting energy from body movement. Triboelectric textiles integrate these generators directly into clothing, offering greater comfort and scalability than other wearable power configurations. Such triboelectric textiles could come in the form of fabrics, made by layering different triboelectric materials and electrodes onto fabric, and triboelectric yarns, composed of a conductive core coated with a dielectric triboelectric layer. While triboelectric fabrics offer a simpler fabrication process and easy scalability, triboelectric yarns provide enhanced breathability, flexibility, and seamless integration with textile manufacturing, making both approaches viable depending on the application.

For wearable energy harvesters to be viable, they must withstand real-world conditions, including repeated mechanical deformation and exposure to moisture. Durability is critical, as textiles must survive washing cycles, abrasion, and prolonged use without losing functionality. Although some triboelectric yarn prototypes have demonstrated resilience over many fatigue cycles, washing remains a challenge, often degrading performance over time. Future research must focus on developing robust triboelectric coatings that maintain efficiency while ensuring long-term wearability.

Beyond energy harvesting, triboelectric textiles can function as self-powered sensors, enabling continuous monitoring of motion, pressure, and physiological signals. These sensors could be integrated into smart clothing for health diagnostics, rehabilitation, and fitness tracking, eliminating the need for external batteries. By leveraging triboelectric energy, wearables could provide real-time feedback on movement patterns and even early detection of neuromuscular disorders.

Sustainability is another key concern. Although triboelectric textiles offer a battery-free alternative, their environmental impact depends on material selection and recyclability. Many triboelectric devices rely on synthetic polymers, which could pose challenges in terms of biodegradability and disposal. Future advancements should explore eco-friendly triboelectric materials, including biodegradable polymers and recyclable conductive fibers, to ensure these technologies align with sustainable manufacturing practices.

Despite their promise, commercialization remains a challenge. Progress has been made in improving power output, durability, and washability, but these technologies are still in the research phase. Issues related to power output, scalable fabrication, long-term reliability, and integration with textile manufacturing must be resolved before triboelectric textiles can be widely adopted. Additionally, wearable energy harvesters will likely require energy-storage solutions such as batteries or capacitors to ensure reliable operation. Although complete power autonomy remains a long-term goal, triboelectric textiles represent a transformative step toward self-powered wearables. By overcoming fabrication and durability challenges, these materials could pave the way for battery-free, continuously powered smart fabrics, revolutionizing healthcare, fitness, and much more.

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TENG-based wearable/implantable electrical-stimulation therapy devices

Electrical-stimulation therapy is a clinical intervention strategy that applies controllable voltage or current to specific tissues of the human body, ultimately achieving the regulation of physiological functions and improving pathological conditions. Electrophysiological characteristics are the mechanistic basis of the effectiveness of electrical-stimulation therapy: electrical stimulation usually opens voltage-gated ion channels, regulates cell transmembrane potential, and triggers a series of biochemical reactions. Currently, electrical-stimulation therapy has been widely used in the fields of neurological disease treatment, pain management, and rehabilitation medicine. However, traditional electrical-stimulation medical devices rely on external power supplies or built-in energy-storage devices, and have defects such as poor portability, insufficient battery life, and the risk of secondary surgery, which restricts its promotion and popularization in the long-term treatment of chronic diseases and complex medical scenarios.

TENGs are a novel energy-conversion technology that captures the multiscale mechanical energy from macroscopic limb movements (walking, arm swinging, joint flexion and extension) or microscopic physiological activities (breathing, heartbeat) of the human body and efficiently converts that energy into electrical signals. Compared with traditional electrical-stimulation devices, TENG-based wearable/implantable electrical-stimulation devices have created a disruptive new treatment paradigm due to the following traits:

Passivity and self-powered characteristics: Electrical-stimulation devices based on TENGs will get rid of their dependence on power sources and batteries. The mechanical energy of the human body can be used to continuously power the devices, improving the portability of the devices and avoiding the risk of secondary surgery.

Safe electrical output for biological regulation: TENGs output high-voltage, low-current pulse electrical signals, which can cause dynamic remodeling of cell membrane potential and induce electrophysiological responses; at the same time, it minimizes the thermal effects and electrochemical reactions produced by traditional electrical-stimulation strategies.

Lightweight, flexible and conformable: TENGs can use flexible and stretchable materials to adapt to various biological interfaces, enabling conformal attachment to skin/organ surfaces as well as long-term non-sensitive wear.

Intelligent feedback and dynamic regulation: TENGs can be used as a self-powered sensor, or power other sensors, to achieve dynamic monitoring of physiological signals. The stimulation parameters can be optimized through feedback regulation to improve the accuracy and safety of treatment.

Currently, TENG-based electrical-stimulation devices have been used to treat a variety of disease models. For example, the TENG-based intracardiac pacemaker can utilize the periodic contraction and relaxation of the heart to power the pacemaker, achieving effective pacing in models of animals with atrioventricular block disease. In tissue engineering, the electrical-stimulation output by TENGs can promote bone-tissue repair, skin-wound healing, and nerve-axon regeneration, providing an innovative treatment strategy for regenerative medicine. In the field of neuromodulation, TENGs can not only change the behavior of experimental animals through electrically stimulating the central nervous system but also regulate the autonomic nervous system to achieve control of body weight and urination. In tumor treatment, the electrical-stimulation output by TENGs can trigger the perforation of tumor cells and promote their immunogenic death or destroy the subcellular structure of tumor cells and synergistically promote tumor drug delivery. Recently, we discovered the self-powered electrical adjuvant effect of TENGs, which can synergistically enhance drug therapy or physical therapy for clinical use.

With the deep integration of materials science, micro-nano processing technology, and biomedicine, TENG is gradually promoting multidimensional innovations in electrical-stimulation therapy technology, such as multifunctional integrated design and the construction of adaptive closed-loop therapy systems. In the future, TENG-based wearable/implantable electrical-stimulation medical devices are expected to break through the limitations of existing electrical-stimulation treatment scenarios and provide innovative solutions in chronic disease management, aging health services, and malignant tumor treatment.

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Nanogenerators from piezoelectric biomaterials for wearable bioelectronics

Nature-derived piezoelectric biomaterials have recently emerged as promising candidates for biomechanical energy harvesting in biomedical applications, particularly through nanogenerator (NG) technologies that convert ambient mechanical stimuli into electrical energy. Although NGs are typically fabricated using inorganic piezoelectric materials and synthetic polymers to leverage their high piezoelectric coefficients and mechanical durability, their integration into wearable or implantable systems is often limited by concerns related to biocompatibility and biosafety. In contrast, natural biomaterials, though generally exhibiting lower piezoelectric responses, offer distinct advantages such as biosafety, physiological compatibility, and biodegradability, making them attractive for sustainable energy solutions in bioelectronic applications.

Among various natural piezoelectric materials, cellulose nanocrystals (CNCs) are among the most extensively studied due to their structural tunability, abundance, and environmental friendliness. However, achieving large-scale alignment of CNCs with uniform dipole orientation remains a major challenge. As a result, many cellulose-based NGs rely on composite structures or harness triboelectric effects to enhance output. Crystalline assemblies of amino acids represent another promising material class. Their small molecular size and hydrophilic functional groups enable both facile crystallization and rapid dissolution in aqueous media, enabling the fabrication of transient, biodegradable devices. For instance, glycine crystals encapsulated in biodegradable polymers have been employed in NGs where the operational lifetime can be precisely tuned by the packaging material. Nature-derived tissues with intrinsic structural anisotropy, such as fish swim bladders and eggshell membranes, offer alternative strategies by leveraging naturally aligned collagen fibers. These biomaterials exhibit appreciable piezoelectric outputs without requiring post-fabrication dipole alignment. Additional materials such as chitin nanofibers and even viruses have also been integrated into NG designs, exhibiting various degrees of efficiency.

Despite their attractive biological properties, the field of piezoelectric biomaterial-based NGs is still in its early stages. A critical limitation is their inherently low piezoelectric coefficients (<10 pC/N), which constrain their electrical output. Strategies such as domain alignment, interfacial engineering, and molecular-level chemical modification are essential to improve dipole density and optimize performance. Advancing this field also requires a deeper molecular-level understanding of piezoelectricity in this group of biomaterials. Natural biomaterials often exhibit multiple polymorphs with low crystal symmetry, resulting in non-uniform dipole orientation and diminished net polarization. Integrating molecular-level structural characterization with theoretical modeling is essential to elucidate their structure-property relationships and guide NG development. In addition, scalable synthesis and device integration remain another significant barrier to practical deployment. Most current studies are still at the level of proof-of-concept demonstrations at the lab scale. Bridging this gap might require the convergence of soft-materials processing, advanced manufacturing techniques, and data-driven design to establish viable production pathways.

In conclusion, natural piezoelectric biomaterials hold considerable promise as biocompatible nanogenerators. Their sustainable nature and adaptability for physiological systems position them as a compelling platform for next-generation wearable and implantable bioelectronics.

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Toward circular bioelectronics: Biomass-derived triboelectric skins

The first generation of skin-interfaced triboelectric sensors (SITSs) drew heavily on synthetic fluoropolymers and silicone elastomers, materials that provide exceptional surface charge density yet raise questions of environmental persistence, end-of-life disposal, and long-term dermal compatibility. Our community has recently begun to confront this paradox by asking whether the tactile intelligence of TENGs be delivered by matter sourced from nature and readily returned to it. Our answer has been an affirmative pursuit of biomass-based architectures (e.g., lignin, chitosan, cellulose) that marry the molecular versatility of biomass with the electromechanical finesse required for self-powered wearable health monitoring. Once regarded as paper-mill waste, lignin offers an abundance of π-conjugated phenolic moieties, the electron-donating propensity of which can be amplified by alkaline activation. Chitosan supplies a nitrogen-rich backbone that is conducive to proton-coupled charge transfer. Through rational engineering and pairing of these complementary tribopositive and tribonegative biopolymers in hierarchical films and aerogels, the community has demonstrated SITS patches capable of harvesting small-scale biomechanical signals across bending elbows and pulsating carotids.

However, material replacement on its own is not the holy grail. The real promise of biomass lies in its programmable functionality that synthetics cannot easily duplicate. Plant and marine macromolecules present intrinsic chirality, redox-active side chains, and abundant hydrogen bonding sites in their chemical structures, which invite post-synthetic enzymatic sculpting, self-healing crosslinks, and even metabolic sensing modules. Recent advances include electrospun lignin nanolattices that thermally aromatize *in situ* to increase the single-electrode TENG output by 40% and an imine-cross-linked chitosan hydrogel with dynamic Schiff-base bonds to recover mechanical and electrical properties over more than 1,000 cut-and-heal cycles. Such abilities suggest a novel paradigm whereby triboelectric skins could be eco-benign, self-powered, and possibly living, self-adaptive interfaces that evolve with the epidermis they monitor.

The next frontier, therefore, will be governed by convergence rather than replacement. Three goals appear particularly urgent.

Bio-nano architectonics: Coupling biomass with two-dimensional piezoelectric/ferroelectric/dielectric flakes and ion-conducting biomass hydrogels to create multiscale, charge-amplifying pathways that break the present limit.

Closed-loop circularity: Integrating photonic debonding chemistries and enzymatic depolymerization triggers so that each sensor can be disassembled into feedstocks on demand for the next production cycle, fulfilling the promises of a circular bioeconomy for wearable electronics.

Data-centric co-design: Harnessing generative artificial intelligence (AI) to mine the vast chemical space of polysaccharides and lignin-phenols, simultaneously optimizing molecular dipole strength, mechanical modulus, and skin microbiome compatibility within the human-device ecosystem.

Realizing these ambitions will demand collaborations that transcend traditional silos, pairing green chemists with device engineers, materials scientists with medical doctors, and policy scholars with supply-chain innovators. If we succeed, biomass-derived triboelectric skins could become the archetype of circular bioelectronics: devices that power themselves, safeguard the body, and ultimately regenerate the resources from which they are built. Such a trajectory addresses the imperative for sustainability and redefines what it means for advanced materials to be in harmony with human conditions.

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Nanogenerators for smart healthcare sensors integrated with an AI system

Accurate, real-time monitoring of multidimensional human health parameters is critical for early disease diagnosis and intervention. Self-powered wearable healthcare sensors represent a promising solution to meet the harsh requirements, including high accuracy, biocompatibility, portability, and lightweight design. Innovative approaches to wearable healthcare, such as pyroelectric, piezoelectric, and triboelectric technologies, have been successfully developed. Pyroelectric self-powered sensors are mainly sensitive to the variable temperature, whereas the piezoelectric sensor has a small-output electrical signal and needs to be detected from environmental interference noise by a complex modulator circuit (https://doi.org/10.1016/j.nanoen.2019.104228), which limits the extensive applications. The TENG coupling effect of contact electrification and electrostatic induction, has significant advantages such as high performance, biocompatibility, and easy fabrication with extensive soft materials, which is suitable for self-powered wearable healthcare sensors.

Beyond advanced sensing technologies, effective human health monitoring also relies on AI algorithms and signal processing systems to extract multiple physiological parameters for comprehensive analysis, disease classification, and diagnostic support. For example, some intelligent algorithms enable us to acquire multiphysiological indexes including breathing frequency, apnea hypopnea index, vital capacity, and peak expiratory flow from human respiratory signal (https://doi.org/10.1016/j.nanoen.2019.104228). This capability facilitates continuous monitoring and auxiliary diagnosis of conditions like sleep apnea, rhinitis, and chronic lung diseases, as well as post-COVID-19 rehabilitation. Furthermore, developing smart self-powered healthcare sensors integrated with AI algorithm system enables real-time transmission of daily physiological data to hospitals, establishing personalized health databases for precise diagnostics and tailored treatment.

DECLARATION OF INTERESTS

The authors declare no competing interests.