Triboelectric Generators and Sensors for Self-Powered Wearable Electronics

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ABSTRACT In recent years, the field of wearable electronics has evolved at a rapid pace, requiring continued innovation in technologies in the fields of electronics, energy devices, and sensors. In particular, wearable devices have multiple applications in healthcare monitoring, identification, and wireless communications, and they are required to perform well while being lightweight and having small size, flexibility, low power consumption, and reliable sensing performances. In this Perspective, we introduce two recent reports on the triboelectric generators with high-power generation achieved using flexible and lightweight textiles or miniaturized and hybridized device configurations. In addition, we present a brief overview of recent developments and future prospects of triboelectric energy harvesters and sensors, which may enable fully self-powered wearable devices with significantly improved sensing capabilities.

The "Internet of Things" (IoT) is a topic that has been discussed frequently in recent years and involves interface systems between human motion and biosignals with machines in our environment in order to realize convenient and healthy lives. Wearable devices are the heart of IoT technologies. With the growing interest in and development of wearable electronics, the fields of power sources and sensors in flexible, lightweight, and miniaturized forms have grown extensively over the past two decades. Accordingly, flexible batteries and supercapacitors have attracted much attention, and there has been significant progress in achieving flexibility with a variety of materials and device structures.[1] However, one of the critical challenges regarding the use of flexible energy-storage devices for applications in wearable and remote monitoring devices is the improvement of energy and power densities, which limit the lifetimes of energy sources and result in a need for periodic replacement (especially for implantable and remote devices) of energy sources. As promising alternatives to nonrenewable energy sources, sustainable energy-harvesting technologies utilizing renewable solar, thermal, and mechanical energy resources have attracted a great deal of attention in wearable device applications. In particular, ambient kinetic or mechanical energy, which is ubiquitous in the environment and our own bodies, has been harnessed *via* electromagnetic, electrostatic, and piezoelectric devices,[2] providing viable options for the sustainable powering of wearable devices.

Recently, flexible triboelectric generators (TEGs) have been introduced as an alternative method for harvesting electrical energy from the ambient mechanical energy in our surroundings.[3] The triboelectric effect, or triboelectric charging, is a well-known phenomenon that refers to the charge generation on the surface of certain materials when they are brought into frictional contact with different materials. We often encounter this phenomenon in our daily life when we perform simple actions such as walking on a carpet or combing our hair. Fan *et al.* employed this phenomenon to convert mechanical motion into the generation of surface charges and combined them with an electrostatic induction phenomenon to drive a flow of electric current through the external circuit, rendering the conversion of mechanical energy into a usable electrical energy. After the introduction of flexible TEGs in 2012, there have been various attempts to harness mechanical energy effectively from ambient vibrations,[4] human motion,[5] and muscle movement.[6]

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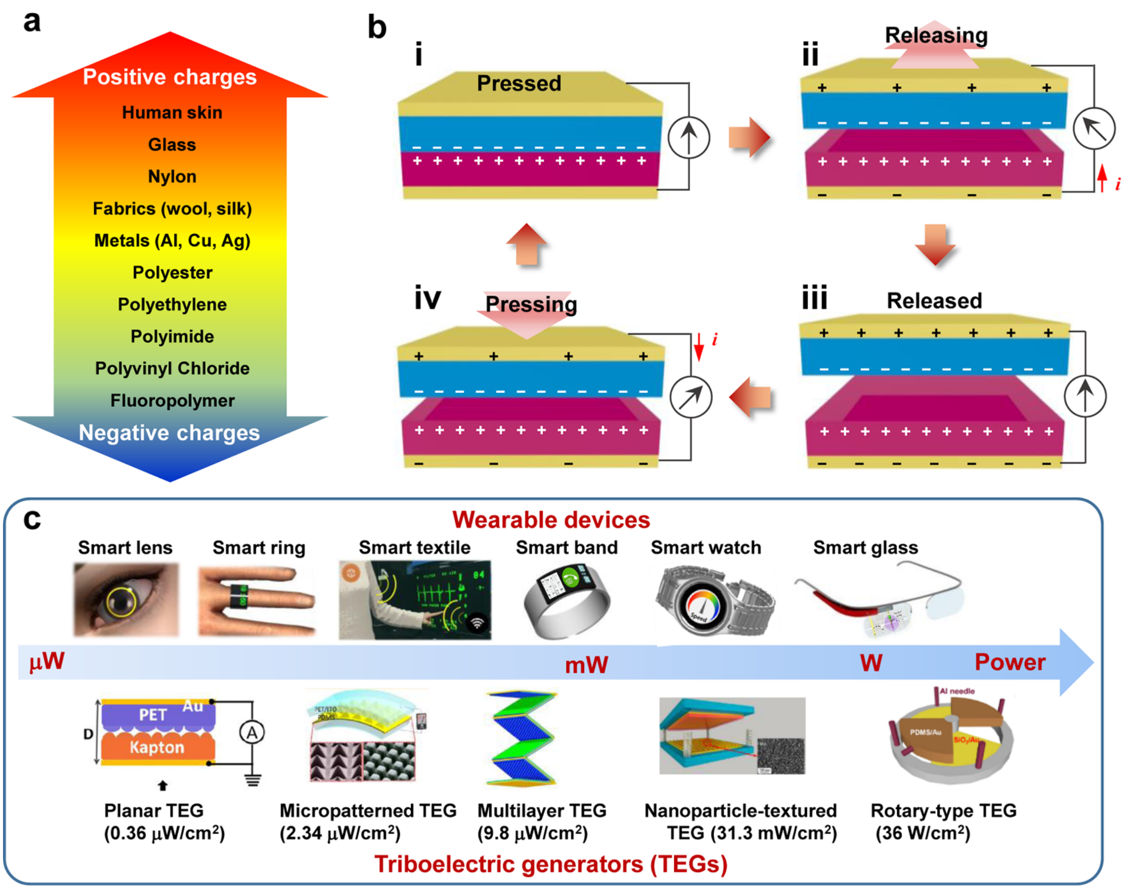

Figure 1. (a) Triboelectric series from positive to negative tendency for common materials. (b) Schematic of operating mechanism for triboelectric generators (TEGs) in a short-circuit system. (c) Power consumption spectrum for commercialized wearable devices (top); increasing power from left to right. The representative TEGs are displayed according to their output power density (bottom). Images reproduced with permission from the following sources: "Planar TEG" from ref 3, copyright 2012 Elsevier; "Micropatterned TEG" from ref 10, copyright 2012 American Chemical Society; "Multilayer TEG" from ref 19, copyright 2013 American Chemical Society; "Nanoparticle-textured TEG" from ref 11, copyright 2013 American Chemical Society; "Rotary-type TEG" from ref 12, copyright 2013 American Chemical Society.

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Although the exact mechanism of contact electrification is still under dispute, the triboelectric charges are believed to be due to the charge (electrons, ions, or both) transfer when two materials come into contact and separate.[7,8] A triboelectric series (Figure 1a) refers to an empirically determined list of materials' tendencies to acquire positive or negative charges on the surface when they go through contact electrifications.[9] The working mechanism of TEGs is based on the triboelectric charging on the surface and the subsequent electrostatic induction of current flows (Figure 1b). When two materials with different triboelectric polarities are brought into contact with each other (inset i in Figure 1b), the triboelectric effects promote charge transfer between the two surfaces, resulting in the formation of opposite charges on each side of the surface. When the two surfaces are separated (inset ii in Figure 1a), compensating charges are built up on the top and bottom electrodes due to electrostatic induction. This induction promotes current flow from the positive to the negative sides of the materials through the external circuit until the accumulated charges are neutralized and balanced on all sides of the electrodes (inset iii in Figure 1a). Similarly, as the two different charged materials are brought closer to each other, the current flows from the negative to positive sides of the materials (inset iv in Figure 1a). Consequently, the cyclic contact and separation between the two materials drive the output current flow back and forth between the positive and negative electrodes.

There has been significant research progress in the development

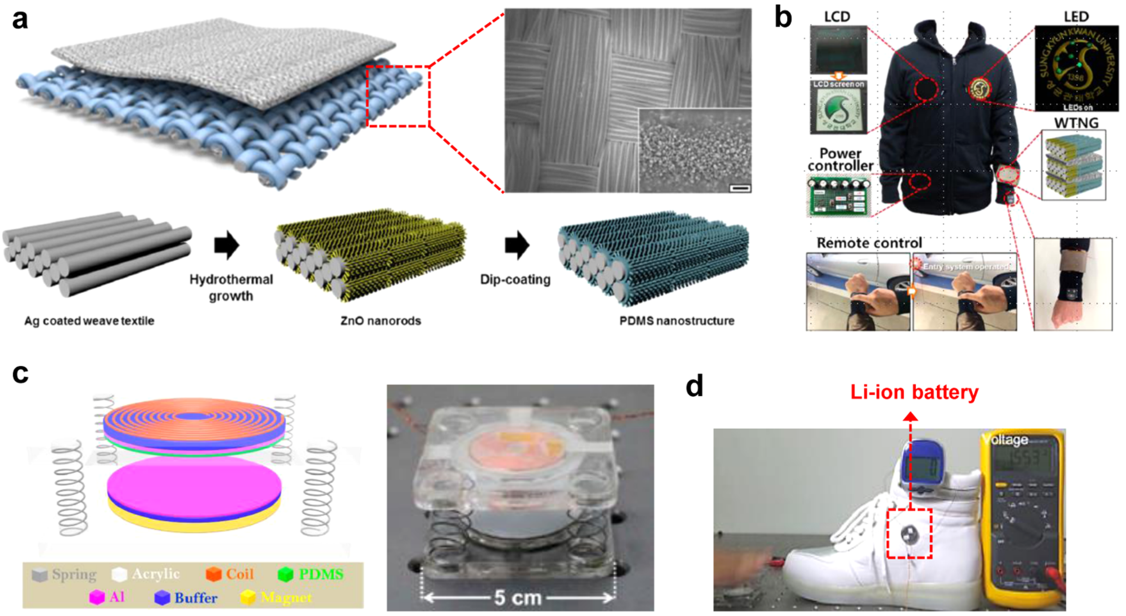

Figure 2. (a) Schematic for nanopatterned textile-based wearable triboelectric nanogenerators (WTNGs). (b) Smart suit including commercialized liquid-crystal display, light-emitting diode, and remote control using self-powered WTNGs. (c) Schematic of hybridized electromagnetic–triboelectric nanogenerator (EMG-TENG) with a photograph of the fabricated device. (d) Photograph and voltage value of charged Li-ion battery obtained by external pressing to a hybridized nanogenerator. Images reproduced from ref 14 (a,b) and ref 15 (c,d). Copyright 2015 American Chemical Society.

of flexible triboelectric energy harvesters by the controlled design of the surface micro/nanostructures of materials and device structures (Figure 1c). Compared to smooth surfaces, the use of micropatterned polymer surfaces in flexible triboelectric nanogenerators has resulted in achieving an output power density of ~2.34 μW/cm^2 (deduced from an output voltage of 18 V at a current density of 0.13 μA/cm^2),[10] which is about seven times higher than the energy density of TEGs that are based on planar plastic films (~0.36 μW/cm^2).[3] The substantial increase of the power densities of TEGs was achieved *via* surface modification with gold nanoparticles, where an increase in the surface roughness and contact area in TEGs produced a high-power density (~31.3 mW/cm^2) that was harvested from human footfalls, where the power is capable of illuminating up to 600 light-emitting diode (LED) bulbs.[11] Until now, the highest power density was achieved using rotary or disk-type TEGs with a power density of ~36 W/cm^2, which is enough to operate most wearable devices (Figure 1c).[12] One limitation of these rotary-type TEGs is the requirement for a separate input power source for motor operation, which is not suitable for portable and skin-attachable wearable electronics. The combination of nanoparticle-enhanced surface areas and the sliding electrification of flexible TEGs showed a power density of 50 mW/cm^2, which is sufficient for self-powered systems in wearable and implantable electronics.[13]

In this issue of *ACS Nano*, two separate papers report TEGs that overcome previous challenges by having features such as reduced size and weight, flexibility, high mechanical durability, and large output power based on the novel design of their harvester devices. Seung *et al.* proposed a flexible and foldable textile that can harness human motion into electricity, demonstrating a self-powered smart cloth.[14] The energy-harvesting textile utilizes the principle of TEGs, where the mechanical contact and separation of two sheets of materials with different triboelectric polarities generate electrical current flow through an external circuit. While there have been various types of TEG devices in flexible platforms, there have only been a few reports of textile-based TEGs with high-power-generating capabilities and mechanical durability. To increase the contact area, and thus the power generation, they employed ZnO nanorod arrays on the Ag-coated textile to fabricate nanopatterned polydimethylsiloxane (PDMS) textures. Consequently, textile-type TEGs are composed of a nanopatterned PDMS textile on one side and a silver-coated textile on the other side (Figure 2a). Textile-type TEGs achieve a high output power (~1.1 mW), which is sufficient to turn on six LEDs and liquid-crystal displays (LCDs). In addition, they exhibit no significant decrease in output voltage for over 12 000 cycles, confirming their high mechanical stability. One of the advantages of the thin and flexible geometry of textile TEGs is the possibility of realizing multilayer stacking to enhance power generation. Consequently, multilayer-stacked textile TEGs can be attached to a cloth to provide power for various electrical devices (*e.g.*, LEDs, LCD, and remote controls) that are embedded in the suit, realizing a self-powered smart suit (Figure 2b). Furthermore, textile-type TEGs can also charge batteries and supercapacitors without the need for an external power source, demonstrating their potential in applications such as self-powered wearable devices, smart healthcare monitoring, and personal electronics.

Although human motion can provide various types of mechanical energy sources for power generation using energy-harvesting devices, in many cases, the human motion is gentle and provides a low frequency and amplitude of mechanical motion. Therefore, the power that is harvested from human motion is sometimes insufficient for the operation of high-power wearable devices. Zhang *et al.* demonstrated a hybridized energy-harvesting device that combines electromagnetic induction and triboelectrification principles to acquire high output power from the motion of human walking (Figure 2c,d).[15] The hybridized generators have synergistic effects. The TEG has a large output impedance and can therefore produce a high output voltage but low current. On the other hand, an electromagnetic induction generator with a small output impedance produces high current but low voltage. Therefore, these complementary current and voltage generation methods can lead to large power generation when they are combined with proper impedance-matching bridge circuits. With electromagnetic induction, the current flow can be induced by the change of magnetic flux between the magnet and coil, which is caused by the variable separation (Figure 2c). During the continuous variation in the separation distance between the top and bottom surfaces, TEGs also generate electricity from the same mechanical motion. Therefore, during the mechanical press and release cycles, the triboelectric and electromagnetic generators showed high output power densities of 5.1 and 3.6 W/m^2, respectively. Moreover, the hybridized generator can be utilized to charge a Li-ion battery (Figure 2d). To demonstrate the proof-of-concept, they embedded the hybridized generator in a commercial shoe to harvest energy from human walking in order to power on-shoe LEDs and a wireless pedometer. Because the hybridized generators are designed to have a small volume (5 cm × 5 cm × 2.5 cm) and be lightweight (60 g), they can find multiple applications in self-powered and wearable devices.

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OUTLOOK AND FUTURE CHALLENGES

Wearable Triboelectric Generators. A potential energy source for wearable electronics is obtained from the various movements of the human body that occur during daily activities such as walking with a swinging arm, joint movements at the knee, wrist, and elbow, and cardiac and lung contraction and relaxation. To harvest energy efficiently from these motions, flexible, lightweight, and miniaturized designs of triboelectric generators are required. Various designs of TEGs have been reported to harvest energy from human motion: textile platforms on an arm sleeve produce an output power of ~110.6 μW/cm^2 from the human arm's bending motion,[16] fabric-type TEG from arm swings,[17] rhombic gridding structure on a self-powered backpack from walking,[18] and multilayer-stacked generators attached onto a shoe pad from walking.[19] For implantable medical device applications, biocompatible device packaging, flexibility, sensitivity of TEGs should be considered. Zheng *et al.* demonstrated an implantable TEG that harvests biomechanical energy from the breathing motions of a live rat, and this generated enough power (~0.7 μW/cm^2) to operate a pacemaker.[6]

Although TEGs utilizing biomechanical energy can provide enough power for low-power devices, most of the mechanical energy obtained from human motion is not sufficiently high to generate power for the operation of medium-power wearable devices. One of the methods employed to harvest biomechanical energy efficiently is to design a TEG that is hybridized with other types of energy-harvesting devices. As shown by Zhang *et al.*, the hybridization of TEGs and electromagnetic generators is one example of such a design. Recent examples of hybrid energy generators based on TEGs and solar cells,[20] triboelectric and piezoelectric generators,[21] and triboelectric/pyroelectric/piezoelectric generators[22] have shown great promise in enhancing the energy-harvesting efficiency. It is expected that hybridized energy harvesters should find many applications in future human healthcare monitoring, cardiac pacemakers, and implantable medical devices.

Several challenges for triboelectric nanogenerators toward wearable electronics still exist: TEGs are sensitive to humidity, vulnerable to mechanical damage by friction, have low harvested power, and they generate AC currents. Because triboelectric energy is an AC signal, it cannot be used directly to power

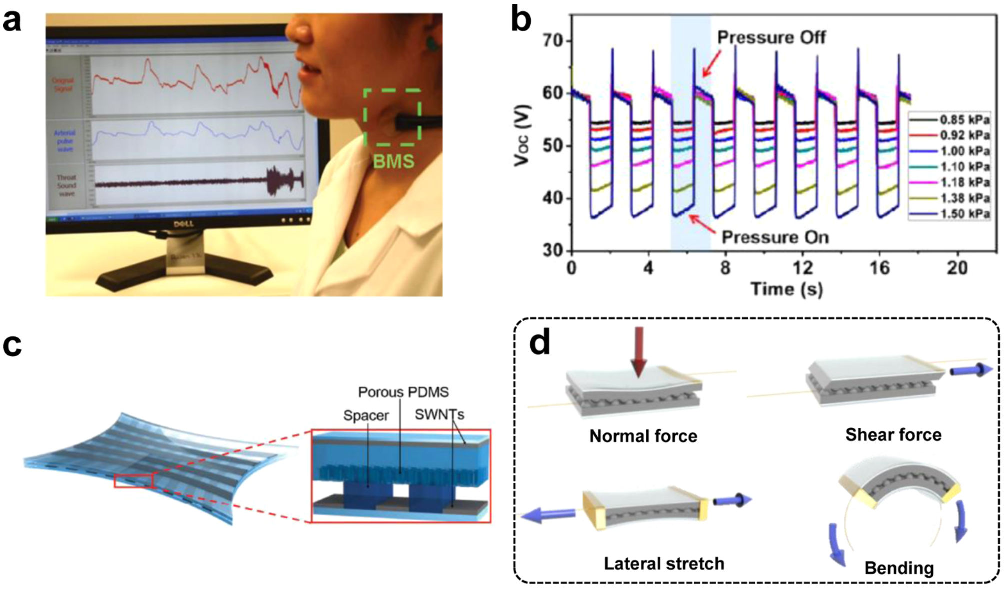

Figure 3. (a) Triboelectric e-skins for the detection of voice vibrations. Reproduced with permission from ref 29. Copyright 2015 Wiley. (b) Open-circuit voltage change of triboelectric e-skins in response to static pressure. Reproduced from ref 26. Copyright 2013 American Chemical Society. (c) Stretchable capacitive e-skins. Reproduced with permission from ref 34. Copyright 2014 Wiley. (d) Piezoresistive e-skins with stretchable and multidirectional tactile sensing capabilities. Reproduced from ref 35. Copyright 2014 American Chemical Society.

other devices and sensors included in the wearable electronic system. In addition, triboelectric nanogenerators produce high output voltages at low currents with high output impedance. All of these constraints require additional energy management circuits composed of rectifiers, converters, and energy-storage devices. The development of flexible and/or stretchable energy-storage devices has attracted great attention, which should lead to widespread applications in wearable electronics. In the future, all of these electronic components should be integrated into wearable electronic systems, which require the design and development of flexible, lightweight, and miniaturized circuit systems.

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Triboelectric Skin Sensors. Electronic skin (e-skin) is a flexible and wearable skin-like sensor that can detect mechanical and thermal stimuli. The integration of power sources for the operation of e-skin is one critical challenge that needs to be overcome to enable the widespread use of e-skin in robotics and wearable healthcare monitoring. Accordingly, self-powered e-skin, which does not require an external power source, has attracted significant attention as an option for wearable skin sensors. In addition to its energy-harvesting capability, triboelectric e-skin can perceive the presence of external mechanical stimuli by converting mechanical forces (*e.g.*, pressure and strain) or environmental changes (*e.g.*, vibration and flow) into electrical outputs, and this aspect has attracted much attention in the development of wearable sensors and human–machine interfacing technologies.[10,23–25] The simple device structures, high sensitivity, and fast response times of triboelectric e-skins have enabled a wide variety of applications in the detection of dynamic and static pressures,[26] tracking of moving objects,[27,28] and vibration sensing (Figure 3a).[29,30]

Although triboelectric e-skin can exhibit outstanding tactile-sensing properties without the need for additional power consumption and structural complexity, a few challenges remain for its use in wearable e-skins. First, the triboelectric signals are sensitive to humidity variations. One of the ways to resolve the humidity issue is with the design of a hydrophobic surface. Lee *et al.* demonstrated triboelectric generators with hydrophobic sponge structures based on polydimethylsiloxane for stable output performance under variable humidity conditions.[31] However, the design and fabrication of hydrophobic surfaces remain difficult for different combinations of materials in a triboelectric series. Further development of packaging and structural design will be required for the stable operation of various triboelectric e-skins under humid conditions. Second, the transient signals in triboelectric e-skins are not suitable for static pressure sensing under persistent pressure loading. While the open-circuit voltage can be employed for the detection of static pressure (Figure 3b),[26] the continued voltage variation over time limits the accurate monitoring of static pressure applied for a prolonged time. Finally, stretchable and multifunctional e-skins are not achievable with the present designs of triboelectric e-skins. The spatiotemporal perception of various tactile forces with different magnitude, direction, and location is critical for precise human and robotic hand manipulation.[32,33] Recently, capacitive (Figure 3c)[34] and piezoresistive (Figure 3d)[35] electronic skins have demonstrated stretchable and multifunctional sensing capabilities. Unlike the aforementioned e-skins that are driven by transient charge formation/dissipation, piezoresistive e-skins provide stable and exact signal output that is sensitive to the direction and magnitude of applied stress in real time.[35] Therefore, rational design of hybrid integration of triboelectric e-skins with other type of e-skins needs to be done for the diverse applications the self-powered e-skins.

Conflict of Interest: The authors declare no competing financial interest.

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REFERENCES AND NOTES

1. Wang, X.; Lu, X.; Liu, B.; Chen, D.; Tong, Y.; Shen, G. Flexible Energy-Storage Devices: Design Consideration and Recent Progress. *Adv. Mater.* **2014**, *26*, 4763–4782.
2. Mitcheson, P. D.; Yeatman, E. M.; Rao, G. K.; Holmes, A. S.; Green, T. C. Energy Harvesting from Human and Machine Motion for Wireless Electronic Devices. *Proc. IEEE* **2008**, *96*, 1457–1486.
3. Fan, F. R.; Tian, Z. Q.; Wang, Z. L. Flexible Triboelectric Generator!. *Nano Energy* **2012**, *1*, 328–334.
4. Wang, S. H.; Niu, S. M.; Yang, J.; Lin, L.; Wang, Z. L. Quantitative Measurements of Vibration Amplitude Using a Contact-Mode Freestanding Triboelectric Nanogenerator. *ACS Nano* **2014**, *8*, 12004–12013.
5. Wang, S. H.; Xie, Y. N.; Niu, S. M.; Lin, L.; Wang, Z. L. Freestanding Triboelectric-Layer-Based Nanogenerators for Harvesting Energy from a Moving Object or Human Motion in Contact and Non-contact Modes. *Adv. Mater.* **2014**, *26*, 2818–2824.
6. Zheng, Q.; Shi, B.; Fan, F.; Wang, X.; Yan, L.; Yuan, W.; Wang, S.; Liu, H.; Li, Z.; Wang, Z. L. *In Vivo* Powering of Pacemaker by Breathing-Driven Implanted Triboelectric Nanogenerator. *Adv. Mater.* **2014**, *26*, 5851–5856.
7. Galembeck, F.; Burgo, T. A. L.; Balestrin, L. B. S.; Gouveia, R. F.; Silva, C. A.; Galembeck, A. Friction, Tribochemistry and Triboelectricity: Recent Progress and Perspectives. *RSC Adv.* **2014**, *4*, 64280–64298.
8. McCarty, L. S.; Whitesides, G. M. Electrostatic Charging Due to Separation of Ions at Interfaces: Contact Electrification of Ionic Electrets. *Angew. Chem., Int. Ed.* **2008**, *47*, 2188–2207.
9. Heilbron, J. L. *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics*; University of California Press: Berkeley, CA, 1979; pp 1–260.
10. Fan, F.-R.; Lin, L.; Zhu, G.; Wu, W.; Zhang, R.; Wang, Z. L. Transparent Triboelectric Nanogenerators and Self-Powered Pressure Sensors Based on Micropatterned Plastic Films. *Nano Lett.* **2012**, *12*, 3109–3114.
11. Zhu, G.; Lin, Z.-H.; Jing, Q.; Bai, P.; Pan, C.; Yang, Y.; Zhou, Y.; Wang, Z. L. Toward Large-Scale Energy Harvesting by a Nanoparticle-Enhanced Triboelectric Nanogenerator. *Nano Lett.* **2013**, *13*, 847–853.
12. Cheng, G.; Lin, Z.-H.; Lin, L.; Du, Z.-l.; Wang, Z. L. Pulsed Nanogenerator with Huge Instantaneous Output Power Density. *ACS Nano* **2013**, *7*, 7383–7391.
13. Zhu, G.; Zhou, Y. S.; Bai, P.; Meng, X. S.; Jing, Q.; Chen, J.; Wang, Z. L. A Shape-Adaptive Thin-Film-Based Approach for 50% High-Efficiency Energy Generation through Micro-grating Sliding Electrification. *Adv. Mater.* **2014**, *26*, 3788–3796.
14. Seung, W.; Gupta, M. K.; Lee, K. Y.; Shin, K.-S.; Lee, J.-H.; Kim, T. Y.; Kim, S.; Lin, J.; Kim, J. H.; Kim, S.-W. Nanopatterned Textile-Based Wearable Triboelectric Nanogenerator. *ACS Nano* **2015**, 10.1021/nn507221f.
15. Zhang, K.; Wang, X.; Yang, Y.; Wang, Z. L. Hybridized Electromagnetic–Triboelectric Nanogenerator for Scavenging Biomechanical Energy for Sustainably Powering Wearable Electronics. *ACS Nano* **2015**, 10.1021/nn507455f.
16. Lee, S.; Ko, W.; Oh, Y.; Lee, J.; Baek, G.; Lee, Y.; Sohn, J.; Cha, S.; Kim, J.; Park, J. Triboelectric Energy Harvester Based on Wearable Textile Platforms Employing Various Surface Morphologies. *Nano Energy* **2015**, *12*, 410–418.
17. Jung, S.; Lee, J.; Hyeon, T.; Lee, M.; Kim, D. H. Fabric-Based Integrated Energy Devices for Wearable Activity Monitors. *Adv. Mater.* **2014**, *26*, 6329–6334.
18. Yang, W. Q.; Chen, J.; Zhu, G.; Yang, J.; Bai, P.; Su, Y. J.; Jing, Q. S.; Cao, X.; Wang, Z. L. Harvesting Energy from the Natural Vibration of Human Walking. *ACS Nano* **2013**, *7*, 11317–11324.
19. Bai, P.; Zhu, G.; Lin, Z. H.; Jing, Q. S.; Chen, J.; Zhang, G.; Ma, J.; Wang, Z. L. Integrated Multilayered Triboelectric Nanogenerator for Harvesting Biomechanical Energy from Human Motions. *ACS Nano* **2013**, *7*, 3713–3719.
20. Yang, Y.; Zhang, H. L.; Liu, Y.; Lin, Z. H.; Lee, S.; Lin, Z. Y.; Wong, C. P.; Wang, Z. L. Silicon-Based Hybrid Energy Cell for Self-Powered Electrodegradation and Personal Electronics. *ACS Nano* **2013**, *7*, 2808–2813.
21. Han, M. D.; Zhang, X. S.; Meng, B.; Liu, W.; Tang, W.; Sun, X. M.; Wang, W.; Zhang, H. X. r-Shaped Hybrid Nanogenerator with Enhanced Piezoelectricity. *ACS Nano* **2013**, *7*, 8554–8560.
22. Zi, Y.; Lin, L.; Wang, J.; Wang, S.; Chen, J.; Fan, X.; Yang, P. K.; Yi, F.; Wang, Z. L. Triboelectric–Pyroelectric–Piezoelectric Hybrid Cell for High-Efficiency Energy-Harvesting and Self-Powered Sensing. *Adv. Mater.* **2015**, 10.1002/adma.201500121.
23. Yang, Y.; Zhang, H.; Lin, Z.-H.; Zhou, Y. S.; Jing, Q.; Su, Y.; Yang, J.; Chen, J.; Hu, C.; Wang, Z. L. Human Skin Based Triboelectric Nanogenerators for Harvesting Biomechanical Energy and as Self-Powered Active Tactile Sensor System. *ACS Nano* **2013**, *7*, 9213–9222.
24. Zhu, G.; Yang, W. Q.; Zhang, T.; Jing, Q.; Chen, J.; Zhou, Y. S.; Bai, P.; Wang, Z. L. Self-Powered, Ultrasensitive, Flexible Tactile Sensors Based on Contact Electrification. *Nano Lett.* **2014**, *14*, 3208–3213.
25. Chen, J.; Zhu, G.; Yang, J.; Jing, Q.; Bai, P.; Yang, W.; Qi, X.; Su, Y.; Wang, Z. L. Personalized Keystroke Dynamics for Self-Powered Human–Machine Interfacing. *ACS Nano* **2015**, *9*, 105–116.
26. Lin, L.; Xie, Y.; Wang, S.; Wu, W.; Niu, S.; Wen, X.; Wang, Z. L. Triboelectric Active Sensor Array for Self-Powered Static and Dynamic Pressure Detection and Tactile Imaging. *ACS Nano* **2013**, *7*, 8266–8274.
27. Yi, F.; Lin, L.; Niu, S.; Yang, J.; Wu, W.; Wang, S.; Liao, Q.; Zhang, Y.; Wang, Z. L. Self-Powered Trajectory, Velocity, and Acceleration Tracking of a Moving Object/Body Using a Triboelectric Sensor. *Adv. Funct. Mater.* **2014**, *24*, 7488–7494.
28. Su, Y.; Zhu, G.; Yang, W.; Yang, J.; Chen, J.; Jing, Q.; Wu, Z.; Jiang, Y.; Wang, Z. L. Triboelectric Sensor for Self-Powered Tracking of Object

Motion inside Tubing. *ACS Nano* **2014**, *8*, 3843–3850.

29. Yang, J.; Chen, J.; Su, Y.; Jing, Q.; Li, Z.; Yi, F.; Wen, X.; Wang, Z.; Wang, Z. L. Eardrum-Inspired Active Sensors for Self-Powered Cardiovascular System Characterization and Throat-Attached Anti-interference Voice Recognition. *Adv. Mater.* **2015**, *27*, 1316–1326.
30. Chen, J.; Zhu, G.; Yang, W.; Jing, Q.; Bai, P.; Yang, Y.; Hou, T. C.; Wang, Z. L. Harmonic-Resonator-Based Triboelectric Nanogenerator as a Sustainable Power Source and a Self-Powered Active Vibration Sensor. *Adv. Mater.* **2013**, *25*, 6094–6099.
31. Lee, K. Y.; Chun, J.; Lee, J. H.; Kim, K. N.; Kang, N. R.; Kim, J. Y.; Kim, M. H.; Shin, K. S.; Gupta, M. K.; Baik, J. M. Hydrophobic Sponge Structure-Based Triboelectric Nanogenerator. *Adv. Mater.* **2014**, *26*, 5037–5042.
32. Birznieks, I.; Jenmalm, P.; Goodwin, A. W.; Johansson, R. S. Encoding of Direction of Fingertip Forces by Human Tactile Afferents. *J. Neurosci.* **2001**, *21*, 8222–8237.
33. Lee, H.-K.; Chung, J.; Chang, S.-I.; Yoon, E. Real-Time Measurement of the Three-Axis Contact Force Distribution Using a Flexible Capacitive Polymer Tactile Sensor. *J. Micromech. Microeng.* **2011**, *21*, 035010–035019.
34. Park, S.; Kim, H.; Vosgueritchian, M.; Cheon, S.; Kim, H.; Koo, J. H.; Kim, T. R.; Lee, S.; Schwartz, G.; Chang, H. Stretchable Energy-Harvesting Tactile Electronic Skin Capable of Differentiating Multiple Mechanical Stimuli Modes. *Adv. Mater.* **2014**, *26*, 7324–7332.
35. Park, J.; Lee, Y.; Hong, J.; Lee, Y.; Ha, M.; Jung, Y.; Lim, H.; Kim, S. Y.; Ko, H. Tactile-Direction-Sensitive and Stretchable Electronic Skins Based on Human-Skin-Inspired Interlocked Microstructures. *ACS Nano* **2014**, *8*, 12020–12029.