



Article

Ultrathin Stretchable All-Fiber Electronic Skin for Highly Sensitive Self-Powered Human Motion Monitoring

Yapeng Shi ^{1,2}, Tianyi Ding ³, Zhihao Yuan ¹, Ruonan Li ¹, Baocheng Wang ^{1,2} and Zhiyi Wu ^{1,2,4,*}

¹ Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China; shiyapeng@binn.cas.cn (Y.S.); 1907301106@st.gxu.edu.cn (Z.Y.); 1504280108@st.gxu.edu.cn (R.L.); wangbaocheng@binn.cas.cn (B.W.)

² School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

³ State Key Laboratory of Physical Chemistry of Solid Surfaces, iChEM, College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China; tyding@stu.xmu.edu.cn

⁴ CUSTech Institute of Technology, Wenzhou 325024, China

* Correspondence: wuzhiyi@binn.cas.cn

Abstract: Advances in the technology of wearable electronic devices have necessitated much research to meet their requirements, such as stretchability, sustainability, and maintenance-free functioning. In this study, we developed an ultrathin all-fiber triboelectric nanogenerator (TENG)-based electronic skin (TE-skin) with high stretchability, using electrospinning and spraying, whereby the silver nanowire (Ag NW) electrode layer is deposited between two electrospinning thermoplastic polyurethane (TPU) fibrous layers. Due to its extraordinary stretchability and prominent Ag NW conductive networks, the TE-skin exhibits a high sensitivity of 0.1539 kPa^{-1} in terms of pressure, superior mechanical property with a low-resistance electrode of 257.3Ω at a strain of 150%, great deformation recovery ability, and exceptional working stability with no obvious fluctuation in electrical output before and after stretching. Based on the outstanding performances of the TE-skin, an intelligent electronic glove was fabricated to detect multifarious hand gestures. Moreover, the TE-skin has the potential to record human motion for real-time physiological signal monitoring, which provides promising applications in the fields of flexible robots, human-machine interaction, and multidimensional sports monitoring in next-generation electronics.

Keywords: stretchable electronic skin; triboelectric nanogenerator; self-powered sensing; human motion monitoring; thermoplastic polyurethane fibers



Citation: Shi, Y.; Ding, T.; Yuan, Z.; Li, R.; Wang, B.; Wu, Z. Ultrathin Stretchable All-Fiber Electronic Skin for Highly Sensitive Self-Powered Human Motion Monitoring. *Nanoenergy Adv.* **2022**, *2*, 52–63. <https://doi.org/10.3390/nanoenergyadv2010003>

Academic Editors: Yogendra Kumar Mishra, Ya Yang and Zhong Lin Wang

Received: 29 November 2021

Accepted: 28 January 2022

Published: 30 January 2022

Corrected: 13 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the current rapid progress in the fields of the Internet of Things [1] and artificial intelligence [2,3], various kinds of wearable and portable electronics have recently attracted intensive research, with different potential applications in human healthcare monitoring [4–6], smart robots [7,8], human motion sensing [9,10] and human–machine interaction [11–13], etc. Pang et al. [14] realized the real-time monitoring of wound temperature by an integrated sensor to release antibiotics from a hydrogel, with on-demand infection treatment by in situ UV irradiation. Li et al. [15] developed a closed-loop system that is fully integrated with a microneedle platform and wearable electronics, which could concurrently monitor and treat diabetes in situ. These devices were generally powered by a sustainable and reliable power supply; however, this power comes from sources such as batteries with the disadvantages of a limited lifespan, high recharging costs and increasingly serious environmental problems. Meanwhile, a great number of wearable electronic devices without integrating batteries have been reported in the same period. Liu et al. [16] proposed a simple and low-cost method to fabricate skin-like electronics, using a material composed of ternary piezoelectric rubber composite, including polydimethylsiloxane

(PDMS), graphene, and lead zirconate titanate (PZT). Due to the customized device geometries and the optimized integration of rubbery electronics with the human body, the developed device could be successfully mounted on human joints to realize excellent output and working stability during a sequence of large deformations, demonstrating the application of skin-integrated electronics for energy harvesting and mechanical sensing. Kim et al. [17] introduced a novel skin-like sensor that could detect the minute signals from small skin deformations through unique laser-induced crack structures. By integrating with a deep neural network, a deep-learned skin-like sensor system was developed to obtain data from different areas of the wrist; the system was also applied to the pelvis to generate dynamic gait motions in real-time, realizing the measurement of human motion remotely. Although battery-free electronic devices have shown great progress in a variety of cutting-edge applications, such as advanced human-machine interfaces for clinical diagnostics [18] and evolvable skin electronics with active accommodation for human physiological measurements and skin condition tracking [19], it is still urgently necessary and highly desirable to develop sustainable, environmentally friendly, and maintenance-free sensing technology.

In recent years, electronic skin, as a significant form of multifunctional wearable electronics, has dramatically facilitated modern life. Among different electromechanical sensing principles, such as capacitance [20,21], piezoresistivity [22,23], piezoelectricity [24,25], and triboelectricity [26,27], triboelectric nanogenerator (TENG)-based electronic skins (TE-skins) as automatic sensors offer various advantages, including pollution-free manufacturing technology, low cost, and diverse material selection. Based on contact electrification and the electrostatic induction coupling effect, TE-skins have been widely applied as self-powered sensors to realize real-time tactile sensing [27,28], sports sensing [29], respiratory sensing [30,31], motion monitoring [32,33], etc. Generally, the developed TE-skins need to be elastic and flexible so that they could be attached to human skin and adapt to all sorts of deformations. Recently, a variety of stretchable TENGs were fabricated, based on thermoplastic polyurethane (TPU), demonstrating great potential for energy harvesting and self-powered sensing [27–29,34]. Unfortunately, it is still a challenge to construct such devices with high stretchability. Jeong et al. [35] prepared a hyper-stretchable and elastic-composite generator (SEG) with extraordinary output performance, strain capacity, and mechanical stability; this is composed of rubber-based piezoelectric elastic composite (PEC) and very long nanowire percolation (VLNP) electrodes. Yu et al. [36] proposed a triboelectric–piezoelectric hybrid nanogenerator (TPHNG) using piezoelectric-polyvinylidene fluoride (PVDF), polydimethylsiloxane (PDMS), and a network of welded silver nanowires (AgNWs), achieving mechanical energy harvesting and physiological signal monitoring. Although a series of stretchable energy devices have been developed [37], the multidimensional conductive networks in these devices can easily be damaged in the stretching process. Therefore, it is crucial to effectively reinforce the adhesion of the conductive networks on the substrate.

Considering the above-mentioned issues, a highly stretchable TENG-based all-fiber electronic skin was fabricated using the industrial manufacturing technologies of electrospinning and spraying. Initially, silver nanowire (Ag NW) is distributed on the surface of thermoplastic polyurethane (TPU) fibers, forming a layer-by-layer network structure by spraying. Subsequently, the Ag NW networks are tightly wrapped by double-layered TPU fibers, effectively enhancing the adhesion of the Ag NW conductive networks on the TPU substrate. The resulting TE-skin, with high stretchability, has excellent mechanical properties, with a low-resistance electrode of 257.3 Ω at a strain of 150%, and shows extraordinary deformation recovery ability, working stability and durability. Due to a sensitivity of 0.1539 kPa^{−1} in terms of pressure, an intelligent electronic glove was constructed to detect different kinds of gestures, including the “ok” sign, the “victory” sign, and the “good” sign. More specifically, the TE-skin was further applied as a wearable self-powered sensor in sports to achieve real-time motion monitoring of different parts of the human body. Consequently, the outstanding performance of the developed TE-skin, including substantial stretchability, light weight, large-scale production feasibility, and high sensitivity promises

future applications in human–machine interaction, multidimensional sports monitoring, and flexible robots.

2. Experimental Section

2.1. Electrospinning of TPU Fibers

First, N,N-dimethylformamide (DMF, $\geq 99.8\%$, ACS reagent) and tetrahydrofuran (THF, $\geq 99.5\%$, ACS reagent) were mixed at a volume ratio of 1:1. After stirring for 10 min, the TPU pellets (Shanghai BASF Polyurethane Specialties Co., Ltd., Shanghai, China) were added to the resulting solution at a concentration of 20 wt%, followed by continuous stirring for 12 h, until it is completely dissolved to form a homogeneous electrospinning solution. In the electrospinning process, the needle-collector distance and the electrospinning voltage of the electrospinning device (DP30, Tianjin Yunfan Technology Co., Ltd., Tianjin, China) were 10 cm and 9 kV, respectively. The manufactured TPU substrate was dried overnight in a vacuum environment at 50 °C for further use.

2.2. Fabrication of the TE-Skin

After electrospinning of TPU fibrous substrate, a spray gun (PS289, 0.3 mm, Mr. HOBBY, Shanghai Henghui Model Co., Ltd., Shanghai, China) connected with a portable air pump (601G, USTAR, Shanghai Henghui Model Co., Ltd., Shanghai, China) was used to implement the spraying of the Ag NW electrode. Specifically, the Ag NW solution (2 mg mL⁻¹) was spray-coated onto the TPU substrate under a discharge speed of 80 μ L/min, and the distance between the mouth of the spray gun and the TPU substrate was set as 10 cm. After the spraying of the Ag NW electrode, the TPU substrate, coated with Ag NW conductive networks, was wrapped by another TPU sensing layer that was fabricated by electrospinning under the same experimental conditions as the TPU substrate.

2.3. Characterization and Measurement

The micromorphologies of TPU fibers and Ag NW were observed using field emission scanning electron microscopy (ZEISS Gemini 300, Carl Zeiss optics (Guangzhou) Co., Ltd., Guangzhou, China) and a transmission electron microscope (JEM-2100plus, JEOL (BEIJING) Co., Ltd., Beijing, China), respectively. A tensile testing machine (ESM303, Shenzhen Chenyi Technology Co., Ltd., Shenzhen, China) was utilized to evaluate the mechanical properties of the TPU and the TE-skin. The hydrophobicity of the TPU film was characterized using a contact angle meter (XG-CAM, Shanghai Xuanyichuangxi Industrial Equipment Co., Ltd., Shanghai, China). The resistances of the stretchable conductive electrodes were measured by a flexible electronic tester (Prtronic FT2000, Shanghai Mifang Electronic Technology Co., Ltd., Shanghai, China). Through the periodic contact and separation movements provided by a commercial linear mechanical motor (Linmot E1100, Shenzhen Nuoxide Trading Co., Ltd., Shenzhen, China), the electrical signals of the TE-skin were acquired using a programmable electrometer (Keithley model 6514, Guangzhou Meidake Data Technology Co., Ltd., Guangzhou, China).

3. Results and Discussion

3.1. Fabrication and Structural Design of the TE-Skin

As illustrated in Figure 1a, the TE-skin was manufactured using electrospinning and spraying technique; details of the fabrication process are described in the Experimental Section. Considering that the properties of the triboelectric layer are crucial to the sensing capability of the TE-skin, a commercial TPU that is widely used for clothing fabric, with good wearability, biocompatibility, and nontoxicity was selected for the top encapsulation layer and the bottom sensing layer [38]. The TE-skin forms a skin contact interface and is composed of three functional layers, with a fiber network and three-dimensional layered porous structure in which the Ag NW layer (Figure 1c) is sandwiched between two TPU fiber layers (Figure 1b). After optimization of the construction parameters, it is worth mentioning that the thickness and the weight of the whole device are only 0.12 mm and

0.0415 g, respectively ($3 \times 3 \text{ cm}^2$, Figure 1d and Supplementary Figure S1), showing a relatively light and thin all-fiber structure that can cope with various kinds of complex mechanical deformations, such as stretching, twisting, and bending, indicating its excellent mechanical properties (Figure 1e). Due to the TE-skin's all-fiber structure with superior breathing ability, there was no discomfort, including itching and inflammation or diseases of the skin, even after the TE-skin had adhered to the arm for 12 h (Supplementary Figure S2). Above all, TPU fibers with hydrophobicity (contact angle, 125° (Supplementary Figure S3)) can guarantee the outstanding waterproof performance of the TE-skin. Therefore, the TE-skin, as a human-friendly skin-interfaced biosensor, can be attached to different parts of the human body to continuously monitor real-time signals during sports activity.

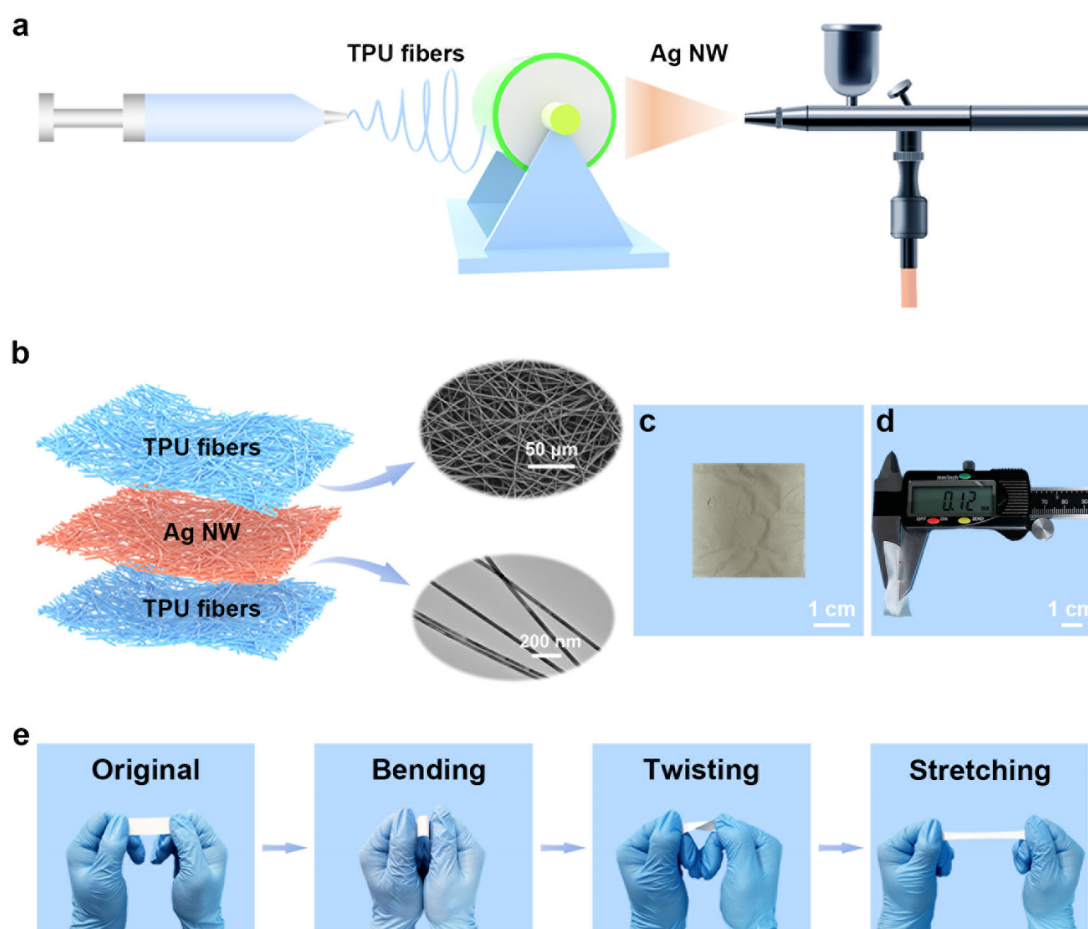


Figure 1. Fabrication and characterization of the TE-skin. (a) Schematic diagram of the experimental process for fabricating the TE-skin. (b) The sandwich structure of the TE-skin. (c) Photograph of the Ag NW electrode layer that is deposited on the TPU fiber substrate. (d) Photograph of the TE-skin with a total thickness of $120 \mu\text{m}$. (e) Photographs of the TE-skin in the original, bent, twisted, and stretched states.

3.2. Characterization and Working Mechanism of the TE-Skin

By using an electrospinning technique, the two TPU layers present a typical stacked-fiber structure (Figure 2a,c), with a corresponding average fiber diameter of $1.9 \mu\text{m}$ (Supplementary Figure S4). In addition, the Ag NW electrode layer is uniformly distributed over the surface of the TPU fibers by spraying (Figure 2b), which process constructs excellent conductive networks. The energy-dispersive spectrometer (EDS) mapping images (Supplementary Figure S5) further confirm this pivotal result. In addition, the TE-skin has numerous micro/nanopores that are formed by the multilayer interconnected compact fiber networks, ensuring good breathability. To explain the working mechanism of the TE-skin in detail, polytetrafluoroethylene (PTFE) film was adopted in order to have a

contact-separation process with the TE-skin in single-electrode mode (Figure 2d), wherein the PTFE is electronegative in comparison with the TPU, due to the diverse triboelectric polarities. Once the TPU is in contact with the PTFE, electrification will occur at their interface, and an equal number of charges with opposite polarities will be generated on the surface of the TPU and PTFE. Due to its ability to attract more electrons, the PTFE will be negatively charged, whereas the TPU will be positively charged in this period (Figure 2d, ii). As the PTFE begins to separate from the TPU, a potential difference is formed. Owing to the electrostatic induction effect, the negative charges will be transferred from the ground to the Ag NW conductive networks (Figure 2d, iii). The electron flow continues until the separation between the PTFE and the TPU is complete; the positive and negative charges are neutralized during this process (Figure 2d, iv). Notably, the accumulated charges will be retained for a sufficiently long time due to the inherent characteristic of the insulator, rather than being lost immediately. In contrast, if the PTFE is close to the TPU, the electrons will flow back from the Ag NW conductive networks to the ground through the external load, compensating for the electrical potential differences (Figure 2d, v) until the whole system reverts to its original state. As a result, an alternating potential and current are produced in the contact-separation process occurring between the PTFE and the TE-skin. To assess the electricity-generating process quantitatively, the COMSOL was utilized to simulate the potential distribution result of the PTFE and the TE-skin in different contact and separation processes. Figure 2e shows that the potential difference will grow moderately from 0 to 80 V with an increase in the separation distance between the PTFE and the TE-skin from 0 to 5 mm.

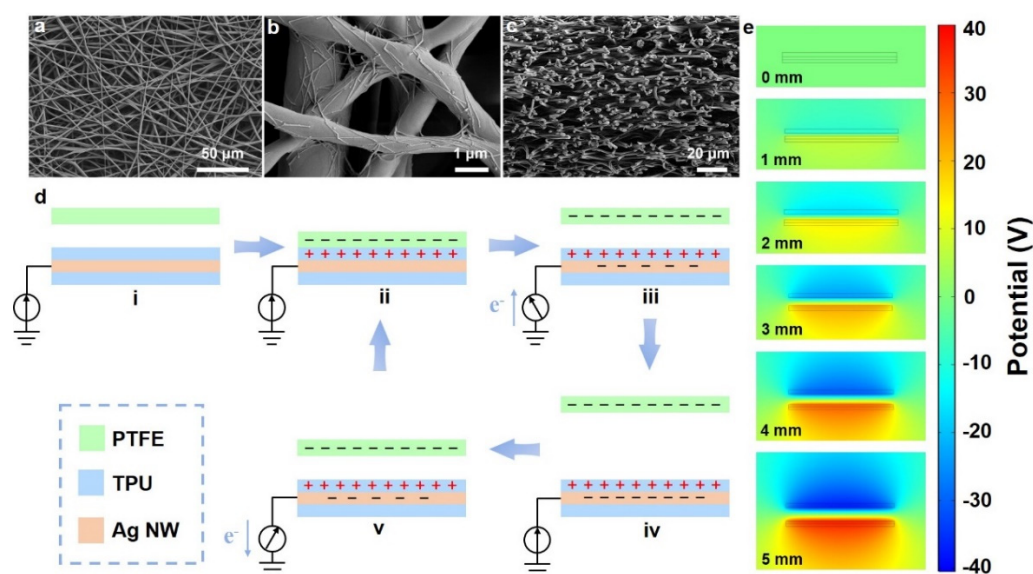


Figure 2. The micromorphologies and working mechanism of the TE-skin. (a) The SEM image of the TPU layer. (b) The SEM image of the Ag NW that is deposited on the TPU fibers. (c) The cross-section SEM image of the TE-skin. (d) The working mechanism of the TE-skin upon contact with skin. (e) The potential simulation by COMSOL to elucidate the working principle of the TE-skin.

3.3. Electrical Output Performance of the TE-Skin

To quantitatively evaluate the electrical output performance, a mechanical linear motor was used to drive the TE-skin at different frequencies (1–5 Hz). It turned out that the open-circuit voltage (V_{OC}) and short-circuit transferred charge (Q_{SC}) remained almost steady (108 V and 35 nC, respectively), while the short-circuit current (I_{SC}) increased gradually (from 0.3 to 3.5 μ A) as the frequencies increased from 1 to 5 Hz (Figure 3a–c, at a fixed load of 1 N). Since V_{OC} and Q_{SC} are independent of speed, the increase in movement frequency does not affect them, whereas the I_{SC} is determined by the relative movement speed, and so presented the characteristics of gradual growth with an increase in speed. Moreover, the power output performance of the TE-skin was systematically investigated by loading

different external resistances at an applied frequency of 1 Hz. As depicted in Figure 3d, the output current decreased dramatically, while the output voltage showed the opposite trend as the resistance increased from 10 k Ω to 1000 G Ω . The output power density (P) of the TE-skin was further calculated using the following formula:

$$p = \frac{U^2}{RA} \quad (1)$$

where R represents the loading resistance; U is the output voltage; A stands for the contact area of the TE-skin. The power density achieved a peak of 28.8 mW m $^{-2}$ with an external load resistance of 0.1 G Ω (Figure 3e), which is greater than that shown in some previous works (Supplementary Table S1). To demonstrate the working stability and durability of the TE-skin, the V_{OC} is shown in Figure 3f (the fixed load is 1 N, with applied frequencies of 1 Hz). Accordingly, there was no obvious reduction in V_{OC} after long-term cycles for 10 h, revealing the impressive working stability and durability of the TE-skin. In addition, the charging ability of the TE-skin with various types of commercial capacitors was also analyzed and compared. The results showed that the voltage value will decrease gradually and the charging speed will become slower at the same time as the capacitances of the capacitors increase (Figure 3g). After being rectified, this delivered output performance could power some small electronics like LEDs (Figure 3h), indicating great potential regarding energy supply for wearable electronics.

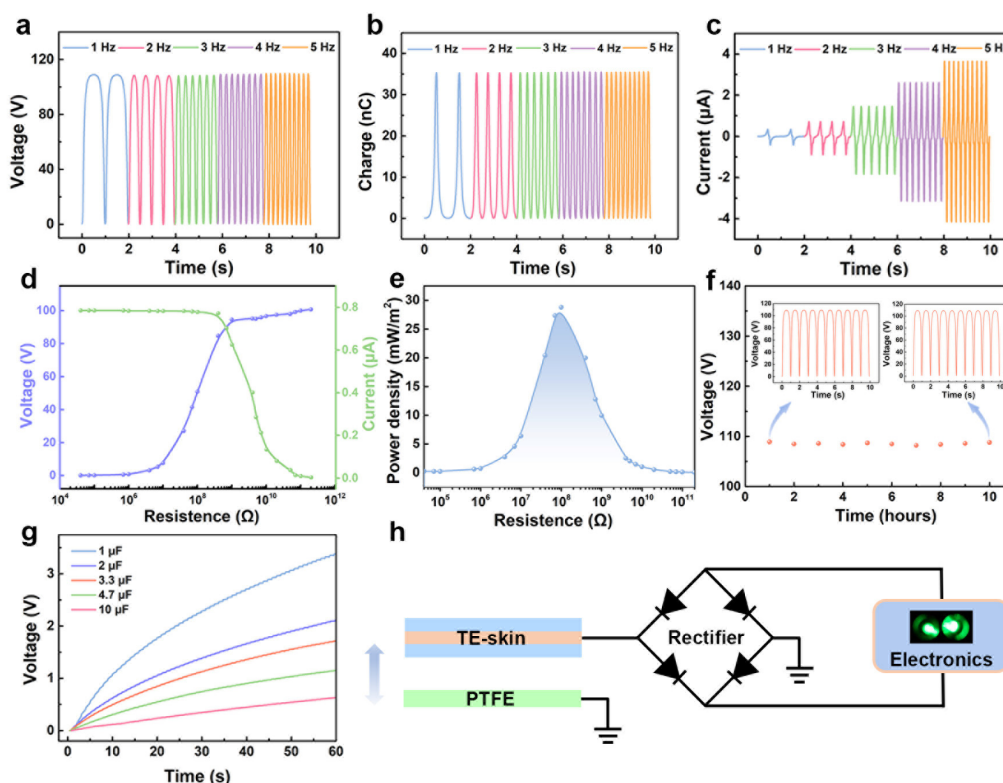


Figure 3. The electrical output performance of the TE-skin. (a–c) The electrical outputs of the TE-skin under the frequencies from 1 Hz to 5 Hz. (d,e) The output voltage, current, and power density of the TE-skin when loading different external resistances from 10 k Ω to 1000 G Ω . (f) The long-term cyclic test of the TE-skin for 10 h. The insets demonstrated in left and right are the corresponding output voltages after testing for 1 h and 10 h. (g) The charging performance of the TE-skin under different capacitors from 1 μ F to 10 μ F. (h) Schematic diagram of powering LEDs with a rectifier circuit by the contact-separation process between the TE-skin and the PTFE.

The pressure sensitivity of the TE-skin (S) as a function of the loading force was also explored, which is calculated as follows:

$$S = \frac{d(\Delta V/V_s)}{dP_A} \quad (2)$$

where ΔV and V_s are the relative change of voltage and the saturated voltage, respectively, and P_A represents the fixed pressure. As diagrammed in Figure 4b, the relationship between normalized voltage and the applied pressure is a nearly linear feature within the pressure range of 3.5 kPa (Figure 4b), and the resulting sensitivity regarding pressure (0.1539 kPa^{-1}) is higher than those of other TENG-based pressure sensors worked in single-electrode mode [39–41]. Due to the high biocompatibility, skin compatibility, and ultrathin structure of the TE-skin, a piece of pigskin ($3 \text{ cm} \times 3 \text{ cm}$) was placed on the linear mechanical motor to achieve a contact–separation process with the TE-skin, further validating the electrical performance characteristics of the TE-skin (Figure 4c). Considering that the human motion frequency range is 1.1–3.8 Hz [42], the applied frequencies were set at 1.5, 2, 2.5, 3, and 3.5 Hz, respectively. Interestingly, the V_{OC} and Q_{SC} were relatively stable, while the I_{SC} gradually increased with the acceleration in frequency (Figure 4d–f), which was consistent with the previous results shown in Figure 4a–c. It is undeniable that the TE-skin has the potential to be driven by human skin to work as a self-powered sensor for human motion monitoring. Given that the human body will sweat during sport, the V_{OC} of the TE-skin in different relative humidity (RH) conditions was also evaluated. Accordingly, although the V_{OC} decreased gradually from 9.28 to 1.18 V with the increase in RH from 30% to 80%, the electrical output at 80% RH was sufficient to ensure that the TE-skin can work well for human motion-sensing in such a high humidity environment (Supplementary Figure S6).

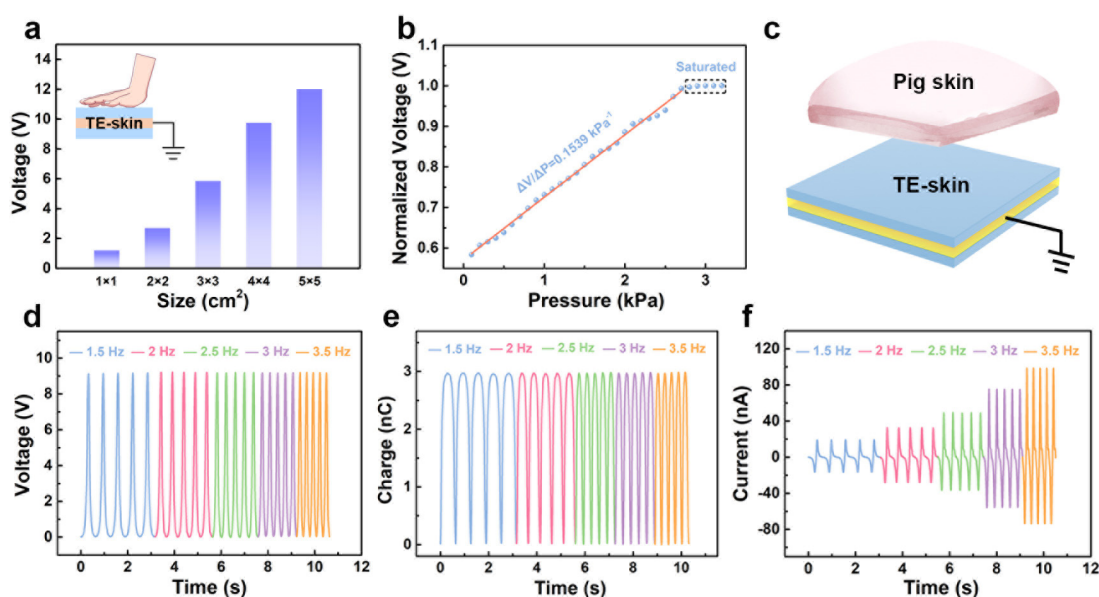


Figure 4. The electrical outputs of the skin-interfaced TE-skin. (a) The V_{OC} of the TE-skin from hand slapping, with the respective increased size. (b) The relationship between the corresponding normalized voltage and a range of applied pressures (0–3.5 kPa). (c) Schematic illustration of the experimental setup for the skin-interfaced electrical output test. (d–f) Skin-interfaced electrical outputs of the TE-skin under frequencies from 1.5 Hz to 3.5 Hz.

3.4. Stretchability Characterization

As a wearable self-powered sensor for human motion monitoring, the TE-skin needs to generate electrical signals under a progression of extreme deformation conditions. Figure 5a shows that the TE-skin was capable of being stretched to a strain of 500% in comparison with the original length, presenting outstanding mechanical properties. Compared with

the failure strain and the ultimate stress of pure TPU film (546%, 1.73 MPa), the TE-skin exhibited enhanced failure strain and ultimate stress, which were 1019% and 2.64 MPa, respectively (Figure 5b). It is worth explicitly noting that the improvement in the tensile strength and toughness of the TE-skin can be attributed to the interface adhesion of the three layers in the process of electrospinning and spraying. More significantly, the cyclic stress-strain curves of the TE-skin under different strains were also investigated to further verify its excellent mechanical properties. Whether it was stretched by 30%, 50%, or 100%, the TE-skin always retained great deformation recovery ability after 5 cycles (Figure 5c and Supplementary Figure S7), which is conducive to the sensing capacity of the TE-skin needed for human motion monitoring. Figure 5d revealed the resistance of the Ag NW electrode under different strains. Although the resistance of the Ag NW electrode grew moderately as the TE-skin was uniaxially stretched, the TE-skin still possessed a great capacity for electron transportation, due to the reserved Ag NW conductive networks during the stretching process. Notably, the V_{OC} of the TE-skin was equivalent to the initial sample after the strain was completely released (Figure 5e), showing extraordinary stretchability and the possibility for numerous applications in the field of flexible and wearable electronics. The V_{OC} of the TE-skin under different strains was tested further. The V_{OC} decreased gradually with the increase in strain from 0% to 100% (Figure 5f), which resulted from the extension of the electron transfer path in Ag NW conductive networks. However, there was still a certain electrical output even at a strain of 100%, and the V_{OC} under each strain was relatively stable throughout 50 cycles. Undoubtedly, the differences of V_{OC} under different strains could be applied in the field of deformation sensing, which further verified the promising prospect of the TE-skin in human motion monitoring.

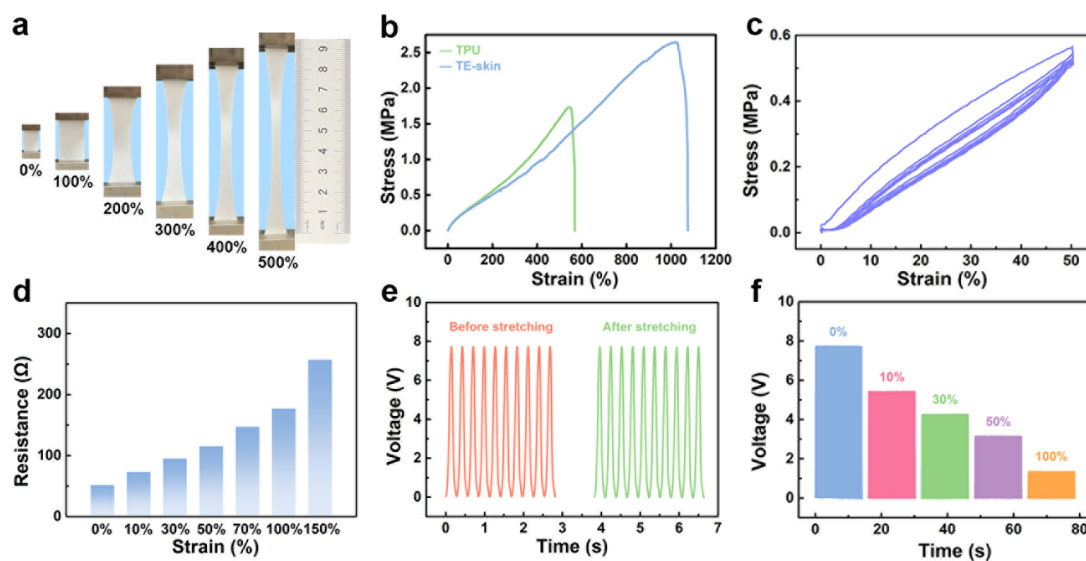


Figure 5. Stretchability characterization of the TE-skin. (a) Photographs of the TE-skin, stretched at different strains. (b) The strain-stress of the TPU film and the TE-skin. (c) The successive loading-unloading stress-strain of the TE-skin, stretched by a strain of 50% for 5 cycles. (d) The resistance of the Ag NW electrode layer under different strains. (e) The V_{OC} of the TE-skin before and after being stretched by a strain of 50%. (f) The V_{OC} of the TE-skin under different strains for 50 cycles (3.5 Hz and 1 N).

3.5. Applications of the TE-Skin in Human Motion Monitoring

A range of experiments was implemented to better investigate the practical applications of the TE-skin in wearable electronics technologies. As shown in Figure 6a, an intelligent electronic glove was developed to monitor the different motions of human hands, in which five TE-skins were attached to the five digits. Furthermore, a data acquisition system integrated with five channels was customized, based on this intelligent electronic glove, for detecting the electrical signals generated by different hand gestures. When a hand

gesture was made, the output signal of the bending finger in the corresponding channel could be acquired significantly, whereas the output signals of the other fingers in the rest of the channels were maintained in the initial state. Supplementary Figure S8 illustrates that the intelligent electronic glove has the potential to record various gestures, including the “ok” sign, the “victory” sign, and the “good” sign. The corresponding detailed electrical signals in each channel of the mentioned gestures are shown in the bottom half of Supplementary Figure S8. Through machine learning and self-training, the recognition of more complicated gestures might be achievable based on the tested TE-skin, with promising applications in the field of multifunctional prostheses or flexible robots in the future. In addition, sports monitoring is a complex multi-dimensional analytical process that needs a process of quantification and the analysis of relevant physiological indicators. Due to the preeminent stretchability and sensing performance of the material under test, the TE-skin can also be used to detect and record human motion for physiological signal monitoring, which is a significant feature in wearable devices. Figure 6b demonstrates that the TE-skin was attached to the elbow (i), finger (ii), wrist (iii), and leg (iv) to realize the real-time monitoring of different human body parts. Different pressures obtained from different parts of the human body will reflect the individual voltage signals of these TE-skins during exercise. Undoubtedly, the coordinated operation of each TE-skin will provide a leap forward in terms of improvement in the performance of the whole human motion monitoring system.

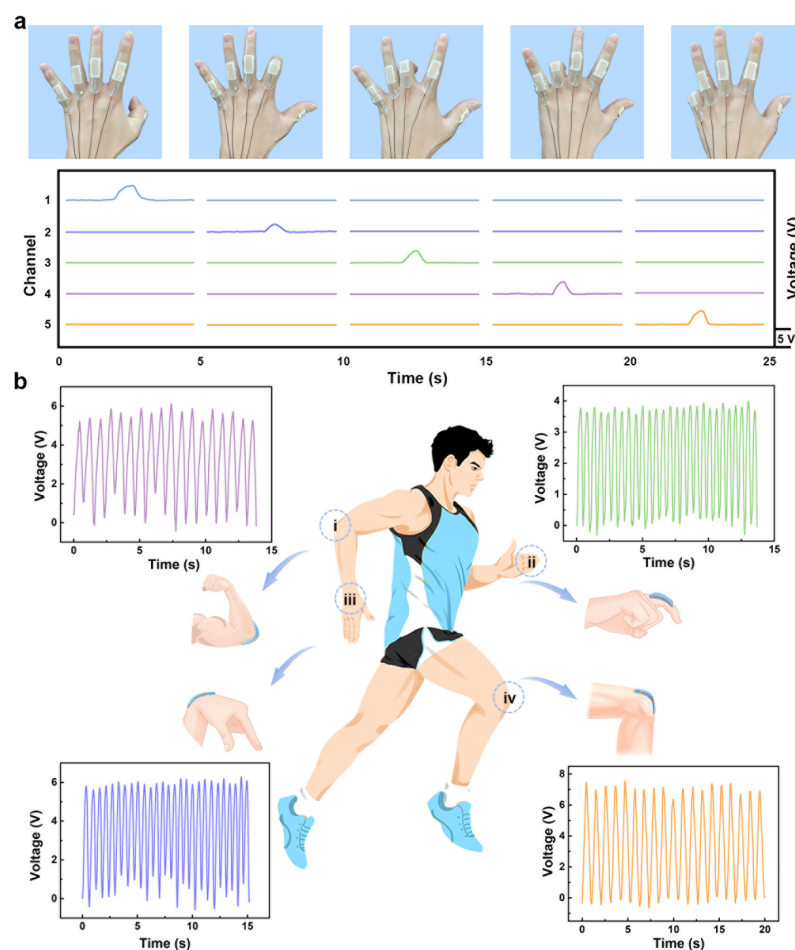


Figure 6. The application of the TE-skin regarding human motion monitoring. (a) The corresponding voltage signals of the five TE-skins that are fixed on 5 digits. Insets are the corresponding hand gestures. (b) The corresponding voltage signals of bending elbow (i), finger (ii), wrist (iii), and leg (iv) in the different states of motion.

4. Conclusions

In summary, an ultrathin stretchable all-fiber TE-skin was created via an electrospinning and spraying technique and is presented in this work. Owing to the Ag NW conductive networks designed in a layer-by-layer structure, the adhesion between the Ag NW and TPU layer is reinforced, and the high stretchability of the TE-skin is achieved with a low-resistance electrode of 257.3Ω at a strain of 150%. In addition, the TE-skin possesses a high pressure sensitivity of 0.1539 kPa^{-1} and outstanding deformation recovery ability. Based on the excellent sensing performances, an intelligent electronic glove has been developed to detect several human gestures, exhibiting its potential in artificial intelligence applications. Moreover, several TE-skins were utilized to achieve the real-time monitoring of different human body parts during sports. It is envisaged that the fabricated TE-skin presented in this paper can be utilized in the field of next-generation electronics for the applications of artificial intelligence, flexible robots, and multidimensional sports monitoring.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/nanoenergyadv2010003/s1>, Figure S1: Photograph of the TE-skin with a total weight of 41.5 mg ($3 \times 3 \text{ cm}^2$). Figure S2: The biocompatibility test of the TE-skin. Figure S3: The contact angle of the TPU film. Figure S4: The diameter distribution of TPU fibers. Figure S5: Energy dispersive spectrometer (EDS) analysis of Ag NW deposited on the TPU fibers. (a) SEM image. (b) element overlay. (c) Ag element mapping. (d) C element mapping. (e) N element mapping. (f) O element mapping. Figure S6: The open-circuit voltage of the TE-skin under different relative humidity. Figure S7: The successive loading-unloading stress-strain of the TE-skin stretched to the strains of (a) 30% and (b) 100% for 5 cycles. Figure S8: Different hand gestures, including (i) the “ok” sign, (ii) the “victory” sign, and (iii) the “good” sign, with the corresponding electrical signals. Table S1. Comparison of the power output with the findings of previous works. Reference [43] is cited in the Supplementary Materials.

Author Contributions: Y.S., T.D. and Z.W. conceived the project, designed the research, and prepared the manuscript. Y.S. fabricated the electronic skin and performed all the experiments. Z.Y., R.L. and B.W. performed the electrical experiment. All authors participated in the analysis and discussions of the results and agreed to publish the manuscript in the current version. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (61503051).

Data Availability Statement: Data are contained within the article and Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yuan, M.; Li, C.; Liu, H.; Xu, Q.; Xie, Y. A 3D-printed acoustic triboelectric nanogenerator for quarter-wavelength acoustic energy harvesting and self-powered edge sensing. *Nano Energy* **2021**, 105962. [\[CrossRef\]](#)
2. Liao, X.; Song, W.; Zhang, X.; Yan, C.; Li, T.; Ren, H.; Liu, C.; Wang, Y.; Zheng, Y. A bioinspired analogous nerve towards artificial intelligence. *Nat. Commun.* **2020**, *11*, 268. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Araromi, O.A.; Graule, M.A.; Dorsey, K.L.; Castellanos, S.; Foster, J.R.; Hsu, W.-H.; Passy, A.E.; Vlassak, J.J.; Weaver, J.C.; Walsh, C.J.; et al. Ultra-sensitive and resilient compliant strain gauges for soft machines. *Nature* **2020**, *587*, 219–224. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Wu, M.; Yao, K.; Li, D.; Huang, X.; Liu, Y.; Wang, L.; Song, E.; Yu, J.; Yu, X. Self-powered skin electronics for energy harvesting and healthcare monitoring. *Mater. Today Energy* **2021**, *21*, 100786. [\[CrossRef\]](#)
5. Wu, H.; Yang, G.; Zhu, K.; Liu, S.; Guo, W.; Jiang, Z.; Li, Z. Materials, devices, and systems of on-skin electrodes for electrophysiological monitoring and human-machine interfaces. *Adv. Sci.* **2021**, *8*, 2001938. [\[CrossRef\]](#)
6. Zhang, S.; Li, S.; Xia, Z.; Cai, K. A review of electronic skin: Soft electronics and sensors for human health. *J. Mater. Chem. B* **2020**, *8*, 852–862. [\[CrossRef\]](#)
7. Liu, Y.-Q.; Chen, Z.-D.; Han, D.-D.; Mao, J.-W.; Ma, J.-N.; Zhang, Y.-L.; Sun, H.-B. Bioinspired soft robots based on the moisture-responsive graphene oxide. *Adv. Sci.* **2021**, *8*, 2002464. [\[CrossRef\]](#)
8. Fu, C.; Xia, Z.; Hurren, C.; Nilghaz, A.; Wang, X. Textiles in soft robots: Current progress and future trends. *Biosens. Bioelectron.* **2022**, *196*, 113690. [\[CrossRef\]](#)

9. Ning, C.; Dong, K.; Cheng, R.; Yi, J.; Ye, C.; Peng, X.; Sheng, F.; Jiang, Y.; Wang, Z.L. Flexible and stretchable fiber-shaped triboelectric nanogenerators for biomechanical monitoring and human-interactive sensing. *Adv. Funct. Mater.* **2021**, *31*, 2006679. [[CrossRef](#)]
10. He, M.; Du, W.; Feng, Y.; Li, S.; Wang, W.; Zhang, X.; Yu, A.; Wan, L.; Zhai, J. Flexible and stretchable triboelectric nanogenerator fabric for biomechanical energy harvesting and self-powered dual-mode human motion monitoring. *Nano Energy* **2021**, *86*, 106058. [[CrossRef](#)]
11. Sim, K.; Rao, Z.; Zou, Z.; Ershad, F.; Lei, J.; Thukral, A.; Chen, J.; Huang, Q.-A.; Xiao, J.; Yu, C. Metal oxide semiconductor nanomembrane-based soft unnoticeable multifunctional electronics for wearable human-machine interfaces. *Sci. Adv.* **2019**, *5*, eaav9653. [[CrossRef](#)] [[PubMed](#)]
12. Dong, B.; Yang, Y.; Shi, Q.; Xu, S.; Sun, Z.; Zhu, S.; Zhang, Z.; Kwong, D.-L.; Zhou, G.; Ang, K.-W. Wearable triboelectric-human-machine interface (THMI) using robust nanophotonic readout. *ACS Nano* **2020**, *14*, 8915–8930. [[CrossRef](#)] [[PubMed](#)]
13. Luo, Y.; Li, Y.; Sharma, P.; Shou, W.; Wu, K.; Foshey, M.; Li, B.; Palacios, T.; Torralba, A.; Matusik, W. Learning human-environment interactions using conformal tactile textiles. *Nat. Electron.* **2021**, *4*, 193–201. [[CrossRef](#)]
14. Pang, Q.; Lou, D.; Li, S.; Wang, G.; Qiao, B.; Dong, S.; Ma, L.; Gao, C.; Wu, Z. Smart flexible electronics-integrated wound dressing for real-time monitoring and on-demand treatment of infected wounds. *Adv. Sci.* **2020**, *7*, 1902673. [[CrossRef](#)]
15. Li, X.; Huang, X.; Mo, J.; Wang, H.; Huang, Q.; Yang, C.; Zhang, T.; Chen, H.-J.; Hang, T.; Liu, F.; et al. A fully integrated closed-loop system based on mesoporous microneedles-iontophoresis for diabetes treatment. *Adv. Sci.* **2021**, *8*, 2100827. [[CrossRef](#)] [[PubMed](#)]
16. Liu, Y.; Zhao, L.; Wang, L.; Zheng, H.; Li, D.; Avila, R.; Lai, K.W.C.; Wang, Z.; Xie, Z.; Zi, Y.; et al. Skin-Integrated graphene-embedded lead zirconate titanate rubber for energy harvesting and mechanical sensing. *Adv. Mater. Technol.* **2019**, 1900744. [[CrossRef](#)]
17. Kim, K.K.; Ha, I.; Kim, M.; Choi, J.; Won, P.; Jo, S.; Ko, S.H. A deep-learned skin sensor decoding the epicentral human motions. *Nat. Commun.* **2020**, *11*, 2149. [[CrossRef](#)]
18. Kim, K.K.; Choi, J.; Ko, S.H. Energy harvesting untethered soft electronic devices. *Adv. Healthcare Mater.* **2021**, *10*, 2002286. [[CrossRef](#)]
19. Kim, K.K.; Choi, J.; Kim, J.-H.; Nam, S.; Ko, S.H. Evolvable skin electronics by in situ and in operando adaptation. *Adv. Funct. Mater.* **2021**, *32*, 2106329. [[CrossRef](#)]
20. Lee, S.; Franklin, S.; Hassani, F.A.; Yokota, T.; Nayeem, M.O.G.; Wang, Y.; Leib, R.; Cheng, G.; Franklin, D.W.; Someya, T. Nanomesh pressure sensor for monitoring finger manipulation without sensory interference. *Science* **2020**, *370*, 966–970. [[CrossRef](#)]
21. Núñez, C.G.; Navaraj, W.T.; Polat, E.O.; Dahiya, R. Energy-autonomous, flexible, and transparent tactile skin. *Adv. Funct. Mater.* **2017**, *27*, 1606287. [[CrossRef](#)]
22. Bae, G.Y.; Pak, S.W.; Kim, D.; Lee, G.; Kim, D.H.; Chung, Y.; Cho, K. Linearly and highly pressure-sensitive electronic skin based on a bioinspired hierarchical structural array. *Adv. Mater.* **2016**, *28*, 5300–5306. [[CrossRef](#)] [[PubMed](#)]
23. Yang, T.; Deng, W.; Chu, X.; Wang, X.; Hu, Y.; Fan, X.; Song, J.; Gao, Y.; Zhang, B.; Tian, G.; et al. Hierarchically microstructure-bioinspired flexible piezoresistive bioelectronics. *ACS Nano* **2021**, *15*, 11555–11563. [[CrossRef](#)] [[PubMed](#)]
24. He, H.; Fu, Y.; Zang, W.; Wang, Q.; Xing, L.; Zhang, Y.; Xue, X. A flexible self-powered T-ZnO/PVDF/fabric electronic-skin with multi-functions of tactile-perception, atmosphere-detection and self-clean. *Nano Energy* **2017**, *31*, 37–48. [[CrossRef](#)]
25. Yuan, X.; Gao, X.; Shen, X.; Yang, J.; Li, Z.; Dong, S. A 3D-printed, alternatively tilt-polarized PVDF-TrFE polymer with enhanced piezoelectric effect for self-powered sensor application. *Nano Energy* **2021**, *85*, 105985. [[CrossRef](#)]
26. Lan, L.; Yin, T.; Jiang, C.; Li, X.; Yao, Y.; Wang, Z.; Qu, S.; Ye, Z.; Ping, J.; Ying, Y. Highly conductive 1D-2D composite film for skin-mountable strain sensor and stretchable triboelectric nanogenerator. *Nano Energy* **2019**, *62*, 319–328. [[CrossRef](#)]
27. Zhou, K.; Zhao, Y.; Sun, X.; Yuan, Z.; Zheng, G.; Dai, K.; Mi, L.; Pan, C.; Liu, C.; Shen, C. Ultra-stretchable triboelectric nanogenerator as high-sensitive and self-powered electronic skins for energy harvesting and tactile sensing. *Nano Energy* **2020**, *70*, 104546. [[CrossRef](#)]
28. Jiang, Y.; Dong, K.; Li, X.; An, J.; Wu, D.; Peng, X.; Yi, J.; Ning, C.; Cheng, R.; Yu, P.; et al. Stretchable, washable, and ultrathin triboelectric nanogenerators as skin-like highly sensitive self-powered haptic sensors. *Adv. Funct. Mater.* **2021**, *31*, 2005584. [[CrossRef](#)]
29. Shi, Y.; Wei, X.; Wang, K.; He, D.; Yuan, Z.; Xu, J.; Wu, Z.; Wang, Z.L. Integrated all-fiber electronic skin toward self-powered sensing sports systems. *ACS Appl. Mater. Interfaces* **2021**, *13*, 50329–50337. [[CrossRef](#)]
30. Peng, X.; Dong, K.; Ning, C.; Cheng, R.; Yi, J.; Zhang, Y.; Sheng, F.; Wu, Z.; Wang, Z.L. All-nanofiber self-powered skin-interfaced real-time respiratory monitoring system for obstructive sleep apnea-hypopnea syndrome diagnosing. *Adv. Funct. Mater.* **2021**, *31*, 2103559. [[CrossRef](#)]
31. Zhu, M.; Lou, M.; Yu, J.; Li, Z.; Ding, B. Energy autonomous hybrid electronic skin with multi-modal sensing capabilities. *Nano Energy* **2020**, *78*, 105208. [[CrossRef](#)]
32. Jiang, Y.; Dong, K.; An, J.; Liang, F.; Yi, J.; Peng, X.; Ning, C.; Ye, C.; Wang, Z.L. UV-protective, self-cleaning, and antibacterial nanofiber-based triboelectric nanogenerators for self-powered human motion monitoring. *ACS Appl. Mater. Interfaces* **2021**, *13*, 11205–11214. [[CrossRef](#)] [[PubMed](#)]
33. Ganesh, R.S.; Yoon, H.-J.; Kim, S.-W. Recent trends of biocompatible triboelectric nanogenerators toward self-powered e-skin. *EcoMat* **2020**, *2*, e12065. [[CrossRef](#)]

34. Zhang, W.; Liu, Q.; Chao, S.; Liu, R.; Cui, X.; Sun, Y.; Ouyang, H.; Li, Z. Ultrathin stretchable triboelectric nanogenerators improved by postcharging electrode material. *ACS Appl. Mater. Interfaces* **2021**, *13*, 42966–42976. [[CrossRef](#)]
35. Jeong, C.K.; Lee, J.; Han, S.; Ryu, J.; Hwang, G.-T.; Park, D.Y.; Park, J.H.; Lee, S.S.; Byun, M.; Ko, S.H.; et al. A hyper-stretchable elastic-composite energy harvester. *Adv. Mater.* **2015**, *27*, 2866–2875. [[CrossRef](#)]
36. Yu, X.; Liang, X.; Krishnamoorthy, R.; Jiang, W.; Zhang, L.; Ma, L.; Zhu, P.; Hu, Y.; Sun, R.; Wong, C.-P. Transparent and flexible hybrid nanogenerator with welded silver nanowire networks as the electrodes for mechanical energy harvesting and physiological signal monitoring. *Smart Mater. Struct.* **2020**, *29*, 045040. [[CrossRef](#)]
37. Jung, J.; Cho, H.; Yuksel, R.; Kim, D.; Lee, H.; Kwon, J.; Lee, P.; Yeo, J.; Hong, S.; Unalan, H.E.; et al. Stretchable/flexible silver nanowire electrodes for energy device applications. *Nanoscale* **2019**, *11*, 20356–20378. [[CrossRef](#)]
38. Tan, C.; Dong, Z.; Li, Y.; Zhao, H.; Huang, X.; Zhou, Z.; Jiang, J.-W.; Long, Y.-Z.; Jiang, P.; Zhang, T.-Y.; et al. A high performance wearable strain sensor with advanced thermal management for motion monitoring. *Nat. Commun.* **2020**, *11*, 3530. [[CrossRef](#)]
39. Gogurla, N.; Kim, S. Self-powered and imperceptible electronic tattoos based on silk protein nanofiber and carbon nanotubes for human-machine interfaces. *Adv. Energy Mater.* **2021**, *11*, 2100801. [[CrossRef](#)]
40. Wang, X.; Zhang, H.; Dong, L.; Han, X.; Du, W.; Zhai, J.; Pan, C.; Wang, Z.L. Self-powered high-resolution and pressure-sensitive triboelectric sensor matrix for real-time tactile mapping. *Adv. Mater.* **2016**, *28*, 2896–2903. [[CrossRef](#)]
41. Peng, X.; Dong, K.; Ye, C.; Jiang, Y.; Zhai, S.; Cheng, R.; Liu, D.; Gao, X.; Wang, J.; Wang, Z.L. A breathable, biodegradable, antibacterial, and self-powered electronic skin based on all-nanofiber triboelectric nanogenerators. *Sci. Adv.* **2020**, *6*, eaba9624. [[CrossRef](#)] [[PubMed](#)]
42. Li, R.; Wei, X.; Xu, J.; Chen, J.; Li, B.; Wu, Z.; Wang, Z.L. Smart wearable sensors based on triboelectric nanogenerator for personal healthcare monitoring. *Micromachines* **2021**, *12*, 352. [[CrossRef](#)] [[PubMed](#)]
43. Du, W.; Nie, J.; Ren, Z.; Jiang, T.; Xu, L.; Dong, S.; Zheng, L.; Chen, X.; Li, H. Inflammation-free and gas-permeable on-skin triboelectric nanogenerator using soluble nanofibers. *Nano Energy* **2018**, *51*, 260–269. [[CrossRef](#)]