Research Progress on Triboelectric Nanogenerator for Sports Applications

Caixia Li [1], Yongsheng Zhu [1], Fengxin Sun [1], Changjun Jia [1], Tianming Zhao [2,3], Yupeng Mao [1,*] and Haidong Yang [1,*]

1. Physical Education Department, Northeastern University, Shenyang 110819, China
2. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China
3. Institutes for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang 110016, China
* Correspondence: maoyupeng@pe.neu.edu.cn (Y.M.); yanghaidong@pe.neu.edu.cn (H.Y.)

Abstract: Progress in science and technology drives the continuous innovation of energy collection and utilization. In the field of sports, the information collection and analysis based on Internet of things have attracted particular attention. Moreover, triboelectric nanogenerator (TENG) has promising applications in the field of sports. Here, we introduce the working principle of the TENG then the progress of the TENG as a wearable energy sensor is examined in the two fields of basic human activities and sports, especially competitive sports. On this basis, it is considered that the stability of devices, the universality of materials, and the scientificity of application of the TENG in the future need to be improved. We provide a direction for further upgrading energy collection technology to promote the high-quality development of human mechanical energy sensing in the field of sports.

Keywords: wearable; energy sensing; body motion; triboelectric nanogenerator

1. Introduction

With the continuous progress of science and technology, the world has been entered the digital age, and great achievements have been made in the field of sports [1]. The in-depth application of the information technology drives the sports field to develop in a scientific direction. Sports data-driven, precise, and intelligent development in the sports field has become a trend. In this context, data collection technology is constantly optimized and updated, and the information collection based on the Internet of things has become more and more important [2]. In recent years, related research topics, such as sensors [3,4] and energy acquisition [5–8], have attracted great attention. The effective collection, identification, and analysis of sports information is the key to intelligent sports. It can help athletes improve their skills, formulate scientific training plans and competitive strategies [9], help sports training digitally, accurately, and intelligently, and comprehensively improve the scientific level. The emergence of the motion sensor, which can realize the measurement of motion-related parameters such as speed and acceleration [10], plays an especially important role in many aspects. With the development of science and technology society, higher requirements are put forward for sports monitoring. The operation of traditional sensors depends on external power supply, such as batteries, which brings serious environmental pollution and takes the required characteristics such as flexibility, comfort, lightweight, convenience, and wearability of unified specification [11,12]. In the research of human motion data acquisition, it is necessary to take advanced science and technology as the support, overcome various adverse conditions, update sensing equipment, optimize sensing performance, expand sensing range, and promote the high-quality development of motion information acquisition.

In 2012, Wang's group proposed the triboelectric nanogenerator (TENG) based on contact electrification and electrostatic induction, which has been proven to be a powerful technology that can convert random low-frequency energy into electrical energy. It has unique advantages of high-power density, high efficiency, low cost, and simple manufacture [13–17]. TENG is considered to have potential development prospects in the direction of human mechanical energy acquisition [18–20] and self-powered induction [21–24]. The sensor based on the TENG shows high sensitivity and efficiency to mechanical motion [8,25,26], and can measure several characteristics at the same time, such as acceleration [27,28], pressure [29], direction [30,31], etc. In addition, such sensors can make full use of various rich and available mechanical energy sources in our daily life or nature environment [16,32], such as vibration [33], human movement [34–37], eye movement [38], etc. So far, various TENGs have been successfully reported [39–43]. Human movement will cause changes in external environmental factors. Therefore, some triboelectric nanogenerators have certain characteristics, such as moisture resistance, flexibility, and stretchability, can be made into wearable motion sensors [44–49], which monitor various motion data of human body successfully.

In recent years, triboelectric nanogenerators have been gradually applied in the field of sports and become an important sensing means for monitoring human activities. In order to grasp the development of triboelectric nanogenerators in the field of sports as a whole and provide basic support for subsequent research, we reviewed the research in this field. Firstly, we introduce the working principle of the TENGs, and then focus on the latest application progress of sensing devices based on the TENGs in monitoring human movement. Energy sensors based on the TENGs are applied to basic human activities, which can achieve the effect of monitoring human daily basic activities and body health condition. In the application of sports, especially competitive sports, the real-time movement and physical faction monitoring of athletes can be realized through intelligent training facilities and wearable devices. This paper not only summarizes the research progress of TENGs, but also shows the research results of our team in recent years. The real experimental results further illustrate the important value of TENGs in sports research. Finally, we made a prospect for the future development of TENGs, which is of great significance to promote the further development of the sports field.

2. Triboelectric Nanogenerator

As a new branch of energy conversion technology, the TENG can convert the mechanical energy into electrical energy effectively, with a self-driving system [50,51]. The operation principle of TENG is based on the coupling effect of contact electrification and electrostatic induction, and its fundamental physics model can be traced back to Maxwell's equations. The TENG has four working modes (Figure 1a): the vertical contact-separation mode, lateral sliding mode, single electrode mode, and freestanding triboelectric-layer mode [14]. The principles of different working modes are roughly the same. It is generally believed that after two different materials come into contact, chemical bonds are formed between some parts of the two surfaces, which is called adhesion. After separation, some bound atoms tend to retain additional electrons, and some tend to release electrons, which may generate friction charges on the surface [52]. In other words, materials with different electron adsorption capacity generate electric charges through mutual friction, and the potential difference drives the transfer of electrons, thus forming an electric current.

Here we select the vertical contact-separation mode for detailed description (Figure 1b). At the original position, there is no charge (Figure 1bI). When two surfaces of different materials are in contact, frictional charges will be generated on the contact surface due to the difference in the ability to adsorb electrons (Figure 1bII). Once two surfaces are separated, a potential difference will occur, causing electrons to flow from the bottom electrode to the top electrode (Figure 1bIII). When the two surfaces are completely separated to the initial position, the charge will reach equilibrium (Figure 1bIV). When the two surfaces are close to each other, the electrons flow from the top electrode to the bottom through the load

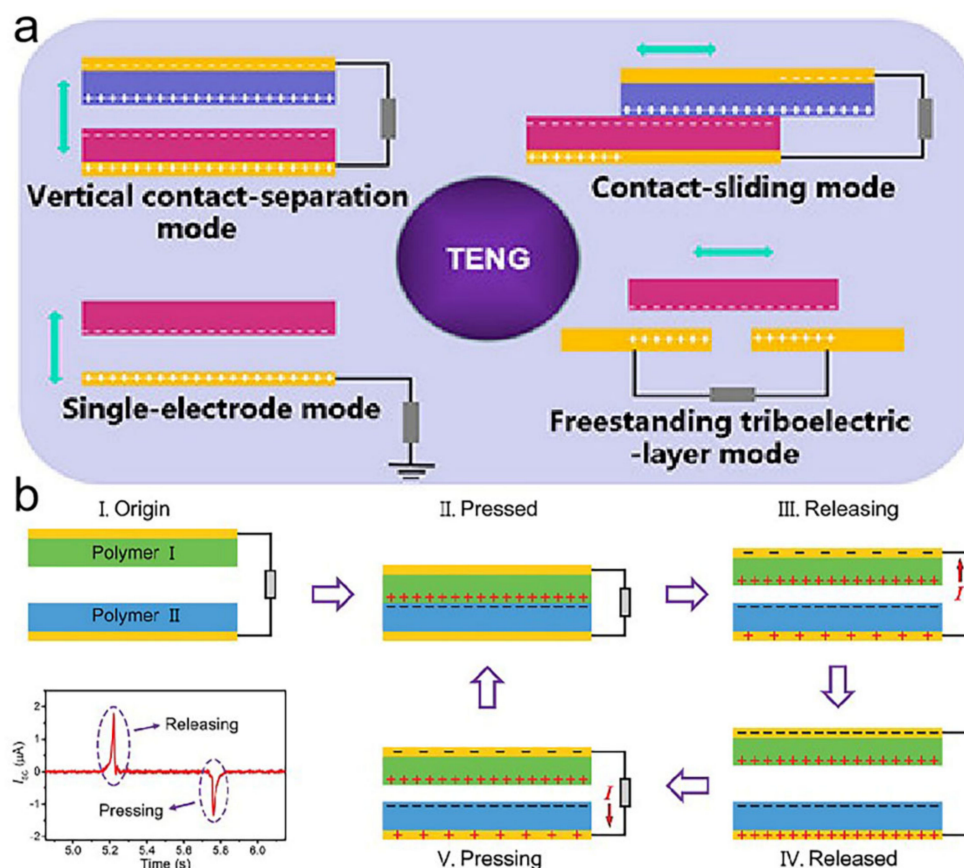again (Figure 1bV). The current change during the whole process is shown in the bottom left of Figure 1.

Figure 1. (**a**) The TENG's four working modes. Reprinted with permission from Ref. [50]. Copyright 2021 American Chemical Society. (**b**) Schematic diagram of working principle of TENG in vertical contact-separation mode. Reprinted with permission from Ref. [1]. Copyright 2021 Wiley Online Library.

3. Research Progress of Wearable Energy Sensor Based on the TENG in the Sports Field

The TENG can be used to make wearable energy sensors to monitor human movement using the special performance. The application in the sports field has a great development prospect. Next, taking TENG's research in the field of sports as the core, this paper combines the previous research from the two aspects of basic human activity monitoring and sports energy monitoring.

3.1. Basic Human Activity Monitoring

The energy sensor used to monitor basic human activities is mainly integrated with the TENG, which can monitor the movement status of various parts of the human body through the combination of weaving technology with clothing [53–55], or direct fitting with the skin [56–58]. Zhu et al. developed a robust and textile-TENG energy collection [59]. By adding MoS2/GO to the friction layer, a large number of micropores are generated in the silicone rubber matrix, which provides more sites for charge generation and improves the working performance of the device. In the process of collecting energy, sandpaper is used as a template to create a rough surface to obtain a larger contact area (Figure 2a). The device can be worn on skin or cloth (Figure 2b,c) to harvest energy from different body movements. Sun et al. designed a highly transparent, stretchable, and self-healable ionic gel. The TENG based on this ionic gel can be used for efficient energy collection [60]. This ionic gel's fibers can be easily woven with ordinary fabrics (such as gloves) (Figure 2d) to

make ITENG. As shown in Figure 2e, the resistance of ITENG increases with the bending degree of fingers. The bending angle can be identified and distinguished by detecting the change of resistance. Because the ionic gel has good elasticity, the monitoring of the device is accurate and repeatable. In the material selection of the TENG, the reuse of waste material is a hot spot [61–64]. Bhaskar et al. proposed a recycled material-based triboelectric nanogenerator (TENG) made of plastic waste and carbon-coated paper wipes (C@PWs) (Figure 2f), and C@PW-Teng has been reshaped into a smart wristband device, as shown in Figure 2g [65]. However, since this device has no waterproof function, the moisture in the external environment will affect its working performance. Therefore, the surface of the wrist strap needs to be wrapped with a layer of polyethylene to prevent interference in the humid environment. Minglu Zhu et al. developed a self-powered and self-functional sock (S2-sock) based on a triboelectric nanogenerator (TENG) and lead zirconate titanate (PZT) piezoelectric chips (Figure 2h) [66]. The S2-sock has diverse functions for energy harvesting and sensing various physiological signals (gait, contact force, sweat level, etc.). Figure 2i,j shows the electrical signals under different synchrony and under the same synchrony, different weights, and different ambient humidity. This proves that the S2-sock can successfully realize walking pattern recognition and motion tracking for smart home applications through changes in environmental factors and human body weight. Textile articles based on TENG can not only contribute to sports monitoring in the future, but also play a huge role in medical care. X.W. Hu et al. proposed a high-output flexible ring-structure TENG (FR-TENG) [67]. Since its fabrication materials are sponge-like porous PDMS and organic flexible hydrogels, it has good tensile properties. By optimizing the concentration of deionized water, the output performance is greatly improved. On this basis, a motion monitoring and protection elastic band is made to monitor human motion data. Wearing the motion monitoring protection elastic band on the arm, as shown in Figure 2k, the measured voltage can reflect the force of the biceps when the arm is naturally bent and the arm is bent hard. Experiments compared the output performance of FR-TENG with pure PDMS and FR-TENG with porous PDMS under different stress conditions (Figure 2l,m), which further verified that FR-TENG with porous PDMS has higher sensitivity and output performance can better reflect the strength of human muscles. Table 1 compares the basic properties of the above five devices in terms of humidity resistance, self-healing, breathability, and electrical output, as well as their application scope. The TENGs based on various conductivity and material properties have different application fields due to their different device characteristics. In a word, the TENG still has a huge development prospect in the monitoring of basic human activities.

Table 1. Features and application comparison of different TENGs in basic human activity.

| Devices	Humidity Resistance	Self-Healing	Breathability	Electrical Output	Applications
Textile-TENG (Zhu et al. [59])	√			~200 V	green electronics
ITENG (Sun et al. [60])		√		~115 V	wearable electronics, E-skin, and soft robotics
C@PW-TENG (Bhaskar et al. [65])	√			~174 V	emergency communication device
S2-sock (Zhu et al. [66])	√		√	~196 V	smart home, sports monitoring, healthcare
FR-TENG (Hu et al. [67])		√		~100 V	health monitoring, self-powered system and human-machine interaction
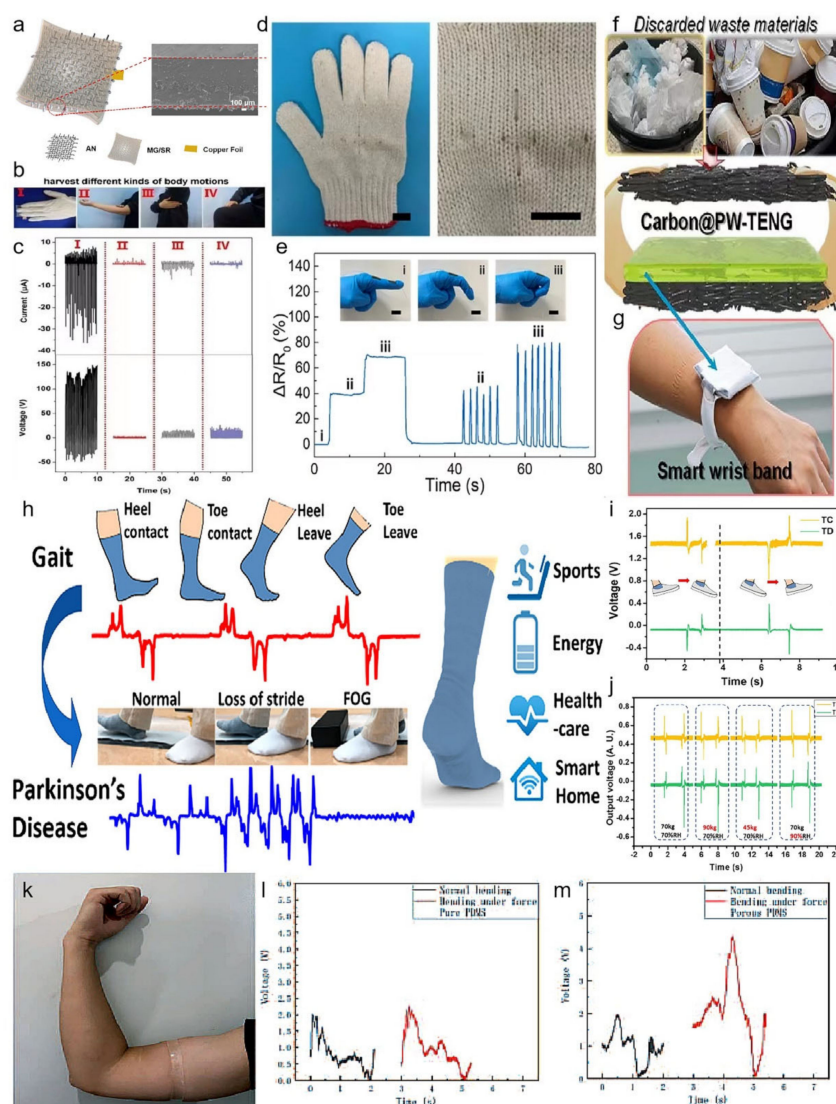
Figure 2. (**a**) Schematic diagram of flexible triboelectric nanogenerator (TENG) based on silicone rubber. The illustration is a cross-sectional view of the FE-SEM image of TENG. (**b**,**c**) Photographic images and corresponding output performance of TENG fixed at different positions of human body. (**a**–**c**) Reprinted with permission from Ref. [59]. Copyright 2022, Springer Nature Switzerland AG. (**d**) Photo of ionic gel fiber woven into fabric. (**e**) The change of relative resistance of ionic gel fiber during continuous action and holding test. (**d**,**e**) Reprinted with permission from Ref. [60]. Copyright 2022, Highly Transparent, Stretchable, and Self-Healable Ionogel for Multifunctional Sensors, Triboelectric Nanogenerator, and Wearable Fibrous Electronics. (**f**) Schematic illustration and characterization of carbon-coated paper wipes (PWs). (**g**) C@PW photos of TENG as a wearable smart wrist strap. (**f**,**g**) Reprinted with permission from Ref. [65]. Copyright 2022, ACS Publications. (**h**) A diagram of the operating mechanism of S2-sock. (**i**) Gait characterization with typical voltage signals under the contact sequences of two motions, forward: heel contact → forefoot contact, backward: forefoot contact → heel contact. All signals are collected from the sock, with the positive peak represents separation and negative peak represent the contact. (**j**) Comparison of TENG gait characterization with different weights (45, 70, and 90 kg) and humidity levels (70% RH and 90% RH). (**h**–**j**) Reprinted with permission from Ref. [66]. Copyright 2019, American Chemical Society. (**k**) Image of a FR-TENG used in testing the strength of the biceps muscle. (**l**) The output voltage of FR-TENG with pure PDMS corresponding to different force conditions. (**m**) The output voltage of FR-TENG with porous PDMS corresponding to different force conditions. (**k**–**m**) Reprinted with permission from Ref. [67]. Copyright 2021 IEEE.

3.2. Energy Monitoring of Sports

With the professionalization and commercialization of competitive sports, it is more and more difficult to improve the performance of athletes for highly developed competitive events [68], and it is increasingly necessary to improve the consciousness and refinement of training [69]. The level of science has gradually become a key factor affecting sports performance [70–74]. In sports, especially in competitive sports, the application of motion sensors can further quantify the athletes' sports behavior and kinematic mode, thus helping to improve athletes' skills and formulate scientific training plans and competitive strategies [75]. On the one hand, in the field of competitive sports, we can monitor the competitive level of athletes by improving sports venues or equipment [76–80]. For example, Hao et al. made a flexible self-rebound cambered TENG. The device has more than 3000 cycles' durability and excellent elasticity and stability. On this basis, a self-powered riding feature sensing system was designed [81]. The structure of SRC-TENG is shown in Figure 3a. The intelligent saddle can provide real-time statistical data and fall prediction for equestrian athletes and coaches (Figure 3b). This expands the application of self-powered systems to intelligent sports monitoring and assistance. Liu and Li used cotton cloth and polydimethylsiloxane (PDMS) as triboelectric layers to design a new TENG (CC-TENG), which has the advantages of portability, flexibility, and folding [82]. On this basis, they designed a self-powered long jump monitoring system based on a series of CC-TENG arrays, as shown in Figure 3c. This self-powered long jump monitoring system makes use of the response signal of TENG to the movement to realize the accurate measurement of the standing long jump performance. Ma et al. proposed a lightweight self-powered sensor based on the TENG, which can convert a small amount of mechanical energy into electrical signals. It is applied to the training of table tennis players to collect the information of the hitting position and speed of the balls (Figure 3d,e), guide the personalized training of athletes, and achieve the purpose of improving the sports level [83]. This work opens a new direction for smart sports facilities and big data analysis. On the other hand, the motion sensor can achieve the monitoring purpose through direct contact with athletes [84–86]. Wang and Gao designed a new wave structure triboelectric nanogenerator (WS-TENG) (Figure 3f), which can realize motion monitoring in arc state. According to this feature, it can be used for foul monitoring in race walking [87]. The self-powered race-walking monitoring system based on the WS-TENG is installed at the athlete's knee, and the electrical signal can reflect the bending degree of the athlete's knee when walking in the competition (Figure 3g). WS-TENG will not generate an electrical signal when the athlete does not commit a foul. However, when an athlete commits a foul due to knee bending, WS-TENG will be activated to generate an electrical signal, as shown in Figure 3h,i. Shi et al. made a flexible, breathable, and antibacterial electronic skin based on the TENG for self-powered sensing of volleyball receiving statistics and analysis [88]. As shown in Figure 3j–l, three sensing units are integrated on each arm, where s1 and s2 are the sweet points. Through the electric signal displayed by the volleyball impact, the judgment of volleyball receiving speed and receiving effect can be obtained in real time after processing, and the statistics and analysis results can also be obtained in the program. Several examples are listed above to fully illustrate the research progress of TENG in the field of sports. Table 2 compares the different properties and applications of those devices. It can be seen intuitively that the difference in the application range of the device due to its performance characteristics. Therefore, it can be seen that the triboelectric nanogenerator plays a key role in the field of sports monitoring, the development of intelligent devices, and the innovation of wearable devices.
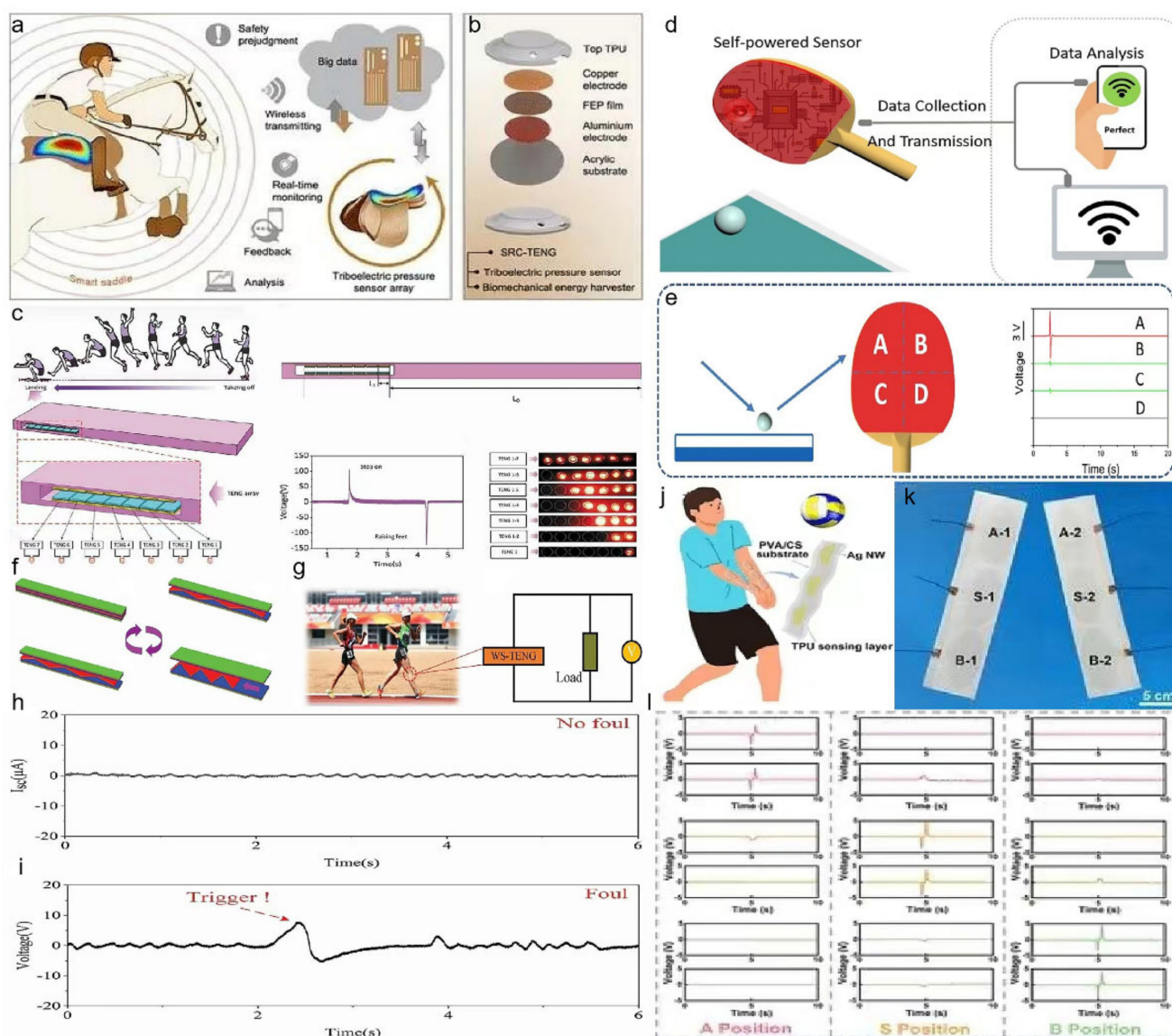
Figure 3. (**a**) Concept diagram of intelligent saddle mounted on horse, which is used to collect information and energy. (**b**) Structural design sectional view of SRE-TENG. (**a**,**b**) Reprinted with permission from Ref. [81]. Copyright 2022 American Chemical Society. (**c**) Schematic diagram of long jump monitoring system with its own power supply, electrical signal generated by CC-TENG and schematic diagram of self-powered reaction system. Reprinted with permission from Ref. [82]. Copyright 2022 Informa UK Limited. (**d**) Experimental design of big data analysis of the intelligent sensor with its own power supply in table tennis training. (**e**) The device for playing table tennis is integrated with four sensor units. The illustration shows the real-time three electric signals of the four sensor units. (**d**,**e**) Reprinted with permission from Ref. [83]. (**f**) WS-TENG workflow. (**g**) Pictures of athletes' walking competition. (**h**) The voltage signal of WS-TENG when there is no foul in the walking competition. (**i**) The voltage signal of WS-TENG when an athlete commits a foul in the walking competition. (**f**–**i**) Reprinted with permission from Ref. [87]. Copyright 2022, Informa UK Limited. (**j**) A 2 × 3 schematic diagram of integrated electronic skin array on both arms. (**k**) Display photos of 2 × 3 integrated electronic skin array. (**l**) The real-time output voltage signal when the volleyball impacts the different positions of the electronic skin array. (**j**–**l**) Reprinted with permission from Ref. [88]. Copyright 2021, American Chemical Society.

Table 2. Features and application comparison of different TENGs in sports.

Devices	Humidity Resistance	Self-Healing	Breathability	Foldability	Biocompatibility	Antibacterial	Electrical Output	Applications
SRC-TENG (Hao et al. [81])		√					~55 V	intelligent athletic facilities, and sport safety
CC-TENG (Liu et al. [82])				√			~400 V	sports training and intelligent sports
PP-TENG (Ma et al. [83])					√		~6.05 V	intelligent athletic facilities and big data analytics
WS-TENG (Wang et al. [87])				√			~420 V	athlete monitoring system
E-Skin (Shi et al. [88])	√		√			√	no clear data	wearable sports electronic device

4. Our Research Findings

In recent years, our team has been devoted to the related research of triboelectric nanogenerators in the field of sports and has made certain research progress. Based on nanogenerators made of PVDF, ionic hydrogel, and PDMS, we fabricated self-powered sensors that can be used to connect athletes' joints (Figure 4a–c) [89]. The device helps monitor the training process and improve the subject's athletic performance. Experiments have shown that it can maintain the stability of device performance in various external environments. To further improve the movement technique of skaters, we propose a portable, flexible, self-powered sensor. Figure 4d shows the output voltage of the speed skating in four states. The real-time sensor signal is used to analyze and guide the skating angle, frequency, and push-off technique of the athlete to improve the technical level of the athlete [90]. We fabricated portable and flexible self-powered biosensors based on ZnO nanowire arrays (ZnO NWs) and flexible PET substrates [91]. This device guarantees stable output performance under different humidity and strong skin adhesion, which can be used to monitor different sports including swimming (Figure 4e–g), and can even be realized by implanting biosensors in vivo to detect angiogenesis (Figure 4h–j). We combine the triboelectric nanogenerator technology with a wireless intelligent host signal processing and visualization system to propose a wireless intelligent motion correction system [92]. The system can realize the monitoring of various physical exercise types, and can accurately determine human motion behavior, as well as correct and score motion techniques (Figure 4k–m). The human–computer interaction application of the intelligent system is realized. We propose a protector and scoring system for Taekwondo competition, which is made by connecting taekwondo protective gear via a flexible lightweight triboelectric nanogenerator (FL-TENG) [93]. The system can be used to monitor the performance of athletes and improve the fairness of the game. Furthermore, FL-TENG can drive a tiny wireless device to wirelessly transmit sports data in real-time during the game (Figure 4n,o). This sustainable green self-powered sensor offers a new path in the field of sports competition monitoring. The above is part of the research results of our team. Table 3 compares the performance of the above different devices, such as moisture resistance and biocompatibility. It can be seen intuitively from the table that the selection of materials varies according to the corresponding monitoring scenarios. For instance, there is a big difference between swimming and Taekwondo. Motion monitoring needs to fully consider various special environments so that the sensor can meet the detection requirements. For example, due to the change of skin surface humidity caused by sports, the moisture resistance of the device should be taken as an important prerequisite in the selection of materials and device manufacturing of the monitoring sensor, so as to ensure the stability of subsequent device work. Our research, such as Taekwondo scoring system and action error correction, provides development prospects for the intelligence improvement of competitive sports and the realization of human–computer interaction. It is believed that in the field of sports, there is still a lot of room for triboelectric nanogenerators to play, so our team's research on triboelectric nanogenerators is ongoing.
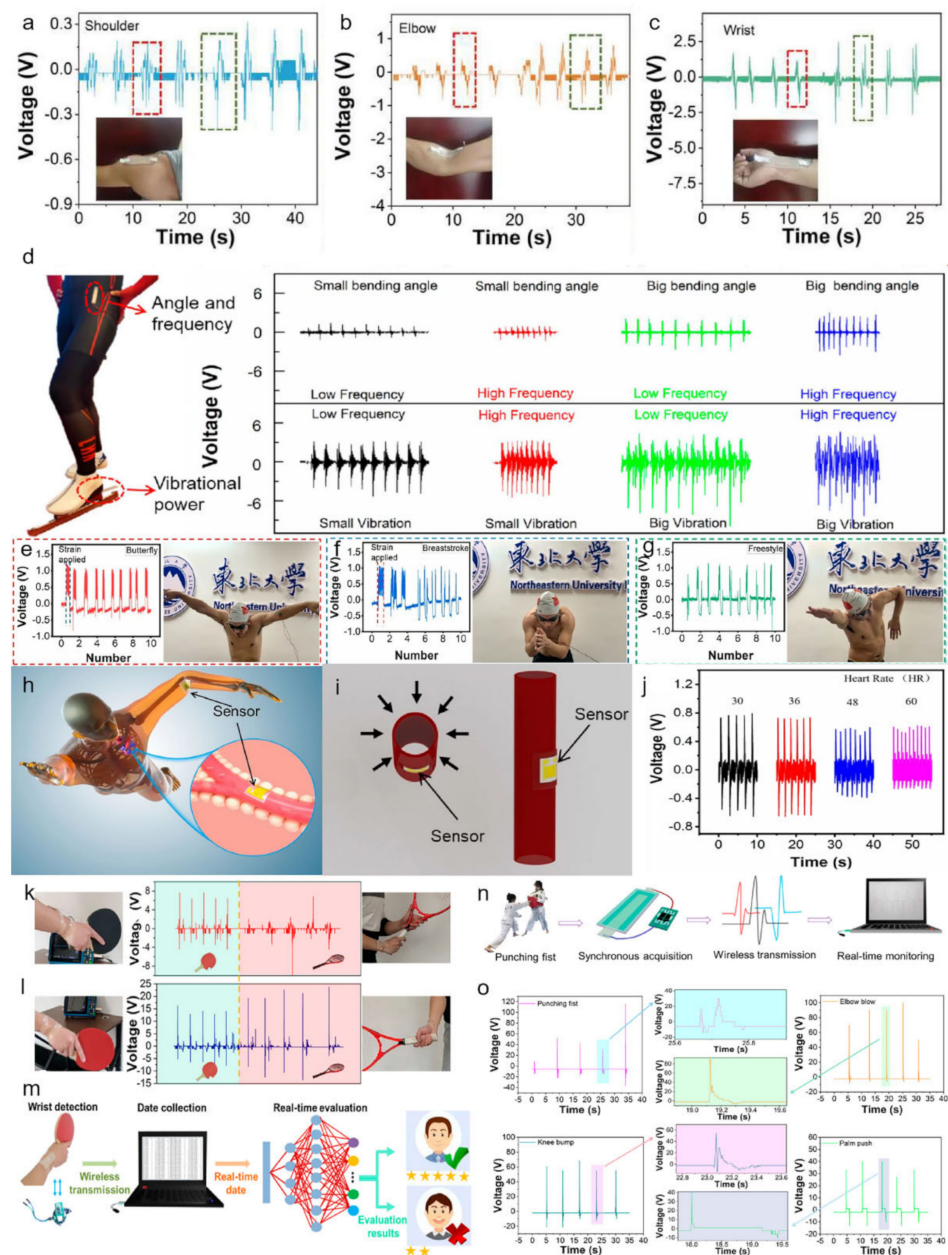
Figure 4. (**a**) Outputting piezoelectric voltage of TSB-PENG on the shoulder that does the bend and stretch motion. (**b**) Outputting piezoelectric voltage of TSB-PENG is fixed on the elbow which protrudes, bends, and stretches. (**c**) Outputting piezoelectric voltage of TSB-PENG is fixed on the wrist that protrudes, bends, and stretches. (**a–c**) Reprinted with permission from Ref. [89]. (**d**) Output piezoelectric voltage of speed skating during four sport states. Reprinted with permission from Ref. [90]. (**e**) Output piezoelectric voltage of butterfly stroke. (**f**) Output piezoelectric voltage of breaststroke. (**g**) Output piezoelectric voltage of freestyle stroke. (**h**) Simulating the monitoring of athlete's elbow joint angle and heart rate. (**i**) Simulation of arterial work and biosensor attachment position. (**j**) Output piezoelectric voltage of the arterial model monitored by biosensor. (**e–j**) Reprinted with permission from Ref. [91]. (**k**) The output voltage of the canonical table tennis attack technique with tennis swing action. (**l**) The output voltage of the incorrect table tennis attack technique and tennis swing action. (**m**) The working process of wireless intelligent motion error correction system. (**k–m**) Reprinted with permission from Ref. [92]. (**n**) Unsportsmanlike action monitoring system. (**o**) Voltage and waveform generated by punching, elbow blow, knee bump, and palm push. (**n**,**o**) Reprinted with permission from Ref. [93].

Table 3. Features and application comparison of different devices in our research.

Devices	Portability	Sensitivity	Humidity Resistance	Anticorrosion	Biocompatibility	Non-Invasiveness	Electrical Output	Applications
TSB-PENG (Jia et al. [89])	√	√		√	√	√		sports training monitoring
Sensor (Lu et al. [90])	√	√	√			√	affected by many factors	big data and IoT technologies in the sport industry
Biosensor (Mao et al. [91])	√	√	√		√	√		human–computer interaction and wireless sport big data
Motion Correction System-FL-TENG (Mao et al. [92])	√	√				√		intelligence sport big data and human–computer interaction
Protector and Scoring System-FL-TENG (Sun et al. [93])	√	√				√		sports competition monitoring

5. Conclusions and Suggestions

With the upgrading of digital technology, the relevant research on intelligent sports will also be in-depth, and intelligent sports facilities and wearable devices for sensing will continue to innovate. By examining the research progress of wearable energy sensors based on the TENG in the field of sports, it can be seen that the TENGs have great development potential in sports monitoring and sensing technology in the future and can provide technical support for the research and development of intelligent sports facilities and wearable intelligent devices.

Although the current triboelectric nanogenerator has developed to a certain extent, with the improvement of the intelligent and scientific level in the sports field, the requirements for sports data collection will gradually increase. Therefore, wearable sensors based on the TENGs need to continue to improve their performance to meet higher requirements if they want to have a broader application prospect in the sports field.

5.1. Stability of Device

In the practical application of devices, there are many environmental factors that will affect the performance of devices, such as ambient temperature, humidity, and so on. Furthermore, when monitoring human movement, the contact between perspiration and the device and other factors may cause pollution to the device. This requires that the properties of various materials should be considered when selecting the manufacturing materials, and optimal materials should be selected according to the scope of application. In addition, it can also be considered to do some treatment on the device surface, such as packaging a protective layer on the device surface to protect the device without affecting the device performance. The movement of the human body is a complex process, so it is very important to ensure the accuracy of the monitoring information data, the device performance, and the stability.

5.2. Universality of Material

At present, there are abundant choices of materials for making triboelectric nanogenerators, but it is believed that there are still many materials with good performance that have not been found and used, which requires the joint efforts of researchers and scholars. When selecting materials in the future, in addition to exploring unknown available materials, there are two aspects that cannot be ignored. First is the reuse of waste materials. The treatment and processing of waste living materials can be made into triboelectric layer to achieve the utilization of waste products and the sustainable development of energy. Second, consider the environmental protection of materials. At present, some materials have the problem of environmental pollution, which brings challenges to the sustainable development of this field. Therefore, environmental issues should be put in the first place in the selection of materials for devices in the future. Try to select green and pollution-free materials that will not cause pressure on the environmental during use and waste.

5.3. Scientificity of Application

The collection and analysis of big data is crucial to the development of intelligent sports. The energy sensor based on the TENG can be integrated and applied to various venues and equipment to realize real-time motion monitoring. However, most sensors based on the TENGs only can distinguish different movements by visually comparing the waveform or amplitude of the output voltage in motion monitoring [94–96]. In the further data analysis, there are still some deficiencies. In the future, digital technology will be fully combined with motion sensors to achieve from mechanical motion capture to physiological and biochemical presentation and behavior prediction, from general data interpretation to accurate visual analysis. Science and technology empower motion sensing equipment, comprehensively upgrade the sensing performance, truly realize the digitization of motion sensing and the scientization of result analysis, and promote the high-quality development of the sports field.

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

References

1. Luo, J.J.; Gao, W.C.; Wang, Z.L. The Triboelectric Nanogenerator as an Innovative Technology toward Intelligent Sports. *Adv. Mater.* **2021**, *33*, 2004178. [CrossRef] [PubMed]
2. Zhang, P.C.; Zhang, Z.X.; Cai, J. A foot pressure sensor based on triboelectric nanogenerator for human motion monitoring. *Microsyst. Technol.* **2021**, *27*, 3507–3512. [CrossRef]
3. Wang, C.; Hu, K.; Zhao, C.; Zou, Y.; Liu, Y.; Qu, X.; Jiang, D.; Li, Z.; Zhang, M.-R.; Li, Z. Customization of Conductive Elastomer Based on PVA/PEI for Stretchable Sensors. *Small* **2020**, *16*, 1904758. [CrossRef] [PubMed]
4. Zhao, L.; Li, H.; Meng, J.; Li, Z. The recent advances in self-powered medical information sensors. *InfoMat* **2020**, *2*, 212–234. [CrossRef]
5. Chen, J.; Huang, Y.; Zhang, N.; Zou, H.; Liu, R.; Tao, C.; Fan, X.; Wang, Z.L. Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. *Nat. Energy* **2016**, *1*, 16138. [CrossRef]
6. Liu, L.; Yu, Y.; Yan, C.; Li, K.; Zheng, Z. Wearable energy-dense and power-dense supercapacitor yarns enabled by scalable graphene-metallic textile composite electrodes. *Nat. Commun.* **2015**, *6*, 7260. [CrossRef]
7. Pu, X.; Li, L.; Liu, M.; Jiang, C.; Du, C.; Zhao, Z.; Hu, W.; Wang, Z.L. Wearable Self-Charging Power Textile Based on Flexible Yarn Supercapacitors and Fabric Nanogenerators. *Adv. Mater.* **2016**, *28*, 98–105. [CrossRef]
8. Pu, X.; Liu, M.; Li, L.; Han, S.; Li, X.; Jiang, C.; Du, C.; Luo, J.; Hu, W.; Wang, Z.L. Wearable Textile-Based In-Plane Microsupercapacitors. *Adv. Energy Mater.* **2016**, *6*, 1601254. [CrossRef]
9. Yang, Y.; Hou, X.J.; Geng, W.P.; Mu, J.L.; Zhang, L.; Wang, X.D.; He, J.; Xiong, J.J.N.; Chou, X.J. Human movement monitoring and behavior recognition for intelligent sports using customizable and flexible triboelectric nanogenerator. *Sci. China Technol. Sci.* **2022**, *65*, 826–836. [CrossRef]
10. Vo, C.P.; Shahriar, M.; Le, C.D.; Ahn, K.K. Mechanically Active Transducing Element Based on Solid-Liquid Triboelectric Nanogenerator for Self-Powered Sensing. *Int. J. Precis. Eng. Manuf. Technol.* **2019**, *6*, 741–749. [CrossRef]
11. Su, M.; Brugger, J.; Kim, B. Simply Structured Wearable Triboelectric Nanogenerator Based on a Hybrid Composition of Carbon Nanotubes and Polymer Layer. *Int. J. Precis. Eng. Manuf. Technol.* **2020**, *7*, 683–698. [CrossRef]
12. Wang, Y.; Jiang, J.; Zhang, H.; Dong, X.; Wang, L.; Ranjan, R.; Zomaya, A.Y. A scalable parallel algorithm for atmospheric general circulation models on a multi-core cluster. *Future Gener. Comput. Syst.-Int. J. Esci.* **2017**, *72*, 1–10. [CrossRef]
13. Wang, Z.L.; Jiang, T.; Xu, L. Toward the blue energy dream by triboelectric nanogenerator networks. *Nano Energy* **2017**, *39*, 9–23. [CrossRef]
14. Wang, Z.L.; Chen, J.; Lin, L. Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. *Energy Environ. Sci.* **2015**, *8*, 2250–2282. [CrossRef]
15. Wang, Z.L. Triboelectric nanogenerators as new energy technology and self-powered sensors-Principles, problems and perspectives. *Faraday Discuss.* **2014**, *176*, 447–458. [CrossRef] [PubMed]
16. Fan, F.-R.; Tian, Z.-Q.; Wang, Z.L. Flexible triboelectric generator! *Nano Energy* **2012**, *1*, 328–334. [CrossRef]

17. Yang, H.M.; Wang, M.F.; Deng, M.M.; Guo, H.Y.; Zhang, W.; Yang, H.K.; Xi, Y.; Li, X.G.; Hu, C.G.; Wang, Z.L. A full-packaged rolling triboelectric-electromagnetic hybrid nanogenerator for energy harvesting and building up self-powered wireless systems. *Nano Energy* **2019**, *56*, 300–306. [CrossRef]

18. Zhu, G.; Chen, J.; Zhang, T.; Jing, Q.; Wang, Z.L. Radial-arrayed rotary electrification for high performance triboelectric generator. *Nat. Commun.* **2014**, *5*, 3426. [CrossRef]

19. Ouyang, H.; Liu, Z.; Li, N.; Shi, B.; Zou, Y.; Xie, F.; Ma, Y.; Li, Z.; Li, H.; Zheng, Q.; et al. Symbiotic cardiac pacemaker. *Nat. Commun.* **2019**, *10*, 1821. [CrossRef]

20. Niu, S.; Wang, X.; Yi, F.; Zhou, Y.S.; Wang, Z.L. A universal self-charging system driven by random biomechanical energy for sustainable operation of mobile electronics. *Nat. Commun.* **2015**, *6*, 8975. [CrossRef]

21. 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. [CrossRef] [PubMed]

22. Wang, Z.L. Triboelectric Nanogenerators as New Energy Technology for Self-Powered Systems and as Active Mechanical and Chemical Sensors. *ACS Nano* **2013**, *7*, 9533–9557. [CrossRef]

23. Lin, Z.; Chen, J.; Li, X.; Zhou, Z.; Meng, K.; Wei, W.; Yang, J.; Wang, Z.L. Triboelectric Nanogenerator Enabled Body Sensor Network for Self-Powered Human Heart-Rate Monitoring. *ACS Nano* **2017**, *11*, 8830–8837. [CrossRef] [PubMed]

24. Heo, D.; Chung, J.; Shin, G.; Seok, M.; Lee, C.; Lee, S. Yo-Yo Inspired Triboelectric Nanogenerator. *Energies* **2021**, *14*, 1798. [CrossRef]

25. Choi, Y.W.; Jang, S.; Chun, M.-S.; Kim, S.M.; Choi, M. Efficient Microfluidic Power Generator Based on Interaction between DI Water and Hydrophobic-Channel Surface. *Int. J. Precis. Eng. Manuf. Technol.* **2018**, *5*, 255–260. [CrossRef]

26. Shi, M.; Zhang, J.; Chen, H.; Han, M.; Shankaregowda, S.A.; Su, Z.; Meng, B.; Cheng, X.; Zhang, H. Self-Powered Analogue Smart Skin. *ACS Nano* **2016**, *10*, 4083–4091. [CrossRef] [PubMed]

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. [CrossRef]

28. Zhang, H.; Yang, Y.; Su, Y.; Chen, J.; Adams, K.; Lee, S.; Hu, C.; Wang, Z.L. Triboelectric Nanogenerator for Harvesting Vibration Energy in Full Space and as Self- Powered Acceleration Sensor. *Adv. Funct. Mater.* **2014**, *24*, 1401–1407. [CrossRef]

29. Lee, K.Y.; Yoon, H.-J.; Jiang, T.; Wen, X.; Seung, W.; Kim, S.-W.; Wang, Z.L. Fully Packaged Self-Powered Triboelectric Pressure Sensor Using Hemispheres-Array. *Adv. Energy Mater.* **2016**, *6*, 1502566. [CrossRef]

30. Li, T.; Xu, Y.; Willander, M.; Xing, F.; Cao, X.; Wang, N.; Wang, Z.L. Lightweight Triboelectric Nanogenerator for Energy Harvesting and Sensing Tiny Mechanical Motion. *Adv. Funct. Mater.* **2016**, *26*, 4370–4376. [CrossRef]

31. Wu, Z.; Ding, W.; Dai, Y.; Dong, K.; Wu, C.; Zhang, L.; Lin, Z.; Cheng, J.; Wang, Z.L. Self-Powered Multifunctional Motion Sensor a, Enabled by Magnetic-Regulated Triboelectric Nanogenerator. *ACS Nano* **2018**, *12*, 5726–5733. [CrossRef] [PubMed]

32. Kim, J.E.; Kim, H.; Yoon, H.; Kim, Y.Y.; Youn, B.D. An Energy Conversion Model for Cantilevered Piezoelectric Vibration Energy Harvesters using Only Measurable Parameters. *Int. J. Precis. Eng. Manuf. Technol.* **2015**, *2*, 51–57. [CrossRef]

33. Yang, W.; Chen, J.; Jing, Q.; Yang, J.; Wen, X.; Su, Y.; Zhu, G.; Bai, P.; Wang, Z.L. 3D Stack Integrated Triboelectric Nanogenerator for Harvesting Vibration Energy. *Adv. Funct. Mater.* **2014**, *24*, 4090–4096. [CrossRef]

34. 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. [CrossRef]

35. 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. [CrossRef]

36. Lu, Z.; Jia, C.; Yang, X.; Zhu, Y.; Sun, F.; Zhao, T.; Zhang, S.; Mao, Y. A Flexible TENG Based on Micro-Structure Film for Speed Skating Techniques Monitoring and Biomechanical Energy Harvesting. *Nanomaterials* **2022**, *12*, 1576. [CrossRef]

37. Zhu, Y.; Sun, F.; Jia, C.; Zhao, T.; Mao, Y. A Stretchable and Self-Healing Hybrid Nano-Generator for Human Motion Monitoring. *Nanomaterials* **2022**, *12*, 104. [CrossRef] [PubMed]

38. Pu, X.; Guo, H.; Chen, J.; Wang, X.; Xi, Y.; Hu, C.; Wang, Z.L. Eye motion triggered self-powered mechnosensational communication system using triboelectric nanogenerator. *Sci. Adv.* **2017**, *3*, e1700694. [CrossRef]

39. Qian, Y.; Yu, J.; Zhang, F.; Kang, Y.; Su, C.; Pang, H. Facile synthesis of sub-10 nm ZnS/ZnO nanoflakes for high-performance flexible triboelectric nanogenerators. *Nano Energy* **2021**, *88*, 106256. [CrossRef]

40. Qian, Y.; Lyu, Z.; Kim, D.-H.; Kang, D.J. Enhancing the output power density of polydimethylsiloxane-based flexible triboelectric nanogenerators with ultrathin nickel telluride nanobelts as a co-triboelectric layer. *Nano Energy* **2021**, *90*, 40527821. [CrossRef]

41. Qian, Y.; Sohn, M.; He, W.; Park, H.; Subramanian, K.R.V.; Kang, D.J. A high-output flexible triboelectric nanogenerator based on polydimethylsiloxane/three-dimensional bilayer graphene/carbon cloth composites. *J. Mater. Chem. A* **2020**, *8*, 17150–17155. [CrossRef]

42. Qian, Y.; Kang, D.J. Poly(dimethylsiloxane)/ZnO Nanoflakes/Three-Dimensional Graphene Heterostructures for High-Performance Flexible Energy Harvesters with Simultaneous Piezoelectric and Triboelectric Generation. *ACS Appl. Mater. Interfaces* **2018**, *10*, 32281–32288. [CrossRef] [PubMed]

43. He, W.; Qian, Y.; Lee, B.S.; Zhang, F.; Rasheed, A.; Jung, J.-E.; Kang, D.J. Ultrahigh Output Piezoelectric and Triboelectric Hybrid Nanogenerators Based on ZnO Nanoflakes/Polydimethylsiloxane Composite Films. *ACS Appl. Mater. Interfaces* **2018**, *10*, 44415–44420. [CrossRef] [PubMed]

44. Rasel, M.S.; Maharjan, P.; Rahman, M.T.; Salauddin, M.; Rana, S.M.S.; Lee, S.; Park, J.Y. Highly Responsive and Robust Micro-/Nano-Textured Self-Powered Triboelectric Humidity Sensor. *ACS Appl. Electron. Mater.* **2021**, *3*, 4376–4387. [CrossRef]

45. Qu, M.; Shen, L.; Wang, J.; Zhang, N.; Pang, Y.; Wu, Y.; Ge, J.; Peng, L.; Yang, J.; He, J. Superhydrophobic, Humidity-Resistant, and Flexible Triboelectric Nanogenerators for Biomechanical Energy Harvesting and Wearable Self-Powered Sensing. *ACS Appl. Nano Mater.* **2022**, *5*, 9840–9851. [CrossRef]

46. Chen, X.X.; Song, Y.; Chen, H.T.; Zhang, J.X.; Zhang, H.X. An ultrathin stretchable triboelectric nanogenerator with coplanar electrode for energy harvesting and gesture sensing. *J. Mater. Chem. A* **2017**, *5*, 12361–12368. [CrossRef]

47. Zhang, L.; Su, C.; Cui, X.; Li, P.P.; Wang, Z.; Gu, L.; Tang, Z.X. Free-Standing Triboelectric Layer-Based Full Fabric Wearable Nanogenerator for Efficient Mechanical Energy Harvesting. *ACS Appl. Electron. Mater.* **2020**, *2*, 3366–3372. [CrossRef]

48. Yang, Y.Q.; Sun, N.; Wen, Z.; Cheng, P.; Zheng, H.C.; Shao, H.Y.; Xia, Y.J.; Chen, C.; Lan, H.W.; Xie, X.K.; et al. Liquid-Metal-Based Super-Stretchable and Structure-Designable Triboelectric Nanogenerator for Wearable Electronics. *ACS Nano* **2018**, *12*, 2027–2034. [CrossRef]

49. Li, H.; Zhang, Y.J.; Wu, Y.H.; Zhao, H.; Wang, W.C.; He, X.; Zheng, H.W. A stretchable triboelectric nanogenerator made of silver-coated glass microspheres for human motion energy harvesting and self-powered sensing applications. *Beilstein J. Nanotechnol.* **2021**, *12*, 402–412. [CrossRef] [PubMed]

50. Wang, Y.F.; Jin, X.; Wang, W.Y.; Niu, J.R.; Zhu, Z.T.; Lin, T. Efficient Triboelectric Nanogenerator (TENG) Output Management for Improving Charge Density and Reducing Charge Loss. *ACS Appl. Electron. Mater.* **2021**, *3*, 532–549. [CrossRef]

51. Matin Nazar, A.; Idala Egbe, K.-J.; Abdollahi, A.; Hariri-Ardebili, M.A. Triboelectric Nanogenerators for Energy Harvesting in Ocean: A Review on Application and Hybridization. *Energies* **2021**, *14*, 5600. [CrossRef]

52. Peng, J.; Kang, S.D.; Snyder, G.J. Optimization principles and the figure of merit for triboelectric generators. *Sci. Adv.* **2017**, *3*, eaap8576. [CrossRef] [PubMed]

53. Chen, C.; Guo, H.; Chen, L.; Wang, Y.-C.; Pu, X.; Yu, W.; Wang, F.; Du, Z.; Wang, Z.L. Direct Current Fabric Triboelectric Nanogenerator for Biomotion Energy Harvesting. *ACS Nano* **2020**, *14*, 4585–4594. [CrossRef] [PubMed]

54. Li, S.; Zhong, Q.; Zhong, J.; Cheng, X.; Wang, B.; Hu, B.; Zhou, J. Cloth-Based Power Shirt for Wearable Energy Harvesting and Clothes Ornamentation. *ACS Appl. Mater. Interfaces* **2015**, *7*, 14912–14916. [CrossRef]

55. Cao, R.; Pu, X.; Du, X.; Yang, W.; Wang, J.; Guo, H.; Zhao, S.; Yuan, Z.; Zhang, C.; Li, C.; et al. Screen-Printed Washable Electronic Textiles as Self-Powered Touch/Gesture Tribo-Sensors for Intelligent Human-Machine Interaction. *ACS Nano* **2018**, *12*, 5190–5196. [CrossRef]

56. Zou, Y.; Raveendran, V.; Chen, J. Wearable triboelectric nanogenerators for biomechanical energy harvesting. *Nano Energy* **2020**, *77*, 105303. [CrossRef]

57. Wang, H.; Han, M.; Song, Y.; Zhang, H. Design, manufacturing and applications of wearable triboelectric nanogenerators. *Nano Energy* **2021**, *81*, 105627. [CrossRef]

58. Yi, F.; Zhang, Z.; Kang, Z.; Liao, Q.; Zhang, Y. Recent Advances in Triboelectric Nanogenerator-Based Health Monitoring. *Adv. Funct. Mater.* **2019**, *29*, 1808849. [CrossRef]

59. Zu, G.Q.; Wei, Y.; Sun, C.Y.; Yang, X.J. Humidity-resistant, durable, wearable single-electrode triboelectric nanogenerator for mechanical energy harvesting. *J. Mater. Sci.* **2022**, *57*, 2813–2824. [CrossRef]

60. Sun, L.J.; Huang, H.F.; Ding, Q.Y.; Guo, Y.F.; Sun, W.; Wu, Z.C.; Qin, M.L.; Guan, Q.B.; You, Z.W. Highly Transparent, Stretchable, and Self-Healable Ionogel for Multifunctional Sensors, Triboelectric Nanogenerator, and Wearable Fibrous Electronics. *Adv. Fiber Mater.* **2022**, *4*, 98–107. [CrossRef]

61. Roy, S.; Maji, P.K.; Goh, K.-L. Sustainable design of flexible 3D aerogel from waste PET bottle for wastewater treatment to energy harvesting device. *Chem. Eng. J.* **2020**, *413*, 127409. [CrossRef]

62. Li, M.J.; Cheng, W.Y.; Li, Y.C.; Wu, H.M.; Wu, Y.C.; Lu, H.W.; Cheng, S.L.; Li, L.; Chang, K.C.; Liu, H.J.; et al. Deformable, resilient, and mechanically-durable triboelectric nanogenerator based on recycled coffee waste for wearable power and self-powered smart sensors. *Nano Energy* **2020**, *79*, 105405. [CrossRef]

63. Feng, X.; Li, Q.; Wang, K. Waste Plastic Triboelectric Nanogenerators Using Recycled Plastic Bags for Power Generation. *ACS Appl. Mater. Interfaces* **2021**, *13*, 400–410. [CrossRef] [PubMed]

64. Yao, C.; Hernandez, A.; Yu, Y.; Cai, Z.; Wang, X. Triboelectric nanogenerators and power-boards from cellulose nanofibrils and recycled materials. *Nano Energy* **2016**, *30*, 103–108. [CrossRef]

65. Dudem, B.; Dharmasena, R.D.I.G.; Riaz, R.; Vivekananthan, V.; Wijayantha, K.G.U.; Lugli, P.; Petti, L.; Silva, S.R.P. Wearable Triboelectric Nanogenerator from Waste Materials for Autonomous Information Transmission via Morse Code. *ACS Appl. Mater. Interfaces* **2022**, *14*, 5328–5337. [CrossRef]

66. Zhu, M.L.; Shi, Q.F.; He, T.Y.Y.; Yi, Z.R.; Ma, Y.M.; Yang, B.; Chen, T.; Lee, C. Self-Powered and Self-Functional Cotton Sock Using Piezoelectric and Triboelectric Hybrid Mechanism for Healthcare and Sports Monitoring. *ACS Nano* **2019**, *13*, 1940–1952. [CrossRef]

67. Hu, X.W.; Liu, L.; Xie, M.J.; Li, J.; Ou-Yang, W. High-Output Flexible Ring-Structure Triboelectric Nanogenerators for Wearable Electronics and Sports Monitoring. In Proceedings of the Photonics and Electromagnetics Research Symposium (PIERS), Hangzhou, China, 21–25 November 2021; pp. 1032–1039.

68. Zhang, B.; Wu, Z.; Lin, Z.; Guo, H.; Chun, F.; Yang, W.; Wang, Z.L. All-in-one 3D acceleration sensor based on coded liquid-metal triboelectric nanogenerator for vehicle restraint system. *Mater. Today* **2021**, *43*, 37–44. [CrossRef]

69. Ahmadi, A.; Mitchell, E.; Richter, C.; Destelle, F.; Gowing, M.; O'Connor, N.E.; Moran, K. Toward Automatic Activity Classification and Movement Assessment during a Sports Training Session. *IEEE Internet Things J.* **2015**, *2*, 23–32. [CrossRef]

70. Luo, Y.; Zhao, T.; Dai, Y.; Li, Q.; Fu, H. Flexible nanosensors for non-invasive creatinine detection based on triboelectric nanogenerator and enzymatic reaction (vol 320, 112585, 2021). *Sens. Actuators A Phys.* **2021**, *324*, 112585. [CrossRef]

71. Zhao, T.; Zheng, C.; He, H.; Guan, H.; Zhong, T.; Xing, L.; Xue, X. A self-powered biosensing electronic-skin for real-time sweat Ca2+ detection and wireless data transmission. *Smart Mater. Struct.* **2019**, *28*, 085015. [CrossRef]

72. Bermon, S.; Hirschberg, A.L.; Kowalski, J.; Eklund, E. Serum androgen levels are positively correlated with athletic performance and competition results in elite female athletes. *Br. J. Sports Med.* **2018**, *52*, 1531–1532. [CrossRef] [PubMed]

73. He, H.; Zhao, T.; Guan, H.; Zhong, T.; Zeng, H.; Xing, L.; Zhang, Y.; Xue, X. A water-evaporation-induced self-charging hybrid power unit for application in the Internet of Things. *Sci. Bull.* **2019**, *64*, 1409–1417. [CrossRef]

74. Zhang, W.; Guan, H.; Zhong, T.; Zhao, T.; Xing, L.; Xue, X. Wearable Battery-Free Perspiration Analyzing Sites Based on Sweat Flowing on ZnO Nanoarrays. *Nano-Micro Lett.* **2020**, *12*, 105. [CrossRef]

75. Nunes Rodrigues, A.C.; Pereira, A.S.; Sousa Mendes, R.M.; Araujo, A.G.; Couceiro, M.S.; Figueiredo, A.J. Using Artificial Intelligence for Pattern Recognition in a Sports Context. *Sensors* **2020**, *20*, 3040. [CrossRef] [PubMed]

76. Zou, Y.J.; Libanori, A.; Xu, J.; Nashalian, A.; Chen, J. Triboelectric Nanogenerator Enabled Smart Shoes for Wearable Electricity Generation. *Research* **2020**, *2020*, 7158953. [CrossRef]

77. He, C.; Zhu, W.J.; Chen, B.D.; Xu, L.; Jiang, T.; Han, C.B.; Gu, G.Q.; Li, D.C.; Wang, Z.L. Smart Floor with Integrated Triboelectric Nanogenerator as Energy Harvester and Motion Sensor. *ACS Appl. Mater. Interfaces* **2017**, *9*, 26126–26133. [CrossRef]

78. Zhang, P.C.; Cai, J. A self-powered grip exerciser based on triboelectric nanogenerator for intelligent sports monitoring. *Mater. Technol.* **2021**, *37*, 753–759. [CrossRef]

79. Shen, X.A.; Han, W.J.; Jiang, Y.F.; Ding, Q.J.; Li, X.; Zhao, X.; Li, Z.Y. Punching pores on cellulose fiber paper as the spacer of triboelectric nanogenerator for monitoring human motion. *Energy Rep.* **2020**, *6*, 2851–2860. [CrossRef]

80. Peng, F.; Liu, D.; Zhao, W.; Zheng, G.; Ji, Y.; Dai, K.; Mi, L.; Zhang, D.; Liu, C.; Shen, C. Facile fabrication of triboelectric nanogenerator based on low-cost thermoplastic polymeric fabrics for large-area energy harvesting and self-powered sensing. *Nano Energy* **2019**, *65*, 104068. [CrossRef]

81. Hao, Y.T.; Wen, J.; Gao, X.B.; Nan, D.; Pan, J.; Yang, Y.H.; Chen, B.D.; Wang, Z.L. Self-Rebound Cambered Triboelectric Nanogenerator Array for Self-Powered Sensing in Kinematic Analytics. *Acs Nano* **2022**, *16*, 1271–1279. [CrossRef]

82. Liu, R.; Li, M.P. A textile-based triboelectric nanogenerator for long jump monitoring. *Mater. Technol.* **2022**. [CrossRef]

83. Ma, X.F.; Liu, X.; Li, X.X.; Ma, Y.F. Light-Weight, Self-Powered Sensor Based on Triboelectric Nanogenerator for Big Data Analytics in Sports. *Electronics* **2021**, *10*, 2322. [CrossRef]

84. Zou, Y.; Tan, P.; Shi, B.; Ouyang, H.; Jiang, D.; Liu, Z.; Li, H.; Yu, M.; Wang, C.; Qu, X.; et al. A bionic stretchable nanogenerator for underwater sensing and energy harvesting. *Nat. Commun.* **2019**, *10*, 2695. [CrossRef]

85. Gogurla, N.; Roy, B.; Park, J.-Y.; Kim, S. Skin-contact actuated single-electrode protein triboelectric nanogenerator and strain sensor for biomechanical energy harvesting and motion sensing. *Nano Energy* **2019**, *62*, 674–681. [CrossRef]

86. Qi, K.; He, J.; Wang, H.; Zhou, Y.; You, X.; Nan, N.; Shao, W.; Wang, L.; Ding, B.; Cui, S. A Highly Stretchable Nanofiber-Based Electronic Skin with Pressure-, Strain-, and Flexion-Sensitive Properties for Health and Motion Monitoring. *ACS Appl. Mater. Interfaces* **2017**, *9*, 42951–42960. [CrossRef] [PubMed]

87. Wang, Z.; Gao, W.Y. A wave structure triboelectric nanogenerator for race walking motion sensing. *Mater. Technol.* **2022**. [CrossRef]

88. Shi, Y.P.; Wei, X.L.; Wang, K.M.; He, D.D.; Yuan, Z.H.; Xu, J.H.; Wu, Z.Y.; Wang, Z.L. Integrated All-Fiber Electronic Skin Toward Self-Powered Sensing Sports Systems. *ACS Appl. Mater. Interfaces* **2021**, *13*, 50329–50337. [CrossRef]

89. Jia, C.; Zhu, Y.; Sun, F.; Zhao, T.; Xing, R.; Mao, Y.; Zhao, C. A Flexible and Stretchable Self-Powered Nanogenerator in Basketball Passing Technology Monitoring. *Electronics* **2021**, *10*, 2584. [CrossRef]

90. Lu, Z.; Zhu, Y.; Jia, C.; Zhao, T.; Bian, M.; Jia, C.; Zhang, Y.; Mao, Y. A Self-Powered Portable Flexible Sensor of Monitoring Speed Skating Techniques. *Biosensors* **2021**, *11*, 108. [CrossRef]

91. Mao, Y.; Zhu, Y.; Zhao, T.; Jia, C.; Bian, M.; Li, X.; Liu, Y.; Liu, B. A Portable and Flexible Self-Powered Multifunctional Sensor for Real-Time Monitoring in Swimming. *Biosensors* **2021**, *11*, 147. [CrossRef]

92. Mao, Y.; Sun, F.; Zhu, Y.; Jia, C.; Zhao, T.; Huang, C.; Li, C.; Ba, N.; Che, T.; Chen, S. Nanogenerator-Based Wireless Intelligent Motion Correction System for Storing Mechanical Energy of Human Motion. *Sustainability* **2022**, *14*, 6944. [CrossRef]

93. Sun, F.; Zhu, Y.; Jia, C.; Ouyang, B.; Zhao, T.; Li, C.; Ba, N.; Li, X.; Chen, S.; Che, T.; et al. A Flexible Lightweight Triboelectric Nanogenerator for Protector and Scoring System in Taekwondo Competition Monitoring. *Electronics* **2022**, *11*, 1306. [CrossRef]

94. Zhao, T.; Fu, Y.; Sun, C.; Zhao, X.; Jiao, C.; Du, A.; Wang, Q.; Mao, Y.; Liu, B. Wearable biosensors for real-time sweat analysis and body motion capture based on stretchable fiber-based triboelectric nanogenerators. *Biosens. Bioelectron.* **2022**, *205*, 114115. [CrossRef] [PubMed]

95. Park, J.H.; Wu, C.; Sung, S.; Kim, T.W. Ingenious use of natural triboelectrification on the human body for versatile applications in walking energy harvesting and body action monitoring. *Nano Energy* **2019**, *57*, 872–878. [CrossRef]
96. Yang, D.; Ni, Y.; Kong, X.; Li, S.; Chen, X.; Zhang, L.; Wang, Z.L. Self-Healing and Elastic Triboelectric Nanogenerators for Muscle Motion Monitoring and Photothermal Treatment. *ACS Nano* **2021**, *15*, 14653–14661. [CrossRef]