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The Triboelectric Nanogenerator as an Innovative Technology toward Intelligent Sports

*Jianjun Luo, Wenchao Gao, and Zhong Lin Wang**

In the new era of the Internet-of-Things, athletic big data collection and analysis based on widely distributed sensing networks are particularly important in the development of intelligent sports. Conventional sensors usually require an external power supply, with limitations such as limited lifetime and high maintenance cost. As a newly developed mechanical energy harvesting and self-powered sensing technology, the triboelectric nanogenerator (TENG) shows great potential to overcome these limitations. Most importantly, TENGs can be fabricated using wood, paper, fibers, and polymers, which are the most frequently used materials for sports. Recent progress on the development of TENGs for the field of intelligent sports is summarized. First, the working mechanism of TENG and its association with athletic big data are introduced. Subsequently, the development of TENG-based sports sensing systems, including smart sports facilities and wearable equipment is highlighted. At last, the remaining challenges and open opportunities are also discussed.

1. Introduction

With the rapid development of the Internet-of-Things (IoT),[1,2] big data,[3,4] and cloud computing[5,6] over the last few decades, the field of sports has undergone a revolutionary change, entering the digital age. Effective data collection and analysis are the prerequisites and crucial aspects for the development of intelligent sports.[7,8] Real-time data acquisition relies widely on distributed sensors, and different sensing technologies have been reported for field of intelligent sports based on various detection mechanisms including optical, capacitive, resistive, geomagnetic, chemical, and thermosensitive,[9–14] which possess advantages of high sensitivity and functional diversification. However, a common drawback of them is that external power supply is generally required for their operation. Although the power for driving each sensor is becoming lower with the technical advances, the number of such units can be huge in sports applications. Considering limitations such as limited lifetime, high replacement cost, and environmental pollution when using batteries, it is highly necessary to develop a maintenance-free and sustainable sensing technology to monitor the sports data during physical activities.

In 2012, the triboelectric nanogenerator (TENG) for converting distributed, irregular, and low-frequency mechanical energy into electric power,[15] with unique advantages of low cost, simple structure, high efficiency, and diverse material options, was developed by Wang and co-workers.[16–22] Moreover, TENGs can also operate as self-powered sensors for tactile, pressure, acceleration, or motion sensing without an external power supply.[23–29] Enhanced triboelectric sensing signals and wireless sensing of TENG-based self-powered system could be further realized by integration with signal processing and transmission modules.[30,31] Therefore, TENG technology will open up bright and broad application prospects in the field of intelligent sports, where large amounts of distributed monitoring devices should be applied.

Here, we focus on recent advances in the development of TENGs for the field of smart sports. We first introduce the working principle of TENG and its association with athletic big data. The recent innovative development of TENG-based intelligent sports sensing systems is then highlighted. **Figure 1** illustrates the constitution of the TENG-based self-powered smart system. First, TENGs can be installed in sports facilities to record various kinds of mechanical triggering signals during physical activities. For monitoring the physiological signals of a human body, TENGs can also be designed as wearable equipment. Such an enormous number of TENG-based smart devices could be connected together into a network and widely applied in the sports domain. With the help of the IoT, athletic big data analysis, and cloud computing technologies, sports training, and competition will become smarter in the future. Lastly, we briefly discuss the current challenges and future perspectives of TENGs toward intelligent sports.

Dr. J. Luo, Prof. Z. L. Wang
CAS Center for Excellence in Nanoscience
Beijing Key Laboratory of Micro-nano Energy and Sensor
Beijing Institute of Nanoenergy and Nanosystems
Chinese Academy of Sciences
Beijing 100083, P. R. China
E-mail: zhong.wang@mse.gatech.edu

Dr. J. Luo, Prof. Z. L. Wang
School of Nanoscience and Technology
University of Chinese Academy of Sciences
Beijing 100049, P. R. China

Dr. W. Gao
Department of Civil Engineering
Monash University
Clayton 3800, Australia

Prof. Z. L. Wang
School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245, USA

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Figure 1. Schematic illustration of TENGs for intelligent sports based on the IoT, big data, and cloud computing technologies.

2. Triboelectric Nanogenerator

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.[32,33] Since its invention in 2012, four different fundamental modes of the TENG have been proposed, including the vertical contact-separation mode, lateral sliding mode, single-electrode mode, and freestanding triboelectric-layer mode.[34,35] Considering the similarity of their working principles, we use the contact-separation mode as an example to illustrate the detailed working principle of TENG (**Figure 2**). During sports activities, mechanical motions are ubiquitous, and the interaction between the human body, sports facility, and wearable equipment will certainly create triboelectric charges, which could provide vast space for the application of TENG technology. In the original state, no charge is generated or inducted (Figure 2I). When the surfaces of two different materials are brought into physical contact, triboelectric charges will be created on the two contacted surfaces (Figure 2II). Then a potential difference can be established once the two surfaces are separated, resulting in an instantaneous electron flow from bottom electrode to top electrode (Figure 2III), finally reaching equilibrium when the two surfaces are fully separated (Figure 2IV). Once the two surfaces are pressed together again, the electrostatic induced charges will flow back through the external load to compensate for the electric potential difference (Figure 2V). The generated current signal in this entire process is shown in the bottom left of Figure 2. Except for the TENG technology, extensive researches have been reported for biomechanical energy harvesting based on various mechanisms, including electromagnetic, electrostatic, and piezoelectric.[32,36,37] **Table 1** presents a detailed comparison between these four technologies in terms of their mechanisms, advantages, and disadvantages. Given that the low-frequency characteristic of most mechanical motions in sports activities, and the broad use of TENGs as self-powered sensors, the TENG technology has obvious advantages for applying in the sports domain. Therefore, TENGs can be rationally designed on the basis of the demand of different sports items for realizing efficient mechanical energy harvesting and self-powered sensing.

3. Athletic Big Data

As defined by Gartner, big data is high-volume, high-velocity, and/or high-variety information assets that demand cost-effective, innovative forms of information processing for enhanced insight and decision making, which will be important for

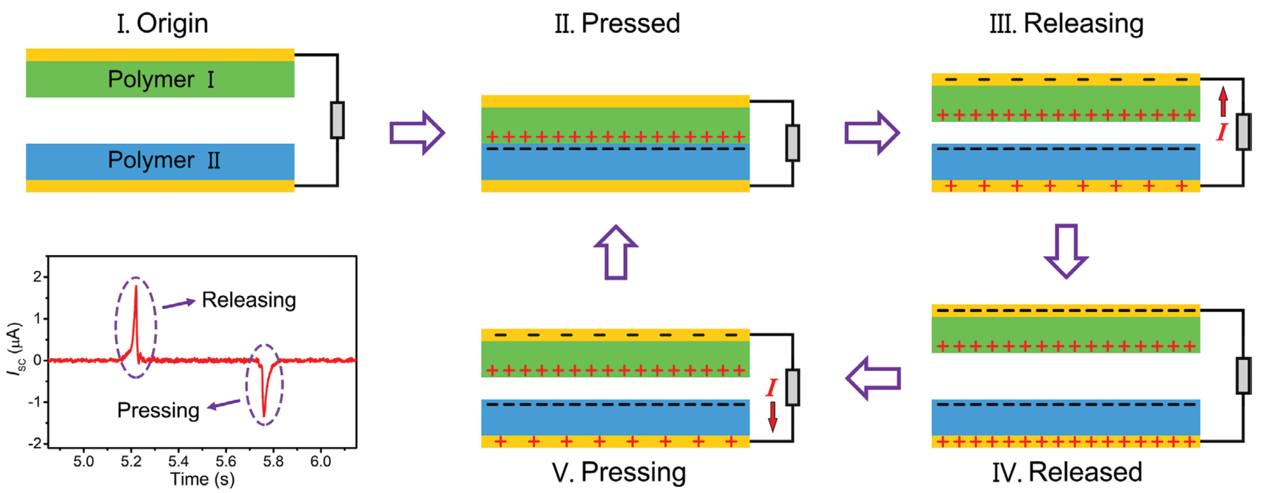

Figure 2. Sketches illustrating the working principle of the TENG in contact-separation mode.

artificial intelligence.[38–40] Athletic big data are coming from everywhere, every second during sports activities, including speed, heart rate, physiological data, racing environment, health data, movements, and so on, which can accurately reflect the exercise performance of the athletes, as shown in **Figure 3**. Most of these sports data are expressed in the form of mechanical signals, which is suitable to be directly transformed into electrical signals by utilizing TENG technology. In the future, athletic big data analytics will bring profound changes to the traditional sports industry as a new driving force. With fabulous advantages of self-powered, maintenance-free, and cost-effective, TENG technology is bound to have extensive application prospects to the sports industry and provide a vital foundation of athletic big data analytics. By employing the artificial intelligence and cloud computing technologies in the near future, the sports data collected by TENGs could be used for improving sports performances, setting up scientific exercise programs and competition strategies, or preventing sports injury after automatic data analysis, as well as creating personal databases for athletes.

4. TENG-Based Intelligent Sports

4.1. Sports Facility

Owing to their characteristics including diverse material selectivity, size controllability, and simple structure, TENGs can be easily installed on the surface or inside sports facilities, including sporting equipment and athletics fields, to record the motion information. A recent study proposed a flexible and durable wood-based TENG for fabricating a smart ping-pong table, which could directly convert the impacts between the ping-pong ball and the table surface into electrical signals (**Figure 4**a).[41] By setting a TENG array on the table, a self-powered falling point distribution statistical system that could perform velocity sensing, motion path tracking, and distribution statistics was successfully realized, as shown in Figure 4b. Through precisely detecting and collecting the training data for big data analytics, scientifically training evaluation and guidance can be provided for athletes. Furthermore, a self-powered edge ball judgement system was also constructed for assisting referees' decision in real time. When the ping-pong ball impacts the top edge of the table, a distinct output signal will be generated by top TENG (Figure 4c). By numeric comparison of the synchronous output of the two TENGs, two kinds of edge balls can be accurately determined. Meng et al. developed a fully enclosed bearing-structured TENG (Figure 4d).[42] Multiple motion parameters of a bicycle could be immediately derived by installing it on a bicycle wheel, solely after analyzing the produced electric signals during riding, including speed, acceleration, and traveling distance (Figure 4e). Wu et al. also reported a cylindrical translational-rotary TENG, which could be used as a self-powered acceleration, force, and rotational parameter sensor.[43] Figure 4f shows the structure diagram of the translational-rotary TENG. By embedding the

Table 1. Comparison of the biomechanical energy harvesting technologies based on electromagnetic, electrostatic, piezoelectric, and triboelectric effects for illustrating their advantages and disadvantages.

	Electromagnetic	Electrostatic	Piezoelectric	Triboelectric
Mechanism	Electromagnetic induction	Electrostatic induction	Piezoelectric effect and electrostatic induction	Triboelectric effect and electrostatic induction
Pros	High efficiency at high frequency; High durability, long life	Light weight	Easy to scale down to nanoscale	High efficiency at low frequency; Low cost, low density, light weight; Multiple working modes; Diverse choice of materials; Broad use as sensors
Cons	Heavy, high density, high cost	Low output, precharge required	Low output, low efficiency	Low durability

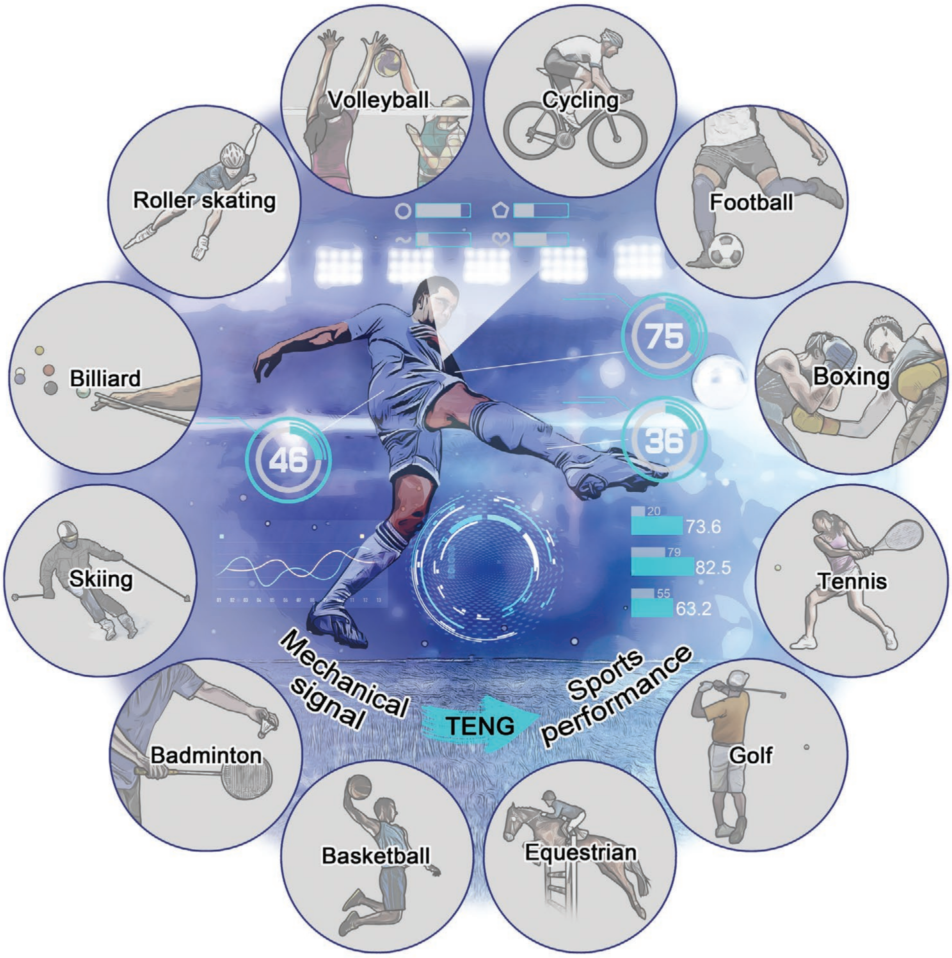

Figure 3. Schematic illustration of the athletic big data.

translational–rotary TENGs, a smart golf club was fabricated to measure the hitting force and swing angle, demonstrating its feasibility in intelligent sports application (Figure 4g). Further, Peng et al. designed a durable and large-area fabric-based TENG and developed a self-powered pugilism training monitoring system (Figure 4h).[44] Compared with high-speed cameras, this system shows various advantages such as low cost and comprehensive information acquisition (including speed, strength, and the quantity of punch). Wang and co-workers designed a yarn-based TENG for developing the self-counting skipping rope (Figure 4i).[45] By collecting the sports data, a rational exercise program can be obtained. Cao and co-workers designed a TENG-based smart floor, which could be used for monitoring the moving information during physical activities.[46] Several other studies also attempted to apply TENGs to smart combat sports or snow-related sports.[47,48] These TENG-based smart sports facilities are capable of effectively measuring and quantifying the movements of athletes in different sports items, as well as recording their exercise habits for big data analysis, which will be beneficial for their performance improvement.

4.2. Wearable Equipment

In addition to sports facilities, TENGs can also be designed as wearable equipment to monitor the physiological signals of the human body using flexible, stretchable, and biocompatible materials, such as fabric or silicone. Recently, to construct an underwater wireless human motion monitoring system, Zou et al. developed a bionic stretchable TENG by mimicking the structure of ion channels in an electric eel (**Figure 5**a).[49] Figure 5b shows the relationship between the curvature of the elbow and the output voltage of the TENG fixed on a human's arm. The motion signals in swimming can be further acquired in real time for sports training and safety by wearing four stretchable TENGs on the elbows and knees, respectively (Figure 5c). Fan et al. reported an all-textile TENG array that could be directly incorporated into different sites of the fabric to monitor the physiological signals (Figure 5d).[50] Figure 5e shows the all-textile TENG stitched into a piece of cloth. Lee and co-workers designed a self-powered haptic-feedback smart glove consisting of triboelectric tactile sensors and piezoelectric mechanical stimulators.[51] Figure 5f shows the structure design of the elastomer-based triboelectric palm

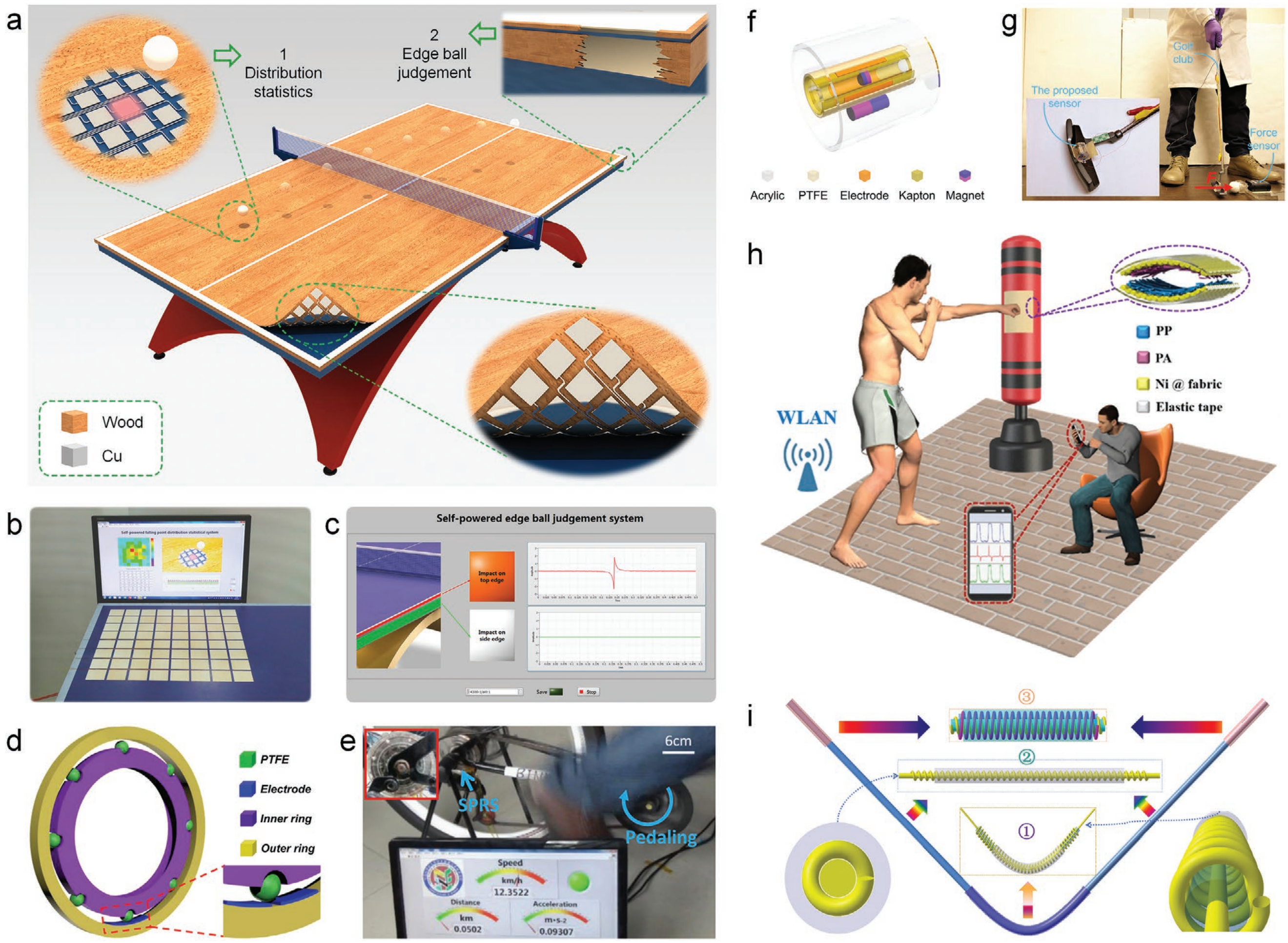

Figure 4. TENG-based smart sports facilities. a) Schematic illustration of the natural wood-based smart ping-pong table. b) Demonstration of the self-powered falling point distribution statistical system. c) Demonstration of the self-powered edge ball judgement system at the moment of top edge ball appeared. a–c) Reproduced with permission.[41] Copyright 2019, Springer Nature. d) Schematic illustration of the fully enclosed bearing-structured TENG. e) Demonstration of the self-powered rotation rate monitoring system for measuring motion parameters of a bicycle. d,e) Reproduced with permission.[42] Copyright 2015, Elsevier B.V. f) Schematic illustration of the translational-rotary TENG. g) Application of the translational–rotary TENG in golf. f,g) Reproduced with permission.[43] Copyright 2019, Wiley-VCH. h) Schematic illustration of the self-powered wireless pugilism training monitoring system. Reproduced with permission.[44] Copyright 2019, Elsevier B.V. i) Schematic illustration of the TENG-based self-counting skipping rope. Reproduced with permission.[45] Copyright 2018, Wiley-VCH.

sensor, which is capable of simultaneously detecting the normal and shear forces. The proposed glove was further applied in a baseball game program to perform the manipulation of the baseball bat and haptic stimulation from the strike event (Figure 5g). Subsequently, they developed a machine learning glove using the self-powered superhydrophobic triboelectric textile.[52] By leveraging machine learning technology, real-time accurate virtual reality/augmented reality (VR/AR) controls including baseball pitching and gun shooting are successfully achieved by gesture recognition based on the TENG. These two works are believed to expand the application area of TENG technology in VR/AR sports training. For detecting the muscle activity, You and co-workers also reported a biocompatible and stretchable TENG bandage.[53] Figure 5h shows the schematic illustration of the TENG band, which is consisted of a rubber tube filling with physiological saline. Figure 5i shows the photographs of the band in twisted and stretched states, demonstrating its excellent softness and stretchability. By tying the TENG band on the arm or leg, quantitative motion information such as the movement distance, steps, and speed can be accurately acquired (Figure 5j). Lin et al. recently reported a TENG-based smart insole for multi-functional gait monitoring.[54] As shown in Figure 5k, two novel designed triboelectric sensors are integrated in the front and rear of the insole. Each sensor consists of two parts: a TENG part on top of an elastic air chamber. Lee and co-workers also designed a self-powered sock using a triboelectric and piezoelectric hybrid mechanism (Figure 5l).[55] By integrating the PEDOT:PSS-coated fabric TENG and piezoelectric sensors, the smart sock could realize diversified functions, including motion tracking, walking pattern recognition, as well as sweat level sensing. Several other TENG-based wearable sports equipment for different body parts were also reported.[56–58] The above-mentioned TENG-based smart wearable equipment will play a significant role in sports, healthcare, and smart home applications.

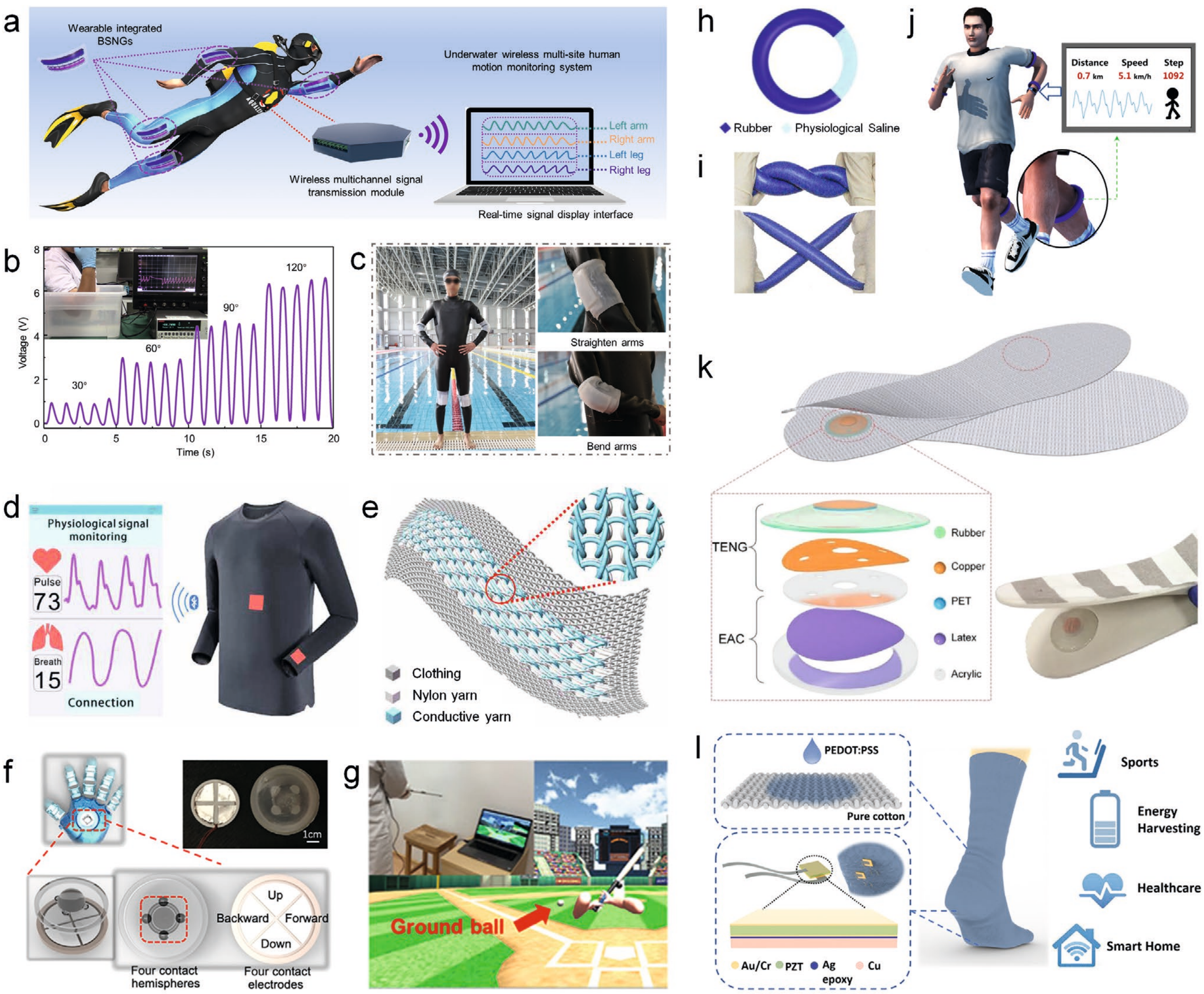

Figure 5. TENG-based smart wearable equipment. a) Illustration of underwater wireless multi-site human motion monitoring system based on bionic stretchable TENG. b) Signal outputs of TENG fixed on the elbow at different curvature motions. c) Photographs of integrated wearable bionic stretchable TENG worn on the arthrosis of human. a–c) Reproduced with permission.[49] Copyright 2019, Springer Nature. d) Illustration of two all-textile TENGs integrated into a shirt for the monitoring of pulse and respiratory signals in real time. e) Schematic illustration of the combination of TENG and clothes. The inset shows the enlarged view of the TENG. d,e) Reproduced with permission.[50] Copyright 2020, The Authors, published by The American Association for the Advancement of Science. f) Design and photograph of the triboelectric palm sensor for fabricating the haptic-feedback smart glove. g) Integrated demonstration of the smart glove in baseball gaming program. f,g) Reproduced with permission.[51] Copyright 2020, The Authors, published by AAAS. Reprinted/adapted from ref. [51]. © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/. h) Schematic illustration of the TENG band. i) Photographs of the TENG band in twisted or stretched status. j) Schematic illustration of the TENG band for quantitative motion information monitoring. h–j) Reproduced with permission.[53] Copyright 2019, Elsevier B.V. k) Schematic illustration of the TENG-based smart insole for gait monitoring. Reproduced with permission.[54] Copyright 2018, Wiley-VCH. l) Schematic illustration of a smart cotton sock using the triboelectric and piezoelectric hybrid mechanism. Reproduced with permission.[55] Copyright 2019, American Chemical Society.

5. Conclusion and Outlook

Smart sports facilities and wearable equipment are being used increasingly in the field of sports, which is developing toward digitalization and intellectualization. Maintenance-free, sustainable, and sensitive sensors are of paramount importance for monitoring the widely distributed sports data. Here, we have briefly summarized recent advances of TENGs for the construction of self-powered smart sports facilities and wearable equipment. It is anticipated that TENG technology will provide critical support for the development of intelligent sports in the near future.

To improve the applicability of the intelligent sports based on TENG technology in the future research, potential challenges and opportunities are also analyzed and discussed in terms of stability, sensing accuracy, miniaturization, sensing capability, big data analytics, and market requirement.

1) Working stability and durability: In practical application, there are many external environmental factors that will

threaten the stability of TENGs, such as humidity, temperature, and absorption. Sweat and salt are constantly released in most sports and could permeate into and contaminate the TENG devices. This will be a big obstacle for the development of TENG-based intelligent sports. To tackle this problem, one of the most effective methods is to improve the hydrophobicity and self-cleanability of the triboelectric layers by creating surface nanostructures or modifying the surface with hydrophobic chemical groups.[59,60] Additionally, developing advanced packaging technologies to protect the TENG devices from sweat infiltration but without significantly reducing their electrical performance is another promising strategy.[61]

2) Sensing accuracy: At the current development stage of TENG-based intelligent sports sensing systems, the sensing accuracy of TENGs has been neglected since most researchers are committed to achieving sensing ability rather than improving it. With the rapid development of the field of smart sports, sensing accuracy will become increasingly important in its commercialization process. The sensing accuracy of TENG is closely relevant to its electrical performance, which could be improved by material modification, structural design, and power management. Further, the signal processing circuit can be used to improve the sensing accuracy.
3) Miniaturization and modularization: For practically adapting TENGs in the field of intelligent sports, miniaturization and modularization of the TENG-based sensing system are two critical challenges. To achieve practical and comfortable use, it is particularly essential to make the TENG system smaller, lighter, and more efficient in the field of sports. Flexibility, stretchability, biocompatibility, and breathability of the TENG devices should also be taken into account, especially for the smart wearable equipment. Furthermore, to construct the wireless sensor network based on the TENG technology, multiple components such as the data processing unit, wireless transmitter, and receiver are required to form a highly modularized sensing system. For realizing the miniaturization and modularization of the TENG-based sensing system, manufacturing technique, output performance improvement, and structure optimization would be key limitations and challenges that need to be addressed in the future.
4) Sensing capability: To meet the needs of future development of the field of intelligent sports, the sensing capability of the TENG-based sensing system should be further improved for achieving a more extensive range of exercise signals detection. Although TENGs can serve as active sensors for monitoring mechanical signals, it is difficult to detect some other non-mechanical signals during sports activities, such as body temperature, sweat, and blood composition. To expand the sensing capability of the smart system, TENGs can be integrated with specific passive sensors to realize a self-powered multifunctional sensing system, through harvesting energy from mechanical motion as their power supply. In such case, TENG serves as a power source. TENG-based self-charging power systems can also be used as a sustainable power supply through harvesting motion energy.[62]
5) Big data analytics: Big data acquisition and analytics are critical for the development of intelligent sports. To collect as much data as possible for sports statistics and analysis, smart TENG devices can be designed as an array and applied in various kinds of athletic equipment or fields according to specific needs. Combining with artificial intelligence and cloud computing technologies, the collected data can be automatically analyzed for providing us with scientific exercise guidance.
6) Market requirement: In the future market of intelligent sports, the uniqueness of the TENG technology among various energy harvesting and sensing technologies depends on its market demand and cost efficiency. In order to improve the applicability and practicability of the smart sports equipment, the material choices of TENGs should be further expanded. Particularly, fabricating TENGs by utilizing the same materials of the sports facilities or wearable equipment will be a great option. Besides, more other TENG-based smart sports items are also needed to developed for meeting the market demand. To improve the market competitiveness of the TENG-based sensing system, we have to focus on enhancing its production efficiency, reducing its production cost, and improving its performance.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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