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Review

Advances in Intelligent Sports Based on Triboelectric Nanogenerators

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Abstract: In the realm of intelligent sports, the integration of triboelectric nanogenerators (TENGs) marks a transformative approach toward energy sustainability and more advanced athletic monitoring. By leveraging the principle of triboelectricity, TENGs ingeniously convert mechanical energy from athletes' movements into electrical energy, which offers a green and efficient power solution for wearable technology. This paper presents an innovative study on the application of TENG technology in sports science, with the results illustrating the potential utility of TENGs in revolutionizing the way we monitor, analyze, and enhance athletic performance. Through the development of self-powered wearables and equipment, TENGs facilitate real-time data collection on physiological and biomechanical parameters, ultimately enabling personalized training adjustments and injury prevention strategies. Our findings underscore the dual benefit of TENGs in promoting environmental sustainability by reducing the overall reliance on traditional energy sources and growing the capabilities of intelligent sports systems. This research contributes to the burgeoning field of nano-energy sports applications while setting the stage for future explorations into the optimization of TENG integration in athletic performance enhancement. Finally, the paper concludes by discussing remaining challenges in this area and opportunities for further research.

Keywords: triboelectric nanogenerator; intelligent sports; monitor; evaluation; protection

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1. Introduction

In today's rapidly evolving society, where digital integration and sustainability are paramount, triboelectric nanogenerators (TENGs) embody a remarkable fusion of innovation and practicality, particularly within the sphere of intelligent sports [1–5]. With the continuous advancements occurring with the internet, big data, and artificial intelligence, the sophistication and complexity of smart technologies are becoming increasingly prominent considerations that have come to permeate various industries [6–9]. Particularly since the COVID-19 pandemic, there has been a heightened focus on personal health management, with sports monitoring aligning with the broader trend toward digitization. The era of sports today is more data-driven than ever, as it encompasses not only the monitoring of physical activity but also assessments of sports posture and proactive protection during activities, all of which are crucial for understanding and improving health conditions, enhancing physical fitness, and planning targeted training [10–14].

Over the past few decades, there has been growing enthusiasm toward the application of different technologies in sports monitoring [15]. Various sensing technologies, including resistive [16–18], inductive [19], capacitive [20,21], chemical [22,23], thermal [24–26], and optical sensors [27–29], have been used in the field of intelligent sports monitoring, and these have showcased high sensitivity and diverse functionalities. Then, in 2012, Professor Wang developed the first TENG,15 which was designed to convert distributed, irregular, and low-frequency mechanical energy—such as human actions (e.g., [30], hand tapping or walking), natural events (e.g., wind, waves, or rain), or vehicle vibrations—into electrical energy, and particularly into usable electric current. TENGs offer unique advantages such as low cost, simple structure, high efficiency, and compatibility with diverse material choices [31–36]. They can also operate under four main modes: vertical contact separation, lateral sliding, single-electrode, or freestanding triboelectric layer. Further, TENGs can function as self-powered sensors, thus eliminating the need to use external power sources [37–41]. Hence, TENGs, with their superior flexibility and stretchability, have been successfully applied as smart monitoring sensors in the realm of intelligent sports [42,43].

In the present work, we primarily aim to discuss the latest developments in the intelligent sports domain based on TENG technology. In sports, the main concerns have always been the monitoring of activities, the evaluation of performance, and the protection of athletes. This review primarily focuses on these three aspects, categorizing and organizing the common commercialized intelligent sports currently available in the market, and highlighting the significance of TENG in sports. We begin by introducing the working modes and principles of TENGs. Subsequently, we highlight recent innovative advancements of TENGs in various intelligent sports sensing systems. Figure 1 illustrates the application of self-powered intelligent systems based on TENGs that are currently used across different sports activities. TENGs can be installed in sports facilities to record various mechanical trigger signals during physical activities, where they are designed in the form of wearable devices to monitor physiological signals of the human body. The signals obtained through TENG technology during sports activities can assist in evaluating athlete performance in competitions, improving training for correct posture during regular training, and providing protection and hazard prediction during activities. A vast array of intelligent devices based on TENGs can be networked together, and such data-sensing networks are extensively applied in the sports field, as they are both efficient and intelligent. Finally, we briefly discuss the current challenges and future prospects of TENGs in intelligent sports.

Figure 1. Schematic of intelligent motion based on TENG.

2. Triboelectric Nanogenerators in Intelligent Sports Applications

In the realm of smart sports, various types of TENGs are tailored to meet the specific requirements of different sports activities. These TENGs not only utilize the general principles of contact electrification and electrostatic induction but are also designed to address the unique challenges presented by different sports environments. The principles of triboelectric nanogenerator (TENG) technology are deeply rooted in the synergistic phenomena of contact electrification and electrostatic induction, and the conceptual framework behind this technology is anchored in the classical Maxwell's equations. Since its inception in 2012, TENG has been categorized into the following four primary operational configurations: vertical contact-separation (commonly used in wearable devices for running and walking, these TENGs are embedded in shoe soles or clothing to monitor step count, gait analysis, and overall physical activity), lateral sliding (for sports like cycling and rowing, where sliding movements are prevalent, these TENGs can be integrated into gloves or handlebars to track hand movements and grip strength), single-electrode (useful for sports such as golf and tennis, where the TENGs can be applied to gloves or grips to monitor swing mechanics and force applied during play), and freestanding triboelectric-layer modes (employed in sports like gymnastics and high jump, these TENGs can be embedded in mats or landing surfaces to monitor impact force and landing techniques) (Figure 2a) [44,45]. Due to the operational similarities among these configurations, the vertical contact-separation mode is frequently used to exemplify the intricate mechanics of the TENG operation. Initially, in the absence of contact, no electrical charge is generated or transferred. However, upon any physical interaction between two disparate materials, triboelectric charges are generated on their respective surfaces. This interaction leads to the formation of a potential difference when the materials are separated, which induces a swift flow of electrons from the lower to the upper electrode until an equilibrium is achieved upon full separation. When the materials are pressed together once more, the previously induced electrostatic charges traverse back through the external circuit, nullifying the electrical potential difference and completing the circuit (Figure 2b). This cycle of charge generation and recombination is depicted in the schematic representation at the bottom left of Figure 2b.

As can be seen in Table 1, beyond TENG, there has been significant academic interest in biomechanical energy conversion leveraging piezoelectric devices, electromagnetic generators, and thermoelectric generators [46–48], and comparative analyses of these technologies have highlighted their unique operational principles, merits, and limitations. Therefore, in the area of smart sports, TENGs have been successfully applied as intelligent monitoring sensors with superior flexibility and stretchability.

Considering the various important roles that TENG plays in today's sports, we have conducted data surveys from 2012 to the present. The primary focus of these surveys was on the response time of TENG in data monitoring, the evaluation of sports rules, and athlete protection. Overall, the application of TENG in monitoring, evaluation, and protection has led to a gradual decrease in response time over time. This reflects the significant improvement in TENG performance that can be attributed to technological advancements and design optimizations. Faster response times make TENG applications more efficient and reliable, allowing them to better meet the needs of real time monitoring, precise evaluation, and effective protection. This improvement can be mainly attributed to the development of materials science, nanomanufacturing technology, and the continuous optimization of TENG design, as shown in Figure 3.

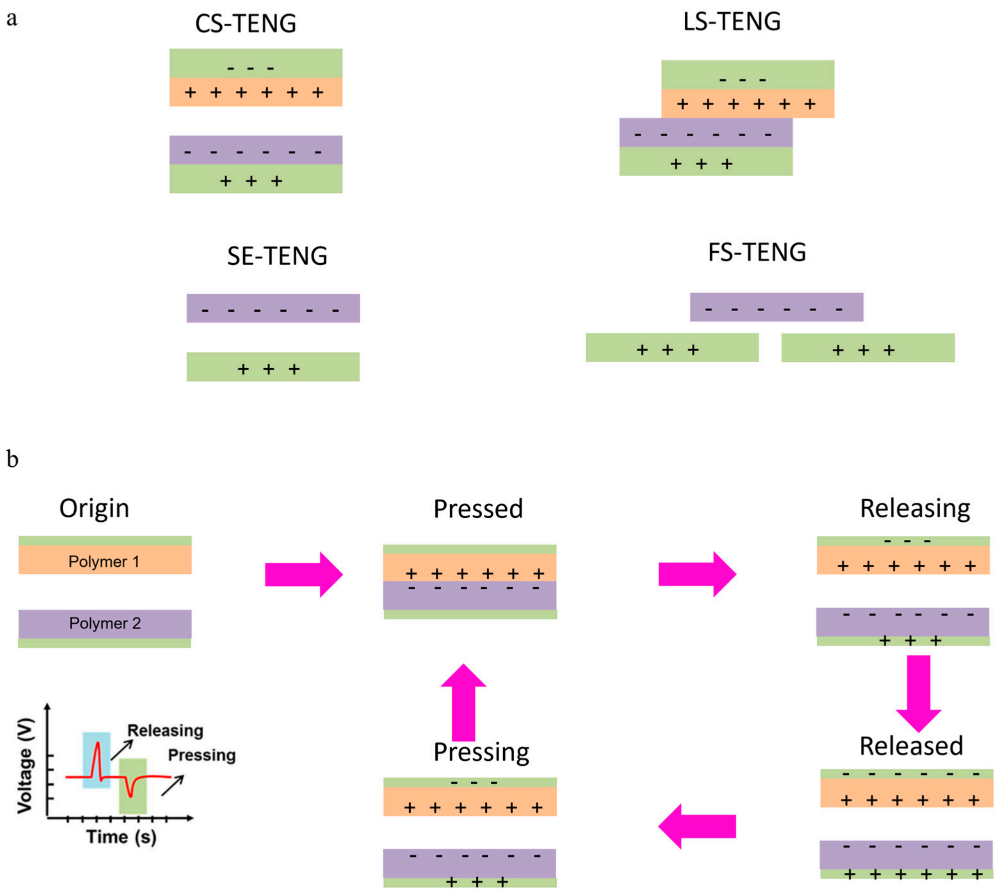

Figure 2. Working principle of TENG. (**a**) Four working principles of TENG. (**b**) The working principle of the TENG in contact-separation mode.

Table 1. Comparison of biomechanical energy harvesting technologies based on voltage devices, electromagnetic generators, thermoelectric generators, and triboelectric effects to illustrate their advantages and disadvantages.

Parameter	Triboelectric Nanogenerators (TENGs)	Piezoelectric Devices	Electromagnetic Generators	Thermoelectric Generators
Principle	Utilizes contact electrification and electrostatic induction to convert mechanical energy into electricity.	Converts mechanical stress or strain into electrical energy through the piezoelectric effect.	Generates electricity through the movement of magnets relative to coils.	Converts temperature gradients directly into electricity.
Energy Source	Mechanical movements, vibrations, and even small motions like walking or tapping.	Mechanical stress, pressure, or vibrations.	Movement or vibration, often requiring larger motions for efficient energy conversion.	Heat sources or temperature differences.
Efficiency	High efficiency in converting low-frequency, irregular mechanical motions into electricity.	High efficiency with specific materials under direct pressure or deformation.	Typically requires larger kinetic movements for optimal energy generation, which might not always be practical with wearable technology.	Efficiency depends significantly on the temperature gradient available, which is often limited in ambient environments.

Table 1. *Cont.*

Parameter	Triboelectric Nanogenerators (TENGs)	Piezoelectric Devices	Electromagnetic Generators	Thermoelectric Generators
Material Flexibility	Can be made from a variety of materials, including lightweight and flexible options that are particularly suitable for wearables.	Materials are often rigid or require ceramic components, thus limiting flexibility for wearables.	Components are usually rigid and can be bulky, posing challenges for integration into wearable devices.	Materials may be rigid or flexible, but flexible versions generally have lower efficiency.
Cost	Relatively low cost due to the simplicity of materials and fabrication processes.	The cost can be high due to the use of specific piezoelectric materials.	The cost varies; it can be high due to the need for magnets and coils.	The cost can be high, especially for high-efficiency materials.
Environmental Impact	Low: materials used can be environmentally friendly and recyclable.	Moderate: depends on the piezoelectric materials used, some of which may involve environmental concerns.	Moderate: depends on the materials used for magnets and coils.	Moderate to high: depends on the materials used, some of which may be rare or have significant environmental impacts.
Application Scope	Broad application in wearable devices, sensors, and small-scale energy harvesting due to its adaptability to various movements and conditions.	Best suited for applications where direct pressure or stress is consistent and predictable.	Suitable for applications with larger or more regular mechanical movements.	Best applied in environments with consistent temperature gradients.

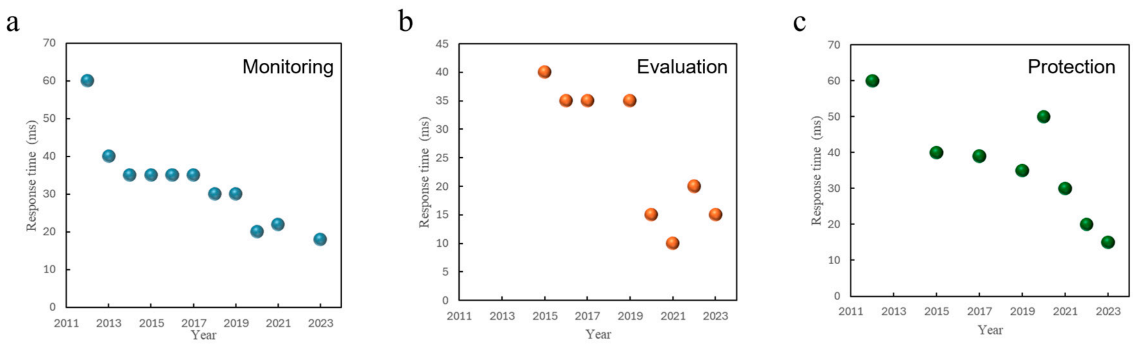

Figure 3. Response time of TENG-based sports in (**a**) monitoring, (**b**) evaluation, and (**c**) protection.

3. TENG-Based Intelligent Sports

3.1. Basketball

In the fast-paced world of basketball, it is crucial to understand and enhance player performance and game dynamics. During basketball training and games, sensors can be used to obtain accurate data about athletes and games. The integration of TENGs as sensors marks a significant leap forward in this arena. For example, TENGs can be used as angle and force sensors to quantitatively analyze different movements made by players. Coaches can use these data to accurately judge the correctness and rationality of athletes' movements. In a recent study, Dang et al. used $LiN(SO_2F)_2$ (LiTFSI) and lipoic acid to create new recyclable and degradable ion elastomers (IEs) [49]. They used these recycled IEs as conductive fillers in transparent ion papers to develop bendable transparent TENGs. The anisotropy of the paper substrate leads to different degrees of deformation along the X and Y directions, which results in differences in both ion migration and friction. This self-powered sensor detects wrist movement in both directions, which provides a unique voltage signal that can help basketball players maintain a correct dribbling posture. This technology fills a gap in unbiased assessment techniques for advanced basketball training, thus enabling thorough observation and analysis of players (Figure 4a).

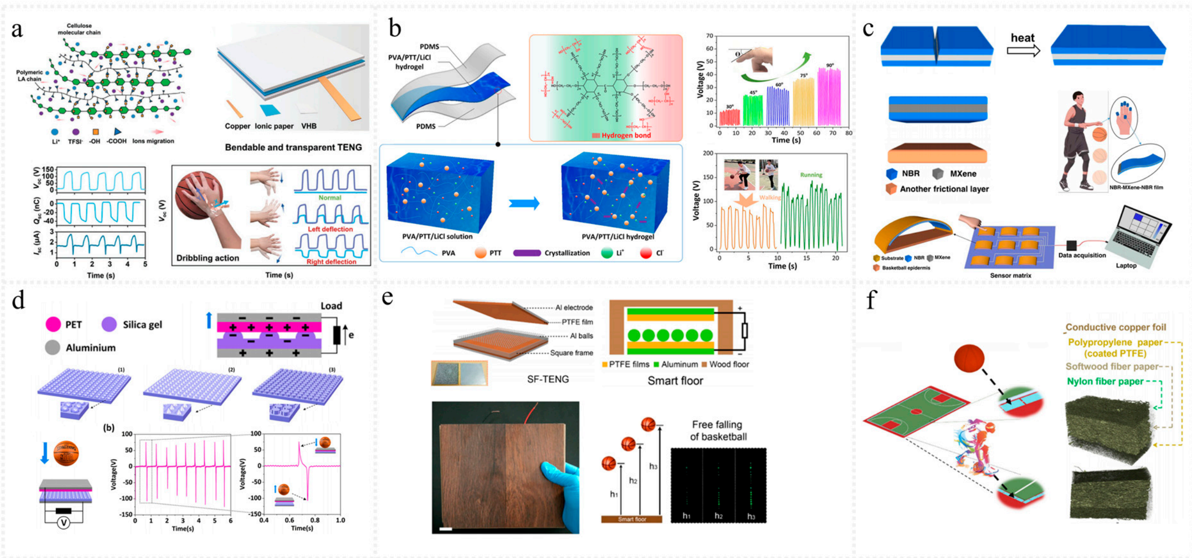

Figure 4. TENG-based sensors applied in basketball. (**a**) Recycled IE-1M was used as the conductive filler in fabricating ionic paper for the soft TENG. Reprinted with permission from Ref. [49]. Copyright 2022, Wiley. (**b**) Output signals of the PPL-TENG device installed at the finger and knee [50]. (**c**) Schematic images of the healing process of NBR/MXene/NBR film and the tactile sensor array for real-time pressure tracking, including the TS array, data acquisition card, and data analysis software that was specially developed by LabVIEW. Reprinted with permission from Ref. [51]. Copyright 2022, Elsevier. (**d**) Schematic diagram of the S-TENG sensing system applied for basketball training. Reprinted with permission from Ref. [52]. Copyright 2022, Elsevier. (**e**) Smart floor and a row of LEDs being lit up by a free-falling basketball at different heights (h1 = 40 cm, h2 = 80 cm, and h3 = 120 cm). Reprinted with permission from Ref. [53]. Copyright 2017, American Chemical Society. (**f**) Ball and person making contact with P-TENG. The black line describes the signal changes at the point where the ball hits. The red line describes the signal changes at the point where the players step on it to save the ball [54].

Moreover, Deng et al. designed a polyvinyl alcohol (PVA)/polytrimethylene terephthalate (PTT)/LiCl hydrogel as a flexible conductive triboelectric nanogenerator (PPL-TENG). The PPL-TENG can be affixed to the finger joint to monitor different degrees of bending of the finger joint, and it shows good stability and excellent repeatability when affixed in this manner, as shown in Figure 4b–d [50–54]. The PPL-TENG sensor installed at the bottom of the shoe generates distinguishable output signals based on the different gaits of basketball players during training, as illustrated in Figure 4e,f. Similarly, PPL-TENG placed at the elbow and knee can also recognize different degrees of joint bending, which offer indirect insights into the athlete's motion posture.

TENG sensors have significant potential in preventing athlete injuries. By monitoring the movements and physiological signals of athletes in real time, TENG sensors can help identify poor posture and potential injury risks. For instance, if an athlete performs an overly aggressive movement or an incorrect posture during training or games, TENG sensors can detect abnormal force or angle signals and promptly issue warnings to remind the athlete to adjust their actions to avoid injuries. Additionally, TENG sensors can monitor joint bending and pressure changes, providing real-time data on joint stress. This information can help coaches develop more scientific training plans, preventing injuries caused by overtraining or improper posture.

TENG sensors play a crucial role not only in enhancing player performance and game analysis but also in providing new methods and tools for injury prevention. As technology continues to advance, TENG sensors are expected to play an increasingly important role in intelligent sports training, real-time monitoring, and injury prevention, offering comprehensive support for basketball athletes.

3.2. Football

It is widely recognized that football demands that players engage in actions that push them to their short-term peak and near-peak physical limits, including jumps, sprints, and rapid direction shifts, all in an effort to outmaneuver opponents and gain possession of the ball. To enhance the lower body explosiveness of football athletes, there are specific muscle training regimens that are extensively employed within the sport. These training methods are intended to induce neuromuscular adaptability and coordination within and between muscles, thus improving the overall ability of football players. In a recent study, Zhang et al. designed a triboelectric nanogenerator based on PET/Graphite composite film (PG-TENG) as a self-powered motion sensor to monitor leg muscle health while an individual played soccer, as shown in Figure 5a [55]. PG-TENG can serve as the motion player to monitor the health of football players' leg muscles and various football sports postures, including the posture of bouncing and dribbling. When an athlete's muscles experience fatigue and damage, the coach can immediately stop the training or game. This can most effectively reduce the athlete's injury risk.

The monitoring of athletes' contact with the football has also attracted extensive attention in this area. For example, Chen et al. proposed a soluble-core method that could be used to fabricate ultra-stretchable SEBS hollow fibers. As shown in Figure 5b [56], these conductive fibers can be applied on the surface of a football, and the fiber net on the football surface precisely performs the sensing function of a spherical coordinate. This device makes it possible to accurately record the position and force of each player's contact with the ball.

Another way to monitor gait is to integrate the TENG into a wearable device such as shoes. Qin et al. introduced a novel TENG integrated with a wave structure electrode (W-TENG) (Figure 5c) [57]. Compared to the traditional flat plate electrode TENG, the W-TENG with a wave structure electrode can achieve higher output performance. The maximum short-circuit current (Isc), transfer charge, and open-circuit voltage (Voc) of 2.56 μA, 29 nC, and 74 V were obtained at 300 N. Moreover, the output voltage signal of W-TENG can clearly reflect the different postures in football, while the W-TENG can perform real-time football monitoring (Figure 5d) [58]. For gait monitoring, Wu et al. proposed a novel PS/MXene-based triboelectric nanogenerator (PM-TENG) that has a drum structure design (Figure 5e) [59]. The PM-TENG can be installed on a football player's shoulders, neck, wrist, elbow, knee, or ankle to achieve comprehensive monitoring.

Guo et al. developed a self-powered wearable multidimensional motion sensor tailored to intelligent indoor sports. By integrating a vertical acceleration sensor and a planar angular velocity sensor, this device can sensitively detect various movement trajectories. When worn with a belt, it tracks waist and lower limb movements like spinning, turning, walking, and running, ultimately achieving 93.8% accuracy in identifying these movements with the SVM machine learning algorithm. The sensor was also used to control a VR fitness game and record calorie consumption. When worn on the ankle, it accurately identified four motions (left, right, straight, and slight straight kicks) with 97.5% accuracy using a 1D CNN-based deep learning analysis. Altogether, this energy-efficient multidimensional sensor shows promise for home-based sports, VR gaming, and rehabilitation (Figure 5f) [60].

Excellent motion sensors are expected to be able to capture arbitrary trajectories, i.e., not only simple straight or circle trails, but also composite trails (Figure 5g) [61]. In football games, the motions of one's shank are affected by the results of their hip joint motions and knee joint motions, which should be more complicated than their waist motions.

Figure 5. Application of TENG-based sensors in football. (**a**) Diagram of the working principle and PG-TENG installed on the human knee [55]. (**b**) Working mechanism of the ultra-stretchable fiber TENG and conductive fibers on a 3D surface of a football to perform the sensing function of a spherical coordinate [56]. (**c**) Structure and application of SRPA sponge for the self-powered scoreboard power supplying system. Reprinted with permission from Ref. [57]. Copyright 2021, American Chemical Society. (**d**) System architecture diagram of self-power football motion monitoring system. Reprinted with permission from Ref. [58]. Copyright 2022. Elsevier. (e) Structural diagram of the PM-TENG and its performance in monitoring different motion postures [59]. (**f**) Structure of the multidimensional sensor and demonstration of the VR football shooting game [60]. (**g**) Configuration of the MC-EH-HL system, which consists of two main components, R-TENG and S-PEG, and detailed motion segments of a kicking process with two R-TENGs fixed on the hip and knee joints [61].

In the future, TENGs are expected to be used in football to achieve promising advancements in monitoring player performance, enhancing training strategies, and preventing injuries. With their ability to track complex lower limb movements and muscle health, TENG-based sensors are expected to become vital tools for coaches and medical professionals. For instance, the self-powered PG-TENG is expected to offer a precise assessment of football players' leg muscle conditions, and it can also aid in tracking rehabilitation progress post-injury. Such functions will ultimately lead to more effective and data-driven recovery interventions. Moreover, ultra-stretchable TENG fibers that are applied to the football surface will provide accurate data on each player's contact position and force, thus enabling coaches to refine their skills and tactics based on actual data. In footwear, wave-structured TENGs will facilitate gait monitoring, thus helping athletes understand and optimize their movement patterns for better performance and injury prevention. Multi-dimensional motion sensors, which combine acceleration and angular velocity sensing with machine learning models, will enable comprehensive tracking of movement trajectories like spins, kicks, and direction shifts. Although the SVM model has shown high accuracy, future developments should focus on more advanced algorithms that are capable of handling the complexity of football movements. Overall, TENGs are set to revolutionize football by providing real-time, reliable data that can be leveraged for smarter training regimens, injury prevention, and rehabilitation, ultimately improving player performance and enhancing the game's quality.

3.3. Baseball

The application of TENG-based motion sensor in baseball sports is similar to that in other ball sports, and in baseball it is mainly used for the monitoring of force, angle, and direction. A recent study proposed a stretchable CNT/PVP-based thermoelectric composite knitted fabric made using a simple ultrasonic coating method (Figure 6a) [62]. During training sessions, as the athlete's wrist underwent repetitive flexion to a specific angle, the sensor documented a sequence of voltage fluctuations. This captured a sequence of voltage fluctuations. This capability assisted baseball players by logging throw counts and enhancing their training outcomes. Based on the advancements of ultra-stretchability and ultra-flexibility, the fabricated conductive fiber offers an outstanding conformability and can be adapted to differently shaped surfaces. In particular, monitoring sports performance and training inherently requires direct contact with the training facilities while maintaining stable sensing performance under sudden deformation and strong external impact. As shown in Figure 6b [56], the fiber-based sensing network was tailored to the 2D inner surface of a baseball glove, thus enabling the identification of impact points across varying catching velocities. This adaptation facilitates a nuanced analysis of interaction dynamics within the glove, ultimately contributing to a deeper understanding of performance metrics in baseball catching techniques.

In the context of baseball, the trajectory of a pitch can vary significantly with the rotation direction of the ball. Conventional methodologies for detecting the spin direction of a baseball involve the use of a complex and costly apparatus, including lasers and high-speed cameras, which not only involve a challenging setup process due to their intricate designs but also require continuous power consumption. Park et al. developed the liquid metal-embedded sponge-typed TENG (LMST) (Figure 6c) [63]. By leveraging the LMST, a more streamlined and energy-efficient detector has been developed to ascertain the spin direction of a ball.

Finally, Wen's study delves into the utilization of a carbon nanotube/thermoplastic elastomer (CNTs/TPE) coating technique to endow triboelectric textiles with superhydrophobic properties, with the ultimate aim of significantly augmenting their performance (Figure 6d) [64]. This innovation is integrated into a glove that boasts remarkable energy harvesting and human motion detection capabilities, thereby offering a low-cost, autonomous interface for gesture recognition. The core application of this glove, which is highlighted by the incorporation of machine learning algorithms, is in facilitating real-time, precise gesture-based commands that are specifically tailored for baseball training and gameplay within virtual reality/augmented reality (VR/AR) environments.

In baseball, TENGs are considered to hold significant potential in player performance monitoring, training, and gameplay. The integration of TENG-based sensors will enable accurate tracking of force, angle, and direction in real time, thus providing players and coaches with crucial data for performance optimization. These innovations will not only enhance the training quality and entertainment value of baseball in virtual settings but also demonstrate the potential utility of TENGs in revolutionizing sports technology. With continued research and development, TENG-based sensors will come to be indispensable in improving player performance, reducing injuries, and refining training techniques in baseball.

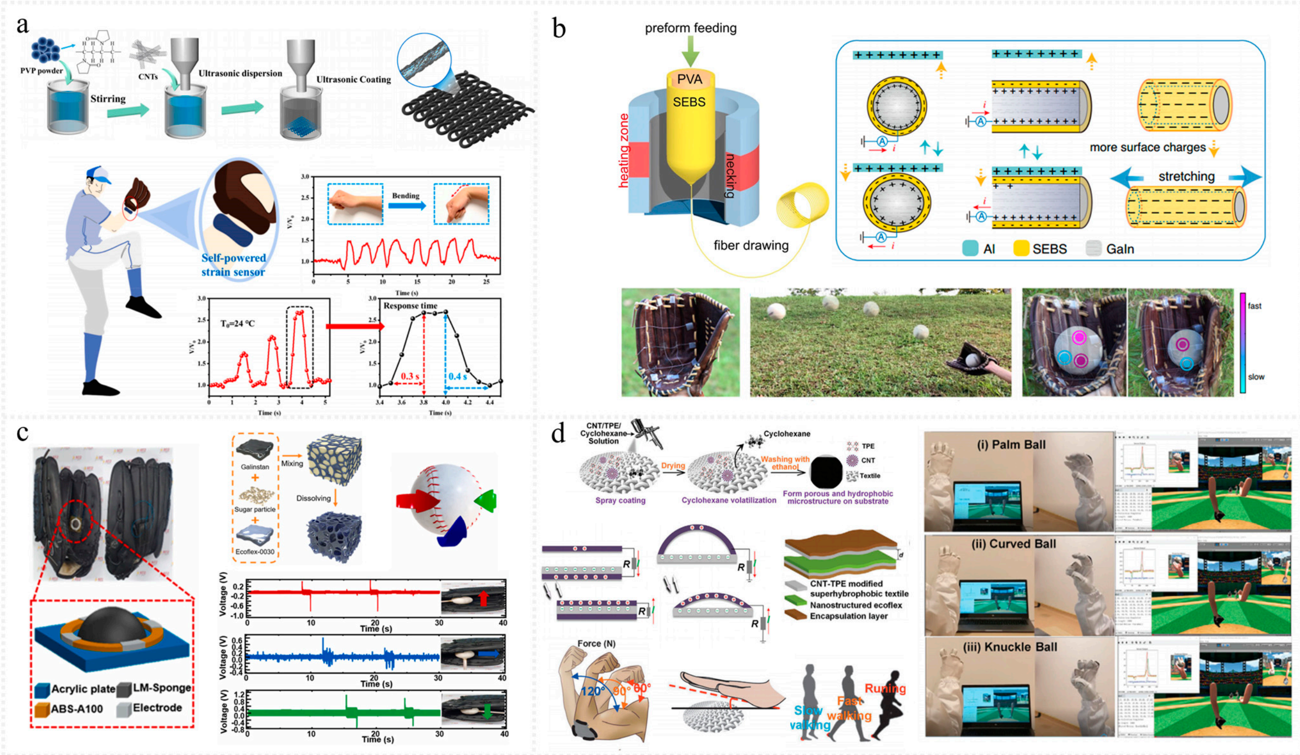

Figure 6. TENG-based sensors applied in baseball: (**a**) Preparation of CNT/PVP thermoelectric composite fabric and its sensing applications. Reprinted with permission from Ref. [62]. Copyright 2022, Elsevier. (**b**) Fiber-based sensing net that was conformally adapted on the 2D inner surface of a baseball glove to locate the hitting points with different catching speeds [56]. (**c**) Schematic of the fabrication process of the LMS and baseball gloves with an LMST detector. Reprinted with permission from Ref. [63]. Copyright 2021, Elsevier. (**d**) Fabrication process of the superhydrophobic textile and application of smart gloves [64].

3.4. Boxing

Boxing has recently been the focus of increasing academic attention in the field of sports. Research and development is a very important aspect of relevant monitoring equipment, and particularly of wearable sports monitoring equipment. Yang et al. introduced an innovative hydrogel-based triboelectric nanogenerator (H-TENG) that is endowed with a self-healing capability, and is designed to both capture biomechanical energy generated during boxing and facilitate the monitoring of boxing training (Figure 7a) [65]. The H-TENG operates on a single-electrode mode, and it utilizes polydimethylsiloxane (PDMS) as the triboelectric layer and an ionic hydrogel as the conductive electrode. Integrating the H-TENG into a boxing glove makes it possible to continuously monitor the dynamics of boxing motions, meaning this approach can be used in the development of self-sustaining sports sensors. These advancements are poised to significantly contribute to the evolution of self-powered sensors in the sporting arena, with a particular emphasis on enhancing the analytical precision of pressure monitoring in the sport of boxing.

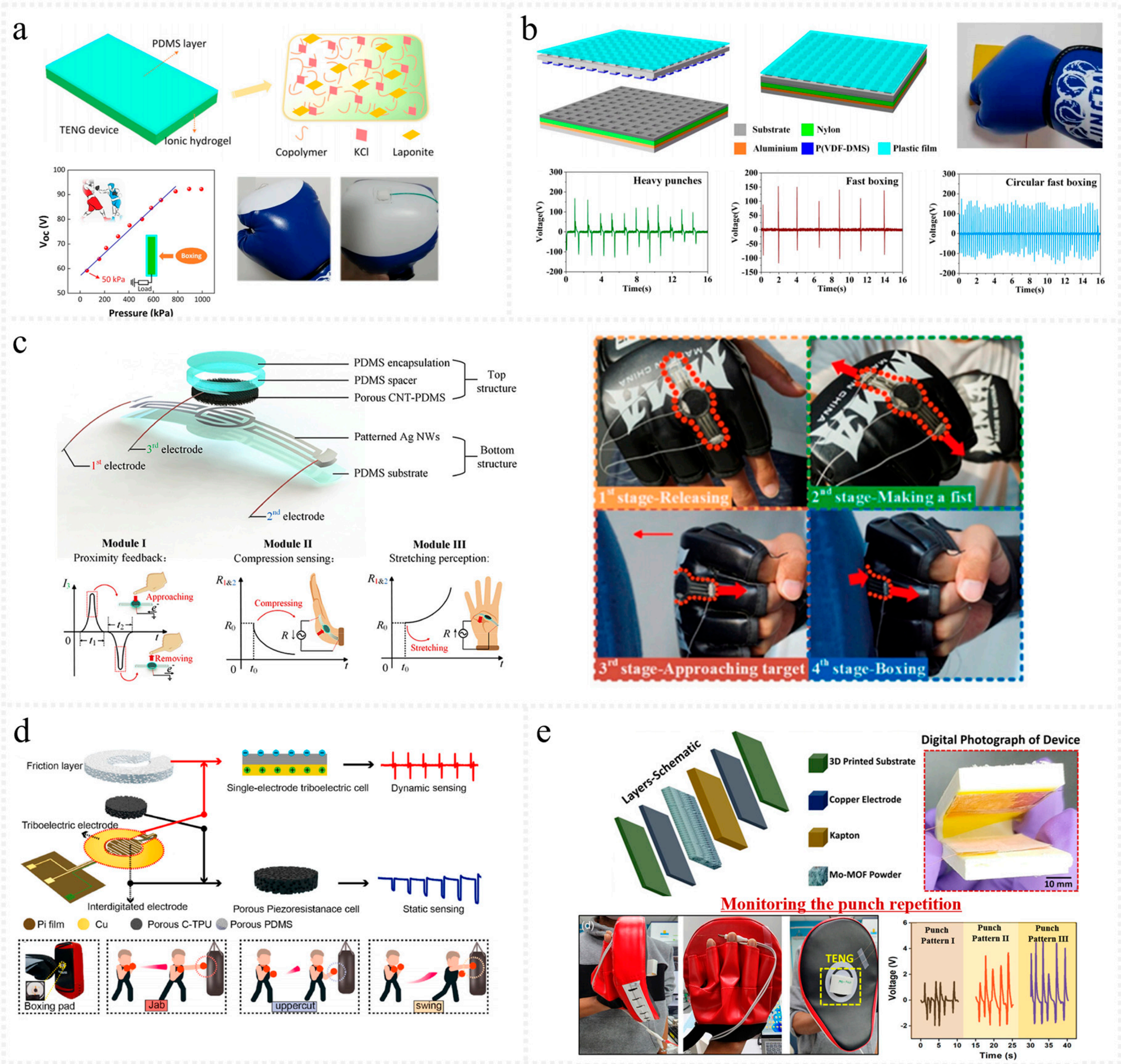

Figure 7. TENG-based sensors applied in boxing: (**a**) Structure diagram of H-TENG device and the output voltage signal of H-TENG under boxing motion. Reprinted with permission from Ref. [65]. Copyright 2023, Springer Nature. (**b**) Schematic illustration of the A-TENG and voltage signals of different punches. Reprinted with permission from Ref. [66]. Copyright 2022, Springer Nature. (**c**) Structural schematic of the device and distinct signals generated from different body motions by the three modules. Reprinted with permission from Ref. [67]. Copyright 2020, Elsevier. (**d**) Design principle of the hybrid sensor and the scheme of the process and application in a smart boxing pad. Reprinted with permission from Ref. [68]. Copyright 2020, Elsevier. (**e**) Layer-by-layer arrangement of various layers and device structure of the fabricated TENG device and application in monitoring punch repetition. Reprinted with permission from Ref. [69]. Copyright 2023, Wiley.

Similarly, Gao et al. introduced a poly [(vinylidene fluoride)-co-dimethyl siloxane] P(VDF-DMS)-based array triboelectric nanogenerator (A-TENG) that was specifically crafted to harness the kinetic energy that is produced during boxing activities (Figure 7b) [66]. This device is not only capable of capturing energy from boxing motions, but can also differentiate between various boxing techniques through the analysis of output voltage signals. Crucially, the electrical output signal of the A-TENG provides insights into the type of boxing maneuver being executed, including heavy punches, rapid jabs, and swift circular movements (Figure 7c) [67]. This innovative approach to the use of triboelectric material, along with the introduction of a self-supporting array structure, significantly broadens the scope of TENG applications in the field of sports monitoring, thus offering a sophisticated method that can be used to analyze and enhance boxing performance (Figure 7d) [68].

The development of tactile sensors has evolved such that it is now necessary to have the ability to detect fleeting mechanical stimuli, thereby extending beyond the confines of mere static detection. Ma et al. introduced a novel hybrid tactile sensor that merges a porous polydimethylsiloxane (PDMS)-based triboelectric active sensing unit with a conductive carbon black (CB)/thermoplastic polyurethane (TPU) composite-based piezoresistive sensing unit (Figure 7e) [69]. This dual-functionality sensor adeptly registers both static and dynamic mechanical forces, which ultimately allows for the precise demarcation of the complete "approach-contact-press-release-separation" sequence that is inherent to tactile interaction. A practical application of this sensor technology is a smart boxing training glove. This glove is designed to identify various types of boxing punches and provide intricate feedback on the force exerted by each punch, thus showcasing the sensor's utility in enhancing the precision and effectiveness of boxing training regimens. Such self-powered TENG applications are expected to see increased usage in intelligent sports sensors and fitness tracking.

In boxing, TENGs are expected to transform training, monitoring, and performance analysis through the continued development of advanced, self-powered wearable technologies. Hybrid tactile sensors that combine triboelectric and piezoresistive sensing units will further expand boxing analytics. Their ability to register static and dynamic forces will offer comprehensive "approach-contact-press-release-separation" tracking for each punch, which will provide valuable feedback on force exertion and movement precision. This will help athletes improve their form, reduce injury risk, and maximize the training benefits they obtain. The future of TENGs in boxing thus lies in enhancing performance, refining training techniques, and altogether providing a solid foundation for injury prevention through the use of intelligent, data-driven sports sensors.

3.5. Badminton

The rapid collection of information and precise feedback greatly enhances the skills of athletes who are trained to effectively cut down on severe physical labor as much as possible. The performance of badminton depends on the coordination of different muscles and joints. However, the common techniques used to analyze biomechanics rely on high-speed cameras and electromyography. This expensive equipment makes it difficult to catch slight and real-time movement. Yuan et al. designed a liquid-polymer tubular triboelectric nanogenerator (L-P TENG) that is filled with liquid for a shape-adaptive sensor that can be used in various working modes. The elevated pliability of the apparatus allows it to conform to any curvature and withstand substantial deformation. The device can be installed on joints such as the wrist and elbow, which facilitates its application in detecting minute variations in pressure resulting from tactile interactions, compression, and elongation, ultimately making it adept at recognizing forces with heightened sensitivity. The height and distance of a badminton flight can be predicted by the electrical signals generated by the player's serve movement, as shown in Figure 8a [70].

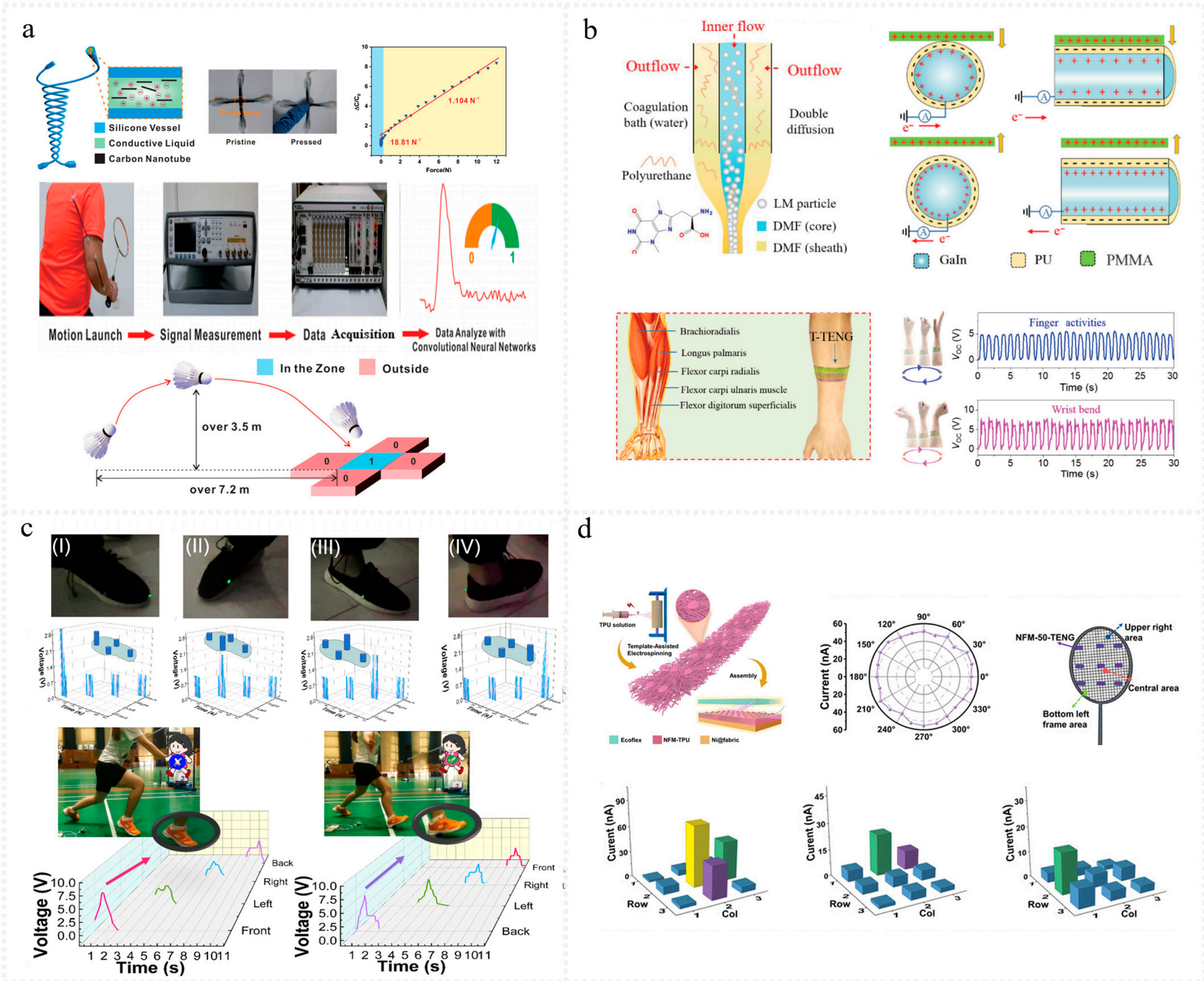

Figure 8. TENG-based sports device in badminton games. (**a**) Demonstration of L-P TENG for human motion detection involves transmitting body movement data through sensors to an analysis system while employing AI-based recognition algorithms for serve analysis, collecting signals from shoulder, wrist, and elbow sensors, and tracking the shuttlecock's flight. Reprinted with permission from Ref. [70]. Copyright 2019, Royal Society of Chemistry. (**b**) Anatomy of forearm muscles and T-TENG position. Reprinted with permission from Ref. [71]. Copyright 2023, Springer. (**c**) Bionic TENG worn on human joints [72]. (**d**) Structure and schematic illustration of PC-TENG. Structure of PC-TENG in closed and open form. Reprinted with permission from Ref. [73]. Copyright 2023, Wiley.

In badminton, athletes need to precisely control different movements operated by the muscles of the forearm. Ning used a continuous, one-step coaxial wet spinning process to synthesize triboelectric fibers featuring a diameter of merely 0.18 mm. These fibers comprise a liquid metal (LM) core enveloped by a polyurethane (PU) sheath. The superior mechanical properties of these materials ensure compatibility at their interface, thus eliminating issues of incompatibility within the triboelectric fibers. For wearable devices to be used for motion monitoring, comfort is a very important index. Through the application of digital embroidery and plain weave techniques, these fibers can be fabricated into extensive areas of textile-based triboelectric nanogenerators (T-TENGs). Such T-TENGs often find practical utility in energy harvesting and self-powered sensing applications. Specifically, when affixed to the forearm, they possess the capability to monitor a variety of stroke types in badminton, as shown in Figure 8b [71].

In the daily training of badminton players, the pace of training accounts for a large area of focus. Therefore, Zheng et al. developed an array of sensors affixed to the insole's surface to adeptly monitor movement gait patterns and alert users to falls using self-powered TENGs. Each sensor cell on this sensor works as an individual air gap TENG (FWF-TENG), namely flexible, waterproof, and fast response, composed of an Eco flex single-electrode array. Each FWF-TENG boasts a fast response time of 28 ms, which is sufficiently fast to quickly monitor pressure changes that occur during various badminton activities. Importantly, these sensors can persistently generate electrical signals at 70% RH humidity (Figure 8c) [72]. The data obtained from these sensors can also be wirelessly transmitted in real time to an upper computer intelligent terminal through multi-grouped FHW-ENG sensing terminals to achieve human–computer interaction applications, including motion technical determinations, feedback, and fall alerts.

The position, speed, and angle of the badminton player at the moment that they hit the shuttlecock determines the flight speed and landing point of the badminton player. To enhance the precision of tailoring individualized training programs through the assessment of batting positions, Cui et al. incorporated a 3 × 3 sensor array into a badminton racket. This integration facilitates the real-time acquisition of data during routine badminton practice sessions. To mimic actual training scenarios, a simulation was conducted wherein a shuttlecock was released from a height of 30 cm above the racket while focusing on various potential impact zones including the central area, upper right quadrant, and lower left perimeter. Subsequent analysis involved the generation of a three-dimensional plot array, as depicted in Figure 8d [73], which was derived from the vibrational pressure data collected upon the shuttlecock's impact at differing locations on the racket.

The integration of triboelectric nanogenerators as sensors in badminton represents a significant advancement in sports technology. By providing detailed and real-time performance data, enhancing injury prevention measures, and supporting sustainable practices, TENGs have the potential to transform both training and competitive play in badminton. Future research will focus on optimizing the sensitivity and durability of TENG sensors, while exploring broader applications within racquet sports, and further enhancing the user experience for players and coaches alike.

3.6. Table Tennis

The integration of triboelectric nanogenerators as sensors in table tennis represents a significant advancement in sports technology. By providing detailed and real-time performance data, enhancing injury prevention measures, and supporting sustainable practices, TENGs have the potential to transform training and competitive play in table tennis. Future research will focus on optimizing the sensitivity and durability of TENG sensors, exploring broader applications within racquet sports, and further enhancing the user experience for players and coaches alike. A recent study proposed the use of a lightweight and sensitive triboelectric nanogenerator (LS-TENG) consisting of transparent polytetrafluoroethylene (PTFE) and polyamide (PA) films as triboelectric layers, polydimethylsiloxane (PDMS) as a support layer, and copper foil as an electrode (Figure 9a) [74]. LS-TENG can be attached to the joints of the human body, and the mechanical energy generated by human motion can be converted into electric energy based on the triboelectric effect, thus realizing self-power supply. LS-TENG can monitor the angle changes in elbow and wrist joints when athletes pull the loop and actively generate the output voltage as a sensing signal, which is convenient as it can allow coaches to monitor the quality of athletes' hitting in real time. Similarly, Mao et al. proposed a design involving a nanogenerator-based wireless intelligent motion correction system that combines triboelectric nanogenerator technology with wireless intelligent host computer signal processing and visualization systems (Figure 9b) [75]. The TENG is attached to the wrist, and when the ping-pong paddle is swung, the friction device detects and obtains the wrist motion data and transmits the data wirelessly through the transmitter of the error correction system to the data receiver.

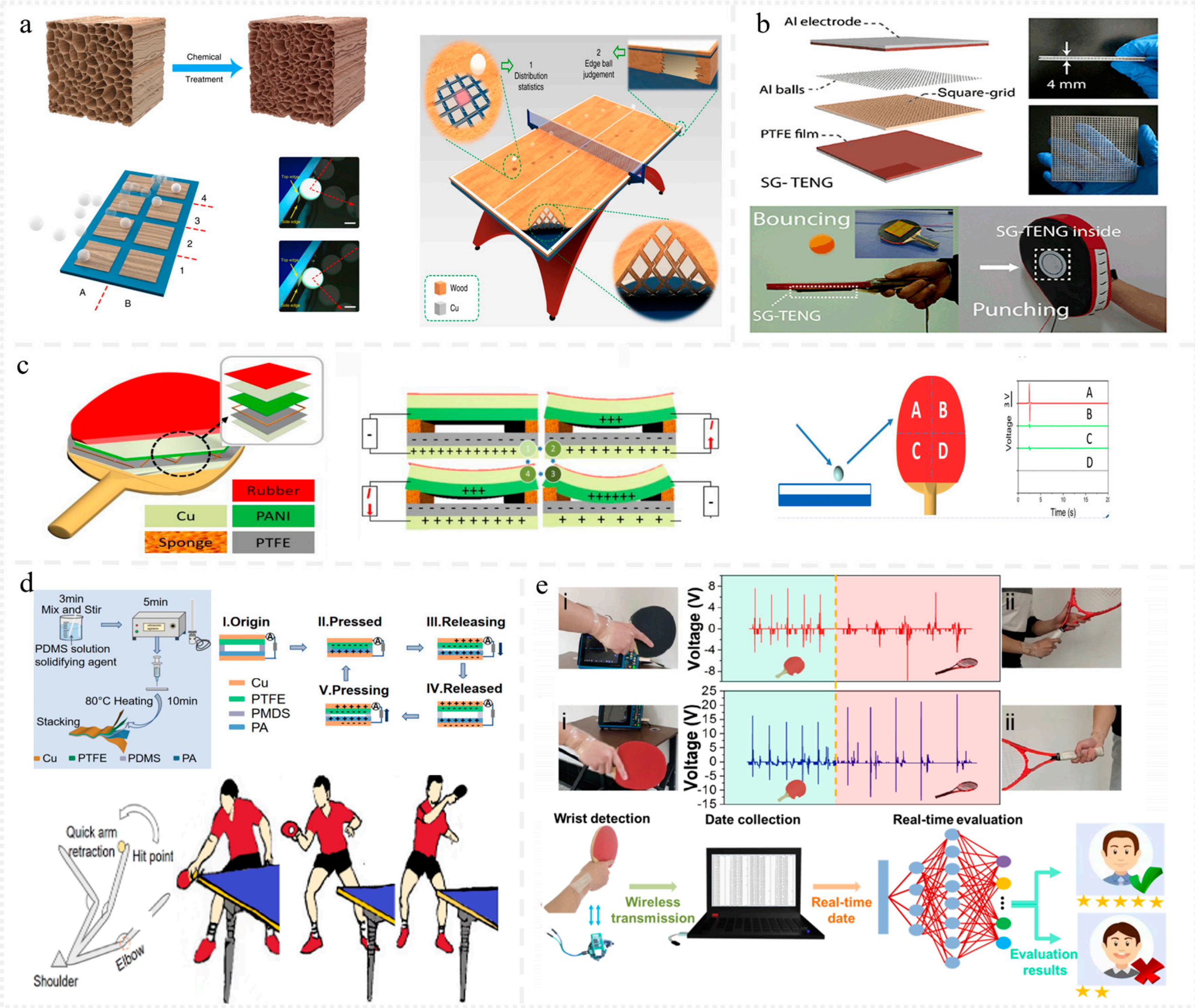

Figure 9. TENG-based sports device in table tennis games. (**a**) Design and application of LS-TENG [74]. (**b**) FL-TENG Application in Wireless Intelligent Motion Error Correction System. Reprinted with permission from Ref. [75]. Copyright 2018, Springer Nature. (**c**) Device structure, the working mechanism to capture table tennis hitting of the device, integrating with four sensing units. The inset shows the triboelectric signals of four sensing units in real time [76]. (**d**) TENG integrated with table tennis paddle and boxer target [77]. (**e**) Wood TENG intelligent table tennis table, self-powered ping-pong ball drop distribution statistics system, and edge ball judgment system [78].

Like in all racket sports, it is important to monitor the contact between the racket and the ball. Ma et al. developed a lightweight, self-powered sensor utilizing the triboelectric effect to analyze athletic performance in table tennis (Figure 9c) [76]. This sensor captures data on ball hit frequency and velocity, thus allowing for personalized training adjustments to enhance athlete performance. Further, Ma designed a square-grid triboelectric nanogenerator (SG-TENG) that features a 3D-printed grid with aluminum spheres in each unit (Figure 9d) [77]. This configuration optimizes vibrational energy harvesting and force sensing across various angles and frequencies.

The out-of-bounds penalty of table tennis has always been controversial. In professional games, high-speed cameras can help referees make fair decisions. However, high-speed cameras are expensive and difficult to use in small competitions and daily training. In this context, Luo et al. have successfully developed a wood-based triboelectric nanogenerator that is both flexible and durable, thereby offering high performance for self-powered sensing within sports equipment and facilitating the analysis of athletic big data (Figure 9e) [78]. This research used Wood TENG to fabricate a smart ping-pong table equipped with multifunctional sensing capabilities. To aid in the training evaluation and guidance of athletes, a self-powered system for the statistical analysis of the falling point distribution was implemented that allows for the real-time recording of training data for big data analytics. A self-powered system for the adjudication of edge balls was also established to assist referees in making real-time decisions.

By providing detailed and real-time performance data, enhancing injury prevention measures, and supporting sustainable practices, TENGs have the potential to transform training and competitive play in table tennis. Future research will focus on optimizing the sensitivity and durability of TENG sensors, exploring their broader applicability within racket sports, and further enhancing the user experience for players and coaches alike.

3.7. Skating

The dynamic and high-energy nature of skating provides an ideal setting for the application of TENG-based sensors. These sensors can be seamlessly integrated into various types of skating equipment, such as ski boots, poles, and suits, where they can capture the kinetic energy generated by the skier's movements. The converted electrical signals can then be utilized to monitor a range of performance metrics, including speed, force, and motion patterns, ultimately offering real-time feedback to both recreational skiers and professional athletes.

The implementation of TENG sensors in skating gear can also substantially improve safety measures. By continuously monitoring the skier's motions, TENG-based systems can detect irregular patterns that may indicate falls, collisions, or other safety hazards, thus triggering immediate alerts to prevent injuries. These real-time data can make a crucial contribution to ski resorts and medical teams in responding promptly to emergencies. One recent study describes a self-powered sensor that can be used to monitor skating frequency and force in real time. A lightweight, portable, self-powered triboelectric nanogenerator is designed for use as a skate monitoring sensor. It is mounted on the heel of a Klap skate and used to monitor an athlete's frequency and force of movement. The sensor is composed of ordinary copper sheets as electrodes along with polytetrafluoroethylene (PTFE) and nylon as friction layers, while the substrate is made by 3D printing. LPS-TENG is cost-effective in terms of materials and is lightweight and portable. The voltage signal is generated by body movement, and the generated voltage signal is transmitted wirelessly through the AD module to monitor the athlete's movement in real time. Based on the signal output, coaches can understand and observe the dynamic changes occurring in sports performance during training and competition in real time, thus allowing them to identify problems in training and helping athletes improve training effects and sports performance. A schematic diagram of a self-powered sensor for monitoring skating technique and collecting movement data is shown in Figure 10(ai). Figure 10(aii) shows how motion data during skating can be obtained by monitoring Klap skates [79].

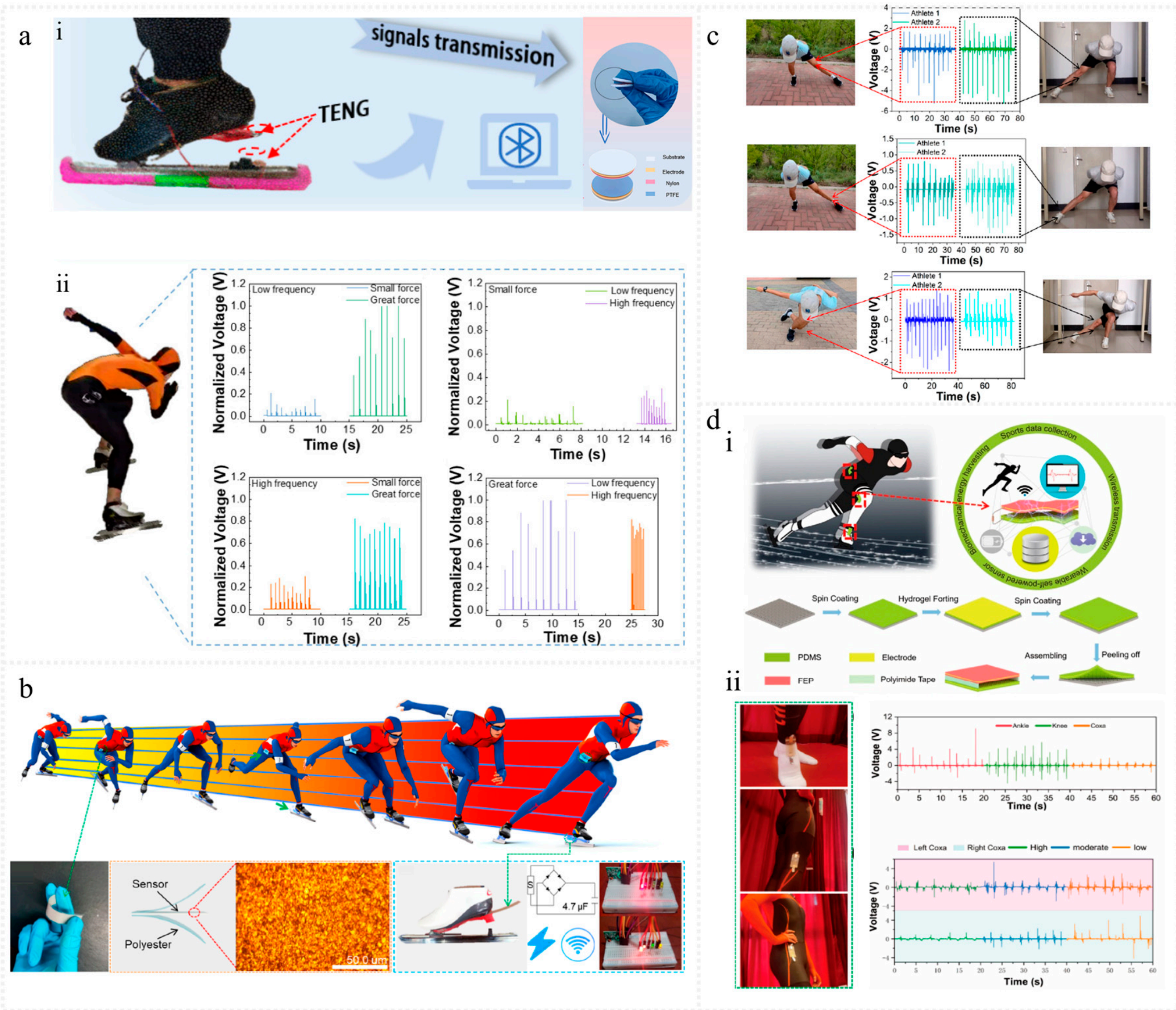

Figure 10. TENG-based sensors applied in skating: (**a**) Experimental design of a self-powered motion sensor for skating technique monitoring. (**i**) Shows the working mechanism of TENG. (**ii**) Signal display of TENG under different pedaling frequencies and pedaling forces [79]. (**b**) Design of self-powered portable flexible sensor [80]. (**c**) Application of TENG in terrestrial training [81]. (**d**) Micro-structured film-based flexible TENG for speed skating technology monitoring and biomechanical energy harvesting. (**i**) The output triboelectric voltage of MS-TENG attached to athlete 1's ankle, knee, and coxa. (**ii**) Output friction voltages of TENG attached to the athlete's ankle, knee, and hip [82].

Moreover, Lu et al. developed a flexible polyester substrate that is composed of polyvinylidene fluoride (PVDF) with a polarization effect after silver-coating the electrodes, as shown in Figure 10b [80]. PVDF was chosen as the sensing material because of its fast response and high output. In the process of speed skating, the hip joint is the most representative joint technologically, and it can better reflect the athlete's specific technical level. The sensor is designed as a flexible, wearable smart sensor to be mounted on the hip joint. The wrapping made of flexible materials greatly improves comfort and does not affect normal sliding. Self-powered portable flexible sensors are designed to monitor physiological joint changing states and sliding motion trajectories in real time. Based on the output signals, coaches can formulate personalized sports technology improvement prescriptions to adjust athletes' technical movements with the ultimate aim of improving sports performance. According to the output signal of TENG, coaches can adjust athletes' technical movements and formulate training plans to make them suitable for athletes, thereby scientifically and systematically improving the efficiency of athletes' land training. Reasonable and effective land exercises can not only lay a good foundation for such athletes, but also improve their physical fitness related to speed skating, as shown in Figure 10c [81].

Finally, Lu et al. developed a microstructured triboelectric nanogenerator (MS-TENG) that consists of a microstructured polydimethylsiloxane (PDMS) film, a fluorinated ethylene propylene (FEP) film, and a lithium chloride polyacrylamide (LiCl-PAAM) hydrogel. By introducing microstructures on the surface of the medium, the output voltage of MS-TENG can be increased by up to 7 times. As shown in Figure 10(di), MS-TENG can be flexibly attached to the skater's joints. Based on the triboelectric effect, the output signal of MS-TENG is a sensing signal. It can collect information such as an athlete's joint-bending angle, movement frequency, movement structure, etc. to provide a basis for big data analysis. Taking advantage of the flexibility of MS-TENG, it can be flexibly attached to the skater's joints. As the target joint flexes and extends, the MS-TENG is compressed and released while converting the captured mechanical signals into voltage signals. The oscilloscope simultaneously collects the voltage signals of the MS-TENG worn on the athletes' ankles, knees, and hips (Figure 10(dii)) [82].

The integration of triboelectric nanogenerators as sensors in skating represents a significant advancement in sports technology. By providing detailed and real-time performance data, enhancing safety measures, and supporting sustainable practices, TENGs have the potential to transform training and competitive skating experiences.

3.8. Swimming

Swimming is a dynamic sport that involves continuous and repetitive body movements, which makes it an ideal setting in which to apply TENG-based sensors. These sensors can be integrated into various types of swimming equipment such as swimsuits, swim caps, goggles, and wearable bands. By capturing the mechanical energy that is generated from a swimmer's strokes, kicks, and turns, TENGs can convert this energy into electrical signals that provide real-time data on various performance metrics. One recent study proposed a biomimetic stretchable nanogenerator (BSNG) inspired by electric eels. By mimicking the structure of ion channels on the cell membrane of electric eel cells, the stress mismatch effect between polydimethylsiloxane (PDMS) and silicone was leveraged to create mechanically controlled channels. Two unique operating modes enable the BSNG to achieve open circuit voltages in excess of 170 V in dry conditions and over 10 V in liquid environments. BSNG is combined with encapsulated multi-channel wireless signal transmission to build a set of underwater human body multi-position motion monitoring and wireless transmission system modules (Figure 11(ai)). An integrated wearable BSNG was developed for this purpose by connecting the BSNG to a silicone wristband. In total, four BSNGs were worn on the human elbow and knee (Figure 11(aii)). The motion signals of the four joints can be obtained in real time through various software installed on the laptop (Figure 11(aiii)) [83]. Superior mechanical responsiveness further makes the BSNG a suitable motion monitor for swimmers and other underwater operators.

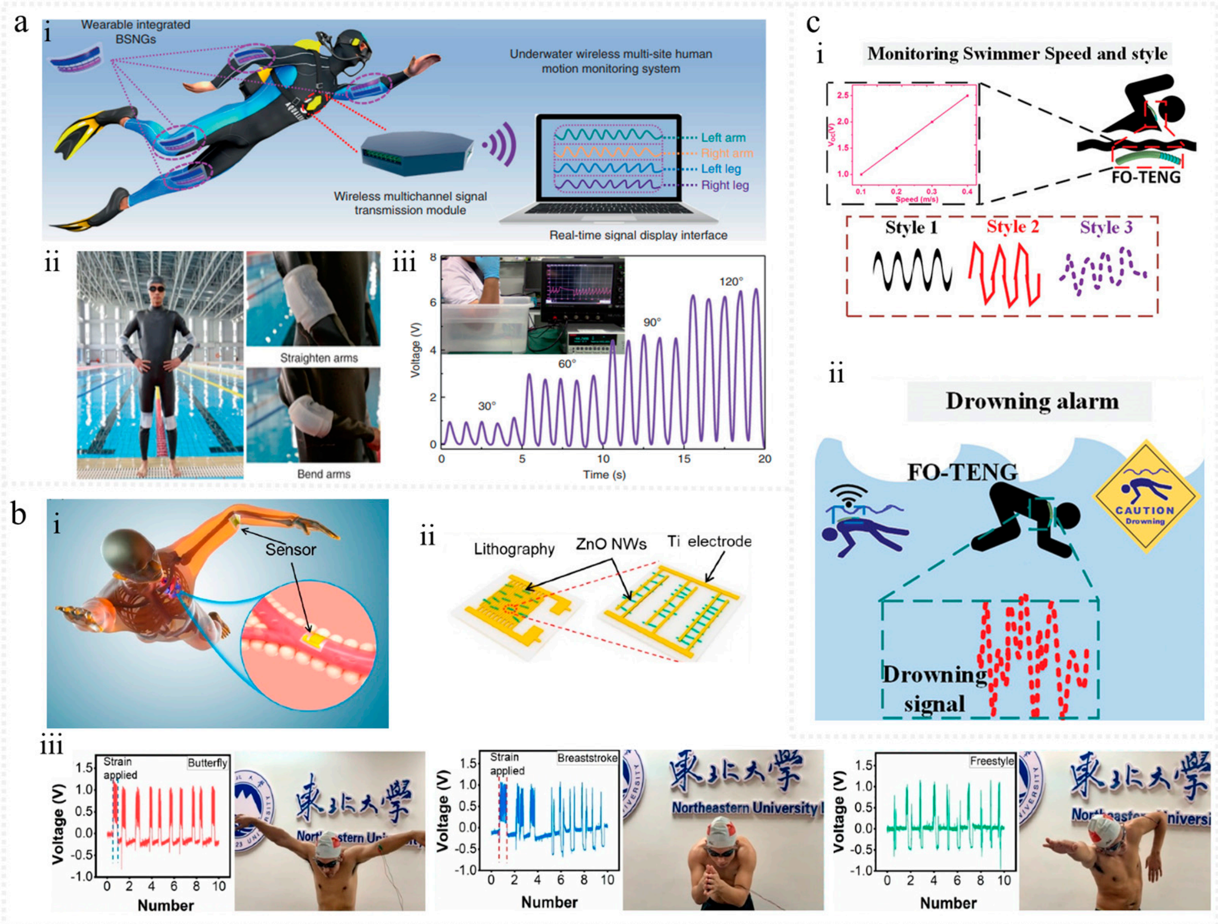

Figure 11. TENG-based sensors applied in swimming: (**a**) Biomimetic stretchable nanogenerator (BSNG) inspired by electric eels. (**i–iii**) Demonstrate the underwater wireless multi-site human movement monitoring system, respectively. Illustration of an underwater wireless multi-site human movement monitoring system based on a bionic stretchable nanogenerator (BSNG) [83]. (**b**) Design and integration of a self-powered, flexible biosensor based on ZnO nanowire arrays and interdigitated electrodes. Different swimming styles can be analyzed using simple wireless transmitting and receiving stations. (**i**) Simulating the monitoring of athlete's elbow joint angle and heart rate. (**ii**) Process of synthesis of self-powered biosensor. (**iii**) Output piezoelectric voltage of butterfly stroke, breaststroke and freestyle stroke [84]. (**c**) Ferrofluid-based friction nanogenerator. (**i**) FO-TENG positioned at the swimmer body to monitor the swimmer speed, and style. (**ii**) The drowning detection system based on FO-TNEG sensor to imitate the alarm as a safety consideration for the swimmer. Reprinted with permission from Ref. [85]. Copyright 2019, Wiley.

Further, Mao et al. developed the design and integration of a self-powered, flexible biosensor based on ZnO nanowire arrays (NWs) and interdigitated electrodes (Figure 11(bi)). This biosensor is based on the piezoelectric effect of polar ZnO, which can collect the mechanical energy that is generated by human body activities and drive the biosensor to monitor the movement process in the air and water. In this way, sports information such as joint angle changes, movement frequency, swimming skills, etc. can be monitored in real time (Figure 11(bii)) [84]. As shown in Figure 11(biii), the flexible self-powered biosensor can be easily attached to the joint of the tester for in vivo monitoring. Athletes adopt various different postures when swimming. Based on the output piezoelectric voltage signal, the frequency and the angle are both quite stable, and the performance of movement skills is extremely good.

Finally, Abdelsalam et al. developed a stretchable, multimodal, ferrofluid-based triboelectric nanogenerator (FO-TENG) that achieves significant multifunctional sensing capabilities with extremely high confirmability. The developed smart sensing platform can be activated/stimulated by different types of mechanical stimuli to promote danger signals, including endogenous forces such as compression, tension, or vibration (body movement), whereas it can also be remotely triggered by exogenous forces such as a magnetic harmonic field. Figure 11(ci) presents a schematic diagram showing an FO-TENG attached to a swimmer. Figure 11(cii) shows that, in the case of drowning, the FO-TENG signal should be higher than normal because the swimmer will struggle violently and move randomly [85].

The integration of triboelectric nanogenerators as sensors in swimming represents a significant advancement in sports technology. By providing detailed and real-time performance data, enhancing safety measures, and supporting sustainable practices, TENGs have the potential to transform the training and competitive landscape of swimming. Future research in this area should focus on optimizing the sensitivity and durability of TENG sensors, exploring broader applications within aquatic sports, and further enhancing the user experience for swimmers and coaches alike.

3.9. Application in Other Intelligent Sports

TENGs have demonstrated significant potential for sports detection by converting mechanical energy into electrical signals. TENGs offer several advantages over traditional sensors, including self-powering capability, high sensitivity, flexibility, and cost-effectiveness. These features make TENGs particularly suitable for various applications in smart motion detection, from wearable devices to implantable health monitoring systems. The comprehensive review of existing research highlights the versatility of TENGs in detecting different types of motion, such as human body movements, sports activities, and subtle physiological signals.

In addition to the commercial sports mentioned above, TENG-based sports, such as shot put, cycling, curling, golf, artistic gymnastics, and sports injury monitoring, all bring unique challenges and opportunities to TENG-based sensing systems. One recent study proposed self-powered smart biosensors to real-time monitor the rear leg rotation technique and performance of artistic gymnastics. It can monitor the buffering and stretching time of rear leg rotation and identify the angle between the hip, knee, and ankle during the stretching stage. The real-time monitoring of the performance of artistic gymnastics athletes' rear leg rotation techniques is beneficial for coaches and athletes to analyze the quality of motion completion based on motion data and assist in formulating scientific training plans (Figure 12a) [86]. Further, Mao et al. developed a recyclable flexible triboelectric nanogenerator (RF-TENG). The resulting RF-TENG achieved real-time sports data transmission with a response time of 17 ms and a recovery time of 26 ms. Remarkably, even after 4200 operations, the proposed RF-TENG exhibited only a 6% variance in output voltage (Figure 12b) [87]. Then, Mao et al. also developed a Metaverse sport interactive system based on TENGs. The system includes a TENG-based self-powered APM, a wireless transmission module, cloud-based personalized data analysis, and an augmented reality application (Figure 12c) [88]. Moreover, the self-powered APM is installed at the bicycle axle and the wireless transmission module is built on the printed circuit board, which transmits data related to bicycle movement, such as the rotational speed, wirelessly to the cloud.

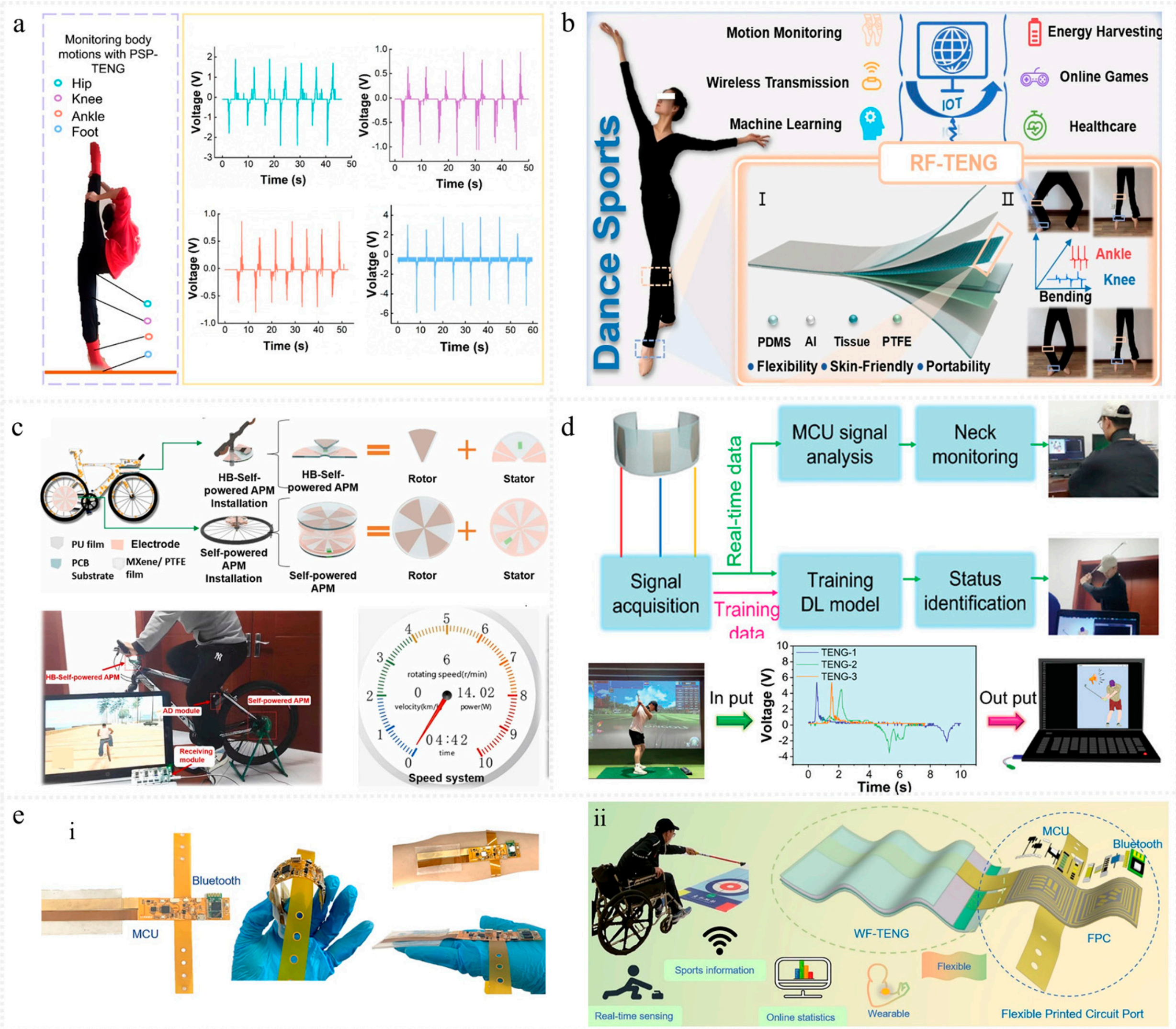

Figure 12. TENG-based sensors applied in other sports: (**a**) A newly designed triboelectric nanogenerator PSP-TENG monitoring the rear leg rotation of artistic gymnastics [86]. (**b**) The sports and injury information of the dancer or crowd is collected by the recyclable flexible triboelectric nanogenerator (RF-TENG) sensor module [87]. (**c**) Scene construction of printed circuit triboelectric nanogenerator-based sport interactive system. Reprinted with permission from Ref. [88]. Copyright 2023, Elsevier. (**d**) Intelligent behavioral monitoring system integrated with deep learning-assisted data analysis. Intelligent behavioral monitoring system to assist golf training. Reprinted with permission from Ref. [89]. Copyright 2024. Wiley. (**e**) Design of the wireless intelligent sensing system for wheelchair curling technology [90].

Moreover, Mao et al. used corn bract leaves as the friction material for constructing naturally biodegradable TENGs (NB-TENGs) for neck-condition monitoring (Figure 12d) [89]. The neck-condition monitoring triboelectric sensor (NCM-TS) consisting of three NB-TENGs was fixed to a neck collar to capture and analyze the neck motion. To establish the practicality of the wearable device, a deep learning model was designed to recognize four types of neck motion in golf sports, which achieved an average recognition accuracy of 94%. Finally, Mao et al. developed a wireless intelligent sensing system (WISS), which includes a WF-TENG sensing port integrated with the wearable flexible triboelectric nanogenerator (WF-TENG), flexible printed circuit (FPC), a Bluetooth wireless transmitter, along with the upper computer digital signal receiving intelligent processing port (Figure 12e) [90].

The system can monitor wheelchair curlers' curling skills and human-computer interactive simulation training in real time.

These advancements underscore the broad applicability and transformative potential of TENGs in sports monitoring and performance enhancement, highlighting the need for continued innovation and research to fully realize their benefits across diverse sports applications.

4. Conclusions

In conclusion, the exploration of triboelectric nanogenerators (TENGs) within the realm of intelligent sports marks a significant leap toward the ultimate goal of harnessing biomechanical energy for sustainable and efficient athletic monitoring and enhancement. This study has demonstrated the profound versatility and potential of TENGs as a pivotal technology in the development of self-powered, smart sports equipment and wearables. Through innovative design and strategic integration, TENGs offer a novel approach to capturing the kinetic energy generated by athletes, specifically by converting it into electrical energy that can be used in real-time data acquisition and analysis. The implementation of TENGs in sports-monitoring devices has shown promising results in improving the quality of training, optimizing performance, and preventing injuries by providing detailed, actionable insights into athletes' biomechanical metrics. The lightweight, cost-effective, and environmentally friendly nature of TENG-based sensors makes them an attractive solution to the challenges of powering wearable technology without contributing to electronic waste or requiring frequent recharging. This study has also highlighted the importance of interdisciplinary collaboration in advancing TENG technology for sports applications. The integration of materials science, mechanical engineering, and sports science is crucial for developing TENG devices that are not only technically feasible but also practically applicable in the sports industry. Future research should focus on enhancing the efficiency, durability, and user-friendliness of TENGs while exploring new materials and designs that might improve their performance and integration into sports wearables.

TENGs have demonstrated significant potential for sports detection by converting mechanical energy into electrical signals. To fully harness this potential and expand their application scope, several key challenges and future research directions need to be addressed.

Material Selection: The performance of TENGs is heavily influenced by the triboelectric properties, mechanical strength, and durability of the materials used. Future research should focus on exploring novel materials, particularly those that are flexible, stretchable, and biocompatible, to enhance the versatility and effectiveness of TENGs.

Implantable Body Detection: TENGs hold promise for detecting physiological signals when used as implantable devices. However, issues related to biocompatibility, safety, and long-term stability of implantable materials remain unresolved. Future studies should develop materials and designs suitable for long-term implantation, ensuring stability and non-toxicity within the body.

Accuracy of Monitoring Data: Reliable motion detection requires TENG-generated data to be accurate and reproducible. Future research should minimize environmental noise and interference to improve data accuracy and consistency. Advanced data processing and analysis methods will be crucial in enhancing the precision of TENG monitoring systems.

Complexity of External Environments: TENGs must operate under various complex environmental conditions, such as humidity, temperature, and dust, which can affect their performance. Future research should investigate the stability and reliability of TENGs in different environments, developing systems with adaptive capabilities and environmental tolerance.

Integration with Modern Technologies: Integrating TENGs with modern technologies, particularly the Internet of Things (IoT), big data, and artificial intelligence (AI), is a promising direction for future research. For instance, using AI to analyze TENG data can achieve more accurate motion monitoring and health management.

Addressing these key issues in future research is essential for overcoming existing technical barriers and advancing the widespread application of TENGs in smart motion detection. Through continuous innovation and optimization, TENGs are expected to play a significant role in motion detection, health monitoring, and various other smart applications.

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