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# Recent advances in intelligent sports based on triboelectric nanogenerators

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A B S T R A C T

The development of emerging technologies such as Internet of Things, big data analysis, and artificial intelligence (AI) has made athlete digitalization crucial in competitive sports. Triboelectric nanogenerator (TENG) is an emerging technology for mechanical energy harvesting and self-powered sensing, which offers significant potential in intelligent sports by reducing battery dependency. This paper reviews the recent advancements in TENG applications for intelligent sports, toward the future application of artificial intelligence for sports. Firstly, the working mechanism of TENG and its relationship with big data in sports are introduced. Subsequently, the focus shifts to the applications of TENGs in sports facilities, wearable equipment, and medical health devices. In addition, the integration of TENG with hybrid nanogenerators is explored for multi-functional and precise motion sensing. Finally, the challenges and future prospects of TENGs in intelligent sports are also discussed.

## 1. Introduction

The advancements in the Internet of Things (IoTs) [1–4], big data analysis (BDA) [5–8], and artificial intelligence (AI) [9–12] have revolutionized intelligent sports by enabling real-time athlete monitoring and data-driven decision-making. IoTs refers to a networked system that integrates sensing, communication, and data processing, generating vast real-time data stream [1,13]. However, despite the powerful automation capabilities of IoTs, the continuous generation of large-scale real-time data streams poses challenges in extracting meaningful insights. Without effective data analysis and interpretation, these data may have limited practical significance [13]. BDA serves as a crucial tool for transforming raw data into actionable insights [14], while AI leverages these insights for predictive modeling and strategy optimization [15]. The integration of these modern information technologies fosters innovation and advancement in the sports industry, paving the way for intelligence-driven and automated sports applications. Among these, effective data collection and analysis are fundamental to the development of intelligent sports. Currently, data collection in sports primarily relies on various sensors and fixed monitoring equipment to monitor and capture physiological signals, such as pressure sensors [16,17], acceleration sensors [18], temperature sensors [19], and respiratory sensors [20,21]. However, when applied to sports performance evaluation, most of these sensors require an external power supply, which limits their practicality. Given that IoTs applications in future intelligent societies will demand a large number of sensors, self-powered sensors have emerged as an ideal solution to address power consumption challenges [22,23].

In 2012, Wang and his colleagues proposed the triboelectric nanogenerator (TENG), which is driven by Maxwell displacement current to efficiently convert mechanical energy into electrical energy [24–27]. With significant advantages such as wide material diversity, multiple working modes, simple preparation, high electrical output, and fast response to mechanical stimuli [28–33], TENG can efficiently harvest various environmental mechanical energy such as human motion [34–37], wind [38–40], and ocean energy [41–45]. Moreover, by

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directly converting mechanical stimuli into electrical signals, TENGs can also function as self-powered sensors for pressure, motion, or tactile sensing without extra power supply, making it vital for developing maintenance-free systems [46–49]. These characteristics underscore the feasibility of TENG for building self-powered systems for intelligent sports, especially in capturing low-frequency and small-amplitude mechanical stimuli. For example, TENG can monitor the joint movement, such as arm bending and waist twisting in real time [50]. TENG can also form a self-rechargeable cardiac pacemaker system by collecting the inertia of the human body, which is a promising internal energy collector [51]. In addition, machine learning (ML) technology is an AI technology widely used in data processing. TENG has a variety of structures and stable output, and the ML algorithm has powerful data processing capabilities. The development of intelligent sensing systems based on TENG and ML has played a key role in pushing the new era of the IoTs [22,52]. Therefore, TENG-based self-powered systems offer a practical solution for multi-dimensional data acquisition in intelligent sports, and represent a core technology with significant potential to support the rapid development of IoTs and AI [22,53,54].

This review focuses on the latest progress of TENG in the field of intelligent sports. We first introduce the fundamental principle and working modes of TENG, as well as its relationship with modern information technology, such as IoTs, BDA, and AI. The recent innovative development of TENG-based self-powered intelligent sports systems is then summarized. As illustrated in Fig. 1, the self-powered intelligent systems based on TENG comprise several key components. TENG can be integrated into sports facilities, such as balls, tables, and rackets, to record real-time mechanical signals generated during athletic activities. At the same time, TENG can also be embedded into wearable devices, including clothes, socks, and shoes, to enhance real-time monitoring of human physiological signals. Beyond sports performance, TENG also holds promise for human health monitoring and treatment, offering valuable insights for guiding sports training, preventing injuries, and facilitating patient recovery. TENG intelligent devices can be connected to a network and are widely used in the field of sports. When networked, TENG-enabled devices can be widely deployed across the sports domain, enabling more intelligent sports applications through the integration of IoTs, BDA, and AI. Finally, we discuss the current challenges and future prospects of TENG in intelligent sports, emphasizing its transformative potential in the era of smart sports.

## 2. Triboelectric nanogenerator

Triboelectrification, also known as contact electrification (CE), refers to the charging effect that occurs when two materials come into contact. During friction between the materials, charge is transferred, leading to an accumulation of static charge. CE is the fundamental source of various electrostatic charges encountered in everyday life, which exist almost anywhere at any time [55–58]. Historically, CE was regarded as a negative impact until the introduction of TENG in 2012, which opened a new era of converting randomly distributed, irregular, and wasteful low-frequency energy into electrical energy [24,59,60]. The power generation principle of TENG is based on the coupling of CE and the electrostatic induction effect, with its underlying physical model rooted in Maxwell's equation [25,61,62]. As illustrated in Fig. 2a, a typical TENG has two different friction layers and one/two metal electrodes. TENG operates in four primary working modes: vertical contact-separation mode, single-electrode mode, lateral sliding mode, and freestanding triboelectric-layer mode [63–68]. Maxwell displacement current is the theoretical origin of TENG. To explain the contribution made by the CE induced electrostatic charges in Maxwell's equations, an additional term $\boldsymbol{P}_S$ was added in displacement vector $D$ by Wang in 2017 [25]. That is

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} + \boldsymbol{P}_s \tag{1}$$

Here, the first polarization vector $\boldsymbol{P}$ is attributed to the existing external electric field, and the additional term $\boldsymbol{P}_S$ is mainly related to the existing surface charge, while the surface charge is independent of the electric field. Substitute Eq. (1) into Maxwell's equation and define


**Fig. 1.** Schematic diagram of TENGs for intelligent sports based on IoTs, BDA, and AI technology.

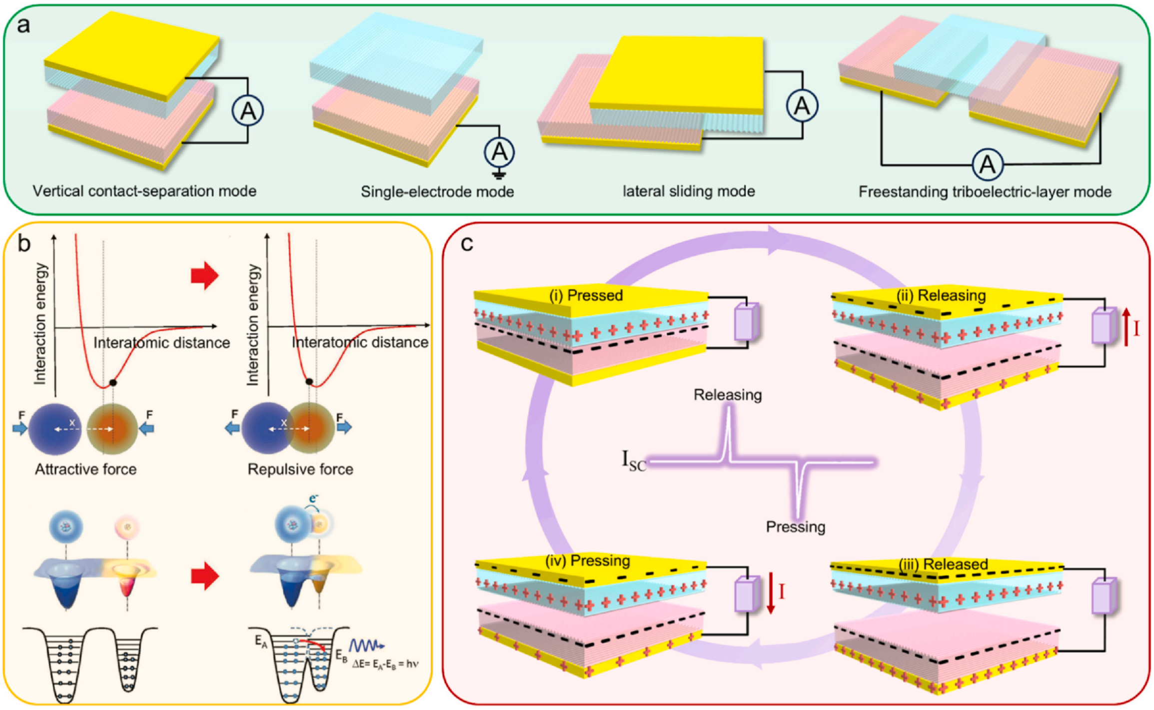


**Fig. 2.** Schematic diagram of TENG's fundamental theory. **a** The working modes of TENG. **b** "Wang transition" model [69]. **c** The working mechanism of TENG.

$$\boldsymbol{D}' = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} \tag{2}$$

Then, Maxwell's equations can be reformulated as follows:

$$\nabla \cdot \boldsymbol{D}' = \rho' \tag{3}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{4}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{5}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}' + \frac{\partial \boldsymbol{D}'}{\partial t} \tag{6}$$

where the density of volume charge and the current density could be redefined as

$$\rho' = \rho - \nabla \cdot \boldsymbol{P}_s \tag{7}$$

$$\boldsymbol{J}' = \boldsymbol{J} + \nabla \cdot \frac{\partial \boldsymbol{P}_s}{\partial t} \tag{8}$$

From Eqs. (1) and (2), the newly Maxwell's displacement current can be revised as:

$$\boldsymbol{J}_D = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_s}{\partial t} \tag{9}$$

Here, the first term $\varepsilon \frac{\partial \boldsymbol{E}}{\partial t}$ is the displacement current due to the time varying electric field and its induced medium polarization. It gives the birth of electromagnetic wave theory. While the second term $\frac{\partial \boldsymbol{P}_s}{\partial t}$, which is referred to as Wang term, represents the displacement current due to the nonelectric field but owing to the external strain field. It leads to the invention of nanogenerators [69].

In sports activities, the interaction between the human body and various equipment inevitably generates frictional charges, offering significant potential for the application of TENG technology. In addition, an atomic-scale "Wang transition" model has been proposed to understand the physical properties of CE and charge transfer across solids, liquids, and gases (Fig. 2b). The model suggests that CE occurs only within the repulsive region of the interaction potential between two atoms, specifically when the distance between them is less than their bond length. As the atoms approach each other, the strong overlap of electron clouds under stress reduces the energy barrier, facilitating electron transition between the atoms and thus inducing CE [69]. To illustrate the working mechanism of TENG, we use the vertical contact-separation mode as an example. Initially, the two friction layers with distinct triboelectric properties do not generate charge. Upon external pressure, the friction layers come into contact, triggering CE and resulting in equal and opposite charges on the surfaces (Fig. 2c i). As the external pressure gradually decreases, the friction layers separate, generating a potential difference between the electrodes, which drives electron flow (Fig. 2c ii). The equilibrium is reached when the two surfaces are completely separated (Fig. 2c iii). When the friction layers are pressed together again, the electrostatically induced charge flows through the external load, compensating for the potential difference (Fig. 2c iv). Except for the TENG technology, extensive researches have been reported for sports and health monitoring based on various mechanisms, including electromagnetic, capacitive, resistive, and piezoelectric [70–73]. Table 1 presents a detailed comparison between these five technologies in terms of their mechanisms, advantages, and disadvantages. Among them, the application of TENG technology in sports offers clear advantages, particularly given the low-frequency nature of most mechanical movements in sports and TENG's capability as a self-powered sensor. Thus, TENG can be strategically designed to meet the specific needs of different sports, enabling efficient mechanical energy harvesting and self-powered sensing.

## 3. Athletic big data

The era of big data has arrived, with computer scientists, physicists and other scholars eager to harness vast amounts of information generated by individuals, things, and their interactions [5]. IoTs plays a pivotal role in generating big data by interconnecting a wide range of devices and sensors, enabling the collection, transmission, and storage of vast amounts of data from diverse systems and objects. Meanwhile, BDA and AI have become key drivers of the fourth industrial revolution, representing a major source of future competitive advantage [74]. Over the past few years, big data has become increasingly integrated into the sports industry, serving as a valuable decision-making tool for institutions and organizations at all levels [75]. Data has always been fundamental to the growth and development of the sports industry [76],

**Table 1**
Comparison of sensing technologies in sports and health monitoring based on electromagnetic, capacitive, resistive, piezoelectric, and triboelectric mechanisms for illustrating their advantages and disadvantages.

| | Electromagnetic | Capacitive | Resistive | Piezoelectric | Triboelectric |
|---|---|---|---|---|---|
| Mechanism | Electromagnetic induction | Capacitive transduction | Resistive transduction | Piezoelectric effect and electrostatic induction | Contact electrification and electrostatic induction |
| Pros | High efficiency at high frequency; High response speed, long life | High sensitivity; Low power consumption | Simple structure; Low cost | High sensitivity, high response speed; Self-powered | High efficiency at low frequency; Low cost, low density, light weight; Multiple working modes; Diverse choice of materials; Self-powered |
| Cons | Heavy, high density, high cost; Susceptible to magnetic interference | High cost; weak environmental adaptability | Low sensitivity; Susceptible to temperature | Low output, low efficiency | Low durability |

benefiting coaches, athletes, and sports rehabilitation professionals. In particular, BDA allows coaches to design personalized training programs for athletes, optimize performance, and improve game outcomes [77]. AI machine learning models, BDA, and other technologies are utilized in player selection, game outcome prediction, and tactical analysis [78,79]. For example, deep neural network models and layer-wise relevance propagation techniques were used to study the differences in gait patterns between higher-mileage runners and low-mileage runners [80]. Deep reinforcement learning (RL) has always been a key component of AI milestones. Gran Turismo Sophy (GT Sophy) is a champion-level racing agent using model-free, off-policy deep RL [81]. As shown in Fig. 3, athletic big data encompasses metrics such as speed, heart rate, and movement, providing precise insights into the performance and health of athletes. This data plays a crucial role in guiding training, preventing injury, and promoting athletes' recovery.

In the field of sports, data is primarily expressed as mechanical signals, which can be directly converted into electrical signals using TENG technology. TENG technology has the advantages of being self-powered, maintenance-free, and cost-effective, making it highly promising for widespread application in the sports industry and providing a solid foundation for athletic big data. In the near future, the data collected by TENG technology can be leveraged to enhance athletic performance, guide sports training, and prevent sports injuries through modern information technologies such as IoTs, BDA, and AI. For instance, TENG-based equipment can capture real-time data on hitting positions and speeds in ball games. Coaches can then use this data to develop personalized training programs aimed at improving hand control, ultimately enhancing athletes' competitive performance [82]. Specifically, ML models can be designed to process and analyze diverse signal types (instantaneous high voltage signal, noise, and combined mechanical motion signals) in real time. This enables real-time monitoring of output current/voltage signals and the extraction of meaningful information from complex data. Therefore, athletic big data can help create individualized athlete profiles, allowing coaches to design tailored training plans that optimize training outcomes based on the unique characteristics of each athlete.

## 4. TENG-based intelligent sports and health

### 4.1. Sports facility

#### 4.1.1. TENG-based sports facility

TENG can be easily integrated into sports facilities to capture real-time sports data, providing valuable insights to guide athlete training and competition. Its advantages include wide material diversity, multiple working modes, and simple structure. A recent study demonstrated a table tennis racket equipped with a self-powered wireless TENG-based sensing system that captures real-time data on impact position and intensity. This system consists of a TENG integrated into the racket, along with a data acquisition card, Wi-Fi module, and human-machine interface (HMI) (Fig. 4a) [83]. As illustrated in Fig. 4b, the HMI's data acquisition feature enables real-time visualization of output voltage, impact force, and sensing position simultaneously. The excellent stability and sensitivity of the system are reflected in its 100 % position discrimination accuracy for more than 340 ball impacts, and it can handle high-speed movements up to 10 kHz. This capability provides athletes with precise and detailed training data, enhancing performance analysis. This study highlights the great potential of integrating TENG-based sensors into intelligent sports equipment. He et al. also integrated TENG with table tennis rackets to collect the vibration energy during impact, as well as in focusing gloves to capture punch frequency and intensity [84]. Intelligent table tennis rackets can not only provide evaluation and personal guidance for athletes' training, but also open up new prospects for the field of intelligent sports [85,86]. Chen et al. explored the use of highly flexible and extensible TENG fibers, which can be attached to baseball gloves to detect hitting points at varying

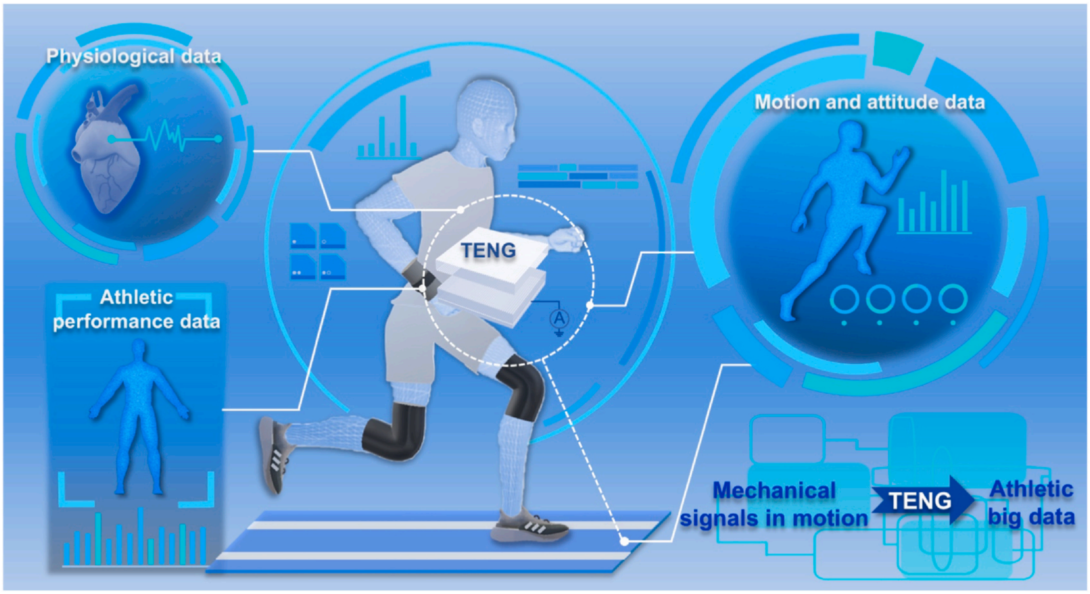


**Fig. 3.** Schematic illustration of athletic big data.

speeds, as shown in Fig. 4c [87]. These fibers can withstand sudden, strong impacts, making them ideal for monitoring athletic performance and training. In addition, the TENG fibers exhibit coordinate sensing function when mounted on the surface of a football. Heo et al. developed an integrated TENG structure within a commercial football to study and analyze its kicking, bouncing, and rolling dynamics [88].

As shown in Fig. 4d, Luo et al. proposed a flexible and durable wooden TENG-based intelligent table tennis table, which can directly convert the impact between the table surface and the ball into electrical signals [89]. This innovation successfully implements a self-powered falling point distribution statistics system and an edge ball judgment system through a TENG array on the tabletop (Fig. 4e). These systems provide valuable training guidance and real-time competition assistance for athletes and referees. This research not only extends the application field of self-powered systems to intelligent sports monitoring and assistance, but also promotes the development of BDA in the intelligent sports industry. Similarly, Hao et al. developed a flexible, self-rebound curved-surface TENG for kinematic analysis and safety prediction in equestrian sports [90]. As shown in Fig. 4f, the information on the riding pitch attitude is obtained by using seven TENG units on the saddle as sensing points. Through big data collection and analysis of statistical results, exercise habits data can be obtained to assist athletes in training and performance enhancement. Wang et al. prepared a TENG with a kernmantle structure mounted on a trampoline, constructing a self-powered, dual-mode sensing system for trampoline jump counting (mode i) and foul monitoring (mode ii) [91]. In mode i, a low-voltage output is generated from contact-separation between the load-bearing rod and the braid when a person jumps. Mode ii generates a higher voltage output due to the contact-separation between the braid and trampoline fabric when stepping on the trampoline spring (Fig. 4g). In the actual game, mode ii can be used to help the referee to judge the foul on the trampoline spring. The development of these TENG-based sports facilities has significantly advanced intelligent sports. In addition to the above-mentioned examples, TENG can also be integrated with various sports equipment such as the take-off board of triple jump [92], golf club [93], track and field track [94], skateboard [95], and taekwondo protector [96]. TENG-based sports facilities can monitor the status of athletes, improving training efficiency, and competitive outcomes. This demonstrates the great potential of TENG as an energy harvester and self-powered sensor in intelligent sports.

#### *4.1.2. Hybrid nanogenerators in sports facility*

TENG can be integrated into sports facilities such as rackets, football, and tables to guide athletes in training and competition. However, its application is partially limited by its inherent characteristics, notably high output voltage but low output current. To address these limitations and enhance device integration, researchers have combined TENG with other energy-harvesting technologies, such as solar cells, piezoelectric nanogenerators (PENG), thermoelectric nanogenerators, or electromagnetic generators (EMG) [97]. Hybrid nanogenerators (HNGs) that integrate TENG with these technologies exhibit superior energy conversion efficiency, output power, and sensitivity compared to standalone TENGs [98,99]. For instance, as shown in Fig. 5a, an HNG combining PENG and TENG demonstrates excellent output performance, sensitivity, durability, and stability [100]. When integrated into a sandbag, this HNG can distinguish between six different boxing techniques based on the unique output signals generated, enabling the identification of an athlete's boxing habits. Such data can assist coaches in designing tailored training plan and improve training efficiency. Additionally, TENG can be combined with EMG to create hybrid systems. As illustrated in Fig. 5b, Wang et al. developed a tire-driven triboelectric-electromagnetic HNG, comprising two TENGs and one EMG for monitoring cyclist performance [101]. The data collected from this system can provide valuable insights for optimizing training and competition strategies for cyclists.

Intelligent sensing technology plays a pivotal role in enhancing badminton training by capturing and analyzing athletes' behaviors to improve sports skills and performance. Yuan et al. designed a self-powered intelligent badminton racket with triboelectric/piezoelectric effect, offering multifunctionality, real-time monitoring, and convenience (Fig. 5c) [102]. The racket incorporates a custom electrode constructed using a silver paste coating method, forming a triboelectric sensor array on the racket shaft to monitor hitting positions. Additionally, a flexible piezoelectric film with a specific shape is embedded in the hand adhesive to determine the grasping posture. Chen et al. also developed a real-time tennis training system based on elastic piezoelectric-triboelectric hybrid yarn (E-PT yarn) with a layered micro-nano structure [103]. The E-PT yarn is composed of an elastic conductive core yarn, a piezoelectric nanofiber layer, and a triboelectric silicone rubber coating, enabling simultaneous generation of triboelectric and piezoelectric signals to enhance energy output efficiency

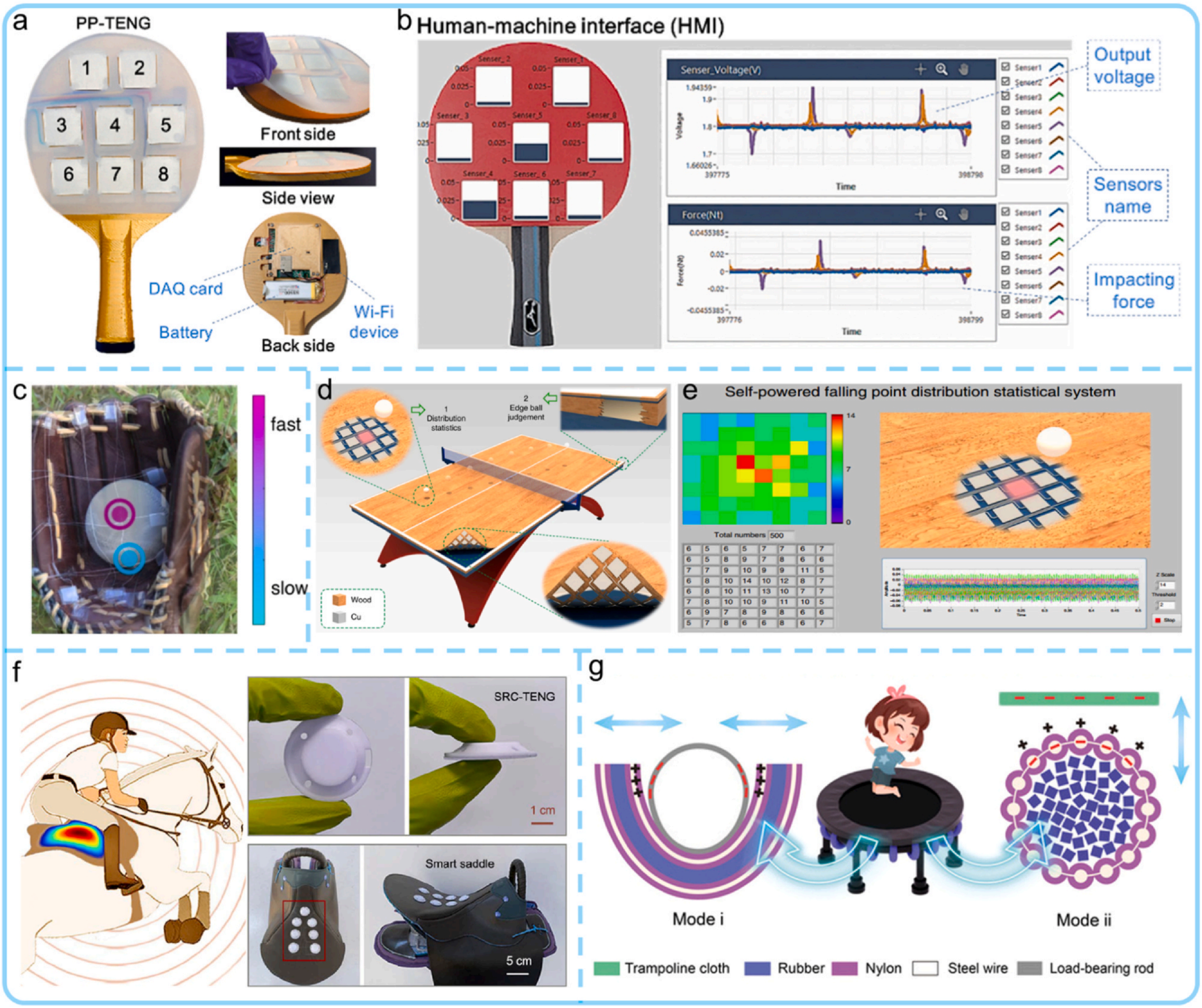


**Fig. 4.** TENG-based intelligent sports facilities. **a** The photographic images of the ping-pong paddle devices integrated [83]. **b** the HMI of the ping-pong paddle simultaneously detects the output voltage, impacting force, and sensing position. [83]. **c** The detection to locate the hitting point with different catching speeds, when the baseball was caught by the TENG-based glove [87]. **d** Schematic illustration of the flexible and durable wooden TENG-based intelligent table tennis table [89]. and **e** The Self-powered falling point distribution statistical system of TENG-based intelligent table tennis table [89]. **f** A schematic illustration of a smart saddle in equestrian sports, which consists of seven TENG units installed on the saddle [90]. **g** The working principle of TENG with a kernmantle structure in mode i and mode ii [91].

and mechanical robustness. As shown in Fig. 5d, a 9-channel sensor array composed of E-PT yarns wrapped around a tennis racket, which can evaluate the player's strike point and strike trajectory, and improve strike accuracy and effectiveness. Fig. 5e illustrates the working mechanism of E-PT yarn in single electrode mode, where triboelectric and piezoelectric signals are superimposed to significantly enhance overall output, surpassing that of individual piezoelectric or triboelectric yarns. The synergy between these two mechanisms makes E-PT yarns highly effective for energy conversion applications. These HNGs demonstrate the potential of self-powered sensing systems in intelligent sports monitoring and training, driving advancements in smart sports training technologies.

### *4.2. Wearable equipment*

#### *4.2.1. TENG-based wearable electronic equipment*

In addition to sports facilities, TENG can also be designed as a wearable device with the advantages of lightweight, portability, flexibility, and self-power supply [104–106]. These attributes make TENG-based wearable devices highly suitable for human motion monitoring, sensing, and mechanical energy harvesting, thereby driving advancements in intelligent sports [107,108]. Recently, Zou et al. developed a bionic, stretchable TENG underwater wireless human motion monitoring system inspired by the ion channel structure of electric eels (Fig. 6a) [109]. The system enables real-time motion signal acquisition during swimming by incorporating four retractable TENGs worn on the elbows and knees. Textiles have been widely explored for wearable electronic devices due to their inherent flexibility and stretchability, as well as their integration into everyday clothing. As shown in Fig. 6b, Zhang et al. developed a low-cost triboelectric smart sock capable of harvesting waste energy from low-frequency body movements [110]. This smart sock demonstrates high stability and adaptability in gait monitoring, including jumping, running, sliding, and walking. In the future, this wearable system could accelerate the development of digital human technologies, enabling the creation of real-time digital human replicas in virtual environments. Wang et al. further designed and mass-produced a kind of woven intelligent yarn based on TENG, which is composed of commercial ultra-high molecular weight polyethylene yarn and conductive yarn (Fig. 6c) [111]. This material was fabricated into a pair of intelligent elbow sleeves with excellent mechanical

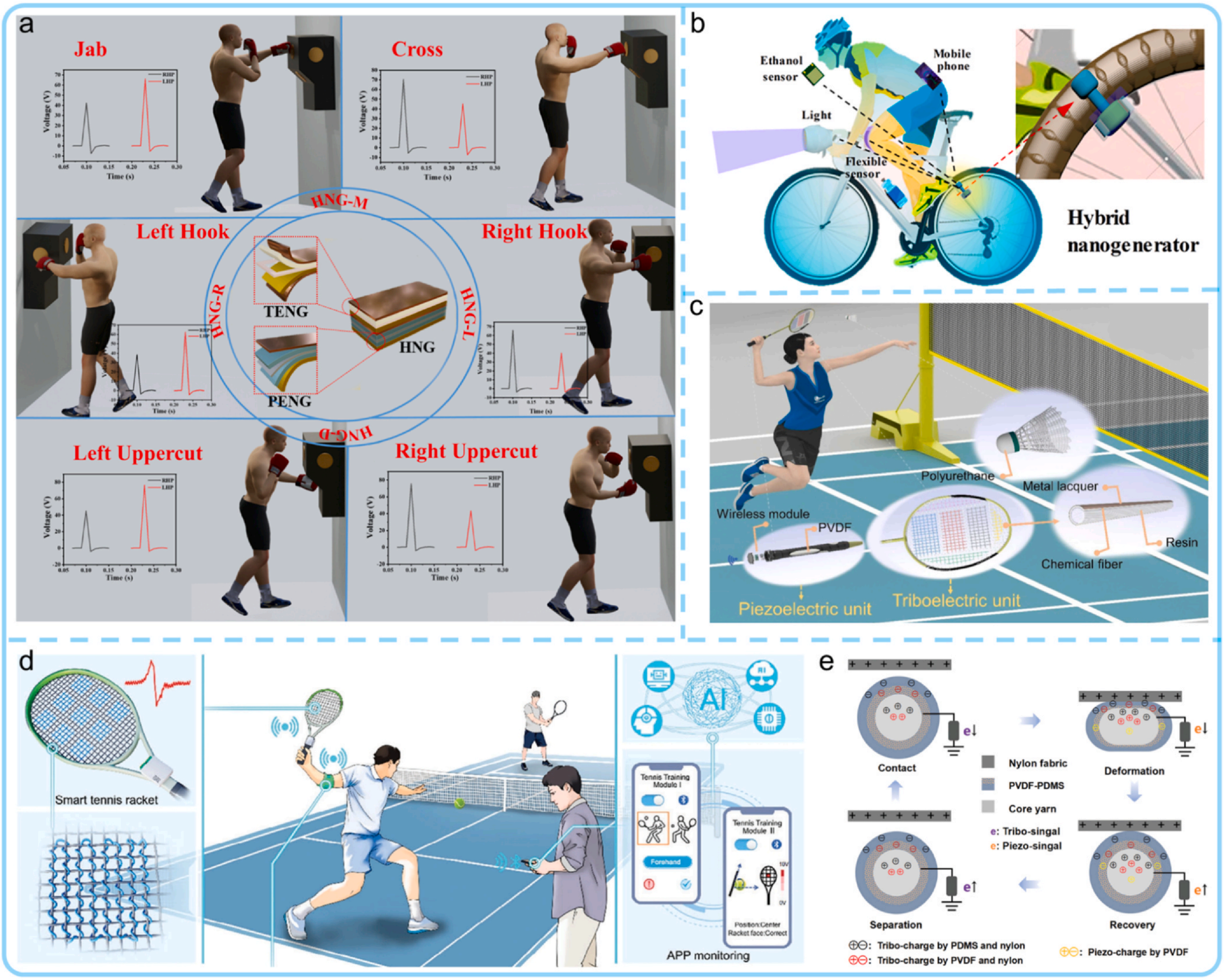


**Fig. 5.** Hybrid nanogenerators in sports facility. **a** Schematic and the output voltage of HNG under six punches by both a right-handed and left-handed athlete [100]. **b** The structure diagram of HNG driven by wheels [101]. **c** The structure diagram of self-powered intelligent badminton racket for badminton training [102]. **d** Schematic diagram of the Intelligent tennis racket [103]. **e** The working mechanism of the E-PT yarn [103].

strength, physical protection, and comfort. As shown in Fig. 6d, the intelligent elbows have a good human motion response and can be used to identify arm bending in boxing and push-ups through different waveforms and frequencies.

Similarly, Wu et al. reported a fiber-based TENG with a helical structure, which can be integrated into electronic textiles for diverse applications, including energy-harvesting insoles, motion-sensing knee pads, and wireless signal-controlling gloves (Fig. 6e) [112]. The smart insole collects mechanical energy from runners and serves as a self-powered lighting device for nighttime running. Since most human movements involve joint bending, smart knee pads can detect a range of knee-related actions, including flexion/extension, walking, running, and jumping. Additionally, smart gloves can recognize relatively subtle movements, such as finger bending. This work promotes the development of multifunctional TENG-based wearable systems and offers new insights into smart sports applications. In addition to textiles, flexible TENG can also functions as wearable sports devices. As shown in Fig. 6f, flexible TENGs attached to the knee and ankle joints can capture mechanical motion signals for dance movement analysis [113]. This system can differentiate between three distinct dance jump techniques of “large, medium, and small”, providing a viable solution for complex joint movement recognition. The sensor also demonstrates great application potential for use in motion assist devices and motion monitoring. Additionally, numerous TENG-based wearable motion devices have been developed for various applications, including monitoring human joints [114–116], hands [117,118], arms [119], elbows [120], waists [121], legs [122] and feet [104]. These smart wearable TENG devices are poised to play a crucial role in smart sports, medical, home, and other fields.

*4.2.2. Hybrid nanogenerators in wearable equipment*

HNGs also have superior performance compared to single TENGs in wearable devices. As shown in Fig. 7a, Du et al. designed an insole hybrid nanogenerator (IHN) combining TENG and PENG with a sandwich and arch structure [123]. This design enhances the synergy between the two generators, enabling applications in gait movement research and dorsalis pedis artery monitoring. The IHN not only converts mechanical energy from footsteps into electrical energy but also differentiates between three motion states: walking, stepping, and jumping. Furthermore, a self-powered dorsalis pedis artery monitoring system was developed to detect pulse signals in real time, offering significant potential for intelligent lower limb blood supply analysis in professional athletes. To achieve high-sensitivity detection and rapid motion recognition, Li et al. developed a portable and reusable

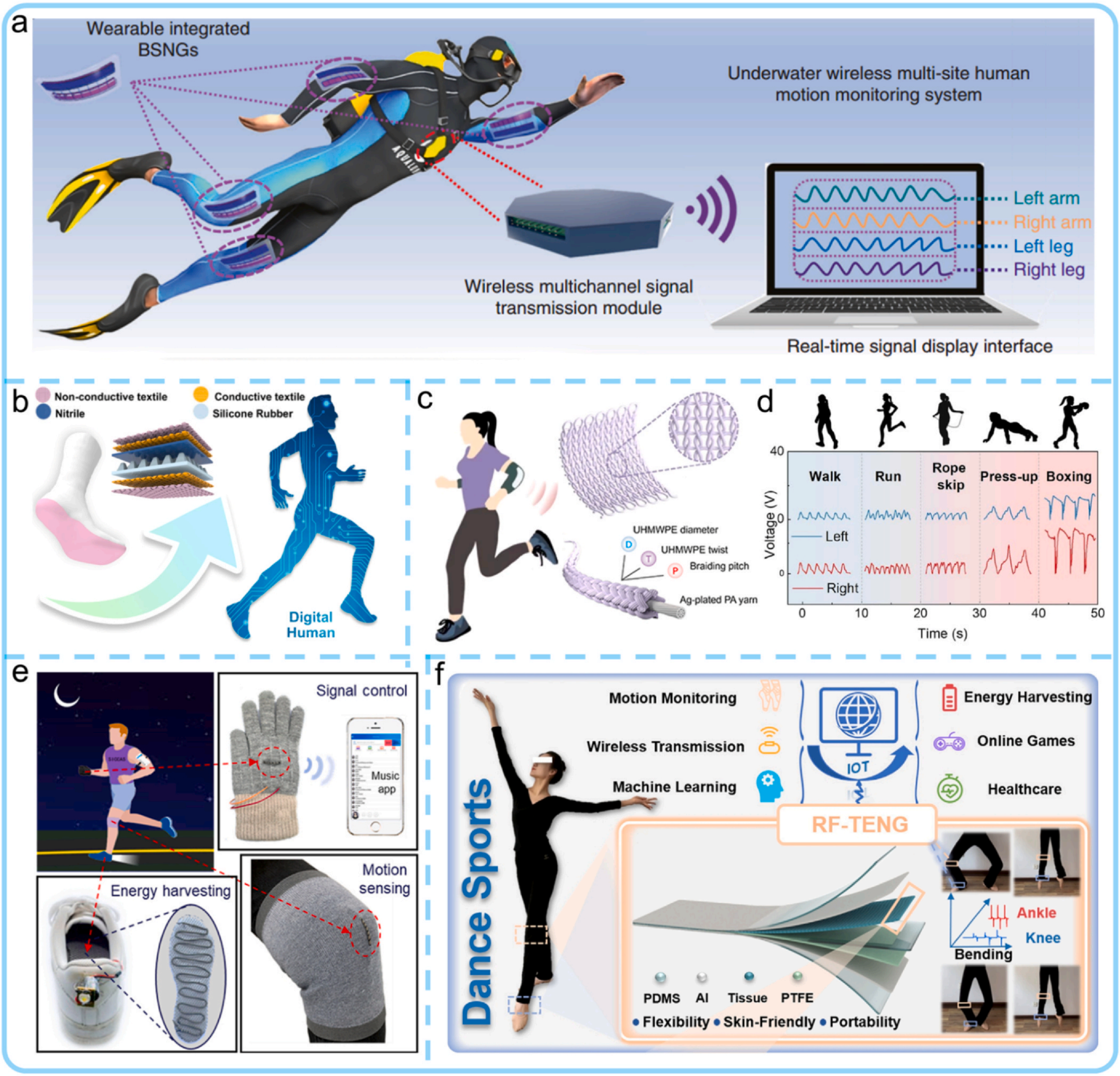


**Fig. 6.** TENG-based wearable equipment. **a** Illustration of underwater wireless multi-point human motion monitoring system based on bionic stretchable TENG [109]. **b** The schematic of smart socks based on triboelectric textile sensors [110]. **c** Schematic illustration of the TENG-based intelligent elbow and its knitting structure [111]. **d** Signal outputs recorded by the outdoor wearable sports management system [111]. **e** Application of TENG-based sensor in energy harvesting, motion sensing, and signal controlling [112]. **f** The schematic diagram of TENG and its dance sports injury monitoring system [113].

triboelectric-electromagnetic vibration sensor (TE-VS), which consists of a rolling TENG and a sliding EMG (Fig. 7b) [124]. Due to its self-powered characteristics, TE-VS can effectively monitor human posture, including arm flexion, striking movements, and variations in walking patterns, such as normal and stiff walking. In addition, lower limb motion monitoring plays a crucial role in sports training applications. Gao et al. reported a motion capture and energy harvesting hybrid lower limb (MC-EH-HL) system, which integrates a sliding block rail piezoelectric generator and a ratchet-based TENG (Fig. 7c) [125]. The MC-EH-HL system enables high-sensitivity and high-accuracy detection of lower limb rotation angle, speed, and direction, facilitating precise motion tracking and low-frequency biomechanical energy harvesting. The multi-dimensional sensing capabilities of this system lay the foundation for future applications in lower limb motion tracking across various sports and rehabilitation scenario. Therefore, leveraging their combined mechanisms, HNGs offer distinct advantages in the development of intelligent motion monitoring system.

As shown in Fig. 7d, Zhu et al. developed a self-powered self-functional sock by integrating TENG with lead zirconate titanate (PZT) piezoelectric chips [126]. This system utilizes machine learning to train a recognition model for evaluating data sets, enabling walking pattern recognition and motion tracking. Similarly, Maharjan et al. designed a novel curved wearable hybrid electromagnetic-triboelectric nanogenerator (WHEM-TENG) for gait analysis, allowing the characterization of different arm swing trajectories (Fig. 7e and 7f) [127]. Furthermore, hybrid nanogenerators composed of TENG and PENG have


**Fig. 7.** Hybrid nanogenerators in wearable equipment. **a** Schematic illustration of the IHN and its self-powered dorsalis pedis artery monitoring system [123]. **b** The schematic diagram of the design and application of TE-VS [124]. **c** A schematic diagram of TENG and piezoelectric generator and the MC-EH-HL system [125]. **d** Schematic of self-powered and self-functioning socks integrated with lead PZT piezoelectric chip coated fabric TENG [126]. **e** and **f** A schematic diagram of a WHEM-TENG and its stepwise illustration of assembly [127].

demonstrated versatility in wearable applications, including detecting arm bending angles [128], accurately distinguishing between walking, running, jumping states [129], and monitoring joints movements [130]. Deng et al. also developed a real-time, self-powered pressure distribution monitoring system based on a hybrid triboelectric-electromagnetic nanogenerator, offering a viable solution for motion data collection [131]. Therefore, HNG wearable devices play a crucial role in athlete training monitoring and significantly contribute to the development of intelligent sports.

### *4.3. TENG-based medical and health device*

#### *4.3.1. In vitro device*

Human movement encompasses a wide range of amplitudes and speeds, from subtle gestures to full-body motions, each carrying valuable physiological health information closely related to various diseases. Beyond its applications in sports facilities and wearable devices for real-time motion monitoring, TENG also holds significant potential as a medical health device in sports-related fields such as disease


**Fig. 8.** In vitro medical health devices based on TENG. **a** Design of wearable triboelectric stimulator for bacterial infection wound healing [137]. **b** A self-powered triboelectric response microneedle releases optogenetically engineered extracellular vesicles for biologically targeted IVDD treatment [138]. **c** A schematic diagram of a wearable TENG stretch sensor placed around the whole body, which can be used to monitor joint and spinal movements and also has continuous wireless monitoring capabilities [50]. **d** Schematic showing vertical shoulder adduction and abduction movement with origami TENG [139]. **e** Schematic diagram of RC-TENG and its wireless intelligent respiratory monitoring system [148]. **f** Schematic illustration of application of the DMWES [149].

diagnosis, injury prevention, and rehabilitation monitoring [132,133]. The TENG-based medical health devices offer a non-invasive alternative to implanted medical technologies, eliminating the risks associated with surgical procedures. Additionally, they provide excellent convenience, flexibility, and adaptability. For example, TENG-based in vitro devices, such as flexible films and smart fabrics, can collect mechanical energy generated during human motion and convert it into electrical energy for pulsed electrical stimulation, promoting tissue repair [134–136].

As shown in Fig. 8a, Qin et al. reported a wearable triboelectric stimulator consisting of a flexible TENG (F-TENG) and a triboelectric-responsive drug delivery hydrogel for treating bacteria-infected wounds [137]. By converting mechanical energy from body movement into pulse currents at the wound site, the F-TENG enables efficient and

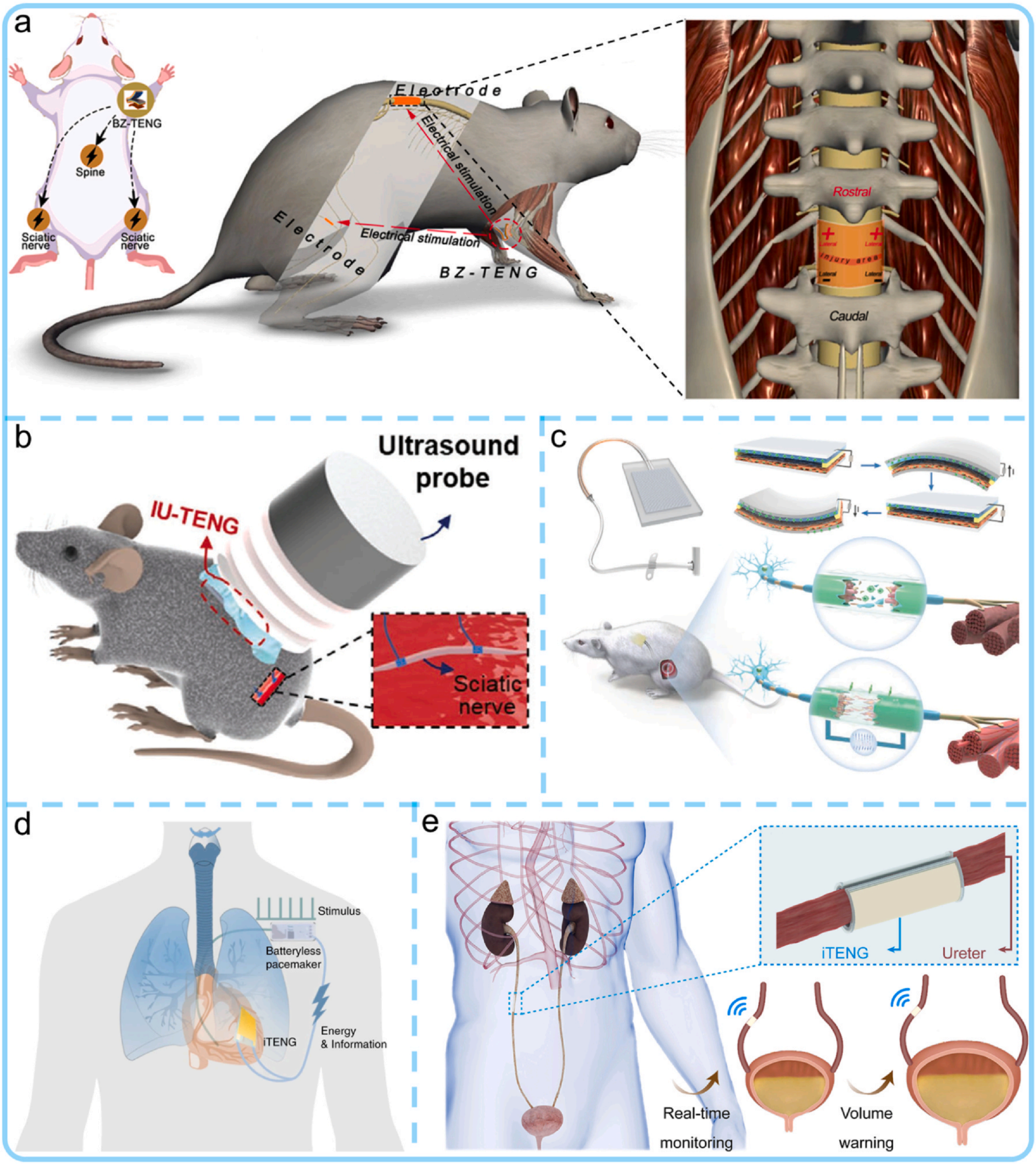


**Fig. 9.** In vivo medical health devices based on TENG. **a** A diagram of the BZ-TENG implanted in rats and the placement of spinal cord surface stimulation electrodes [161]. **b** Schematic of the IU-TENG was implanted into the back of mice [162]. **c** Schematic illustration of the ISR-NES system is integrated by a Cs-TENG and a sciatic nerve cuff electrode [163]. **d** Illustration of SPM based on TENG [164]. **e** Schematic of sensor for bladder volume monitoring, it sensor based on TENG monitors ureteral peristalsis to evaluate bladder capacity [165].

controlled drug release. This system offers a promising strategy for chronic wound healing and intelligent drug delivery. Excessive physical exercise can disrupt biomechanical homeostasis, leading to severe musculoskeletal damage, particularly in individuals with pre-existing abnormalities. One major cause of intervertebral disc degeneration (IVDD) is persistent abnormal biomechanical loading during physical activity. As shown in Fig. 8b, Zhang et al. developed a motion-powered triboelectric response microneedle capable of continuously releasing optogenetically engineered extracellular vesicles for IVDD repair [138]. This innovative approach provides precise inflammatory response regulation and holds significant potential for disease-modifying therapy. Human movement generates valuable biomechanical data, such as joint and spine bending or stretching, which can aid in diagnosing, rehabilitating, and preventing orthopedic and neurological disorders. To enable more accurate and accessible motion data collection, Li et al. developed an emblem coil stretch sensing device integrated with a grating-structure TENG (Fig. 8c) [50]. This TENG-based stretch sensor records real-time joint movements, including knee and arm bending as well as neck and waist distortion. Furthermore, it facilitates spinal monitoring, helping to mitigate the risk of posture-related diseases induced by prolonged abnormal positioning. In recent years, rehabilitation through sports-based gaming has emerged as an innovative approach to enhancing patient engagement and recovery outcomes. As shown in Fig. 8d, Bhatia et al. designed a gravity-supporting origami TENG for shoulder rehabilitation. This system functions both as a self-powered sensor for game tasks and an energy harvester for exercise tasks. When worn by stroke patients, the origami TENG enables real-time feedback during table tennis-based rehabilitation games, providing a highly motivating and immersive rehabilitation experience [139].

Breathing is a fundamental physiological process essential for human health. Respiratory monitoring plays an important role in assessing athletes' endurance levels, enhancing performance, and regulating psychological states by tracking respiratory rate, depth, and rhythm. Additionally, exercise-induced respiratory monitoring is of great significance for the prevention of sports injury [140–142]. Numerous studies have explored TENG-based respiratory monitoring systems for real-time tracking, disease diagnosis, and respiratory disorder prevention [143–147]. For example, Zhang et al. proposed a wireless intelligent respiratory monitoring system based on chitosan-carbon nanotubeand and Ecoflex-graphene TENG (RC-TENG) (Fig. 8e) [148]. This system is expected to provide critical support for human health monitoring, dangerous diseases prediction, and sports performance assessment. Electronic skin technology has recently emerged as a promising tool in medical diagnosis and HMI, capable of detecting subtle physiological changes on the skin and reflecting the body's overall condition. As shown in Fig. 8f, Zhi et al. designed an ultra-sensitive bioinspired directional moisture-wicking electronic skin (DMWES) with dual-mode sensing capability and biomechanical energy harvesting [149]. The single-electrode triboelectric DMWES enables a full range of medical sensing, including accurate pulse monitoring, speech recognition, and gait recognition. In addition, TENG-based in vitro devices have been applied in various medical and healthcare fields, including sleep behavior monitoring [150–152], diabetes diagnosis via wrist pulse analysis [153], eye muscle and heartbeat monitoring [154], monitoring and rehabilitation of neck movement [155], and high blood glucose detection [156]. With the growing demand for personal medical monitoring and non-invasive sensing technologies, TENG-based precise, wearable, and durable devices are poised to make a significant impact on personal health sensing and sports rehabilitation.

#### 4.3.2. In vivo devices

In the field of medical sensing and sports rehabilitation, in vivo devices directly interact with the human body or internal organs, offering more accurate and long-term health monitoring data than in vitro devices, especially when it comes to pathological and physiological information. As a result, in vivo medical electronic devices have rapidly developed in recent decades, significantly improving the quality of life and extending the life span of millions of patients [157–159]. However, challenges such as limited miniaturization, power limitations, and a lack of reliable interfaces between implants and external devices still persist [160]. TENGs offer a notable advantage in that they are self-powered, making them highly promising for in vivo medical applications. Spinal cord injuries, which disrupt nerve transmission and lead to paralysis, underscore the importance of developing effective treatments. To address this, Lu et al. developed a novel bionic Z-structured triboelectric nanogenerator (BZ-TENG), implanted in the posterior side of rats' elbow joint of rats (Fig. 9a) [161]. The kinetic energy from joint flexion and extension is converted into electrical energy, which is then transmitted to the sciatic nerve and lateral spinal cord, significantly promoting the recovery of motor and sensory functions in rats with spinal cord injuries. This in vivo electrical nerve stimulator shows great potential for treating neurological diseases. Similarly, Jeon et al. reported an implantable ultrasound-driven TENG (IU-TENG) that can stimulate the sciatic nerve of mice to introduce ankle movement (Fig. 9b) [162]. In another development, Zhou et al. developed an implantable self-regulated neural electrical stimulation (ISR-NES) system integrated by a contact-separated triboelectric nanogenerator (Cs-TENG) and a sciatic nerve cuff electrode (Fig. 9c) [163]. This system accelerates axonal growth by increasing the accumulation of growth-associated protein at the injury site, while also restoring neuromotor function and other physiological capabilities. These TENG-based in vivo medical and health devices provide a practical, self-responsive, and battery-free solutions for neural stimulation, offering promising prospects for the treatment of neurological diseases.

Self-powered in vivo medical electronic devices, which harvest biomechanical energy from cardiac motion, respiratory movement, and blood flow, hold significant promise for the future of healthcare. Ouyang et al. designed a fully implantable symbiotic pacemaker (SPM) based on TENG, which consists of three parts: an energy harvesting unit, a power management unit (PMU), and a pacemaker unit (Fig. 9d) [164]. The system first collects energy from heart movement via the TENG, storing it in the PMU capacitor. When activated by a wireless passive magnet trigger, the PMU powers the pacemaker unit, generating pulses to regulate the heart's contraction rate. This self-powered pacemaker has been successfully tested in large animals, demonstrating its ability to not only pace the heart but also correct sinus arrhythmia, helping to prevent disease progression. Beyond cardiac applications, TENG can also be applied to monitor and treat urinary system diseases, which affect the quality of life for millions globally. For example, Huo et al. designed an in vivo TENG-based sensor that was implanted into the outer wall of the ureter in large animals to monitor ureteral peristalsis in real time (Fig. 9e) [165]. This device can track disease states and estimate bladder capacity, offering the potential for real-time warnings related to bladder volume. This indicates that TENG-based in vivo sensors may provide a new method for urinary system monitoring. In addition, research on biodegradable in vivo TENGs is gaining momentum. These devices, after completing their functional cycle, degrade and are absorbed by the body without adverse long-term effects. This biodegradable TENG has applications in fields such as neuronal repair [166], abnormal breathing recognition [167], targeted drug release stimulation [168], and infection prevention through elimination of microorganisms [169]. Compared to traditional in vitro devices, these in vivo systems provide continuous and efficient rehabilitation support without interfering with daily activities. With continued technological advancements, in vivo TENGs are expected to play an increasingly vital role in sports rehabilitation and other medical fields, further driving the development of precision medicine and intelligent rehabilitation technologies.

## 5. Conclusion and outlook

This review provides a comprehensive summary of the research progress in TENG-based sports facilities, wearable equipment, and medical health devices within the realm of intelligent sports. We discuss the working modes and principle of TENG, as well as its combination with IoTs, BDA, and AI, which collectively advance the development of sports big data. TENG exhibits superior characteristics such as flexibility, lightweight, self-power capability, and high sensitivity to mechanical stimulation. These attributes make TENG-based devices highly effective for collecting sports big data, which provides precise insights into the performance and health of athletes. By integrating TENG with other energy harvesting technology, hybrid nanogenerators have also demonstrated significant success in high-precision motion sensing, medical health, and sports rehabilitation. In the future, sports training and competition are expected to become increasingly intelligent, offering personalized services for athletes' physical health. Despite the remarkable advancements made by triboelectric devices in intelligent sports, challenges remain in the development of this emerging field, which are summarized as follows:

1) Material performance optimization is the key to improve the reliability of TENG. Many flexible TENGs are made of organic polymer materials, which are more susceptible to temperature and humidity fluctuations compared to rigid microelectronic devices. Therefore, the materials used in TENG must exhibit high durability, low wear, and corrosion resistance to effectively extend the sensor's lifespan and mitigate performance degradation caused by environmental factors. Identifying and optimizing materials that generate efficient and stable charges is essential. Additionally, to meet the diverse and

complex demands of actual sports activities, the material selection and structural design should strike a balance between high sensing performance and versatility. Key considerations include air permeability, transparency, biocompatibility, degradability, and self-healing ability.

2) The combination of packaging technology and hydrophobic materials offers a dual-protection strategy for TENGs, addressing both physical and environmental challenges. By providing physical isolation, packaging not only prevents mechanical deformation and contaminant intrusion but also minimizes charge leakage in humid environments, thereby ensuring stable output performance. By regulating the interaction between material surface and water, hydrophobic coatings can significantly reduce the adverse effects of moisture on triboelectric performance. To fully realize the potential of TENGs in real-world applications, future studies should focus on optimizing material properties and packaging designs. This includes investigating novel hydrophobic materials with enhanced durability, exploring biodegradable packaging options for implantable devices, and developing smart packaging systems that adapt to dynamic environmental conditions.
3) New AI algorithms need to be developed for TENG-based self-powered sensors for sports applications. As IoTs systems generate vast amount of real-time data streams from numerous TENG-based sensors, BDA provides essential tools for processing and analyzing this data. In addition, AI can use these analysis results to make intelligent decisions. However, AI technology must be able to recover incomplete information and improve its accuracy by learning from the characteristics of complete datasets. In other words, TENG requires new ML designs and training methods. The advancement of modern information technologies will thus drive innovation in the sports industry, enabling a future of intelligence and automation.
4) The sensing accuracy and capability of TENG-based sensors must be further enhanced. To support the future development of intelligent sports, the sensing capability and accuracy of the TENG-based sensing system need to be further improved to enable more precise and expansive motion signal detection. Integrating TENG with EMG or PENG to form hybrid nanogenerators can created a self-powered multi-functional sensing system with improved accuracy and performance. Moreover, hybrid nanogenerators offer superior energy conversion efficiency, output power, and sensitivity than single TENG systems. In addition, improvements in material properties, structural design, and power management can further enhance the sensing capabilities of TENG-based devices.
5) Another challenge is to establish industrialized and commercialized standard manufacturing processes and calibration methods. In laboratory settings, the repeatability of a single TENG device is often constrained by manual fabrication processes, which impede large-scale production and escalate manufacturing costs. Furthermore, the practical application of TENG in intelligent sports necessitates advanced equipment design and miniaturization strategies to enhance device practicality. Achieving miniaturization and modularization of TENG-based sensing systems remains a critical goal, with key challenges including the development of scalable manufacturing technologies, improvement of output performance, and optimization of device structures.

Despite these challenges, the rapid development of TENG technology has opened up new avenues for intelligent sports. We believe that future efforts to address these challenges will provide great opportunities in this field. It provides a completely self-sufficient, flexible, wireless, multi-functional, and personalized platform for sports applications, enabling transformative advancements in sports training, injury prevention, and patient recovery. By overcoming current limitations, this technology will pave the way for a more intelligent and data-driven future in sports.

## CRediT authorship contribution statement

**Huang Lijun:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Wu Jiamin:** Writing – original draft, Methodology, Investigation, Data curation. **Cai Huaihong:** Writing – review & editing, Methodology, Investigation. **Ji Minglan:** Writing – review & editing, Methodology, Investigation. **Pang Yaokun:** Writing – review & editing. **Luo Jianjun:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Zhou Haibo:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Wang Zhong Lin:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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