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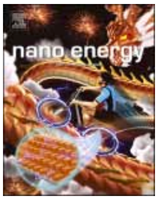

Review

Emerging sensing systems based on triboelectric nanogenerator

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ABSTRACT

Triboelectric nanogenerators (TENGs), harnessing contact electrification and electrostatic induction, have emerged as a foundational technology for self-powered, high-sensitivity, and multimodal sensing. In response to the growing demand for autonomous, integrated, and multifunctional perception, TENG-based systems are evolving into advanced intelligent sensing platforms capable of real-time, adaptive environmental monitoring. This review classifies recent developments in TENG-based sensing across three paradigms: contact sensing, non-contact sensing, and tele-perception. We examine key milestones in structural design, signal transduction, and application domains spanning human-machine interfaces, spatial detection, health monitoring, and intelligent terminals. Special emphasis is placed on tele-perception strategies underpinned by charge-trapping mechanisms and machine learning integration. Finally, we outline emerging directions including multidimensional sensing, multi-field coupling, and neuromorphic architectures, offering a framework for the scalable deployment of TENG-based intelligent sensing in next-generation Internet of Things and adaptive perception systems.

1. Introduction

The demand for high performance sensing technologies in modern intelligent systems is rapidly increasing, with widespread adoption of various sensing mechanisms such as resistive [1–3], capacitive [4–6], piezoelectric [7–9], thermoelectric [10–12], and Hall effect sensors [13–15]. Among these, resistive and capacitive sensors generally rely on external power sources to maintain continuous signal acquisition and processing due to their fundamental detection principles. Piezoelectric sensors, based on the intrinsic piezoelectric effect of materials, can generate electrical signals spontaneously under mechanical stress, exhibiting certain self-powered capabilities. However, their practical energy output is often limited by low charge generation efficiency and material constraints, making them insufficient for supporting more energy-intensive tasks such as wireless data transmission or multi-functional sensing in autonomous systems [16–18]. Furthermore, the performance of piezoelectric materials may degrade over time under repeated stress, and their sensitivity can be influenced by environmental conditions such as humidity and temperature. Despite the maturity of conventional sensing technologies in measuring temperature [19–21], pressure [22–24], displacement [25–27], vibration [28–30], and electromagnetic fields [31–33], system-level applications still typically rely on external power sources to support signal conditioning and wireless transmission. This dependency fundamentally constrains the scalability, autonomy, and deployment of sensor networks, particularly in remote or densely distributed environments [34]. As the Internet of Things (IoTs) [35,36] expands exponentially, the limitations of traditional power schemes, high energy consumption, restricted operational lifespan, and intensive maintenance, have become increasingly untenable. These challenges underscore the urgent need for breakthroughs in energy-autonomous and seamlessly integrated sensing technologies that can meet the stringent demands of future intelligent systems.

TENGs [37–39], as a novel platform integrating energy conversion and signal sensing functions, provide key technological support for the next generation of self-powered sensing systems [40–42]. Based on contact electrification and electrostatic induction mechanisms, TENG can efficiently convert ambient mechanical energy such as human motion [43–45], wind [46–48], and water waves [49–51] into electrical energy. Their output signals can simultaneously serve as power sources and sensing information, enabling real time detection without external power supply. These devices offer structural flexibility, broad material tunability, high sensitivity, and scalable fabrication, rendering them

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Fig. 1. An overview of the latest advancements of TENG-based novel sensing systems [88–96]. Copyright 2025 Springer Nature. Copyright 2018 American Association for the Advancement of Science. Copyright 2024 Wiley. Copyright 2020 Elsevier. Copyright 2024 Wiley. Copyright 2022 Wiley. Copyright 2023 American Chemical Society. Copyright 2021 Elsevier. Copyright 2024 American Association for the Advancement of Science.

Table 1
Quantitative comparison of key performance metrics for various sensing technologies.

	Resistive Sensor	Capacitive Sensor	Piezoelectric Sensor	Thermoelectric Sensor	Hall Effect Sensor	Triboelectric Nanogenerator (TENG)
Self-powered Operation	×	×	✔ (Limited)	✔	×	✔ (Fully)
Power Output	External only	External only	~10–100 μW/cm^2	~1–10 μW/cm^2	N/A	~100 μW–mW/cm^2
Sensitivity (Pressure)	~0.1–10 kPa^{-1}	~0.01–1 kPa^{-1}	~0.1–1.2 kPa^{-1}	$<$ 0.1 kPa^{-1}	N/A	$>$ 1.2–8.4 kPa^{-1}
Response Time	10–100 ms	$<$ 10 ms	$<$ 1 ms	$>$ 100 ms	~1–10 μs	$<$ 10 ms
Detection Range	~0.1–10 MPa	~0.1–1 MPa	~0.01–10 MPa	Small gradient only	~10 mT–1 T	~Pa to MPa scale; cm-scale spatial detection
Material Flexibility	Limited	Moderate	Moderate	Rigid	Rigid	Excellent (flexible, soft, bio-safe)
Signal Type	Resistance change	Capacitance change	Voltage (AC)	Voltage (DC)	Voltage	Voltage or current (AC/DC)
Environmental Stability	Affected by temp/ humidity	Affected by temp/ noise	Affected by humidity/ fatigue	Strong temp dependence	Sensitive to EMI	Tunable via materials/structure
Integration with AI	Moderate	Mature	Limited	Low	Low	High (signal–ML ready)
Typical Applications	Flexible pressure mats	Touchscreens, wearables	Ultrasound, vibration, motion	Heat flow, wearables	Magnetic field sensing	Wearables, HMI, robotics, remote sensing

well-suited for integration in complex and dynamically changing environments [52–54]. Recent advances in flexible electronics, micro/-nanofabrication, and intelligent materials have markedly enhanced the performance and versatility of TENG-based sensing platforms, enabling their widespread application in wearable systems [55–58], medical diagnostics [59–61], and environmental monitoring [62,63]. Recent advances in materials science [64–66] and device engineering [67–69] have propelled TENG-based sensing systems beyond simple contact detection toward non-contact sensing and tele-perception capabilities. This evolution reflects a paradigm shift from isolated signal acquisition to fully integrated intelligent sensing platforms, enabled by the incorporation of flexible electronics [70–72], neuromorphic computing [73–75], and electromechanical actuation [76]. Contemporary systems now enable multisource data fusion [77], adaptive feedback control [78], and autonomous energy management [17,18], markedly broadening their functional landscape. These capabilities support deployment across a range of sectors, including smart cities [79–81], smart healthcare [82–84], and autonomous driving [85–87], where energy autonomy and seamless sensing integration are essential for scalable and sustainable operation. A comprehensive review of recent advances in sensing mechanisms, device architectures, application domains, and persisting challenges is therefore timely and critical to inform the future design and practical realization of TENG-based intelligent sensing technologies. The evolution of sensing modes was divided into three stages: contact sensing, non-contact sensing, and tele-perception, each representing significant advancements in materials science and device engineering. This developmental trajectory, which provides a clear visual framework for understanding the progression of TENG-based

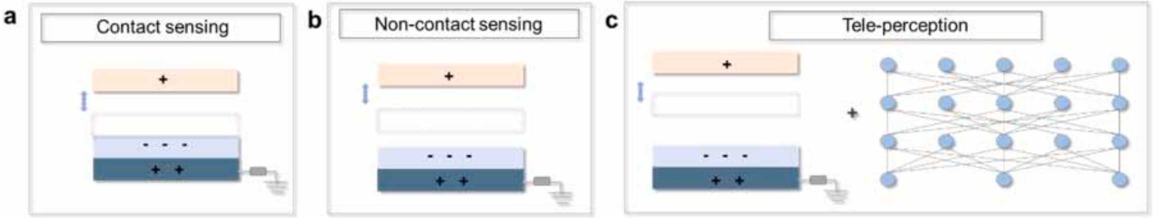

Fig. 2. The operating principles of (a) contact sensing (b) non-contact sensing and (c) tele-perception based on TENG.

intelligent sensing systems (Fig. 1). To provide a comprehensive assessment of TENG technology in this framework, a quantitative comparative analysis against other mainstream sensing mechanisms was performed (Table 1). This comparison evaluated critical performance parameters including self-powered operation, sensitivity, response time, and material adaptability across resistive, capacitive, piezoelectric, thermoelectric, Hall effect, and TENG-based sensors. The findings emphasized the unique advantages of TENGs in delivering energy-autonomous, high-performance, and flexible sensing capabilities, highlighting their considerable promise for next-generation intelligent applications.

This review systematically summarizes the development trajectory and key technological progress of TENG-based intelligent sensing systems from the perspective of sensing mode evolution. First, we review the extensive applications of TENG in contact sensing since 2012, highlighting their high sensitivity, low power consumption, and self-powered sensing capabilities demonstrated in tactile perception, human machine interaction, wearable biomedicine, and smart city scenarios. Subsequently, with optimized material design and structural engineering, sensing systems have progressively advanced toward non-contact sensing. In 2018, this shift expanded the sensing dimension from surface physical contact to spatial electric field perturbations, achieving precise perception and functional expansion in vehicle monitoring, smart healthcare, spatial positioning, and intelligent interactive terminals such as smart screens. Building on this, the emerging tele-perception paradigm in 2024 marks a significant shift. By leveraging charge trapping modulation, extended induction fields, and integration with machine learning networks, these systems exhibit capabilities for long distance, multi target, contactless environmental perception and event recognition, substantially enhancing their generalization and intelligence. In the final section, we discuss future trends in sensing systems, including far field signal decoding, neuromorphic perception cognition integrated architectures, multi-dimensional sensing enhancements, and deep coupling with artificial intelligence algorithms. Through a comprehensive summary of the evolution of sensing modes and representative application scenarios, this review provides valuable guidance and technical insights to advance the transformation of TENG from fundamental energy harvesters into intelligent sensing terminals.

2. Mechanistic insights into TENG-based advanced sensing systems

In contact sensing [40], the operation principle of TENG is primarily governed by the coupling of contact electrification and electrostatic induction. When two materials with differing triboelectric polarities undergo repeated contact and separation, surface charge transfer occurs due to triboelectric effects. The dynamic displacement between the charged surfaces then induces a periodic electrostatic potential difference, which drives electron flow through an external circuit. This current or voltage output is directly correlated with external mechanical stimuli such as pressure, force, or deformation, enabling real-time monitoring of tactile events. This mechanism underpins applications in wearable sensors, electronic skins, and interactive interfaces, where high sensitivity, self-powered operation, and structural flexibility are critical (Fig. 2a).

Table 2
Comparative summary of TENG-based contact, non-contact, and tele-perception sensing paradigms.

	Contact sensing	Non-contact sensing	Tele-perception
Working principle	Charge transfer via mechanical contact and separation between tribo-surfaces	Electrostatic field perturbation induced by nearby objects without physical contact	Long-range field coupling via charge trapping layers, combined with AI-based signal decoding
Detection range	Direct contact (~0 mm)	Short to moderate range (cm to meters)	Long-range (multi-meter scale, depending on field strength and algorithm)
Sensitivity	High mechanical sensitivity (pressure, force, deformation)	High proximity/ motion sensitivity with fast response	Capable of weak signal recognition, enhanced by deep learning
Durability	May degrade over time due to repeated contact and wear	Improved durability due to frictionless operation	High durability; stable under environmental variations due to AI filtering and charge-trapping design
System complexity	Relatively simple device design and signal processing	Requires surface pre-charging or special dielectric layers	Involves complex signal processing (e.g., CNN, FEM), multiparameter tuning, and advanced materials
Integration feasibility	High compatibility with flexible electronics and wearables	Easily integrated with gesture interfaces, smart displays	More challenging; requires multi-unit arrays and computational backend for real-time classification and interpretation
Representative applications	Wearable biosensing, tactile interfaces, prosthetics, smart city sensing	Vehicle monitoring, non-contact health monitoring, gesture-based HMIs	Remote human-machine interface, ambient perception, robotic behavior triggering, 3D object recognition
Key limitations	Mechanical fatigue, surface abrasion, limited range	Moisture sensitivity, limited field strength	Signal complexity, reliance on AI/ML for decoding, higher computational cost

Non-contact sensing [97] relies on the disturbance of a pre-established electrostatic field, typically formed by pre-charging the TENG surface or incorporating a charge trapping layer. When a dielectric or conductive object approaches the sensing surface without physical contact, it perturbs the local electric field, inducing charge redistribution across the device electrodes. The resulting signal reflects the proximity, motion, or dielectric properties of the object, enabling touchless position tracking or material classification. This mode extends TENG functionality beyond surface interactions, offering enhanced durability, faster response times, and reduced mechanical wear. It is

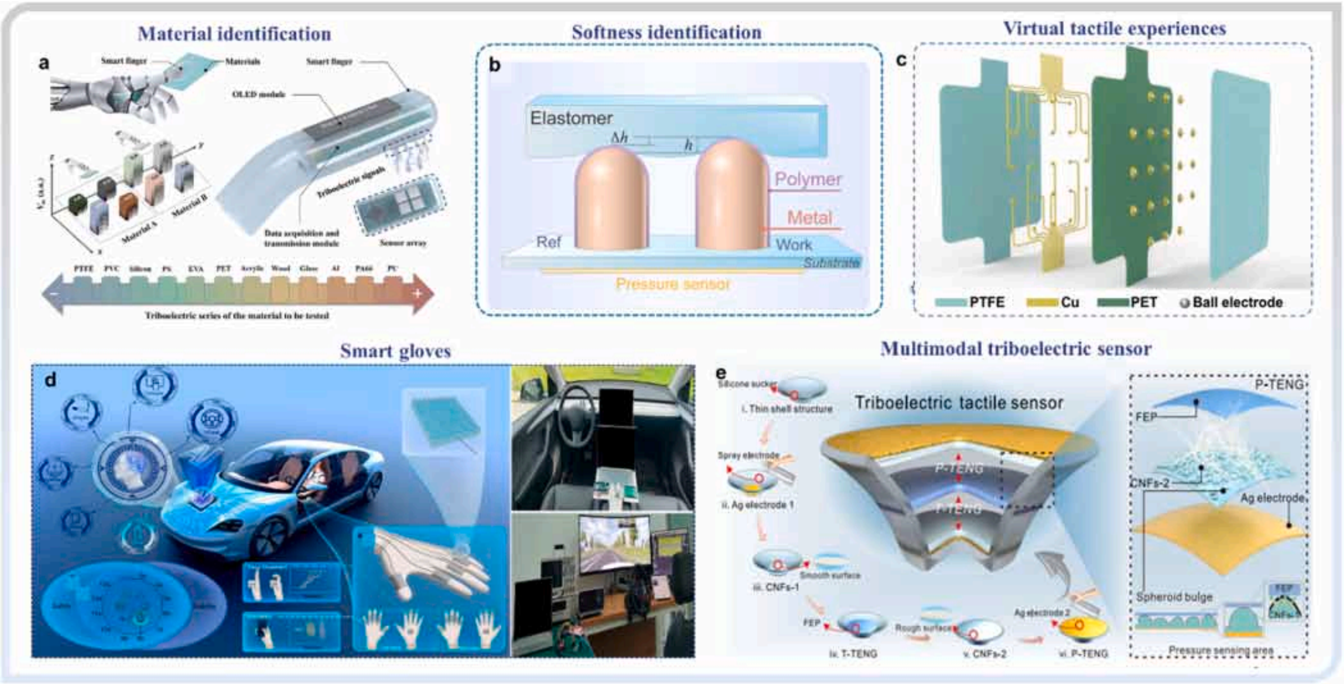

Fig. 3. Triboelectric tactile sensor systems. (a) Structural schematic of the triboelectric tactile perception smart finger [99]. Copyright 2022 American Association for the Advancement of Science. (b) Schematic diagram of the bioinspired bimodal intelligent tactile sensor (BITS) and the machine learning confusion matrix for material type recognition [100]. Copyright 2024 American Association for the Advancement of Science. (c) Schematic illustration of electro-tactile (ET) system for transmitting virtual spatial tactile patterns [101]. Copyright 2021 American Association for the Advancement of Science. (d) Conceptual framework and key components of the intelligent takeover assistance system [102]. Copyright 2025 Springer Nature. (e) Pressure/temperature-responsive triboelectric sensors adapted to extreme environments, enabling tactile perception beyond human capability [88]. Copyright 2025 Springer Nature.

particularly suitable for applications in gesture recognition, intelligent displays, and biomedical diagnostics (Fig. 2**b**).

The emerging tele-perception [96,98] paradigm integrates charge trapping strategies with advanced algorithms to enable long-range, multi-object environmental sensing. In this configuration, persistent electrostatic fields are generated by engineered charge trapping layers (e.g., electret films), which interact with distant objects via field coupling. These weak and spatially complex signals are difficult to interpret using conventional methods. Therefore, artificial intelligence (AI)-based machine learning algorithms are employed to decode signal patterns, distinguish targets, and extract high-dimensional features. This synergy facilitates remote motion recognition, spatial localization, and environmental monitoring without physical contact, establishing a foundation for intelligent perception in robotics, smart infrastructure, and ambient interactive systems (Fig. 2**c**).

To provide a clearer comparison of the three sensing paradigms, namely contact sensing, non-contact sensing, and tele-perception, we have included a summary table (Table 2) that outlines their respective operating principles, spatial ranges, sensitivity levels, integration complexity, and representative application scenarios. This comparative overview helps to elucidate their functional evolution and guides appropriate selection for specific use cases.

3. Functional evolution of TENG-based sensing systems

3.1. Contact sensing systems

Contact sensing systems based on TENG have garnered significant attention for their ability to convert mechanical stimuli into electrical signals without external power. As triboelectric tactile sensors, they offer high spatial resolution, fast response, and material adaptability, making them ideal for detecting subtle pressure and texture variations. In human-machine interfaces, these systems enable intuitive and real-time control through physical touch, enhancing interaction efficiency and user experience. For intelligent health monitoring, contact-mode TENG support continuous, wearable sensing of physiological parameters such as pulse, respiration, and joint motion. Additionally, their self-powered and scalable nature allows for large-area deployment in smart city applications, enabling infrastructure monitoring and interactive public terminals.

3.1.1. Triboelectric tactile sensor

Tactile perception is essential for both humans and intelligent machines to effectively interact with their environment, encompassing the ability to detect pressure, texture, material type, and compliance through direct mechanical contact. Artificial tactile sensing systems based on TENG have rapidly advanced, offering self-powered, highly sensitive, and flexible solutions that mimic or even surpass human touch sensitivity. These sensors convert mechanical contact signals into electrical outputs, enabling detailed characterization of surface properties and material types, which are essential for applications ranging from prosthetics to intelligent robotics.

To surpass limitations in material identification and roughness discrimination, Li et al. [99] developed a smart triboelectric finger capable of tactile perception beyond human sensitivity, as shown in Fig. 3**a**. By leveraging the material-dependent triboelectric response during contact, the system generated unique electrical fingerprints, enabling accurate classification through machine learning. A sensor array was used to enhance stability, achieving an identification accuracy of 96.8 %, and offering potential in prosthetics and robotic manipulation. Building on the need for more comprehensive haptic interfaces, Zi et al. [100] designed a hemispherical bimodal intelligent tactile sensor (BITS) inspired by insect antennae (Fig. 3**b**). This sensor simultaneously enabled material type recognition, modulus quantification, and softness detection. The BITS array exploited the differing deformation and electron affinity properties of objects to generate distinctive triboelectric

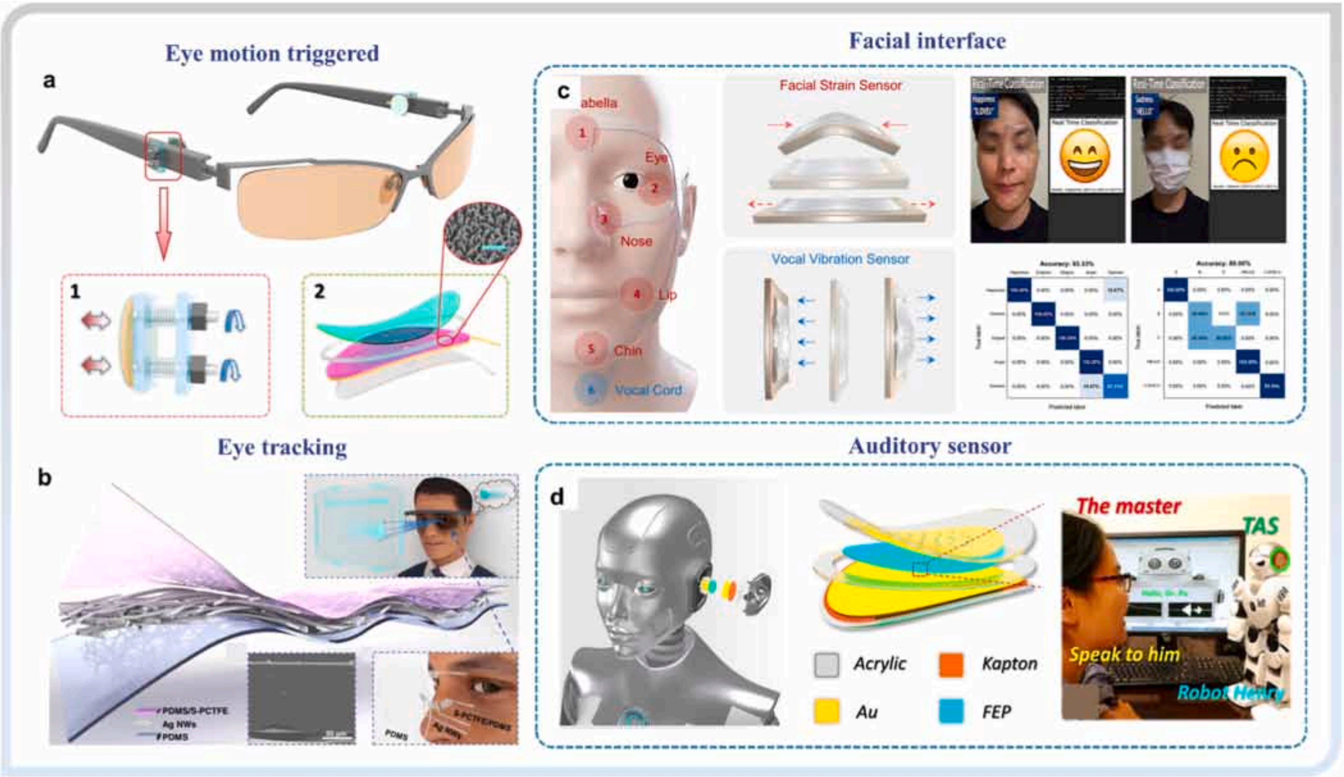

Fig. 4. Triboelectric sensor enabled human–machine interface. (a) Structure and application of the multifunctional stretchable TENG (msTENG) [103]. Copyright 2017 American Association for the Advancement of Science. (b) Schematic illustration of TENG-based electrostatic interface [104]. Copyright 2023 Springer Nature. (c) Two-dimensional layout of the PSiFI demonstrated in the form of a wearable facial mask, depicting two different types of triboelectric sensors (TES) responding to sensory stimuli such as smiling and tension [105]. Copyright 2024 Springer Nature. (d) Structure and application of the triboelectric auditory sensor (TAS) for mimicking an auditory system [89]. Copyright 2018 American Association for the Advancement of Science.

outputs, resulting in accuracy rates of 99.4 % for material identification and 100 % for softness classification. This work expanded the functionality of triboelectric tactile systems toward real-time multimodal sensing for immersive interfaces. Extending the application scope to virtual and augmented reality, Wang et al. [101] introduced a self-powered, highly sensitive electro-tactile (ET) system using a TENG and a ball-shaped electrode array as shown in Fig. 3**c**. The electrostatic discharge generated by the TENG induced skin stimulation, whose intensity could be tuned by adjusting the electrode-skin distance. The system accurately replicated touch location and motion trajectory, demonstrating applications in virtual tactile displays, Braille interfaces, and neurostimulation.

Beyond static perception, the dynamic monitoring of driver behavior poses distinct and complex sensing challenges. Chen et al. [102] addressed this challenge by introducing a TENG-based intelligent takeover assistance system for automated vehicles **(**Fig. 3**d)**. The system employed triboelectric glove sensors to capture fine hand movements and detect six types of non-driving behaviors with 94.72 % accuracy. Combined with a real-time takeover time estimation module, the system enhanced the safety and adaptability of conditionally autonomous driving scenarios. Further pushing the limits of human perception, Nie et al. [88] developed a multimodal triboelectric sensor capable of operating in extreme environments **(**Fig. 3**e)**. With an asymmetric structure that independently output pressure and temperature signals, the sensor achieved parallel recognition of surface characteristics and high-temperature stimuli (up to 200 °C). A recognition rate of 94 % was obtained for complex object features, marking a substantial advance in environmental adaptability and multimodal artificial skin systems.

Collectively, these studies demonstrate the rapid functional evolution of TENG-based tactile sensors from simple contact devices to intelligent systems capable of complex haptic perception. Their development underpins a new generation of artificial tactile interfaces for human-machine symbiosis and advanced interactive technologies. Beyond replicating the basic capabilities of human touch, these systems enable superior performance in extreme conditions, offer multimodal sensing functionalities, and seamlessly integrate with machine learning algorithms for intelligent decision-making. As TENG-based tactile systems continue to mature, their role will expand in applications such as neuroprosthetics, virtual and augmented reality, autonomous driving, and humanoid robotics, ultimately paving the way for fully adaptive and immersive tactile experiences.

3.1.2. Human-machine interfaces

Human-machine interfaces (HMI) based on contact sensing offer an effective strategy for enabling intuitive and responsive communication between users and electronic systems. By utilizing triboelectric sensing to capture subtle biomechanical signals, such as skin deformation, muscle activity, and localized pressure, these systems facilitate precise, low-power control modalities. Representative implementations include eye-muscle tracking, facial expression monitoring for emotional feedback, and acoustic vibration sensing for voice command recognition. These capabilities establish a robust foundation for next-generation HMIs across smart environments, virtual and augmented reality, assistive technologies, and socially interactive robotics.

Traditional biopotential-based HMI suffer from low signal-to-noise ratios and limited stability, restricting their broader applications. For example, electrooculogram signals generated by corneal-retinal potentials during eye motions are inherently weak, while mechanical micromotion of skin around the eyes remains an underexplored but promising signal source. Wang et al. [103] developed a novel TENG-based micromotion sensor leveraging triboelectricity coupled with electrostatic induction **(**Fig. 4**a)**. This flexible, transparent sensor, employing an indium

Fig. 5. Wearable sensors and systems for biomedical applications. (a) Schematic illustration of cardiac sound sensing using a triboelectric stethoscope, along with an exploded view of its overall structural design [90]. Copyright 2024 Wiley. (b) Schematic illustration and performance evaluation of the rehabilitation brace system [106]. Copyright 2022 Wiley. (c) The conformal self-powered inertial displacement sensor (CSIDS) for assessing the functionality of human upper limb joints [107]. Copyright 2024 Wiley. (d) Schematic illustration and pH test results of a wearable sweat-monitoring patch (WSMP) worn on the leg for detecting sweat pH levels [108]. Copyright 2022 Wiley. (e) Schematic illustration and performance of fingertip pulse wave monitoring [109]. Copyright 2021 Wiley. (f) Applications as self-powered sensors and the volleyball reception statistical and analytical system [110]. Copyright 2021 American Chemical Society. (g) Structure of the pressure-sensing insole and smart ski poles based on CF-TENG and their application in skiing sports monitoring [111]. Copyright 2021 Springer Nature.

tin oxide electrode and two opposing tribo-materials, effectively captured eye blink motions with signals (~750 mV) vastly exceeding traditional electrooculogram amplitudes (~1 mV). Integrated onto eyeglasses, the system enabled two real-time HMI applications, namely smart home control and wireless hands-free typing, while exhibiting high sensitivity, operational stability, user convenience, and cost-effectiveness. This work offers a novel design framework for advanced intelligent sensing technologies. Eye tracking offers valuable insights into visual attention and cognitive processes through precise eye movement analysis. Che et al. [104] introduced a transparent, flexible, and durable electrostatic sensing interface based on electrostatic induction for active eye tracking (AET) (Fig. 4**b**). Utilizing a triple-layer dielectric and rough-surface Ag nanowire electrode structure, this interface achieved unprecedented charge density (1671.10 $\mu C \cdot m^{-2}$) and high retention (>96 % after 1000 cycles), enabling oculogyric detection with a 5° angular resolution. The AET system supports real-time eye movement decoding for applications in consumer behavior analysis, virtual reality and medical diagnostics.

Beyond visual cues, emotional and auditory perception represent additional essential dimensions for enriching human-machine interaction. Emotional states are increasingly vital parameters in enhancing HMI, yet accurately extracting these signals remains challenging. Kim et al. [105] proposed a multimodal emotion recognition system combining verbal and non-verbal expression data through a personalized skin-integrated facial interface (PSiFI) (Fig. 4**c**). The self-powered, stretchable, and transparent system features a bidirectional triboelectric strain and vibration sensor that simultaneously captures diverse emotional cues. Fully integrated with wireless data transmission and machine learning algorithms, it enables real-time emotion recognition even when masks are worn and was demonstrated in a VR-based digital concierge. Auditory perception remains one of the most effective communication methods between humans and robots. Wang et al. [89] designed a self-powered triboelectric auditory sensor (TAS) for electronic hearing systems in intelligent robotics (Fig. 4**d**). Exhibiting ultrahigh sensitivity (110 mV/dB) and broadband response (100–5000 Hz), the TAS utilizes an optimized annular inner boundary geometry. When integrated with robotic platforms, it enables high-quality music recording and precise voice recognition.

These advancements demonstrate the significant potential of contact sensing to enhance HMIs with high sensitivity, stability, and multifunctionality. By integrating flexible materials, optimized structures, and intelligent signal processing, such systems enable natural, real-time interactions across multiple modalities. Nonetheless, further optimization is needed in improving device durability, reducing noise interference, and enhancing adaptability to diverse user conditions. Addressing these challenges will be essential to advancing triboelectric-based HMIs as key components in future intelligent systems.

3.1.3. Intelligent health monitoring

Wearable triboelectric sensors based on contact sensing have emerged as powerful platforms for next-generation biomedical diagnostics, providing self-powered, highly sensitive, and conformal solutions for real-time health monitoring. These systems support multimodal detection of subtle physiological and biomechanical signals, including acoustic vibrations, joint movements, biochemical markers, and cardiovascular pulsations, thereby addressing key challenges in continuous, unobtrusive, and personalized healthcare applications.

To overcome the limitations of conventional piezoelectric stethoscopes in detecting low-frequency, low-intensity heart sounds, Guo et al. [90] developed a triboelectric stethoscope based on fast-saturating constitutive behavior (Fig. 5**a**). It exhibited ultrahigh sensitivity (1215 mV Pa^{-1} vs. 21 mV Pa^{-1} for piezoelectric sensors) within 50–80 dB, and a 36 dB signal-to-noise ratio through a trumpet-shaped auscultation cavity. Combined with machine learning, the system enabled classification of five cardiac states with 97 % accuracy, offering a novel sensing strategy for cardiac diagnostics. Wearable triboelectric sensors have shown great potential in personalized rehabilitation and musculoskeletal health monitoring by enabling real-time, accurate biomechanical data acquisition. To support rehabilitation in aging populations, Tang et al. [106] introduced a modular wearable brace for total knee arthroplasty (TKA) recovery (Fig. 5**b**). Featuring a triboelectric force transducer and angle sensor, the system quantified isometric muscle strength and knee flexion in real-time. Clinical studies demonstrated enhanced rehabilitation via personalized monitoring, and new metrics such as the isometric muscle test score were proposed, showing the system's potential for intelligent eldercare and remote medical engineering. Addressing musculoskeletal disorders (MSDs), particularly in the upper limbs, Wei et al. [107] designed a conformal self-powered inertial displacement sensor (CSIDS) for in situ joint motion monitoring (Fig. 5**c**). Through geometric optimization of semi-cylindrical tribo-structures and COMSOL simulation, CSIDS achieved high accuracy in capturing shoulder joint angles and humeral acceleration. With multilayer perceptron (MLP)-based deep learning, recognition rates of 99.38 % and 99.58 % were realized, demonstrating a comprehensive motion-tracking solution for occupational health and ergonomic monitoring.

In addition, advanced wearable biochemical and physiological sensors have enabled precise, real-time health monitoring through innovative material and device integration. For biochemical analysis, Wen et al. [108] developed a droplet-based wearable sweat monitoring platform (WSMP) integrating electrowetting-on-dielectric (EWOD) and TENG technology (Fig. 5**d**). The TENG-generated high-voltage field actively controlled sweat droplet motion by tuning wettability, with a $>30\,\%$ change in contact angle at 5 kV. Real-time manipulation, merging, and pH-responsive color reaction were demonstrated on the shank, enabling spatially resolved biochemical sensing with multifunctional capabilities. Beyond contact-based biosensing, Wang et al. [109] proposed an ultrathin flexible sensor (UFS) for unconstrained epidermal pulse wave monitoring (Fig. 5**e**). Constructed with multilayer microstructures and thin-film materials, UFS exhibited high shape-adaptability and broad-range pressure sensitivity. Mounted onto common surfaces, it accurately captured fingertip pulse waves and extracted cardiovascular parameters under variable force. Integrated with flexible electronics (e.g., foldable phones), it supported a proof-of-concept IoTs based continuous health monitoring system.

Building upon these healthcare applications, intelligent sports monitoring [112,113] represents a rapidly emerging extension of wearable triboelectric sensor technology. By combining structural adaptability, biomechanical coupling, and data intelligence, TENG-based systems are enabling real-time, multi-site motion capture and performance analytics. Chou et al. [110] developed a customizable and flexible triboelectric nanogenerator (CF-TENG) utilizing 3D-printed thermoplastic polyurethane as both the elastic shell and friction layer (Fig. 5**f**). The device showed high responsiveness to joint motions of the fingers, wrists, and elbows, and was further integrated into a pressure-sensing insole and a smart ski pole system. These components collectively formed a comprehensive motion capture platform for cross-country skiing. By applying a self-developed peak recognition algorithm (P-Find) and a subspace k-nearest neighbors (KNN) classifier, the system achieved 98.2 % and 100 % accuracy in distinguishing four common movement behaviors and three major skiing techniques, respectively. This work establishes a robust framework for personalized sports analytics using TENGs. In another example, Yang et al. [111] introduced a TENG-based electronic skin (E-skin) designed for volleyball reception training and analytics (Fig. 5**g**). The device was fabricated by embedding a silver nanowire (Ag NW) electrode between a thermoplastic polyurethane (TPU) layer and a poly(vinyl alcohol)/chitosan (PVA/CS) substrate. The E-skin featured excellent breathability ($10.32\ kg\cdot m^{-2}\cdot day^{-1}$) and antibacterial properties against E. coli and S. aureus. With a pressure sensitivity of $0.3086\ V\cdot kPa^{-1}$ in the 6.65–19.21 kPa range, a 2×3 E-skin array was implemented to construct a self-powered volleyball reception statistical system, demonstrating the feasibility of integrating wearable TENGs in performance evaluation and training feedback for athletes.

Contact sensing technologies demonstrate outstanding adaptability, sensitivity, and multifunctionality in intelligent health monitoring applications, including cardiac, joint, biochemical, and hemodynamic assessments. Future research should prioritize the development of fully integrated wearable systems that incorporate edge computing, cloud diagnostics, and AI-driven decision-making. Additionally, efforts to enhance system reliability, data security, and user comfort will be crucial to realizing autonomous and intelligent healthcare ecosystems.

3.1.4. Smart city

Contact sensing technologies have also been pivotal in advancing smart city infrastructure by enabling self-powered, high-resolution monitoring across urban systems. TENG-based sensors embedded within buildings, transportation networks, and public spaces facilitate real-time acquisition of data related to structural integrity, dynamic load fluctuations, and human activity patterns. Applications span smart homes for

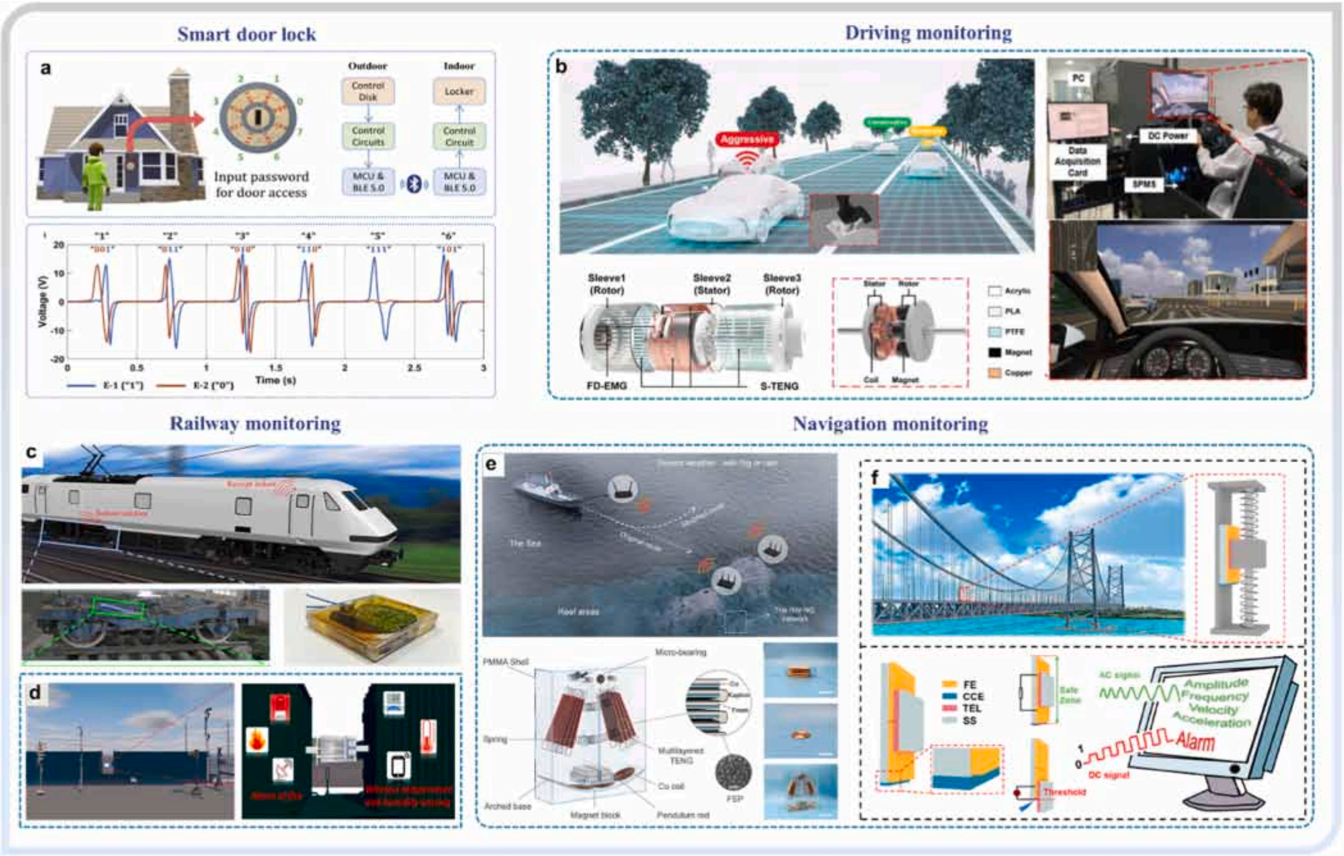

Fig. 6. Triboelectric technologies for smart city applications. (a) Authentication and access control using a self-powered TENG control disk [91]. Copyright 2020 Elsevier. (b) Application scenario and system architecture of the self-powered monitoring system (SPMS) [114]. Copyright 2024 Wiley. (c) Structural design of a self-powered wireless smart sensor for train monitoring [115]. Copyright 2017 Elsevier. (d) The multiple mode TENG (MM-TENG) for on-board mechanical energy harvesting and its application in powering sensors [116]. Copyright 2021 Elsevier. (e) Design and working principle of the hybrid wind nanogenerator (HW-NG) [117]. Copyright 2021 Wiley. (f) Schematic and experimental structure of a fully self-powered vibration monitoring sensor driven by TENG [118]. Copyright 2020 American Chemical Society.

energy-efficient control, transportation systems for traffic and safety monitoring, railway infrastructure for vibration and fault detection, and marine environments for navigational and condition sensing. Owing to their robustness, scalability, and energy autonomy, these systems are particularly well-suited for continuous, large-scale deployment, supporting the evolution of intelligent, responsive, and sustainable urban ecosystems.

Smart home applications have emerged as a key area of focus, particularly in enabling intuitive, wireless control through real-time detection of physical interactions and environmental stimuli. Mehmet Rasit et al. [91] developed a sliding-operation TENG-based control disk interface (Fig. 6**a)** that generates a 3-bit binary-reflected Gray code (BRGC) by integrating copper electrodes, polytetrafluoroethylene (PTFE) film, photovoltaic cells, and signal processing circuits. Eight sensing transitions were achieved using two electrodes to represent binary states "0" and "1," with a third electrode indicating the sliding direction. Output signals are processed and transmitted wirelessly via Bluetooth, while a hybrid energy harvester, combining triboelectric and photovoltaic modalities, powers the entire circuit. This triboelectric control disk demonstrates notable reliability and versatility for smart home control and secure password authentication.

Beyond indoor applications, the integration of TENG into intelligent transportation systems has shown great promise. Cheng et al. [114] designed an intelligent driving monitoring system based on a TENG and an electromagnetic generator (Fig. 6**b)**. The system includes a self-powered pedal motion sensor (SPMS), which combines a six-phase TENG (S-TENG) and a free-rotating disk electromagnetic generator (FD-EMG). S-TENG detects pedal movement direction, amplitude, and speed, while FD-EMG provides self-powered driver behavior warnings. An intelligent data processing unit (IDPU) uses machine learning to classify driving styles based on data collected by SPMS. Experimental results confirm the system's accuracy, highlighting its potential in traffic safety and intelligent driving applications. In the domain of public transportation, particularly railway systems, reliable monitoring technologies are essential for operational safety and efficiency. Yang et al. [115] reported a self-powered wireless smart sensor powered by vibration energy harvested via a maglev porous nanogenerator (MPNG) integrated with TENG and electromagnetic generators (Fig. 6**c)**. The MPNG delivers peak power densities of 0.34 milliwatts per gram at 50 megaohms and 0.12 mW/g at 700 ohms, respectively. The device powers 400 commercial LEDs and charges supercapacitors and lithium-ion batteries efficiently. A wireless sensor powered by MPNG arrays transmits real-time data to mobile devices, demonstrating great potential for IoT applications in train monitoring. Railway freight transport requires self-powered monitoring due to lack of onboard power. To address this, Hu et al. [116] designed a multiple mode TENG (MM-TENG) composed of multilayer floating sliding and wave-shaped contact-separation parts to harvest mechanical energy from train carriage joints (Fig. 6**d)**. The multilayer floating sliding part reduces abrasion and efficiently captures small trigger energy. The wave-shaped part is divided into units, one of which supplements charge to the entire system, enhancing output performance. The device produced a transferred charge of 3.2 microcoulombs at 2.5 hertz and charged a 470-microfarad capacitor to 5.2 volts in 100 s. The power supplied

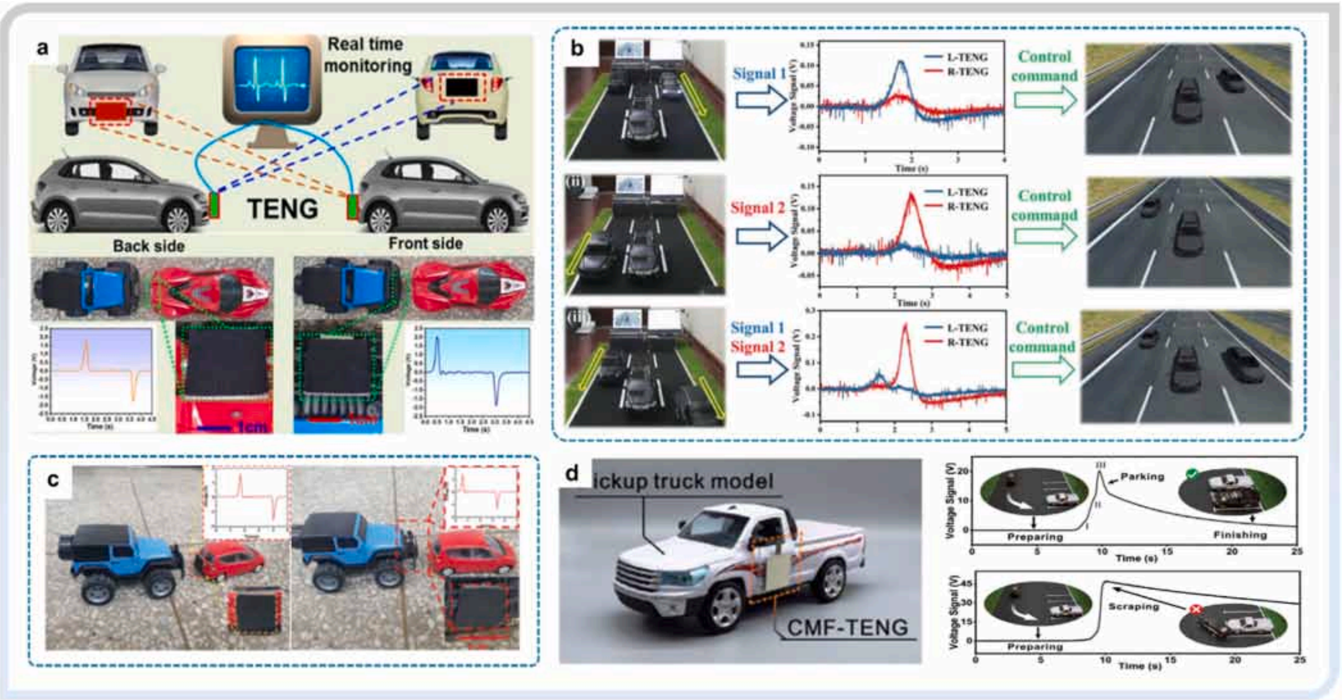

Fig. 7. Non-contact sensor based TENG applications for vehicle monitoring. (a) Potential application of the contact/non-contact mode TENG (CNM-TENG) in obstacle avoidance for a robotic car and its associated electronic systems [119]. Copyright 2022 Elsevier. (b) Application of the self-powered non-contact TENG (SNC-TENG) in blind spot detection and potential theft detection in a real vehicle [120]. Copyright 2023 Wiley. (c) Potential application of a TENG-based system for obstacle prevention in robotic cars and related electronic modules [121]. Copyright 2021 Wiley. (d) Sensing demonstrations for real-time vehicle status tracking and feedback [92]. Copyright 2024 Wiley.

supported lighting 944 LEDs, operating a temperature-humidity meter and a fire alarm after energy management. This strategy offers effective in situ energy harvesting for self-powered monitoring.

Extending beyond terrestrial applications, navigation monitoring in maritime environments has emerged as a critical frontier for self-powered sensing technologies. Navigation monitoring encompasses both real-time vessels positioning under dynamic oceanic conditions and the structural health assessment of maritime infrastructure, including bridges. In this context, Wang et al. [117] proposed a hybrid wave energy harvesting nanogenerator (HW-NG) for powering long-distance wireless transmission and demonstrated a self-powered route avoidance warning system (Fig. 6**e**). The HW-NG integrates a TENG and electromagnetic generator within a pendulum structure featuring a spring-assisted multilayered design. Powered solely by wave energy, HW-NG establishes communication nodes over 1.5 km. A network of hundreds of thousands of HW-NGs around islands or reefs could deliver second-level forewarning signals via spontaneous wireless emission through an automatic switch module. This system presents a viable solution for sea transportation safety. Vibration sensors are essential for structural health monitoring but often face challenges in achieving real-time, continuous assessment with early warning in simple, self-powered devices. Wang et al. [118] developed a self-powered vibration sensor system based on a dual-mode TENG capable of producing alternating current or direct current in different operation modes (Fig. 6**f**). Within safe vibration levels, the sensor generates alternating current (AC) for continuous monitoring and powers data transmission. When vibration exceeds the danger threshold, the output switches to direct current (DC), triggering an alarm immediately. This system offers a straightforward and accurate tool for structural health monitoring and early incident warning.

Advances in TENG-based contact sensing systems have significantly contributed to smart city development, with applications in smart homes, intelligent transportation, railway safety, maritime navigation, and bridge monitoring. By combining innovative energy harvesting designs with advanced sensing and data processing, these systems enable continuous, wireless, real-time monitoring independent of external power sources. Future research should focus on improving energy conversion efficiency, device miniaturization, and AI integration to realize more autonomous and intelligent monitoring networks. Such efforts are critical for promoting sustainable, self-powered IoT solutions that enhance safety and operational efficiency in transportation and infrastructure sectors.

3.2. *Non-contact sensing systems*

While contact-based sensing technologies have laid a solid foundation for diverse applications by enabling direct mechanical-to-electrical signal conversion with high sensitivity and structural simplicity, the evolution of functional requirements has catalyzed the development of non-contact sensing paradigms. In this context, TENG-based non-contact sensing systems have garnered considerable attention, offering high-resolution detection of motion, proximity, and position without the need for physical interaction. These systems provide inherent advantages in terms of mechanical durability, operational safety, and sanitary performance. In driving monitoring, such sensors are employed for non-contact environmental perception, including object approach detection and blind-spot monitoring, enhancing safety without relying on complex electronics. In smart healthcare, they enable continuous, contact-free monitoring of vital signs, reducing discomfort and risk of cross-contamination. For position tracking, TENG provide precise spatial resolution by detecting air-induced electrostatic changes, suitable for wearable-free localization. In intelligent screens, non-contact TENG interfaces support gesture recognition and proximity sensing, paving the way for next-generation HMIs.

3.2.1. *Vehicle monitoring*

Non-contact TENGs represent a cutting-edge strategy for frictionless sensing, offering enhanced durability and environmental robustness.

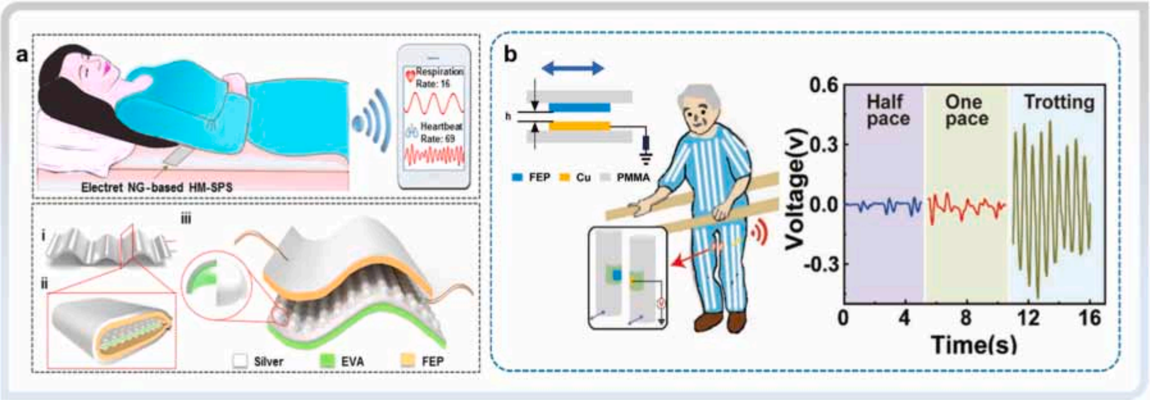

Fig. 8. Non-contact sensor based TENG applications for smart healthcare. (a) Hollow microstructure self-powered pressure sensors (HM-SPS) for non-contact heartbeat and respiration monitoring [122]. Copyright 2018 American Chemical Society. (b) The non-contact sensing performance of the non-contact motion vector sensor (NMVS) in gait monitoring for patients after lower extremity surgery [93]. Copyright 2022 Wiley.

Their high sensitivity and contactless operation render them especially suited for real-time ambient perception within intelligent vehicle systems. To address the need for dual-mode sensing in multifunctional platforms, Park et al. [119] developed a contact/non-contact mode TENG (CNM-TENG) by introducing a laser-carbonized MXene/ZiF-67 nanocomposite as an intermediate charge enhancement layer (Fig. 7**a**). The porous architecture effectively boosts charge density and retention, leading to superior output performance in both modes. Under optimal conditions, the CNM-TENG achieved a power density of 65 W/m^2 and demonstrated stable non-contact charge output (15.3 μC/m^2 at 2 cm), supporting applications in human gait analysis, robot obstacle detection, and touchless HMI. Building upon the need for high-sensitivity, long-range environmental sensing in smart vehicles, Lai et al. [120] proposed a self-powered non-contact TENG (SNC-TENG) utilizing a MXene/silicone nanocomposite embedded with a conductive sponge (Fig. 7**b**). This structure substantially enriches surface charge generation, allowing the device to detect human presence up to 2 m away. Its integration in vehicle blind-spot monitoring and sentry mode validates its practical applicability, setting a benchmark for ambient perception sensors in next-generation automotive systems.

Expanding the functional landscape of non-contact TENG, Park et al. [121] also developed a contactless double-layer TENG (CDL-TENG), which is composed of cobalt nanoporous carbon (Co-NPC)/Ecoflex and a MXene/Ecoflex nanocomposite layer (Fig. 7**c**). The double-layer configuration enhances charge storage and reduces output decay through efficient charge trapping. The device enables non-contact position detection up to 20 cm and exhibits high sensitivity to humidity (0.3 V per % RH) and acceleration (2.06 Vs^2·m^{-1}). Its successful deployment in mobile robots and authentication systems exemplifies its potential in real-time motion tracking and secure access control. To ensure stable sensing under extreme environmental conditions, Lu et al. [92] designed a moisture-resistant TENG-based sensor using a hierarchical assembly strategy that integrates an intermediate energy storage layer with a superhydrophobic triboelectric surface (CA = 162°) (Fig. 7**d**). The sensor maintains 95.2 % output retention at 99 % RH and achieves human activity detection at distances up to 3 m. Furthermore, its capability for continuous environmental monitoring around vehicles underscores its potential for robust, self-powered sensing in demanding IoT environments.

Non-contact TENG-based sensors offer a promising approach for advanced vehicle monitoring, enabling real-time detection of surrounding objects, environmental changes, and driving conditions without mechanical wear or signal loss. Their robustness and ease of integration make them well-suited for applications including blind-spot detection, driver assistance, and autonomous navigation. Future work should focus on improving sensor sensitivity, environmental robustness, and integration with vehicle AI systems to further enhance safety and intelligence in transportation.

3.2.2. *Smart healthcare*

The increasing demand for intelligent, user-friendly healthcare solutions, particularly for real-time, non-invasive monitoring of vital signs, has catalysed the advancement of non-contact triboelectric sensors within smart medical systems. In contrast, conventional wearable sensors typically rely on direct skin contact, which can compromise user comfort and long-term reliability, especially under high-pressure conditions such as sustained body weight. To address these challenges, Zhou et al. [122] introduced a non-contact respiration and heartbeat monitoring system based on a flexible self-powered pressure sensor enhanced by a hollow microstructure self-powered pressure sensors (HM-SPS) (Fig. 8**a**). The HM-SPS design offers superior deformation capability compared to solid counterparts, enabling a high dynamic pressure sensitivity of 18.98 V·kPa^{-1} across a wide range (up to 40 kPa). This allows for stable detection of physiological signals such as heartbeat and respiration under high-pressure, non-contact scenarios, with real-time data transmission to mobile devices, paving the way for battery free and comfortable health monitoring at home.

Beyond physiological sensing, attaining spatial and directional resolution in non-contact motion tracking is critical for broadening the functional capabilities of HMIs. To this end, Ding et al. [93] reported a self-powered non-contact motion vector sensor (NMVS) leveraging a TENG for vector-resolved motion detection (Fig. 8**b**). The system detects motion direction and amplitude through electrostatic induction and spatial signal distribution, with simulation and experimental validation revealing the impact of device structure and movement parameters on sensing accuracy. The NMVS demonstrated high-resolution capabilities in diverse applications such as micro-vibration monitoring, rehabilitation gait analysis, contactless smart locks, and non-contact alarms. This study provides a novel strategy for constructing multifunctional HMIs with enhanced intelligence and broad utility in health, robotics, and industrial safety.

Recent advances in non-contact sensing technologies have greatly expanded their use in intelligent healthcare and motion perception systems. Through innovative structural designs and material strategies, these sensors achieve high sensitivity, durability, and multifunctionality under dynamic, high-pressure conditions. This progress overcomes limitations of traditional contact-based systems and establishes a foundation for developing unobtrusive, self-powered, and highly integrated sensing platforms for future smart diagnostics and human-machine interfaces. Future efforts should aim to enhance sensor miniaturization, signal stability, and seamless integration with wearable and implantable devices.

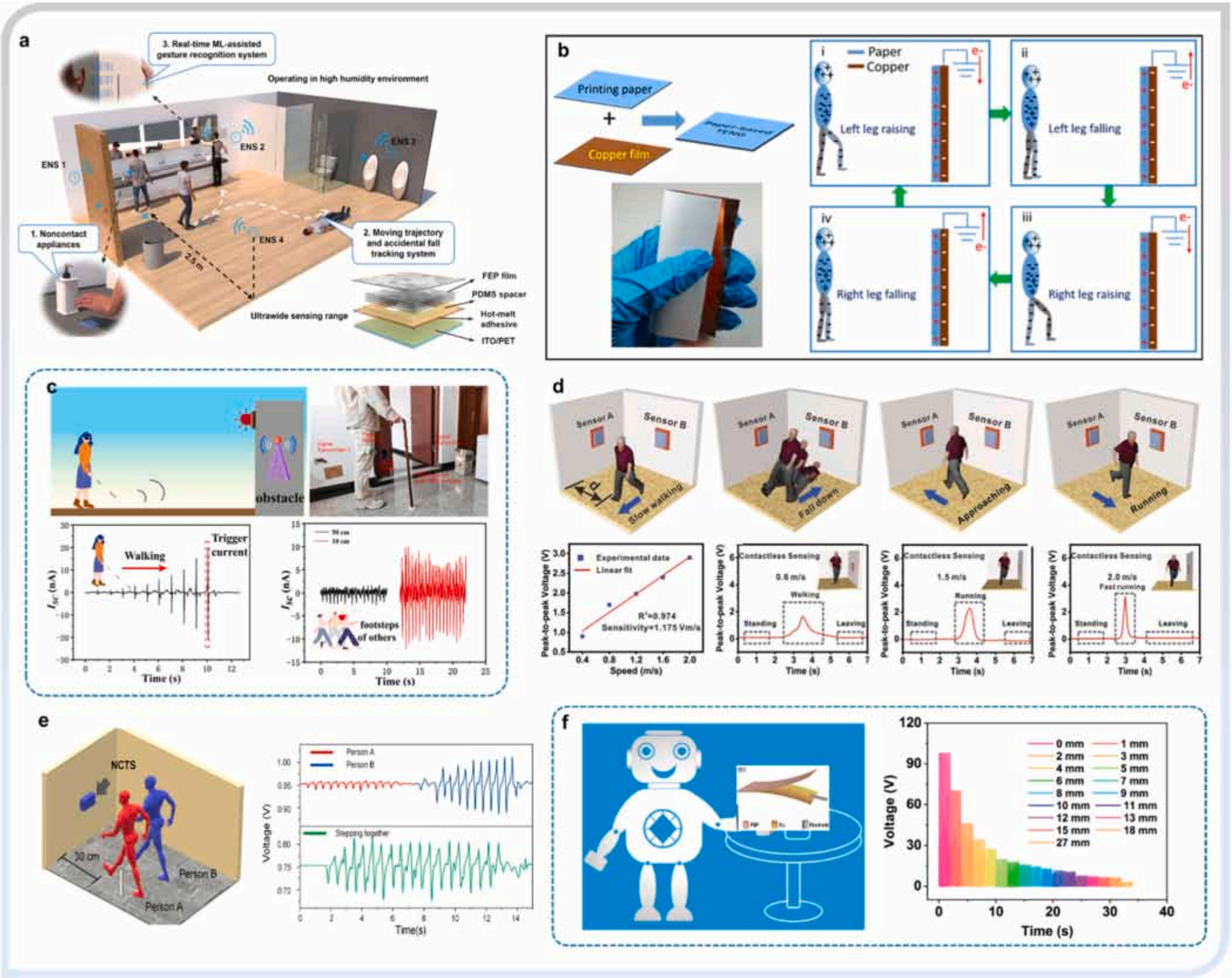

Fig. 9. Non-contact sensor based TENG applications for position detection. (a) The electret-based non-contact sensor (ENS) enabled non-contact sensing system applied to private spaces in harsh environments [94]. Copyright 2023 American Chemical Society. (b) Photograph and working principle of the non-contact TENG [123]. Copyright 2020 Elsevier. (c) Application of navigation sensors for the blind [124]. Copyright 2022 Elsevier. (d) Time and frequency domain analysis of walking [125]. Copyright 2022 Wiley. (e) Monitoring of two people walking and differentiation using frequency spectrum analysis [126]. Copyright 2021 Elsevier. (f) Potential application diagram of the FBF TENG as a distance sensor [127]. Copyright 2020 American Chemical Society.

3.2.3. Position detection

Non-contact triboelectric sensors have shown significant potential in precise spatial perception and motion tracking, enabling real-time, wearable-free monitoring of human activities. The latest progress has centred on extending sensing range, improving spatial resolution, and enhancing environmental adaptability, thereby enabling applications ranging from gait recognition and fall detection to obstacle avoidance and navigation. To address the challenge of short interaction distance and moisture sensitivity, Zhong et al. [94] developed a self-powered electret-based non-contact sensor (ENS) with strong environmental robustness and a sensing range exceeding 2.5 m (Fig. 9**a**). By engineering a megascopic air-bubble structure and integrating multilayer electret films, the sensor significantly enhanced charge retention and field strength through heterocharge-synergy and electrostatic superposition effects. The ENS demonstrated reliable functionality in high-humidity environments, enabling contactless appliance control, fall detection, and real-time machine learning–assisted gesture recognition with 99.21 % accuracy. Building on the potential for non-contact monitoring and energy harvesting, Shi et al. [123] proposed a paper-based TENG as a self-powered human motion sensor (Fig. 9**b**). Operating entirely in non-contact mode, the device successfully detected leg movement patterns, gait direction, and walking speed with distinct voltage signatures. Remarkably, it also captured human motion through solid obstacles such as walls, with sufficient signal strength measurable via standard multimeters, demonstrating its feasibility for unobtrusive motion tracking and kinetic energy harvesting.

Addressing the need for simplified architectures and scalable fabrication in assistive technologies, Wang et al. [124] developed a copper–PTFE-based non-contact motion sensor capable of detecting human approach and proximity without physical contact (Fig. 9**c**). The device achieved a spatial resolution of 1 cm and operated effectively within a 2 m range, with a current output of 57 nA at 20 cm. It was further integrated into a blind-assist navigation system, showcasing precise distance recognition and obstacle avoidance, thereby expanding the utility of non-contact TENG in wearable-free assistive technologies. Addressing the limitations of low charge density in conventional contactless systems, Nie et al. [125] developed a self-powered non-contact sensor based on a polyvinylidene fluoride (PVDF) @MXene composite film featuring vapor-induced phase separation and Rayleigh instability-driven structures (Fig. 9**d**). The resultant film achieved charge and power outputs of 128 μC/m^2 and 200 μW/cm^2, respectively, along with excellent motion discrimination accuracy, detecting walking,

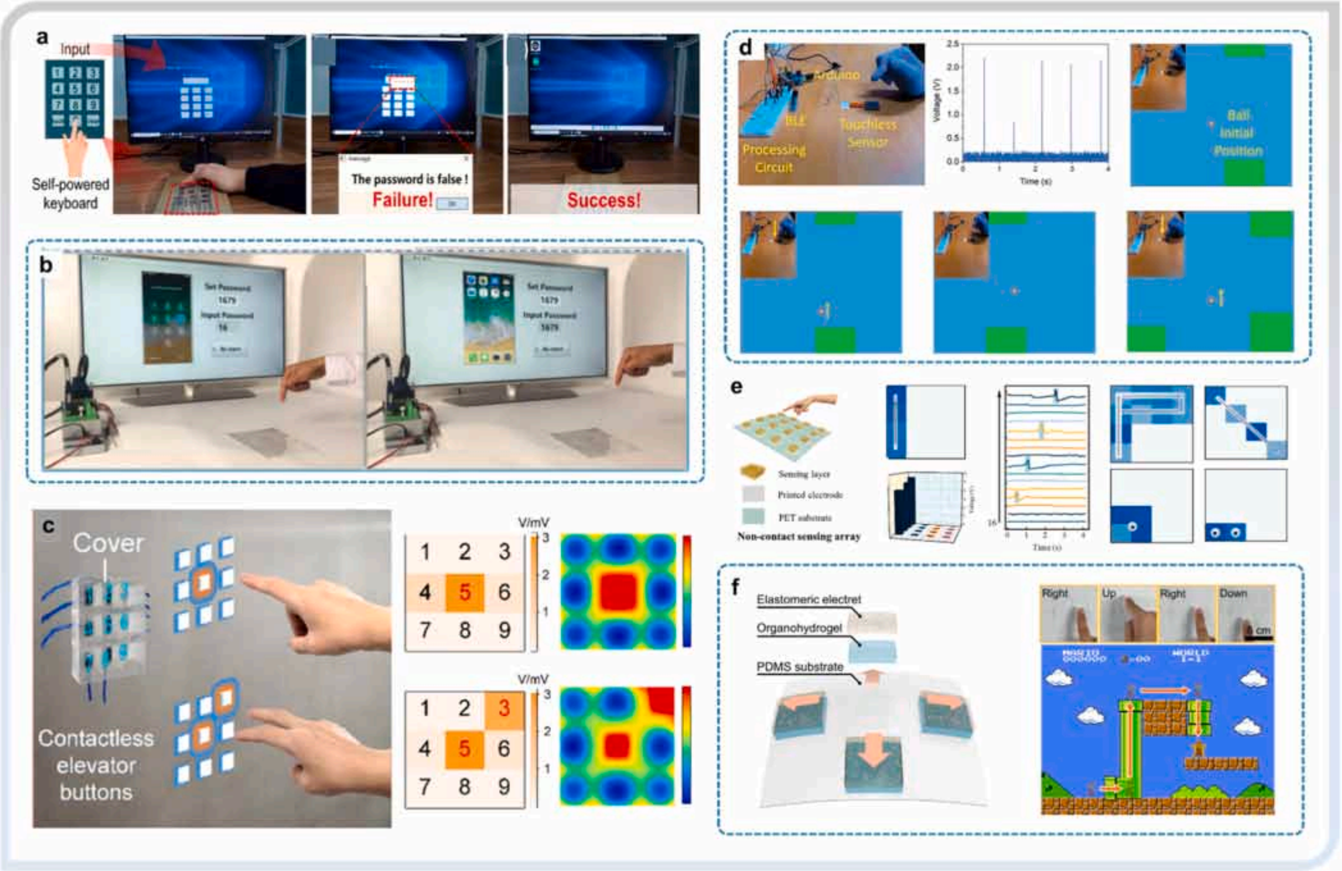

Fig. 10. Non-contact sensor based TENG applications for smart screens. (a) The hybrid electronic skin (CNES) array serving as a self-powered keyboard for inputting passwords to access and manage the application process of a wireless intelligent greenhouse IoT system [128]. Copyright 2022 Elsevier. (b) Application of the touch-free screen sensor (TSS) in an intelligent non-contact screen control system [129]. Copyright 2019 Wiley. (c) The non-contact TENG (NTENG) array functioning as non-contact self-powered elevator button sensors [95]. Copyright 2021 Elsevier. (d) Demonstration of the triboelectric sensor as a wireless game controller [130]. Copyright 2022 Wiley. (e) Applications of the printed non-contact TENG (PNC-TENG) in multi-site and multi direction motion monitoring [131]. Copyright 2023 Elsevier. (f) Demonstration of playing Super Mario using a touchless control pad [132]. Copyright 2022 American Association for the Advancement of Science.

running, and jumping at distances up to 70 cm. The system delivered real-time signal differentiation across various dynamic states, offering a path forward for high-performance contactless biomechanical monitoring.

In healthcare settings where privacy, comfort, and continuous monitoring are critical, Tuncay et al. [126] designed a flexible non-contact triboelectric sensor (NCTS) based on a PDMS/Al structure (Fig. 9**e**). The sensor achieved remote motion tracking at up to 1.5 m and distinguished movement types and directions without requiring wearables. It also enabled dual-subject trajectory analysis, collision prevention for the visually impaired, and indoor navigation through distributed sensor arrays, reinforcing the potential of NCTS platforms for eldercare, rehabilitation, and people-counting applications. Finally, exploring sustainable materials for biointegrated electronics, Cao et al. [127] developed a flexible fish bladder film–based TENG (FBF-TENG) for smart electronic skin (Fig. 9**f**). The natural triboelectric layer exhibited high output current and charge density (4.56 mA/m^2 and 25 μC/m^2), along with humidity and acceleration sensitivities of 50 nA/% RH and 446 nA·s^2/m, respectively. The device also demonstrated reliable non-contact position sensing within 27 mm, underscoring its multifunctional potential in prosthetics, intelligent interfaces, and wearable electronics.

Non-contact sensing technologies have made substantial progress in precise spatial perception and real-time position tracking. Through advances in material engineering and sensing architectures, these systems provide reliable, high-resolution detection, enabling new applications in ambient perception, indoor navigation, and intelligent mobility. Future work should focus on enhancing robustness in complex environments, reducing power consumption, and improving integration with AI-driven navigation systems.

3.2.4. *Smart screens*

Intelligent screens have become critical platforms for next-generation HMI, prompting the development of advanced non-contact sensing technologies that enable touch-free operation, enhanced user experience, and improved environmental adaptability. Nam Young et al. [128] first demonstrated a hybrid electronic skin (CNES) combining a TENG and a humidity sensor on a flexible substrate fabricated via a hydrothermal method (Fig. 10**a**). The integration of an Ag nanowire electrification layer enhanced the contact sensing capability and electrical output, while a SnO_2 humidity sensing layer enabled non-contact monitoring of respiration. This dual functionality not only improved tactile sensing performance but also introduced environmental sensitivity relevant for smart screen interfaces requiring contact and proximity detection. Leveraging the integration of human body charge in sensing, Mao et al. [129] developed a triboelectric touch-free screen sensor (TSS) capable of recognizing multiple non-contact gestures, including finger drop and lift at varied speeds, fist clenching, palm opening, and directional palm flipping (Fig. 10**b**). By harnessing naturally occurring charges on the human body, the TSS significantly extended the gesture recognition range beyond conventional capacitive sensors. This sensor was further incorporated into an intelligent non-contact screen control system for smartphone unlocking, pioneering a novel touch-free interaction paradigm critical for next-generation

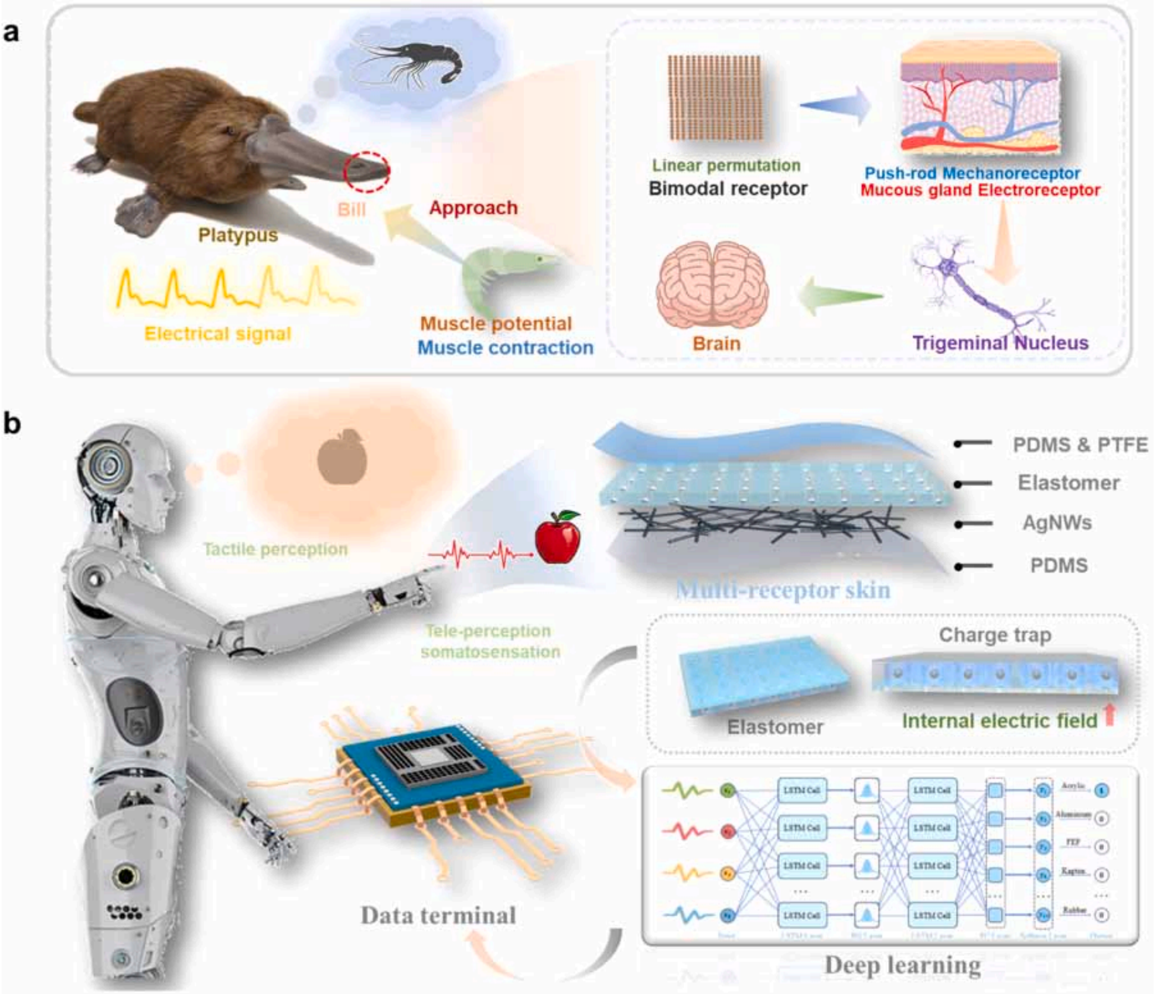

Fig. 11. The multi-receptor skin sensing system. (a) Schematic demonstration of the dual receptor system that is distributed on the platypus's bill for environmental perception. (b) Schematic diagram of intelligent perception system based on the multi-receptor skin and deep learning [96]. Copyright 2024 American Association for the Advancement of Science.

smart devices.

Addressing the growing demand for durable, self-sustained sensing systems in interactive electronics, Gong et al. [95] introduced a non-contact TENG (NTENG) featuring self-healing and impact-resistant capabilities (Fig. 10**c**). The device employed a graphene and shear stiffening gel composite with an elastomeric matrix, enabling detection of object distance and motion speed through electrostatic induction without physical contact. Its superior mechanical resilience and stretchability suggest promising applications in non-contact screen controls and wearable interfaces, where durability and responsiveness are crucial. To enhance charge generation and retention in contactless sensing environments, Jae et al. [130] reported a high-performance contactless TENG-based on a Siloxene/Ecoflex nanocomposite (Fig. 10**d**), which generated abundant surface charges due to strong electron affinity. The addition of molybdenum disulfide incorporated laser-induced graphene as a charge trapping interlayer enhanced surface potential fourfold, significantly improving output performance and charge retention. The device exhibited excellent humidity sensing with high sensitivity, while its non-contact mode minimized wear. Demonstrations included self-powered touchless hand sanitizers and wireless controllers for gaming, highlighting its potential for hygienic and responsive screen interaction in various environments.

Advancing toward more complex screen-based spatial interaction, Song et al. [131] employed freeze-drying assisted three-dimensional printing to produce a cellulose nanofiber/MXene-based hierarchical architecture for non-contact TENG (Fig. 10**e**). The intermolecular hydrogen bonding between cellulose nanofiber (CNF) and MXene nanosheets improved ink stability and printability, while MXene introduced porous structures that enhanced charge generation and prolonged charge retention. These advances enabled multi-site and multi-dimensional motion trajectory monitoring, paving the way for sophisticated spatial gesture recognition in smart screen interfaces and safe navigation systems. To further enrich the functionalities and applications of human-interfaced electronics, Wang et al. [132] reported a soft artificial electroreceptor for sensing approaching targets (Fig. 10**f**). Enabled by an elastomeric electret, the electroreceptor is capable of encoding environmental precontact information into a series of voltage pulses functioning as unique precontact human interfaces. Applications were demonstrated in a prewarning system, robotic control, game operation, and three-dimensional object recognition.

Together, these studies underscore the rapid advancement of non-contact triboelectric sensing in intelligent screen applications. By leveraging advanced materials, innovative device architectures, and the human body's triboelectric effect, they extend gesture recognition and environmental sensing beyond conventional contact-based approaches. Moving forward, efforts should focus on improving detection accuracy in complex interaction scenarios, enhancing system responsiveness, and ensuring long-term stability to accelerate the development of intuitive, hygienic, and multifunctional smart screen technologies.

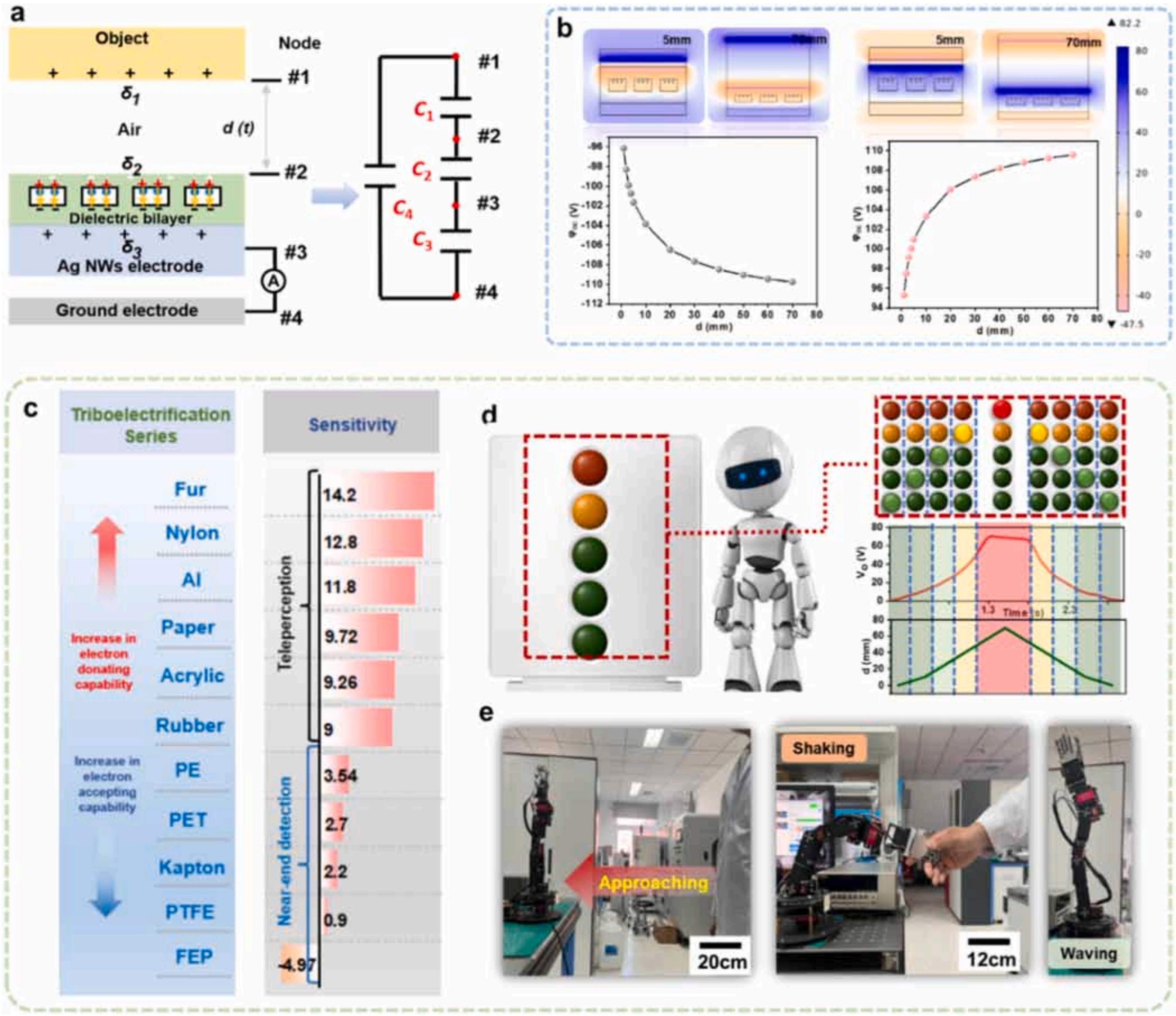

Fig. 12. Tele-perception somatosensation of the bionic electroreceptor [96]. (a) A simplified physical model of the bionic electroreceptor. (b) The behavior of the bionic electroreceptor was simulated through the finite element method. (c) The applicability of the bionic electroreceptor for different materials. (d) A virtual distance alarm robot based on the bionic electroreceptor. (e) Demonstrate how to operate a robotic arm to wave and shake hands when adult approaches. Copyright 2024 American Association for the Advancement of Science.

3.3. *Tele-perception systems*

As non-contact sensing capabilities continue to evolve, extending the perception range beyond immediate proximity has become a key direction for enabling remote interaction and enhancing system intelligence. In nature, biological organisms exhibit a wide range of exceptional mechanisms for perception, offering valuable inspiration for the design of artificial sensory systems. A representative example is the platypus, whose bill features an orderly distribution of mechanoreceptors and electroreceptors capable of simultaneously detecting weak mechanical disturbances and bioelectric signals. This dual-sensory system significantly enhances the animal's ability to detect prey and perceive its environment, characterized by high sensitivity and refined information integration (Fig. 11**a**). Inspired by the sensory system of the platypus, Wei et al. proposed the concept of tele-perception and developed a bioinspired multi-receptor skin that integrates bionic electroreceptors and mechanoreceptors through structured doping of inorganic nanoparticles (Fig. 11**b**). This multimodal sensory system enables both tele-perception and tactile recognition, demonstrating great potential in robotics and HMIs.

The electroreception module operates through a capacitive-like mechanism that responds to variations in environmental charge by sensing changes in surface potential across the elastomer layer. Through the optimized design of parasitic capacitance within the system, it maintains signal stability even under complex interference conditions (Fig. 12**a**). Finite element modeling and experimental validation confirmed the system's ability to effectively recognize a variety of common materials, underscoring its broad applicability (Fig. 12**b, c**). In practical deployment, the bionic electroreceptor has been integrated into robotic platforms for dynamic distance sensing and motion triggering. For instance, a customized virtual alert system enables intuitive feedback by activating color-coded indicators based on proximity thresholds (Fig. 12**d**). Beyond basic sensing, the system also facilitates complex HMI, such as initiating robotic gestures like waving or handshaking in response to human approach (Fig. 12**e**).

At its core, tele-perception transcends conventional perceptual

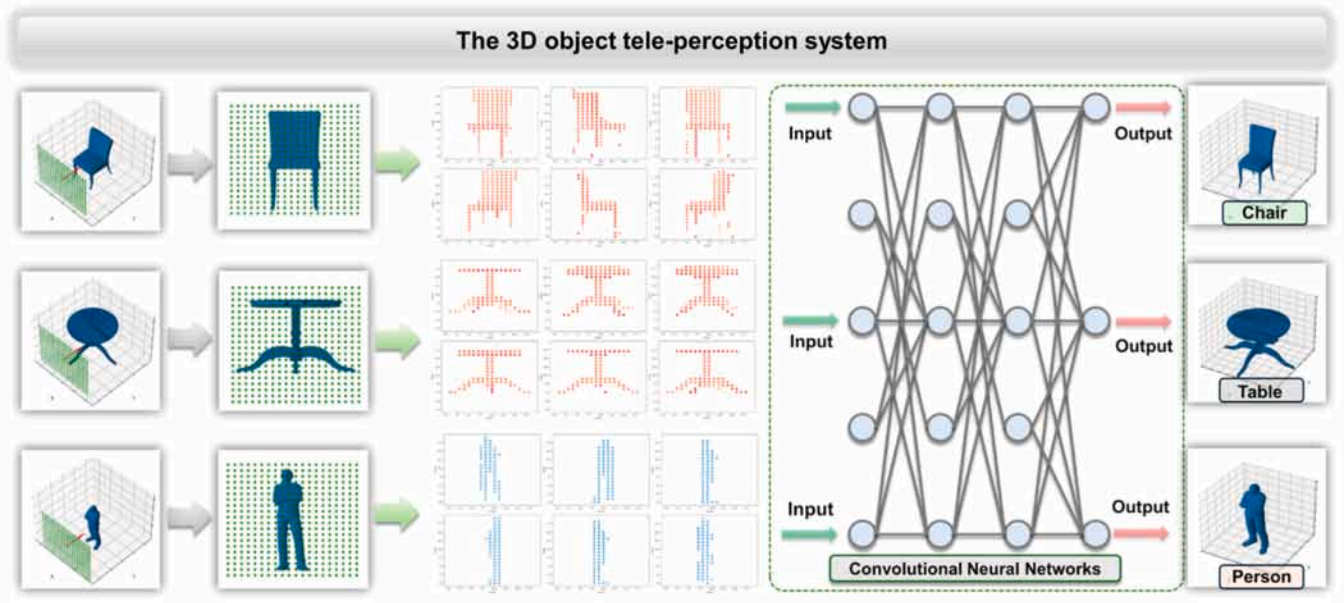

Fig. 13. The 3D object tele-perception system based on the bionic electroreceptor matrix (20 × 20 units) and the CNN [96]. Copyright 2024 American Association for the Advancement of Science.

boundaries, extending sensing capabilities across spatial and multidimensional domains. When combined with deep learning techniques, the system achieves high-accuracy identification of common three-dimensional indoor structures such as humans, chairs, and tables. By constructing a miniature convolutional neural network (CNN), stable classification performance was achieved with a relatively small training dataset. Furthermore, by learning spectral features associated with different materials, the system can identify object composition even under long-range or non-visible conditions (Fig. 13).

Overall, tele-perception systems constitute a pivotal frontier in artificial sensory technologies, driving the evolution of machines toward autonomous, context-aware intelligence. By enabling long-range detection of environmental and physiological signals, these platforms overcome intrinsic limitations of conventional sensing, particularly in complex or inaccessible environments. The convergence of advanced materials, multimodal transduction architectures, and intelligent algorithms, including machine learning and neuromorphic computing, promises future tele-perception systems with ultra-high sensitivity, spatial resolution, and adaptive capabilities. This progress not only narrows the gap between artificial and biological sensing but may ultimately surpass human performance in fields such as intelligent robotics, autonomous vehicles, remote healthcare, and industrial diagnostics.

4. Conclusion and prospect

TENG have evolved from simple energy harvesting devices into multifunctional platforms that integrate power generation and sensing. This review comprehensively examined the progression of TENG-based intelligent sensing technologies across three paradigms: contact sensing, non-contact sensing, and tele-perception. From initial applications in tactile interfaces and wearable health monitors to recent breakthroughs enabling spatial detection and remote interaction, the development of advanced material systems, device architectures, and integration strategies has substantially expanded the functional scope of TENG. These systems demonstrate high sensitivity, adaptability, and self-sufficiency, offering promising solutions for future distributed, intelligent, and energy-autonomous sensing networks. As the boundaries between sensing, computation, and energy become increasingly integrated, TENG stand out as a key enabling technology for next-generation perception systems in diverse domains such as healthcare, smart infrastructure, and robotics.

Looking forward, the advancement of AI-assisted TENG tele-perception systems will hinge on addressing several core challenges and enabling key technological directions. One primary challenge lies in the instability of long-range electrostatic field coupling, especially in dynamic or unstructured environments. Additionally, current machine learning models rely heavily on high-quality, context-rich datasets, which remain limited in scope. Power-efficient, real-time signal processing also remains a major bottleneck for embedded and wearable applications. To overcome these obstacles, future efforts should focus on three main areas. First, the integration of in-sensor computing architectures, such as neuromorphic or memristive components, can enable real-time, low-power signal interpretation. Second, adaptive signal extraction techniques and robust algorithms will be essential to enhance reliability in noisy and cluttered settings. Third, the construction of multimodal, large-scale datasets is critical to support generalizable learning and improve model robustness across scenarios. In parallel, expanding the spatial resolution and functional diversity of TENG sensors through micro/nanostructured array design and hybrid sensing integration (e.g., combining tactile and chemical cues) will further enhance their applicability. Ultimately, embedding TENG systems into AI-driven closed-loop feedback architectures will pave the way for intelligent perception platforms capable of real-time decision-making, with transformative impact in smart healthcare, autonomous robotics, and ambient sensing.

CRediT authorship contribution statement

Di Wei: Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Yan Du:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Zhong Lin Wang:** Writing – review & editing, 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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Data availability

This is a review article. No new data or code were generated or analyzed in this study.

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