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Triboelectric Tactile Sensors for Intelligent Systems

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1 | Introduction

Tactile perception underpins high-dimensional HMIs, integrating mechanical and thermal stimuli into rich, multiscale sensory and cognitive information [1–3]. Beyond direct physical interactions, touch encodes higher-order cognitive information, including material discrimination and action strategy, thereby spanning multiple spatial and temporal scales. Replicating such capabilities in artificial systems remains a formidable challenge. Although conventional piezoresistive [4], capacitive [5, 6], piezoelectric [7], and iontronic pressure sensors [8–10] can accurately quantify basic physical parameters, they remain fundamentally limited in capturing higher-order features such as shape, texture, and material identity. This gap fundamentally limits the deployment of skin-mimetic tactile systems in intelligent robotics, advanced manufacturing, and prosthetics, underscoring the critical need to bridge low-level signal acquisition with high-level perceptual and cognitive functions.

Triboelectric nanogenerators (TENGs) offer a promising solution by directly converting mechanical stimuli into high-dimensional electrical signatures through contact electrification and electrostatic induction [11–14]. With intrinsic self-powered operation, high sensitivity, and designable flexibility, TENGs enable rich signal encoding compatible with pattern recognition and machine learning [15–17]. Crucially, the integration of advanced artificial intelligence algorithms with TENG-derived signals enables efficient feature extraction, adaptive learning, and decision-making, thereby amplifying their capability for intelligent system implementation [18, 19]. As such, TENG-based sensors provide a viable pathway toward intelligent tactile systems capable of unified physical sensing and cognitive perception [20, 21].

This perspective examines multidimensional strategies for triboelectric tactile sensors (TTS), including material system design, interface structure optimization, signal regulation, and intelligent algorithm integration, to enhance tactile information acquisition, signal representation, multimodal analysis, and high-dimensional information integration. It further analyzes their potential in sensitivity, spatial resolution, and environmental adaptability. Through systematic implementation of these strategies, TTS are expected to advance toward high-resolution, intelligent, and multifunctional performance, providing technical support for applications in intelligent systems of wearable electronics, biomimetic robotics, and environmental sensing, etc.

2 | Strategies for Enhancing the Performance of TTS

2.1 | Material-Structure Synergy: Establishing the Physical Basis for Tactile Perception

In intelligent TTS, performance enhancement fundamentally relies on the synergistic design of materials and structures. The sensing capability of TTS depends not only on the charge generation efficiency of the triboelectric materials but also on the spatial resolution of the arrayed structure. Optimizing both aspects in a coordinated manner is crucial for improving sensor sensitivity, response speed, spatial resolution, and environmental adaptability. Rational selection and physicochemical modification of triboelectric materials form the foundation for performance enhancement [22] (Figure 1A). Depending on the application requirements, material systems can be constructed from metals, liquid metals, nonmetallic inorganics, organic polymers, nanocomposite textiles, and piezoelectric materials to match key properties such as flexibility, conductivity, and triboelectric

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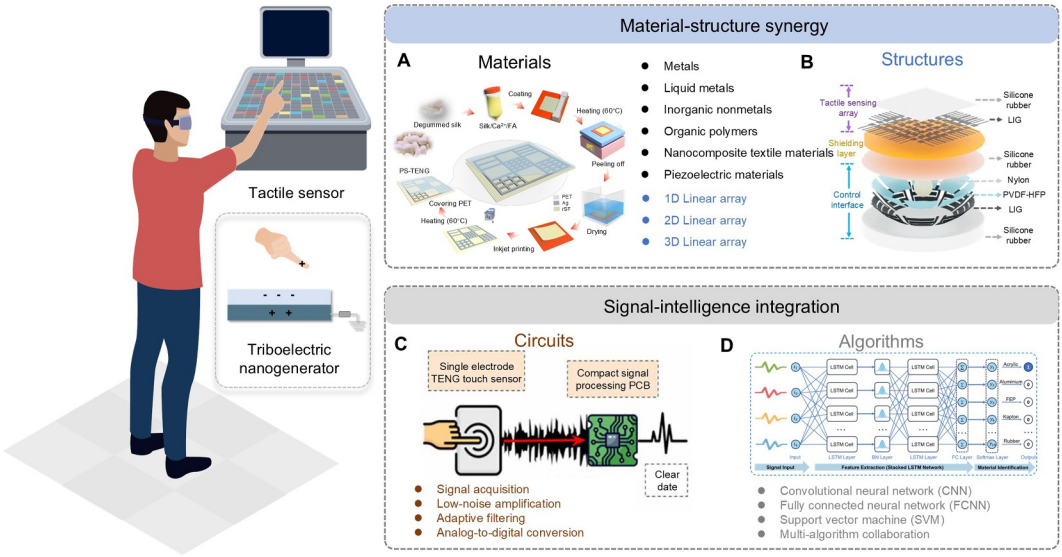


FIGURE 1 | Strategies for enhancing the performance of TTS. (A) Design of material systems. Reproduced with permission from Ref. [22]. Copyright 2024, Elsevier. (B) Interface structure optimization. Reproduced with permission from Ref. [23]. Copyright 2023, Elsevier. (C) Signal regulation. Reproduced with permission from Ref. [24]. Copyright 2018, Elsevier. (D) Integration of intelligent algorithms. Reproduced with permission from Ref. [25]. Copyright 2024, American Association for the Advancement of Science.

polarity. Physical modification techniques, such as templating [26] and electrospinning [27], can be used to tune surface morphology, whereas chemical modifications, including doping [28] and vapour deposition [29], can introduce functional groups or nanofillers, simultaneously enhancing charge generation and separation efficiency, charge density, mechanical durability, and environmental stability [30].

On this basis, array design must be closely coupled with material properties to achieve efficient spatial mapping of tactile information [23] (Figure 1B). One-dimensional (1D) linear arrays are suitable for linear motion and single-point pressure detection [31], two-dimensional (2D) planar arrays enable large-area pressure distribution mapping and tactile imaging [32], three-dimensional (3D) volumetric arrays can detect multidirectional and multidimensional mechanical stimuli [33]. Flexible deformable and independently distributed arrays are particularly compatible with flexible polymers or nanocomposite textiles, facilitating conformal integration on curved surfaces and personalized layouts. Precise matching of material and structural properties is essential for optimizing sensor performance: structure designs that disregard material characteristics may lead to redundancy or insufficient performance, whereas material modifications that lack structural adaptation cannot fully exploit their potential. Only the synergistic co-design of materials and device architectures enables the simultaneous optimization of sensitivity, spatial resolution, and environmental robustness in sensing systems.

2.2 | Signal-Intelligence Integration: High-Dimensional Decoding of Tactile Information

Building on high-quality tactile signals generated through material–structure synergy, the integration of signal processing and intelligent algorithms is central to achieving high-dimensional tactile information interpretation. TTS face technical bottlenecks in weak signal detection, multichannel crosstalk, and limited dynamic range [24] (Figure 1C). To address these challenges, customized front-end circuits can enable high-precision signal acquisition [34], whereas low-noise amplifiers suppress system noise [35]. High-resolution analog-to-digital conversion ensures continuous and fine-grained digitization of electrical signals, significantly improving signal-to-noise ratio and minimizing crosstalk between array units [36]. This process standardizes and structures raw signals, and through multichannel synchronized acquisition and temporal sequence integration, provides stable, high-quality input for subsequent intelligent algorithms. Such a framework ensures data integrity, reproducibility, and interpretability under complex conditions, laying a robust foundation for high-dimensional tasks including tactile pattern recognition, pressure imaging, and gesture or motion classification.

Based on these processed signals, embedded intelligent algorithms can extract high-dimensional tactile features and perform pattern recognition [25] (Figure 1D). Convolutional neural networks (CNNs) [37], with local receptive fields and weight-sharing mechanisms, effectively capture spatial distribution features and local correlations making them suitable for spatially related tasks such as pressure imaging and motion trajectory recognition. Fully connected neural networks (FCNNs) perform deep nonlinear mapping and classification on high-dimensional features, significantly improving gesture recognition and motion pattern discrimination [38]. Support vector machines (SVMs) provide robust generalization under small-sample conditions, enhancing system performance in complex environments [39]. The coordinated application of multiple algorithms enables quantitative mapping between tactile electrical signals and physical stimuli, achieving precise interpretation of tactile information from electrical responses. Through signal-intelligence integration, the system can quantitatively map electrical outputs to mechanical stimuli, thereby providing intelligent decoding capabilities for tactile sensing.

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3 | Challenges and Opportunities

3.1 | Key Challenges

Despite the broad prospects of TTS in intelligent perception, their development faces multiple challenges [40]. First, the comprehensive performance of advanced triboelectric materials remains limited. Existing materials struggle to simultaneously achieve high triboelectric output, tolerance to extreme environments (e.g., high temperature, high humidity, and strong electromagnetic interference), self-healing capability, and biocompatibility. Material modifications that enhance charge generation often do so at the expense of mechanical robustness and long-term stability, whereas key attributes for wearable applications, such as biocompatibility, comfort, self-cleaning capability, and wash durability, remain inadequately addressed, potentially leading to skin irritation and performance degradation.

Second, engineering challenges persist in array-level signal processing and transmission. Signal crosstalk between TTS array units has not been fully resolved, and high-precision detection of weak signals and low-power amplification remain difficult in miniaturized designs. Existing wireless transmission technologies also struggle to balance signal stability with the flexibility and power constraints of wearable devices, and high-integration soft circuit design and fabrication techniques remain immature.

Finally, commercialization and standardization are constrained. Most TTS are still produced at small laboratory scales, and the cost of scaling up techniques such as 3D printing and micro–nano fabrication remains high, hindering mass production. In addition, inconsistent testing parameters and evaluation criteria across research groups limit comparability of device performance, and industry-wide design and testing standards have yet to be established. The high cost of materials and fabrication for high-performance sensors further challenges the balance between performance and economic feasibility.

3.2 | Future Opportunities

Future opportunities for TTS lie in the synergistic advancement of materials, systems, and interdisciplinary integration. The rational design of next-generation multifunctional triboelectric materials, integrating high charge density, mechanical robustness, environmental stability, and biocompatibility, will be pivotal for performance enhancement particularly in wearable and biomedical contexts [41, 42]. The incorporation of sustainable, self-cleaning, and washable functionalities further broadens their practical applicability. Concurrently, the integration of micro/nano-fabrication and advanced characterization techniques enables precise control over surface morphology and interfacial physicochemistry, thereby improving device stability and operational reliability.

At the system level, expanding application domains and accelerating commercialization remain key directions. Tailored, arrayed TTS architectures can support high-resolution tactile mapping across diverse scenarios, including robotics [43], wearable electronics [44], healthcare monitoring [45], and industrial sensing [46]. Progress in standardized performance metrics and scalable manufacturing processes will be essential to ensure reproducibility, reduce costs, and facilitate industrial translation.

Looking forward, cross-disciplinary convergence will be a major driver of innovation. The integration of materials science, mechanics, electronics, artificial intelligence, and biomedical engineering will enable biomimetic, skin-like tactile systems with enhanced functionality and intelligence. Moreover, coupling triboelectric sensing with complementary transduction mechanisms, such as piezoelectric and piezoresistive effects, will enable multimodal, synchronous detection of pressure, vibration, and temperature, advancing comprehensive information acquisition and intelligent signal processing.

Author Contributions

Yan Du: conceptualization, formal analysis, writing – original draft. **Daping Chu:** data curation, formal analysis. **Gehan Amaratunga:** conceptualization, formal analysis. **Di Wei:** data curation, funding acquisition, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data can be requested from the corresponding author.

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