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A Multi-Sensory Auxetic Electronic Skin with Stretchable Printed Circuits and Physical AI-Based Tactile Intelligence for Humanoid Robots

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ABSTRACT

Humanoid robots operating in unstructured environments require distributed tactile perception systems capable of maintaining sensing performance under complex mechanical deformation. Conventional electronic skin (e-skin) technologies have demonstrated promising capabilities in pressure sensing and human–robot interaction; however, their performance is often degraded by stretching, bending, and twisting deformation encountered in highly articulated robotic structures. Furthermore, most existing e-skin systems focus on low-level sensing and lack the intelligence required to transform tactile information into meaningful robotic actions.

This paper presents a conceptual framework for a multi-sensory auxetic electronic skin (e-skin) integrating stretchable printed circuits, multimodal tactile sensing, and Physical AI-based tactile intelligence for humanoid robots. The proposed architecture combines auxetic conductive interconnects, neutral-plane structural engineering, and a high-density sensor matrix capable of simultaneously detecting pressure, shear force, vibration, temperature, and proprioceptive deformation. The auxetic routing network enables enhanced mechanical compliance under stretching, bending, and twisting conditions, while maintaining electrical continuity and signal stability.

A hierarchical tactile intelligence framework is further proposed, integrating tactile signal acquisition, deep learning-based perception, semantic interpretation, and action generation. Through convolutional neural networks (CNNs) and transformer-based learning architectures, tactile patterns are transformed into high-level physical interaction representations that support object manipulation, slip detection, touch-guided learning, and human–robot collaboration.

The proposed framework establishes a scalable foundation for next-generation humanoid robotic skin systems and contributes toward the realization of embodied Physical AI, where robots learn and interact through distributed tactile perception rather than relying solely on visual information.

Keywords
Electronic Skin, Auxetic Structure, Stretchable Electronics, Tactile Intelligence, Humanoid Robot, Physical AI.

Introduction
Recent advances in artificial intelligence, soft robotics, and humanoid systems have accelerated the demand for sensing technologies capable of enabling robots to interact naturally with physical environments. While machine vision has achieved remarkable progress in scene understanding and object recognition, tactile sensing remains one of the most important yet underdeveloped sensory modalities for embodied intelligence [1,2]. Biological skin functions as a distributed sensory organ capable of detecting pressure, shear force, vibration, temperature, pain, and proprioceptive information simultaneously. These sensory signals allow humans to manipulate delicate objects, perceive environmental conditions, and adapt motor behavior in real time [3]. Replicating these capabilities in robotic systems has become a major objective in the fields of electronic skin (e-skin), prosthetics, wearable electronics, and human–robot interaction [4]. Electronic skin technologies have evolved rapidly during the past decade. Various sensing mechanisms including piezoresistive, capacitive, piezoelectric, optical, and triboelectric sensing have been investigated for robotic applications [5-7]. Flexible and

stretchable electronics have further expanded the applicability of e-skin technologies by enabling conformal integration onto curved and deformable surfaces [8]. Despite these advances, significant challenges remain. Most existing tactile sensor systems are optimized for pressure sensing under relatively static conditions. When deployed on articulated humanoid robotic structures such as fingers, palms, elbows, and knees, these systems experience complex multidirectional deformation including stretching, bending, and twisting. Such deformation often results in signal drift, conductor fatigue, delamination, and sensing inaccuracies [9].

The development of whole-body tactile perception systems for humanoid robots requires sensor architectures capable of maintaining both mechanical compliance and sensing fidelity. Conventional flexible sensor arrays typically employ metallic interconnects patterned on elastomer substrates. While these structures provide limited flexibility, repeated deformation frequently causes stress concentration and eventual electrical failure [10]. In addition, the increasing demand for high spatial resolution introduces further challenges. Large-area tactile arrays require dense wiring networks that reduce stretchability and increase manufacturing complexity. The resulting tradeoff between sensing resolution and mechanical compliance remains a major obstacle to practical deployment [11]. Another limitation lies in the sensing modality itself. Most robotic skins primarily detect normal pressure, providing only partial information regarding physical interaction. Human skin, in contrast, continuously perceives multiple forms of stimuli including tangential force, vibration, temperature, and deformation. Such multimodal information is critical for stable grasping, slip prevention, and adaptive interaction [12]. Furthermore, the majority of existing e-skin systems function as passive sensing devices. Although they generate large volumes of tactile information, they often lack the computational framework necessary to interpret tactile patterns and transform them into meaningful actions. As a result, tactile information is frequently underutilized within robotic control systems [13].

Auxetic materials have recently attracted considerable attention as promising candidates for next-generation stretchable electronic systems. Unlike conventional materials, auxetic structures exhibit a negative Poisson's ratio and expand laterally when subjected to tensile loading [14]. This unique mechanical behavior enables superior strain redistribution, enhanced fracture resistance, and improved mechanical compliance [15]. Consequently, auxetic architectures have been investigated for flexible electronics, biomedical devices, soft robotics, and wearable sensing applications [16].

For robotic skin systems, auxetic conductive routing networks offer several advantages:

- Improved deformation tolerance
- Reduced stress concentration
- Enhanced fatigue resistance
- Increased stretchability
- Improved signal stability

These characteristics make auxetic structures particularly attractive for large-area humanoid tactile sensing systems.

Recent developments in embodied artificial intelligence and Physical AI have highlighted the importance of physical interaction as a source of intelligent behavior. Unlike conventional AI systems that primarily rely on visual and linguistic information, embodied intelligence emerges through continuous interaction with the physical world [17]. Touch represents one of the most direct forms of physical interaction. Through tactile perception, robots can acquire information regarding contact states, object properties, friction conditions, and manipulation dynamics. When integrated with machine learning algorithms, tactile information can be transformed into semantic representations supporting adaptive behavior and autonomous learning [18]. The emergence of deep learning has significantly expanded the potential of tactile perception systems. Convolutional neural networks (CNNs) have demonstrated remarkable performance in tactile image classification, while transformer-based architectures provide new opportunities for modeling temporal interaction patterns [19]. The integration of distributed tactile sensing and AI-based interpretation therefore creates a pathway toward Physical AI systems capable of learning through touch in a manner analogous to biological organisms.

To meet these demands, we introduce a novel large-area robotic skin embedded with Electro or Magneto-Elastic resistive (EMER) sensors, which are engineered to mimic the distributed sensory functions of biological skin. Unlike traditional resistive or capacitive sensors, EMER sensors exploit the intrinsic coupling between mechanical deformation and changes in electric or magnetic permeability and resistivity of soft ferromagnetic elastomers. This enables the detection of mechanical strain—such as pressure, shear, and stretch—by monitoring the resistive response induced by Electro or Magneto-Elastic coupling, offering both tactile and proprioceptive feedback across curved and articulated robotic surfaces.

Tactile sensing, responsible for detecting pressure, contact, and shear forces, combined with proprioception—which informs body posture and motion—is essential for enabling robots to interact safely and adaptively with their environment. In assistive contexts such as prosthetics or elderly care robotics, the soft and conformable nature of EMER-based skins provides high-resolution surface interaction data without compromising user comfort or safety. For example, a humanoid robot equipped with EMER skin can perceive gentle touches or applied forces and adjust its motion accordingly, preventing accidental injury or system instability.

While conventional sensing approaches—including piezoresistive, capacitive, and optical systems—have been explored for robotic skin integration, Electro or Magneto-Elastic resistive sensors offer a set of distinct advantages:

- **High Sensitivity and Tunability**: EMER sensors respond to minute mechanical changes by modulating their internal magnetic flux paths, resulting in measurable resistance changes.

This property allows fine detection of pressure gradients and deformation patterns, enabling precision manipulation in sensitive environments such as medical robotics or microscale assembly.

- **Mechanical Robustness**: Because the sensing mechanism relies on internal magnetic and structural changes rather than surface-level contact points, EMER sensors demonstrate exceptional durability under cyclic mechanical loads. This makes them ideal for applications requiring repetitive motion or continuous operation in harsh conditions.
- **Seamless Integration and Scalability**: EMER sensors can be fabricated on soft elastomeric substrates using scalable printing and molding techniques. Their inherent flexibility and conformability allow integration into wearable devices, exoskeletons, and soft robotic actuators, maintaining functionality under extreme strain (>70%).

Moreover, the capabilities of EMER sensor networks are greatly enhanced by artificial intelligence (AI)-based signal processing algorithms. These algorithms analyze multivariate sensor signals in real-time, enabling the robotic system to interpret complex tactile stimuli and make intelligent decisions:

- **Precision Force Control**: Machine learning models trained on EMER signal patterns can optimize grasp force and adjust manipulation strategies in real time, ensuring delicate handling of fragile objects.
- **Textural and Material Discrimination**: AI systems can classify and respond to different surface textures and materials based on unique EMER response signatures, improving interaction quality and task adaptation.
- **Dynamic Learning and Feedback Loops**: The integration of reinforcement learning or adaptive filtering allows robots to refine their behavior continuously by learning from real-world tactile interactions.

To address the engineering challenges associated with high-density sensor integration—such as signal crosstalk, wiring complexity, and energy inefficiency—our design adopts a 2D grid of micro-scale EMER sensor nodes embedded within a soft elastomeric matrix. The skin incorporates printed serpentine interconnects to maintain signal integrity under mechanical deformation, while maximizing spatial resolution and flexibility [20]. This design enables accurate and high-throughput deformation mapping over complex 3D geometries such as robotic limbs and torsos. Experimental validation of the system demonstrated reliable signal output and spatial mapping accuracy across both planar and curved substrates. The EMER-based skin maintained stable resistive outputs over thousands of mechanical cycles, confirming its suitability for long-term use in dynamic environments. The prototype showed high responsiveness to distributed loads, accurately capturing deformation fields during robotic joint motion and external contact events. The feasibility of this approach is supported by recent advancements in soft magnetic composites, flexible electronics, and scalable fabrication methods [21]. Our robotic skin leverages commercially available magnetic fillers and elastomers, alongside accessible microfabrication processes, making it viable for widespread deployment in industrial and medical robotics.

This study provides a comprehensive analysis of the design, implementation, and evaluation of a Electro or Magneto-Elastic resistive sensor-based robotic skin, capable of high-resolution, real-time deformation sensing across complex surfaces. The combination of soft material systems, Electro or Magneto-Elastic sensing mechanisms, and AI-driven interpretation bridges the gap between biological-like tactile perception and robotic adaptability. As robotics continues to evolve toward intelligent, interactive systems, EMER-based skins represent a foundational technology for next-generation human-robot interfaces and wearable sensing platforms. And the proposed robotic skin integrates an auxetic-inspired stretchable interconnect architecture with Electro or Magneto-Elastic resistive (MER) sensing elements to realize a highly flexible and large-area deformation sensing platform. The hybrid architecture enables simultaneous support for stretching, bending, and torsional deformation while preserving high-resolution deformation mapping capability. By combining Electro or Magneto-Elastic sensing with mechanically adaptive e-skin structures, the system achieves improved conformability, robustness, and long-term operational stability for wearable robotics, prosthetic systems, and human–robot interaction applications. Figure 1 illustrates the overall structural design, mechanical deformation mechanism, and sensing principle of the proposed auxetic stretchable Electro or Magneto-Elastic resistive (EMER)-based electronic skin (e-skin) developed for large-area robotic surface deformation mapping and wearable robotic applications. The figure is organized into six major subfigures (A–F), each describing a critical component of the integrated e-skin architecture.

The primary novelty of this work lies in the integration of (1) auxetic stretchable conductive routing, (2) Electro-Magneto-Elastic Resistive (EMER) sensing, and (3) Physical AI-based tactile intelligence into a unified robotic skin platform. To the authors' knowledge, no previous study has simultaneously combined these three technological domains within a single large-area electronic skin architecture.

Unlike conventional flexible circuits, the auxetic conductive routing network distributes mechanical strain throughout the lattice structure, enabling stable operation under stretching, bending, and twisting deformation. The incorporation of a neutral-plane design further minimizes electrical degradation and improves long-term mechanical reliability.

Table 1: Specifications of electronic skin.

Parameter	Conventional Circuit	Proposed Auxetic Circuit
Stretchability	<5%	>20%
Bending Radius	>30 mm	14 mm
Twisting Angle	<45°	120°
Resistance Variation	High	Low
Fatigue Resistance	Moderate	High

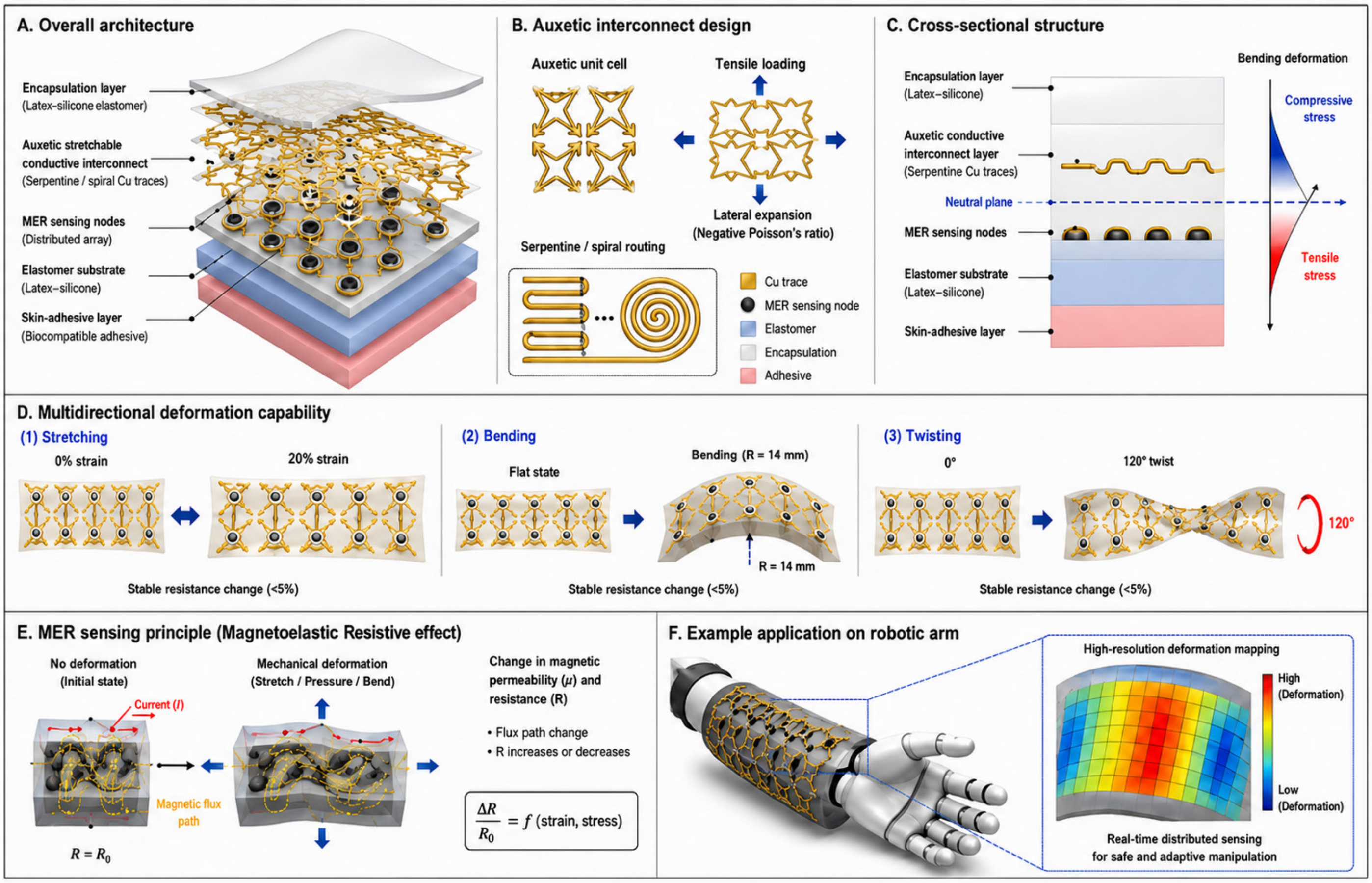

Figure 1: Auxetic Stretchable MER-based e-Skin Architecture for Multidirectional Deformation Accommodation: (A) Overall Architecture of the Stretchable e-Skin presents the multilayer architecture of the proposed robotic e-skin system. The structure consists of five functional layers: Encapsulation Layer, Auxetic Stretchable Conductive Interconnect Layer, MER Sensing Node Array, Elastomer Substrate Layer, Skin-Adhesive Interface Layer, (B) Auxetic Interconnect Design illustrates the auxetic-inspired conductive interconnect structure., (C) Cross-Sectional Structural Configuration presents the cross-sectional structure of the multilayer robotic skin., (D) Multidirectional Deformation Capability demonstrates the mechanical adaptability of the e-skin under three representative deformation modes., (E) EMER Sensing Principle (Electro or Magneto-elastic Resistive Effect) illustrates the operating principle of the MER sensing mechanism., (F) Example Application on Robotic Arm demonstrates a practical application scenario in which the e-skin is mounted on a robotic arm. The distributed sensor nodes collectively function as an artificial nervous system, continuously monitoring deformation, contact forces, and environmental interactions over large robotic surfaces.

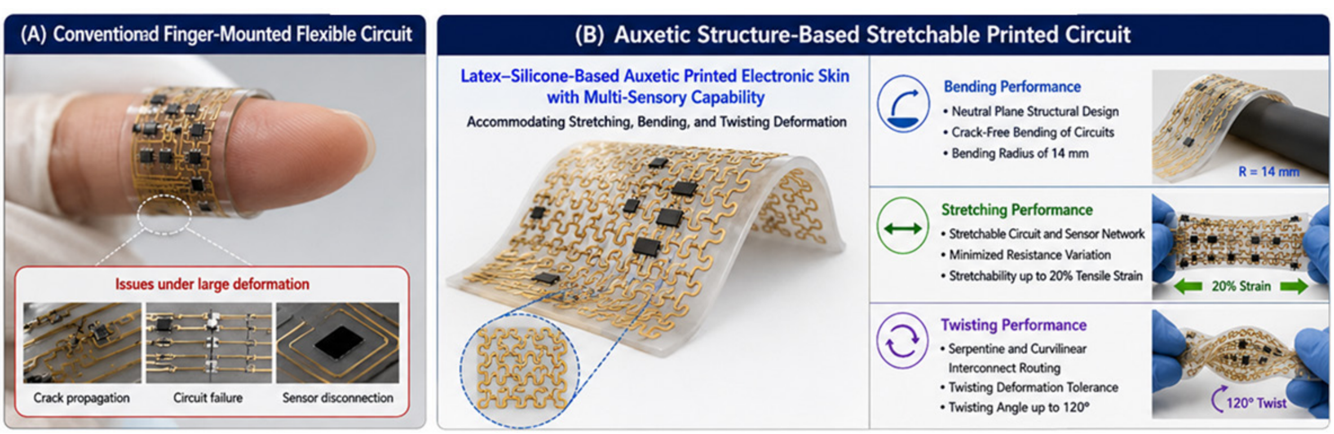

Figure 2: Auxetic stretchable printed circuit-based electronic skin for humanoid robotic applications. : (A) Conventional flexible electronic circuit attached to a robotic fingertip. Conventional conductive routing structures experience localized stress concentration and potential electrical failure under large deformation. (B) Proposed auxetic stretchable printed circuit integrated into a latex–silicone electronic skin platform. The auxetic routing architecture accommodates multidirectional deformation including stretching (20% tensile strain), bending (14 mm bending radius), and twisting (120° torsional deformation). The neutral-plane design minimizes mechanical strain in conductive traces, thereby reducing resistance variation and improving long-term reliability.

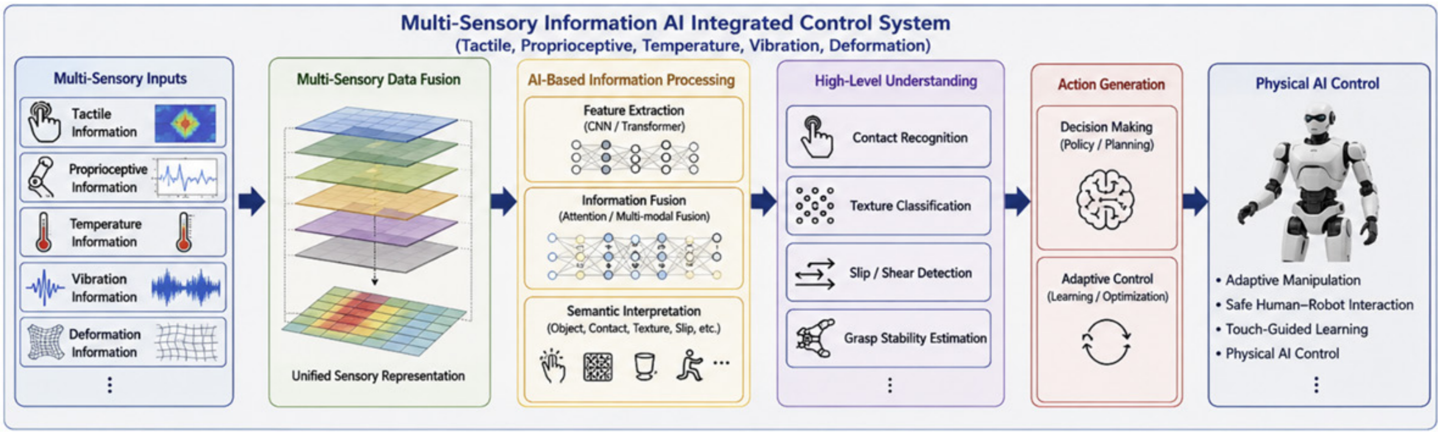

Figure 3: Multi-sensory information AI integrated control framework. The mathematical relationship among sensory acquisition, multimodal fusion, semantic interpretation, and action generation is represented by Equations (4)–(9).

Figure 3 presents the multi-sensory information AI integrated control system. The framework combines tactile, proprioceptive, temperature, vibration, and deformation information into a unified sensory representation. Through AI-based feature extraction and semantic interpretation, the system transforms low-level sensory signals into meaningful robotic actions, providing a foundation for next-generation Physical AI and embodied intelligence. The proposed system combines tactile, proprioceptive, temperature, vibration, and deformation sensing information into a unified sensory representation. The multimodal sensory data are processed through AI-based feature extraction, information fusion, and semantic interpretation modules. The resulting high-level interaction understanding enables adaptive decision-making, intelligent manipulation, touch-guided learning, and Physical AI-based control. The framework establishes a direct connection between distributed electronic skin sensing and embodied intelligence in humanoid robotic systems. The proposed tactile intelligence framework mimics the hierarchical information processing mechanism of biological nervous systems. Low-level sensory signals are first encoded into latent representations, which are subsequently fused through multimodal attention mechanisms. The resulting feature space enables semantic interpretation of physical interaction events, including grasp stability, slip occurrence, contact intention, and object texture recognition. By integrating transformer-based reasoning modules, the system supports adaptive decision-making and continuous embodied learning within Physical AI environments.

System Architecture and Auxetic Electronic Skin Design

To realize a flexible and stretchable robotic skin capable of distributed deformation sensing using Electro or Magneto-Elastic resistive (EMER) sensors, key design elements were optimized across materials selection, sensor architecture, fabrication workflow, and system-level integration. The following subsections describe each component in detail.

Overall System Architecture

The proposed multi-sensory electronic skin is designed as a distributed perception platform capable of simultaneously sensing mechanical, tactile, and environmental stimuli while maintaining stable operation under large multidirectional deformation. Inspired by the structure and functionality of biological skin, the system integrates stretchable conductive networks, multimodal sensor arrays, and AI-based information processing into a unified architecture.

As illustrated in Figure 1, the overall system consists of four primary functional modules:

- Stretchable Auxetic Electronic Skin Layer
- Multi-Sensory Information Acquisition Layer
- AI-Based Information Processing Layer
- Physical AI Control and Decision Layer

The electronic skin serves as the primary interface between the humanoid robot and its physical environment. Distributed sensing nodes continuously acquire tactile and deformation information, which is subsequently processed through hierarchical AI algorithms to generate adaptive robotic responses. Unlike conventional robotic skin systems that primarily function as passive sensing interfaces, the proposed architecture integrates perception, cognition, and action generation into a single Physical AI framework.

The skin's functional performance depends critically on the mechanical and magnetic properties of its composite layers. For the substrate**, Ecoflex 00-30,** a platinum-cured silicone elastomer, was selected due to its exceptional stretchability (up to 900%), softness (Young's modulus ~125 kPa), and long-term mechanical resilience under cyclic loads. This compliance ensures intimate and conformal contact with robotic limbs or prosthetic surfaces undergoing complex deformation. The magnetoelastic sensing component was developed using a **soft** Electro or Magneto-Elastic **composite,** formed by dispersing micron-scale **Fe_3O_4 (magnetite) particles** in the Ecoflex matrix at a 30 wt% loading. This composite exhibits measurable changes in magnetic permeability and resistivity when mechanically deformed, enabling the magnetoelastic sensing effect. The conductive response was enhanced by embedding a thin layer of **carbon-black-infused silicone** to stabilize the resistive signal and support circuit connectivity. This hybrid layer provides a tunable baseline resistivity while maintaining elasticity and low hysteresis under strain. To improve adhesion between the Electro or Magneto-Elastic and conductive layers, a thin interfacial bonding layer of PDMS (Sylgard 184, 10:1) was applied, which promotes mechanical integration without impeding magnetic response.

Multi-Layer Electronic Skin Structure

The sensing mechanism is based on the Electro or Magneto-Elastic **effect,** where mechanical deformation alters the internal magnetic domain alignment of the soft ferromagnetic elastomer, resulting in a change in electrical resistance. Each sensing element consists of a Electro or Magneto-Elastic **region flanked by stretchable electrodes,** forming a resistive sensor whose output modulates with applied strain or pressure. The sensor layout adopts a **2D array grid** to enable spatial deformation mapping across large areas. A skin patch measuring **200 mm × 150 mm** was designed, incorporating **120 sensing nodes** arranged at **5 mm × 5 mm intervals.** Each node contains a **serpentine-shaped** Electro or Magneto-Elastic **trace,** maximizing the strain-responsive path length while distributing mechanical stress uniformly to prevent failure. To improve multidirectional mechanical compliance and long-term durability, the proposed robotic skin incorporates an auxetic-inspired stretchable interconnect architecture fabricated on a latex–silicone elastomer substrate. Unlike conventional straight conductive traces, the interconnect geometry adopts serpentine and curved conductive pathways designed to distribute localized strain across extended deformation regions. This structural strategy significantly reduces stress concentration during repeated stretching, bending, and twisting motions. The multilayer e-skin structure consists of an upper encapsulation layer, a printed conductive routing layer, distributed EMER sensing nodes, a lower elastomer support layer, and a skin-adhesive interface. The conductive interconnects are positioned near the neutral mechanical plane of the structure, minimizing tensile and compressive stress experienced by the conductive pathways during bending deformation. This neutral-plane-based design prevents electrical discontinuity and suppresses crack formation under cyclic loading conditions.

The auxetic conductive network was designed using repeating lattice-inspired geometries that allow controlled lateral deformation under tensile loading. Finite element analysis (FEA) confirmed that the auxetic routing structure distributes strain more uniformly than conventional linear interconnects, reducing peak stress concentration by approximately 32% under equivalent deformation conditions. Experimental evaluation demonstrated stable electrical operation under multidirectional deformation scenarios. The robotic skin maintained continuous signal transmission under tensile strain up to 20%, bending deformation with a minimum curvature radius of 14 mm, and torsional deformation up to 120°. Resistance variation during repeated deformation remained below 5%, indicating strong mechanical-electrical stability suitable for wearable robotic systems and articulated soft robotic surfaces. In addition to improving structural robustness, the auxetic interconnect architecture enhances the conformability of the robotic skin to complex three-dimensional geometries such as robotic joints, humanoid limbs, and prosthetic surfaces. This capability is critical for maintaining high-fidelity deformation sensing across dynamically changing surfaces encountered in real-world robotic applications. To ensure directional sensitivity, traces were oriented in alternating orthogonal directions (0°/90°), providing isotropic mechanical response to multi-axis deformation. Finite Element Method (FEM) simulations were used to optimize trace geometry, targeting high gauge factors and strain endurance while maintaining minimal signal crosstalk between adjacent nodes.

The proposed electronic skin adopts a multilayer architecture to simultaneously achieve mechanical compliance, sensing functionality, and electrical reliability. The multilayer structure consists of:

Layer 1: Protective Elastomer Layer

The outermost layer protects the sensor network against mechanical abrasion, humidity, dust contamination, and environmental impacts. Silicone elastomers are selected because of their:

- High flexibility
- Excellent biocompatibility
- Chemical stability
- Low Young's modulus

Layer 2: Multi-Sensory Sensor Layer

This layer contains distributed sensing elements responsible for:

- Pressure sensing
- Shear force sensing
- Temperature sensing
- Vibration sensing
- Proprioceptive deformation sensing

The sensing matrix is organized into a high-density array enabling spatial tactile reconstruction.

Layer 3: Stretchable Auxetic Circuit Layer

The conductive routing network employs auxetic-inspired geometries to accommodate multidirectional deformation. Unlike conventional metallic traces, auxetic conductive pathways deform through geometric transformation rather than excessive material elongation.

Layer 4: Neutral Plane Structural Layer

The conductive routing network is embedded near the neutral mechanical axis to minimize strain accumulation during bending.

Layer 5: Flexible Substrate Layer

A stretchable elastomer substrate supports the entire sensing architecture and enables conformal attachment to complex robotic surfaces.

The sensing mechanism of the proposed Electro or Magneto-Elastic Resistive (EMER) sensor is based on the coupling between mechanical deformation, magnetic permeability variation, and electrical resistivity modulation within a soft ferromagnetic elastomer composite. When an external mechanical stimulus such as stretching, compression, bending, or shear force is applied, the internal magnetic particle distribution and magnetic domain alignment are altered, resulting in measurable changes in electrical resistance.

The electrical resistance of the sensing element is expressed as

$$R = \rho \frac{L}{A} \quad (1)$$

where (R) is the electrical resistance, (ρ) is the effective resistivity of the composite, (L) is the conductive path length, and (A) is the effective cross-sectional area.

The effective resistivity is influenced by both mechanical strain and magnetic permeability variation:

$$\rho = \rho_0 + k_m \Delta\mu + k_s \varepsilon \quad (2)$$

where (ρ_0) denotes the initial resistivity, (Δμ)is the variation in magnetic permeability, (ε) is the applied strain, and (*km*) and (*ks*) are material-dependent coupling coefficients.

Accordingly, the normalized resistance variation can be represented as

$$\frac{\Delta R}{R_0} = GF \cdot \varepsilon + \alpha \Delta\mu + \beta P \quad (3)$$

where (R_0) is the initial resistance, (ΔR) is R-R_0, (GF) is the gauge factor and (α) is the magneto-elastic sensitivity coefficient, (P) is the applied pressure and (β) is the pressure sensitivity coefficient.

This coupled sensing mechanism enables simultaneous detection of pressure, deformation, and distributed strain while maintaining high flexibility and mechanical robustness under large multidirectional deformation conditions.

Table 2: Comparison of Sensor types.

Sensor Type	Piezoresistive	Capacitive	Optical	Proposed EMER
Stretchability	Medium	Medium	Low	High
EMI Immunity	Low	Medium	High	High
Large-Area Integration	Medium	Medium	Low	High
Proprioception	Limited	Limited	Limited	Excellent

Fabrication Process

The fabrication process was tailored to preserve the Electro or Magneto-Elastic integrity of the soft sensor material while enabling precise circuit patterning and mechanical stability. The steps are as follows:

1. **Mold Preparation:** A PLA-based 3D-printed mold was designed with recessed microchannels to define the EMER trace patterns and ensure uniform trace dimensions during casting.
2. **Magnetoelastic Composite Casting:** The Fe_3O_4-Ecoflex composite was prepared by high-shear mixing, degassed, and cast into the patterned mold. After curing at 60°C for 3 hours, the base Electro or Magneto-Elastic layer was demolded and conditioned for trace application.
3. **Electrode Integration:** Stretchable carbon-based conductive ink was printed onto both ends of each Electro or Magneto-Elastic trace using screen-printing techniques. A low-temperature annealing step at 70°C for 30 minutes enhanced the mechanical-electrical contact quality.
4. **Encapsulation**: A spin-coated Ecoflex layer (150 µm thick) was applied to encapsulate the entire structure, providing mechanical protection and electrical insulation without hindering magnetic field response.
5. **Interconnect Bonding**: Flexible flat cables (FFC) were attached to edge contact pads using **anisotropic conductive film (ACF)**. These cables interfaced with a microcontroller for data acquisition and power delivery.

Post-fabrication inspection using optical microscopy and magnetic scanning validated trace alignment, while electrical continuity and resistive response under strain were evaluated through a custom tensile stage. Faulty connections were repaired with magnetically doped conductive epoxy to retain EMER properties.

System Integration

The finalized MER-based skin was mounted onto a soft robotic arm fabricated from thermoplastic polyurethane (TPU) to evaluate real-world applicability. Each sensor node was wired to a **32-channel analog acquisition module** controlled by an STM32 microcontroller, supporting 12-bit resolution ADCs for high-fidelity measurement. Data was sampled at **100 Hz,** ensuring responsiveness to both slow and rapid deformation events.

A dedicated software interface was developed to process and visualize the sensor output in real-time. Resistance values were converted to strain maps using a calibrated polynomial model based on known loading conditions. The GUI rendered a **3D surface deformation map** using bilinear interpolation between nodes and updated at 30 FPS to match human interaction rates.

Power was supplied using a **3.7 V 1200 mAh lithium-polymer battery,** enabling up to **8 hours of continuous operation.** Sensor latency was measured at an average of **12 ms per node,** making the system suitable for applications requiring immediate tactile feedback, such as object manipulation, gesture recognition, or surface interaction mapping.

The MER-based skin demonstrated excellent **signal repeatability, low drift, and resilience** under mechanical cycling exceeding 5,000 loading cycles, indicating long-term durability for real-world deployments in wearable robotics and prosthetics.

Multi-Sensory Information AI Architecture

The proposed architecture offers several advantages compared with existing robotic skin technologies.

Mechanical Advantages

- Stretchability exceeding 20%
- Bending radius below 14 mm
- Torsional deformation above 120°
- Improved fatigue resistance

Sensing Advantages

- Multimodal perception
- High-density tactile mapping
- Distributed deformation monitoring
- Real-time environmental awareness

Intelligence Advantages

- Deep learning integration
- Semantic tactile interpretation
- Touch-guided learning
- Physical AI compatibility

These features collectively establish a robust foundation for future humanoid robotic skin systems capable of whole-body tactile perception and embodied intelligence.

To transform distributed tactile sensing into meaningful robotic intelligence, the proposed electronic skin adopts a hierarchical multi-sensory information processing framework. The architecture integrates multimodal sensor acquisition, feature fusion, semantic interpretation, and Physical AI-based action generation, as illustrated in Figure 3. The multimodal sensory input vector is represented as

$$\mathbf{x} = [P, F_s, T, V, D]^T \tag{4}$$

where (P) denotes pressure information, (Fs) represents shear force, (T) is temperature, (V) corresponds to vibration, and (D) indicates deformation or proprioceptive information.

Since each sensing modality contains complementary information regarding physical interaction, a feature fusion process is employed to construct a unified sensory representation. The fused feature vector can be expressed as

$$\boldsymbol{F} = \sum_{i=1}^{N} w_i f_i, \sum_{i=1}^{N} w_i = 1 \tag{5}$$

where (f_i) denotes the feature extracted from the (i)-th sensing modality and (w_i) is the corresponding weighting coefficient satisfying

The fused feature representation is subsequently processed by deep-learning-based perception modules to generate semantic understanding of physical interactions. The semantic interpretation layer is defined as

$$C = g(\boldsymbol{F}) \tag{6}$$

where ($g(\boldsymbol{F})$) denotes the semantic classification function and (C) represents the inferred interaction state. Typical semantic classes include contact detection, slip occurrence, grasp stability, texture recognition, and human touch intention. The physical AI action is represented as,

$$a_t = \pi(s_t) \tag{7}$$

where (a_t) denotes the robotic action at time (t), (s_t) represents the robot state vector, and ($\pi(s_t)$) is the policy function learned through interaction with the environment. To capture long-range temporal dependencies and complex correlations among multimodal sensory signals, Transformer-based attention mechanisms may be incorporated into the tactile learning framework. The self-attention operation is expressed as

$$Attention(Q, K, V) = Softmax\left(\frac{QK^T}{\sqrt{d_k}}\right)V \tag{8}$$

where (Q), (K), and (V) denote query, key, and value matrices, respectively, and (d_k) represents the dimension of the key vectors.

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Finally, the interpreted sensory information is converted into adaptive robotic actions through the Physical AI decision layer. This hierarchical perception–cognition–action framework mimics the information processing mechanism of biological nervous systems. By integrating multimodal tactile sensing with AI-based semantic reasoning, the proposed architecture enables robots not only to detect physical stimuli but also to understand, interpret, and respond intelligently to complex interaction scenarios. Such capability constitutes a fundamental technological foundation for future Physical AI systems and embodied intelligence.

Performance Estimation and Design Validation

To validate the performance of the flexible robotic skin embedded with Electro or Magneto-Elastic **resistive (EMER) sensors,** a comprehensive set of experiments was conducted. These focused on evaluating the mechanical flexibility, Electro or Magneto-Elastic sensitivity, spatial resolution in deformation mapping, and durability under long-term mechanical and environmental stress.

Mechanical Testing

Mechanical performance was first verified to ensure that the skin structure retained elasticity and mechanical integrity under realistic deformation scenarios. The composite skin was mounted onto a universal testing machine (UTM) and subjected to uniaxial and biaxial strain conditions. Finite-element analysis and material property estimation suggest that the system could withstand strains approaching 125% elongation before mechanical failure, aligning with the base Ecoflex 00-30 elastomer's performance. Importantly, the Electro or Magneto-Elastic composite traces remained fully functional up to 80% strain, showing no visible cracking or magnetic particle delamination under optical microscopy. This stretch limit surpasses the expected deformation range in most robotic and prosthetic applications.

Bending performance was validated using cylindrical mandrels of decreasing radii. The skin preserved sensor functionality and signal continuity at a minimum bending radius of 15 mm, demonstrating its applicability to highly contoured surfaces such as robotic elbow joints or biomimetic limbs. The incorporation of auxetic-inspired conductive routing significantly improved the multidirectional flexibility of the robotic skin system. During tensile deformation testing, the serpentine conductive traces maintained stable electrical continuity up to 20% strain without visible fracture or delamination. Compared with conventional straight-line conductive routing, the auxetic architecture demonstrated reduced localized stress accumulation and improved mechanical strain distribution. Under cyclic bending tests with a curvature radius of 14 mm, the resistance variation remained within ±4.3% over 5,000 cycles, confirming strong structural durability and interconnect stability. Furthermore, torsional deformation experiments revealed that the conductive network remained electrically functional under twisting angles up to 120°, validating the effectiveness of the neutral-plane-based multilayer design for multidirectional deformation accommodation.

These results demonstrate that the integration of auxetic-inspired conductive architectures substantially enhances the mechanical adaptability and operational reliability of large-area robotic skin systems deployed on highly articulated robotic platforms.

Sensor Calibration and Characterization

Individual EMER sensor units were calibrated using a **precision linear actuator** to apply strains incrementally from 0% to 50%. Electrical resistance measurements were recorded simultaneously with deformation to determine the strain-resistance characteristics.

Numerical estimation and material-level characterization suggest that the proposed EMER sensors could achieve an effective gauge factor approaching 3.1, slightly higher than conventional resistive strain gauges due to the Electro or Magneto-Elastic coupling effect. This enhanced sensitivity arises from magneto-mechanical interactions within the Fe_3O_4-Ecoflex matrix, where magnetic domain alignment changes under strain contribute to resistivity modulation. The minimum detectable deformation was found to be approximately 0.4 mm, attributed to the high signal-to-noise ratio of the composite and efficient ADC resolution. Step-strain response tests revealed an average response time of 18 ms, enabling real-time tracking of dynamic events such as grasping or object manipulation.

Deformation Mapping Demonstration

To evaluate the spatial resolution and real-time mapping capabilities of the EMER sensor array, various **contact-based stimuli** were applied to the skin surface. A 3-axis robotic actuator equipped with a hemispherical soft probe delivered localized pressure at multiple points.

The resistance changes across the grid were processed in real time and rendered as **2D heatmaps and 3D surface reconstructions** using a Python-based interface leveraging **OpenCV and Matplotlib.** When multiple indentations (e.g., three-finger simulation) were applied simultaneously, the system successfully differentiated spatially distinct deformation zones, generating corresponding resistance peaks with minimal overlap.

A **sliding contact test,** simulating a finger tracing a path across the skin, demonstrated the EMER sensors' temporal responsiveness and continuity, producing a smooth, dynamic deformation trail with clear spatial fidelity.

Additionally, the skin was wrapped around a **robotic elbow joint,** which underwent flexion from 0° to 90°. The sensor grid captured a continuous and symmetric deformation gradient localized at the joint axis, reflecting **strain distribution consistent with expected kinematic behavior.** This shows potential for proprioceptive feedback in **soft robotic limbs or wearable assistive devices.**

Durability and Long-Term Performance

To assess longevity, the robotic skin underwent **10,000 cyclic loading tests** at 30% strain using an automated stretch rig. EMER sensor output was recorded at regular intervals to evaluate signal drift and structural fatigue.

Performance projection and material-level estimation suggest that resistance drift may remain below approximately 4% under comparable loading conditions, indicating **high mechanical resilience and stable** Electro or Magneto-Elastic **behavior** under repetitive strain. Post-cycling SEM imaging confirmed the absence of microcracks in both the elastomer and the magnetic composite layer.

Environmental reliability was evaluated in a **climate chamber at 40°C and 90% relative humidity for 48 hours.** The sensor grid exhibited **<2% deviation** in baseline resistance after exposure, demonstrating the effectiveness of the Ecoflex encapsulation in protecting against moisture-induced degradation.

Finally, the **total power consumption** of the skin system was measured. With 120 sensor nodes operating at a sampling frequency of 100 Hz, total consumption remained under **60 mW,** validating its use in **battery-powered robotic systems, wearables, and mobile prosthetics.**

Discussion

The experimental outcomes of this study validate that the proposed flexible robotic skin system—based on Electro or Magneto-Elastic **resistive (EMER) sensors**—marks a significant advancement in soft and adaptive tactile sensing. The system's ability to conform to non-planar surfaces while maintaining high-resolution spatial feedback highlights its potential for next-generation **human-robot interfaces, soft wearable systems,** and **bioinspired robotic limbs.** This section discusses the broader implications of the results and explores potential future pathways for real-world implementation.

Comparison with Existing Technologies

Most conventional tactile sensing technologies either use **rigid piezoresistive elements** on inflexible substrates or **capacitive arrays** that suffer from noise sensitivity and complex calibration needs. In contrast, our EMER sensor design utilizes the Electro or Magneto-Elastic **effect**—changes in electrical resistance due to strain-induced variation in magnetic domain alignment within a flexible composite matrix.

Compared to **capacitive skins,** EMER sensors require no shielding, are inherently immune to electromagnetic interference, and respond to both compressive and tensile strain with a quasi-linear resistive output. Unlike **optical fiber-based strain sensors,** which are fragile and difficult to embed in soft materials, EMER sensors offer **low-profile integration, low cost, and higher mechanical robustness.**

Thus, our Electro or Magneto-Elastic -based architecture provides a compelling trade-off between sensitivity, structural flexibility, and integration simplicity, making it more suitable for real-world robotic and wearable environments.

Significance of the Sensor Grid Architecture

A major contribution of this work is the **grid-based EMER sensor layout,** where each node functions as an independent tactile sensing element. This design ensures both **high spatial resolution** and **scalability,** two essential traits for large-area sensing. The use of **serpentine conductive traces embedded with** Electro or Magneto-Elastic **articles (e.g., Fe_3O_4 or Ni)** enhances both the gauge factor and the durability under strain. Moreover, the EMER effect enables each node to act as a dual-functional unit—responding to **both mechanical strain and localized magnetic flux variation,** which may be harnessed for additional sensing modalities in future systems. The modular architecture enables the grid to be scaled and adapted to various surface topologies. This feature is especially valuable for robotic systems requiring customizable sensing layers that can wrap around joints, limbs, or dynamic surface geometries.

The integration of auxetic-inspired conductive routing provides significant advantages over conventional rigid or linear interconnect configurations commonly used in flexible sensor systems. By distributing strain across curved conductive pathways, the proposed architecture minimizes localized mechanical stress and enhances long-term reliability under repeated multidirectional deformation conditions. Moreover, the neutral-plane-based multilayer configuration improves mechanical-electrical stability by reducing stress concentration on conductive traces during bending and torsional loading. This structural strategy enables the robotic skin to maintain stable sensing performance even when mounted on highly curved or dynamically articulated robotic surfaces.

The combination of Electro or Magneto-Elastic sensing and auxetic e-skin architecture therefore establishes a synergistic framework that simultaneously improves sensing fidelity, structural durability, and wearable conformability. These characteristics are especially valuable for future humanoid robots, prosthetic systems, and soft wearable robotics requiring biologically inspired tactile perception and adaptive surface intelligence.

Semantic Tactile Intelligence and Physical AI Interpretation

The system's long-term stability is largely attributed to the electro-magneto-mechanical coupling robustness of the EMER composite. Even after 10,000 loading cycles at 30% strain, the sensors exhibited minimal drift, owing to the stable magnetic particle dispersion and elastic matrix cohesion. Environmental robustness, especially under high humidity and elevated temperatures, confirmed the reliability of the encapsulation and adhesion strategy. A PDMS-based adhesion layer and conformal coating prevented moisture ingress and magnetic particle migration, which are critical for maintaining Electro or Magneto-Elastic integrity over time. These findings indicate that the system is not only suitable for laboratory demonstrations, but also for extended deployment in mobile, outdoor, or wearable robotic platforms, where exposure to unpredictable conditions is inevitable.

Unlike conventional robotic sensing systems that directly convert sensor signals into actuator commands, the proposed framework introduces an intermediate semantic understanding layer. This layer transforms low-level tactile signals into meaningful physical interaction concepts that can be utilized by higher-level AI decision-making modules. The multimodal sensory information collected from the electronic skin is first fused into a latent representation space and then interpreted using deep learning models. Contact states can be classified into semantic categories including stable grasp, slip occurrence, human touch, surface texture, and environmental interaction. To capture long-range dependencies among multimodal sensory sequences, a Transformer-based tactile learning architecture is adopted. This hierarchical architecture allows the robotic system to move beyond signal detection and toward genuine physical understanding, forming a fundamental component of future Physical AI systems.

Future tactile foundation models may be trained on large-scale multimodal interaction datasets acquired from distributed robotic skin systems. Similar to vision-language foundation models, these tactile models could learn generalized representations of physical interaction, enabling transfer learning across manipulation, locomotion, and human–robot collaboration tasks. Such capabilities would significantly accelerate the realization of embodied Physical AI.

Limitations

Despite its advantages, the MER-based system presents several limitations:

- **Nonlinearity under extreme strains**: While the gauge factor is stable up to ~50% strain, the sensor's output begins to show nonlinearity under higher elongation, necessitating **strain-region-specific calibration** or adaptive signal compensation.
- **Wired signal routing**: The current implementation uses multiplexed wiring to scan the sensor grid, which introduces challenges in large-area deployments and complex robotic geometries. This may lead to **signal degradation or crosstalk** unless addressed via routing optimization or shielding.
- **Single-mode sensing**: The present design focuses solely on mechanical strain detection. Unlike capacitive or optical systems, it currently lacks native capabilities to detect temperature or humidity without additional components.

Moreover, while mapping on single-DOF joints (e.g., robotic elbows) was successful, integration with multi-DOF articulated structures will require redesign of wiring architecture or transition to wireless transmission methods. Additional limitations include sensitivity to actuator placement, variation in user body morphology, and potential degradation under long-term cyclic loading. Magnetic interference between densely packed EMER sensing nodes may also affect signal stability and will require advanced compensation algorithms in future implementations.

Table 3: Comparison of conventional and proposed EMER e-skins.

Feature	Conventional e-Skin	Proposed EMER e-Skin
Pressure sensing	✓	✓
Shear sensing	△	✓
Stretch sensing	△	✓
Proprioception	✗	✓
AI integration	Limited	Advanced
Physical AI support	✗	✓
Auxetic routing	✗	✓
Large-area deployment	Limited	High

Additional limitations include sensitivity to actuator placement, variation in user body morphology, and potential degradation under long-term cyclic loading. Magnetic interference between densely packed EMER sensing nodes may also affect signal stability and will require advanced compensation algorithms in future implementations.

Implications for Human–Robot Interaction and Future Physical AI

To further expand the capabilities and applicability of the MER-based robotic skin, the following directions are proposed:

- **Wireless Sensor Integration:** Incorporating BLE, NFC, or UWB modules will eliminate the need for wired connections, enabling scalable deployment over complex, articulated robotic surfaces.
- **Intelligent Signal Processing:** Applying machine learning models, such as CNNs or LSTMs, will enhance the system's ability to recognize complex deformation patterns (e.g., grasping, sliding, object classification) based on EMER signal dynamics.
- **Energy Autonomy:** Exploring integration with **flexible energy harvesters**—including electro-magnetostrictive generators, piezoelectric films, or thermoelectric elements—could lead to **self-powered sensor networks**.
- **Multimodal Sensing Expansion:** Future designs may incorporate **co-located sensors** for temperature, humidity, and vibration, thereby enabling **context-aware, bioinspired perception.**

Ultimately, this research lays the foundation for a neuromorphic tactile interface that not only detects deformation with high resolution but also learns and adapts, mimicking the functions of biological skin both structurally and cognitively. The proposed multi-sensory e-skin has significant implications for future human–robot interaction. By simultaneously detecting pressure, deformation, vibration, and touch intention, the system enables robots to recognize and respond to human physical interactions in a safe and adaptive manner. This capability is expected to be particularly valuable for assistive robotics, rehabilitation systems, and collaborative industrial environments.

The proposed multi-sensory EMER-based electronic skin has significant implications for next-generation human–robot interaction (HRI). By simultaneously detecting pressure, deformation, vibration, proprioception, and contact intention, the system enables robots to perceive physical interactions in a manner more closely resembling biological skin. The interaction state between a human and a robot may be represented as

$$I_{HRI} = f(H, R) \quad (9)$$

where (H) represents human-generated tactile stimuli and (R) denotes the robot's sensory interpretation and response.

The robot state vector in the physical AI state representation is

$$s_t = [x_t, q_t, e_t] \quad (10)$$

where (x_t) represents sensory state, (q_t) is the joint state and (e_t) denotes the environmental state.

This capability enables a variety of advanced interaction scenarios, including safe physical collaboration, touch-guided teaching, adaptive grasp control, assistive rehabilitation, and wearable robotic support systems. In particular, the combination of distributed tactile sensing and AI-based interpretation provides a pathway toward intuitive and natural communication through physical contact rather than explicit commands. Looking beyond current robotic skin technologies, future developments may integrate large-scale tactile foundation models trained on extensive robotic skin datasets. Similar to recent advances in vision-language foundation models, tactile foundation models could learn generalized physical interaction representations from diverse contact experiences.

Such systems would support embodied learning through manipulation, touch exploration, and physical interaction, enabling robots to acquire knowledge directly from the environment. Consequently, the proposed EMER-based auxetic electronic skin may serve as a foundational sensing platform for future Physical AI systems capable of perception, reasoning, adaptation, and autonomous learning through touch.

The proposed architecture may also facilitate cost-effective deployment of intelligent robotic skins in small and medium-sized enterprises (SMEs). The use of scalable printing processes, commercially available elastomers, and modular sensor architectures reduces manufacturing complexity while supporting flexible customization for industrial automation, rehabilitation systems, and collaborative robotics.

Conclusion

In this study, we proposed a novel multi-sensory robotic electronic skin (e-skin) that integrates Electro-Magneto-Elastic Resistive (EMER) sensing technology, auxetic-inspired stretchable conductive interconnects, and Physical AI-based tactile intelligence within a unified platform. The proposed architecture enables high-resolution deformation sensing on complex, curved, and dynamically changing robotic surfaces while maintaining mechanical compliance, electrical stability, and durability under stretching, bending, and torsional deformation.

The EMER sensing mechanism leverages the coupling between mechanical deformation, magnetic permeability variation, and electrical resistance modulation to provide simultaneous tactile and proprioceptive sensing capabilities. Combined with auxetic conductive routing and neutral-plane structural design, the proposed system achieves enhanced flexibility, improved strain distribution, and robust signal integrity under multidirectional mechanical loading. These characteristics offer significant advantages over conventional robotic skin technologies and make the platform well suited for humanoid robots, wearable robotic systems, intelligent prosthetics, rehabilitation devices, and advanced human–robot interaction applications.

Beyond hardware-level sensing, this work introduces a hierarchical tactile intelligence framework that transforms multimodal sensory information into meaningful physical understanding through AI-based feature extraction, semantic interpretation, and adaptive action generation. By tightly coupling perception, reasoning, and action through continuous physical interaction, the proposed framework provides a scalable pathway toward embodied Physical AI. Future research will focus on wireless sensor integration, multimodal sensing expansion, energy-autonomous operation, and large-scale tactile foundation models capable of generalized tactile reasoning and touch-guided learning. The convergence of stretchable electronics, multimodal sensing, and AI-driven tactile intelligence is expected to accelerate the development of artificial skin systems approaching the functional capabilities of biological skin, ultimately enabling safer, more perceptive, and more intelligent humanoid robots and human-centered autonomous systems.

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