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A Review of Bioinspired Tactile Sensing Systems for Intelligent Robotic Interaction

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Abstract. Bioinspired tactile sensing systems, which take cues from the human somatosensory system, are vital for improving how intelligent robots perceive and interact. These technologies enable safe and efficient human–robot interaction by mimicking human touch flexibility. They are crucial for applications like collaborative automation, assistive technologies, and prosthetics that need physical human-robot interaction (pHRI). This review explores recent developments in flexible sensor materials, microstructural innovation, and transduction methods. The focus is on integrating multimodal strategies that pair tactile feedback with visual and electromyographic (EMG) signals, enhancing accuracy in intent recognition and fine manipulation. Additionally, this paper showcases real-time feedback systems and learning-based control frameworks that foster adaptive robotic behavior. It analyzes practical applications in rehabilitation robotics, highlighting the significance of tactile sensing in scenarios that prioritize safety and user needs. Despite substantial advancements, challenges remain, particularly regarding integration complexity, demands on signal processing, and energy efficiency. Future research directions highlight neuromorphic computing, self-supervised learning, and scalable sensor manufacturing. This study reveals that bioinspired tactile systems signify a revolutionary interface between robots and humans, presenting exciting opportunities for more natural, responsive, and intelligent interactions.

Keywords: Bioinspired tactile sensing, intelligent robotics, flexible sensors, multimodal fusion, human-robot interaction

1. Introduction

Tactile perception is fundamental to human sensory experience, enabling precise motor control, safe physical interaction, and adaptive decision-making in dynamic environments. Inspired by the complex structure and functionality of human skin and mechanoreceptors, artificial tactile sensing systems have emerged as crucial components in robotics [1]. These systems allow robots not only to detect pressure and texture but also to interpret physical contact with humans and objects, forming the basis of physical human–robot interaction (pHRI). Unlike vision or auditory sensing, tactile feedback provides direct, localized, real-time information essential for tasks requiring dexterity, safety, and contextual awareness. Advances in soft electronics and nanomaterials have enabled

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flexible e-skins that mimic human skin's properties. These innovations have expanded the potential of robots in fields such as prosthetics, rehabilitation, and collaborative service robotics [2-3].

This review explores recent advancements in bioinspired tactile sensing technologies, emphasizing their applications in intelligent robotic systems. By analyzing progress in sensor materials, structural designs, multimodal integration, and real-time control, it highlights how tactile sensing fosters responsive, adaptive, and human-centric robotic behaviors. The review's significance lies in its integrated perspective—bridging material innovations with system-level intelligence and interaction, critical for advancing safe and intuitive human-robot collaboration.

2. Materials and structural design in tactile sensing

Bioinspired tactile sensors primarily adopt flexible polymer substrates, such as Polydimethylsiloxane (PDMS), Ecoflex, or hydrogels, combined with conductive fillers, including carbon nanotubes (CNTs), graphene, and ionic liquids. These materials mimic skin softness and conductivity with durability [4]. Microstructure patterns, such as micro pyramids, micro domes, and ridge arrays, significantly enhance sensitivity by concentrating local stress and increasing contact area [5].

Beyond single-material designs, hybrid architectures combining organic–inorganic composites have garnered attention for their superior multifunctionality. By layering ionic gels, dielectric elastomers, and thermally stable nanocomposites, researchers have developed tactile systems capable of simultaneously detecting pressure, temperature, and vibration. Wang et al., for instance, fabricated a multilayer sensor comprising ionic gel-based microsomes and gradient-stiffness elastomers, which enabled both low-frequency static force detection and high-frequency dynamic vibration sensing (up to 400 Hz) [6]. This dual-mode design enhanced the piezoelectric output while ensuring fast mechanical recovery, making it suitable for dynamic robotic interaction.

The transduction mechanism—how mechanical stimuli are converted into electrical signals—is a central design choice influencing the sensor's responsiveness, resolution, and signal fidelity. Table 1 summarizes tactile sensor types and features. Multimodal frameworks, Capacitive sensors offer high spatial resolution but are sensitive to parasitic interference and environmental noise. Piezoresistive designs, while simpler to fabricate, may experience signal drift and hysteresis. Piezoelectric sensors, such as those based on polyvinylidene fluoride (PVDF), excel in detecting dynamic forces but cannot perceive static pressure. Recent developments in optical and ionic conduction-based sensors have opened avenues for high-resolution, low-latency tactile acquisition in soft robotic platforms [7].

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Table 1: Representative tactile sensing mechanisms and their characteristics [4-7]

Sensing Type	Materials Used	Typical Sensitivity	Frequency Response	Applications
Capacitive	PDMS + CNTs	~0.1 kPa[1]	Low	Pressure mapping, e-skin
Piezoresistive	Graphene/Ecoflex	~0.05–1.2 kPa[1]	Low–mid	Prosthetics, robotic grippers
Piezoelectric	PVDF-based membranes	~1–100 mV/N or 1–10 pC/N [6]	High (~kHz)	Slip detection, impact monitoring
Optical	PDMS+ waveguide	~0.05–0.4 kPa[1]	Medium	Shape reconstruction, deformation
Ionic conduction	Gel electrolytes + microtome array	~0.03 kPa[1]	High (static + dynamic)	Soft robots, wearable devices

3. Multimodal perception and signal processing

In complex environments, tactile feedback alone is often insufficient for robust robotic perception. Modern systems integrate tactile sensing with complementary modalities such as vision, electromyography (EMG), and proprioception to overcome this. Each contributes distinct advantages: vision offers object context, EMG reflects user intent, and tactile input captures localized contact dynamics. Fusion of these signals enables robots to build more adaptive models of their surroundings.

These frameworks process individual modalities before merging via feature fusion or embeddings. Convolutional Neural Networks (CNNs) are standard for vision, while recurrent networks or 1D convolutions handle EMG and tactile time series. Transformer-based models now surpass traditional approaches in capturing long-range dependencies and aligning asynchronous inputs.

These architectures offer enhanced performance in manipulation and classification. For instance, Zhang et al. Integrated RGB vision with tactile input using attention-enhanced CNNs, improving object recognition accuracy even under occlusion by over 15% [8]. Liu et al. further developed a transformer encoder, aligning EMG spike sequences with tactile force profiles using cross-modal attention, enabling real-time grasp classification [9]. Geng et al. proposed a self-supervised method using vision-guided contrastive loss to train tactile encoders, yielding generalizable feature embeddings with minimal supervision [10].

Temporal synchronization is critical to avoid fusion accuracy loss from misaligned timestamps, necessitating calibration or dynamic time warping (DTW). End-to-end systems, which co-train perception and control modules, outperform fragmented pipelines by maintaining task coherence. Hardware modularity facilitates deployment: distributed tactile arrays, cameras, and EMG electrodes at strategic joints feed centralized processors, enabling real-time applications like grasping and exoskeleton control. Multimodal systems also enhance fault tolerance—tactile feedback provides reliable contact cues in visually degraded environments, while vision or EMG compensates for impaired tactile signals, ensuring robustness in safety-critical scenarios.

In conclusion, multimodal perception enables context-aware robotic behavior by combining vision, EMG, and tactile information. Advances in transformers, self-supervised learning, and cross-modal alignment are driving next-generation fusion architectures. Future directions include hierarchical abstraction and task-aware fusion for real-time adaptability.

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4. Feedback mechanisms and intelligent interaction

Real-time tactile feedback is essential for closed-loop robotic control, enabling systems to dynamically adjust grip strength, modulate compliance, and respond to disturbances. Compared to open-loop models, closed-loop architectures leverage continuous sensory input to refine control strategies, enhancing stability in unpredictable environments.

Veiga et al. introduced a decentralized tactile feedback controller that employs distributed slip prediction at each robotic fingertip [11]. Rather than relying on global coordination, each node independently adjusts local contact pressure based on high-frequency skin deformation signals. This approach resulted in faster grasp corrections (averaging 120 ms) and a 26% increase in task success under perturbations.

Tactile data are also critical in reinforcement learning (RL) frameworks. These models learn through trial-and-error by mapping tactile feedback to reward-based action refinement. Lin et al. demonstrated that soft robotic fingers trained using only tactile input could generalize to novel objects with over 85% success, showing the sufficiency of touch for learning nuanced manipulation [12].

Integration with model-predictive control (MPC) is gaining traction, leveraging tactile signals to dynamically update object property models (e.g., stiffness, friction) for anticipatory force modulation. In compliant hands, this enhances in-hand stability and slip resistance. Neuromorphic tactile processors—inspired by biological mechanoreceptors—address latency and power constraints by encoding pressure/vibration into sparse spike trains. Devices like Intel's Loihi chip utilize spiking neural networks (SNNs) to achieve closed-loop tactile responses with sub-5ms latency and ultra-low power consumption, enabling efficient real-time operation.

Advances in representation learning enable tactile signals to be abstracted into shared embeddings, guiding cross-task policies and enhancing multi-task generalization in dynamic environments. In human-in-the-loop systems like prosthetics or teleoperation, tactile feedback remains critical for natural interaction. Real-time contact cues transmitted via vibrotactile or haptic actuators allow users to naturally adjust actions, enhancing safety and dexterity.

In summary, the convergence of tactile sensing with learning-based control, neuromorphic encoding, and distributed architectures enhances robotic responsiveness and autonomy. These intelligent feedback systems not only replicate biological strategies but also pave the way for adaptive and energy-efficient interaction.

5. Applications and system-level functions in rehabilitation robotics

Bioinspired tactile sensing technologies have become vital components in rehabilitation robotics, enhancing safety, adaptability, and the overall human–machine experience. These sensors enable nuanced physical human–robot interaction (pHRI), particularly benefiting individuals with neuromuscular disorders or motor impairments. Table 2 outlines six application areas in rehab robotics, each addressing specific therapeutic or assistive needs through tailored sensing mechanisms and integration strategies.

Robot-assisted therapy systems employ tactile arrays—using piezoresistive or capacitive materials—to monitor contact forces and detect slippage during interactions. These sensors deliver real-time feedback, enabling safe and responsive robotic adjustments. For instance, flexible piezoresistive arrays embedded in exoskeleton joints enable precise force tracking, avoiding excessive pressure to ensure user safety and comfort.

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Smart haptic gloves integrate gesture recognition and real-time tactile feedback via soft actuators and capacitive sensors. These systems aid fine motor rehabilitation by enabling virtual grasping and manipulation tasks with localized force cues, enhancing immersion in virtual environments. Such gloves also promote sensorimotor relearning through active engagement [13].

Intelligent insoles embedded with pressure-sensitive conductive foams or piezoresistive films are critical for lower-limb rehabilitation. These systems monitor plantar pressure distribution and gait symmetry, delivering real-time data to adaptive exosuits or feedback interfaces. For instance, Lee et al. demonstrated insoles that dynamically modulate exosuit torque to improve gait in post-stroke patients, underscoring tactile sensing's potential for personalized therapy [14].

Medical exoskeletons often benefit from EMG-tactile fusion modules, which combine muscular activity signals with mechanical contact feedback to more accurately decode user intent. These multimodal systems enhance control granularity and reduce actuation latency, making them suitable for assist-as-needed therapy protocols. Tactile sensors positioned on contact pads or joint interfaces help adapt robotic responses based on detected interaction forces.

In VR/AR-based rehabilitation, tactile augmentation simulates realistic physical interactions within immersive environments. Wearable devices such as haptic gloves or skin-stretch actuators provide localized force feedback synchronized with virtual movements. Integrated with EMG-driven control systems, this sensory synergy significantly enhances motor recovery and training engagement [15]. Finally, Physiological monitoring platforms leverage stretchable ionic hydrogels with embedded wiring to sense joint angles, muscle contractions, and contact forces across the body. These sensors enable continuous health tracking and adaptive robotic assistance adjustments. When combined with machine learning algorithms, they identify fatigue or instability, improving performance and safety in home or clinical environments.

Table 2: Tactile sensing applications in rehabilitation robotics

Application Area	Functionality	Technological Feature
Robot-Assisted Therapy	Contact force detection, slippage monitoring	Flexible piezoresistive arrays
Smart Haptic Gloves	Gesture recognition, real-time force feedback	Soft actuators + capacitive sensors
Intelligent Insoles	Gait analysis, foot pressure distribution	Pressure-sensitive conductive foams
Medical Exoskeletons	Torque sensing, intent decoding through EMG-tactile fusion	Hybrid multimodal modules
VR-based Sensorimotor Rehab	Tactile augmentation of virtual environments	Vibrotactile or skin-stretch actuators
Physiological Monitoring	Muscle contraction, joint kinematics, and localization	Stretchable ionic hydrogels with embedded wiring

In summary, Tactile sensing in rehabilitation robotics integrates intelligent control with user-centered design by converting tactile inputs into therapeutic functions, improving adaptability, safety, and recovery efficiency. Advancements in wearable sensors and closed-loop controllers further enable personalized and responsive rehabilitation solutions.

6. Challenges and prospects

As bioinspired tactile sensing continues to mature, its integration into real-world robotic systems presents both notable strengths and persistent limitations. Understanding these aspects is essential to guiding future research and practical deployment.

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One of the most promising advances lies in neuromorphic tactile encoders, which emulate biological mechanoreceptors by converting mechanical stimuli into sparse, event-based signals. This approach reduces computational load and enables ultra-low-latency control, ideal for mobile and wearable robotics. Coupled with embedded processors, neuromorphic sensing supports energy-efficient and reflexive robotic behavior. Self-supervised learning further enhances adaptability by enabling robots to learn tactile representations without extensive labeled datasets. By predicting contact states or reconstructing tactile input from multimodal data, systems adapt autonomously to new environments, critical for personalized assistive applications. Material innovation also plays a key role: stretchable, self-healing, and biodegradable tactile materials improve durability and sustainability, ensuring robust performance under dynamic conditions. Even with these developments, there are still many obstacles to overcome. The technological complexity of embedding dense sensor arrays on non-planar, deformable surfaces without compromising sensitivity or durability makes mechanical integration a significant challenge. Over time, delamination, uneven strain distribution, and material fatigue can all impair sensor performance.

On the computational front, tactile signals exhibit inherent high dimensionality and temporal dynamics, necessitating substantial computational resources for real-time processing. This demand often compromises responsiveness in embedded or battery-dependent systems. Multimodal integration further introduces synchronization overhead and architectural complexity when aligning tactile data with visual or physiological inputs. Power constraints remain critical, as continuous data streams from high-resolution sensor arrays strain energy reserves and communication bandwidth, particularly in wireless or wearable platforms.

7. Conclusion

In conclusion, the next generation of tactile sensing platforms must balance material innovation, computational efficiency, and simplicity of integration. By addressing these interconnected challenges, tactile systems can transition from research prototypes to robust, deployable technologies that enhance human–robot interaction across healthcare, industry, and everyday life.

However, this review acknowledges limitations, such as the variability in sensor performance under different environmental conditions and the need for more comprehensive testing in real-world scenarios. Additionally, the integration of tactile sensors with existing robotic systems remains a complex challenge that requires further exploration to ensure seamless functionality and reliability.

Future research should focus on scalable fabrication techniques that facilitate the deployment of large-area tactile arrays on soft or articulated robotic surfaces. Advancements in modular sensor design will also aid in streamlining integration across various platforms. At the algorithmic level, real-time fusion models adapting to task context and operating conditions will be crucial. With the backing of distributed learning and centralized coordination, robots can continuously refine their tactile strategies based on shared experiences, making them more responsive and intelligent over time.

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