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Recent Advances in Tactile Sensing Technologies for Human-Robot Interaction: Current Trends and Future Perspectives

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ABSTRACT

Tactile sensing technology has witnessed remarkable advancements, significantly expanding its applications across robotics, medical diagnostics, and consumer electronics. This paper reviews the latest developments in tactile sensing technologies, with a particular focus on their critical role in enhancing human-robot interaction. It highlights advancements in mechanoreceptor technologies, emphasizing innovations in material science and sensor design that improve the functionality and adaptability of tactile sensors. The review critically examines the evolution of key sensing modalities—piezoresistive, capacitive, and piezoelectric sensors detailing their operational principles, performance improvements, and integration into robotics systems for intuitive and responsive interactions. Emerging trends in sensor flexibility, sensitivity, and energy efficiency are explored, addressing their importance for creating adaptive, sustainable solutions in human-centered robotics. Additionally, the paper discusses challenges such as scalability, durability, and cost-effectiveness, which remain barriers to widespread adoption in robotic and clinical applications. The work concludes with future research directions, advocating for the integration of tactile sensors with artificial intelligence to develop self-learning systems capable of sophisticated decision-making and seamless human-robot collaboration. This review aims to bridge the gap between current technologies and future possibilities, charting a path toward transformative innovations in tactile sensing for human-robot interaction.

1. Introduction

The information acquired through the human tactile perception system during physical interaction is known as the "sense of touch". It is a vital sensory function that allows humans to perceive and interact with their environment (Zhanat Kappassov et al., 2015). Tactile data also plays a crucial role in enabling both humans and robots to communicate with their surroundings (Hanna Yousef et al., 2011). Touch is an extremely delicate sense that can directly measure the qualities of objects and environments. Humans use their tactile organs to sense an object's warmth, grasp it properly, and recognise objects that are similar in appearance but distinct in materials via touch. Tactile information can offer the contact force between the fingers and the objects, the contact position, and other critical information for the prosthetic hand, which can increase the dexterous hand's fine gripping ability. Exploration and operation of unknown items in the external environment are critical for prosthesis users. Tactile sensors are being researched for use in medical devices and artificial intelligence beyond traditional touch displays and motion sensing applications, thanks to recent technological advancements (Kuan-Hua Huang et al., 2019; Yeongin Kim et al., 2018; Husam A. Neamah and Al-Gburi Mousa, 2024).

In the medical field, tactile sensors have been applied in pulse oscillators, breast cancer screening devices, pressure mapping systems, and ascites prevention mats (Anastasios Valkanis et al., 2020; Rajesh Gupta et al., 2019). High-resolution tactile sensors, such as those used in robotic fingertips, are essential for artificial intelligence applications (Markellos Ntagios et al., 2020; William Navaraj and Ravinder Dahiya, 2019). Data must be gathered directly from the daily activities of the object being tested in order for the tactile sensor to be used in the above application field (Tao Jin et al., 2020; José A. Hidalgo-López et al., 2018). To do this, the tactile sensor device must solve challenges with many sensor element arrangements and wiring processing, be flexible and thin, and be mounted to a wide free curved surface. Furthermore, when physical contact is made, it must be long-lasting and capable of detecting a variety of physical quantities (Fernando Vidal-Verdú et al., 2011; Alin Drimus et al., 2014; Trong-Danh Nguyen and Jun Seop Lee, 2021). This review outlines the many operating principles of touch sensors and discusses the most recent development trends for each principle-based device to overcome its limitations.

Studies on touch were confined in the early days of tactile sensor development to whether the sensor was in contact with the object or the degree of contact (Uriel Martinez-Hernandez, 2016). More comprehensive works on the design, concepts, and procedures of sensors were done, followed by tremendous efforts, in order to increase their performance (Ning Chen et al., 1995). Fig. 1(a) below shows the rise in the number of published articles in the field of tactile sensors within the period 2010 to 2024. In the mentioned figure we can recognize the high increase in the number of published articles, especially between the years 2016 and 2021 when it increased from 459 to 829. Fig. 1(b) illustrates the related keywords used in the tactile sensors field according to their correlation and recurrence, the larger the circle the higher the recurrence. From Fig. 1, we can notice that tactile sensors are strongly related to the robotic field as well as artificial human sensing approaches along with the development of wearable sensors.

This paper offers a comprehensive review of tactile sensing technologies, highlighting advancements in piezoresistive, piezoelectric, capacitive, and optoelectronic mechanisms while addressing emerging trends such as stretchability, self-healing, biodegradability, and self-powered capabilities. Unlike previous reviews that often focus on isolated aspects, this work bridges material science and practical applications, providing a holistic perspective on the field's evolution from its origins to its current state. It emphasizes interdisciplinary applications in robotics, healthcare, and wearable technologies, underscoring the critical role of tactile sensors in enhancing human-robot interaction, minimally invasive surgery, and energy-efficient devices. Additionally, the paper identifies key challenges such as scalability, durability, and cost-effectiveness and offers strategic recommendations for future research, including integrating tactile sensors with artificial intelligence for self-learning systems. By combining historical insights, bibliometric data, and actionable design criteria, this review serves as a valuable resource for advancing tactile sensing technologies and addressing real-world demands.

This paper is organized as follows: The Introduction outlines the importance of tactile sensing technologies and the motivation for this review. Section 2 discusses the Human Tactile System as a foundation for sensor design. Section 3 reviews the Mechanisms of Tactile Sensing Technologies, including piezoresistive, piezoelectric, capacitive, and optoelectronic sensors, along with their performance and applications. Section 4 highlights Key Design Features, such as stretchability, self-healing, biodegradability, and self-powered capabilities. Section 5 examines Applications of Tactile Sensors across robotics, biomedical technologies, and wearable electronics. Section 6 addresses Challenges and Future Directions, focusing on scalability, durability, and AI integration. The Conclusion summarizes key insights and offers recommendations for advancing tactile sensing research.

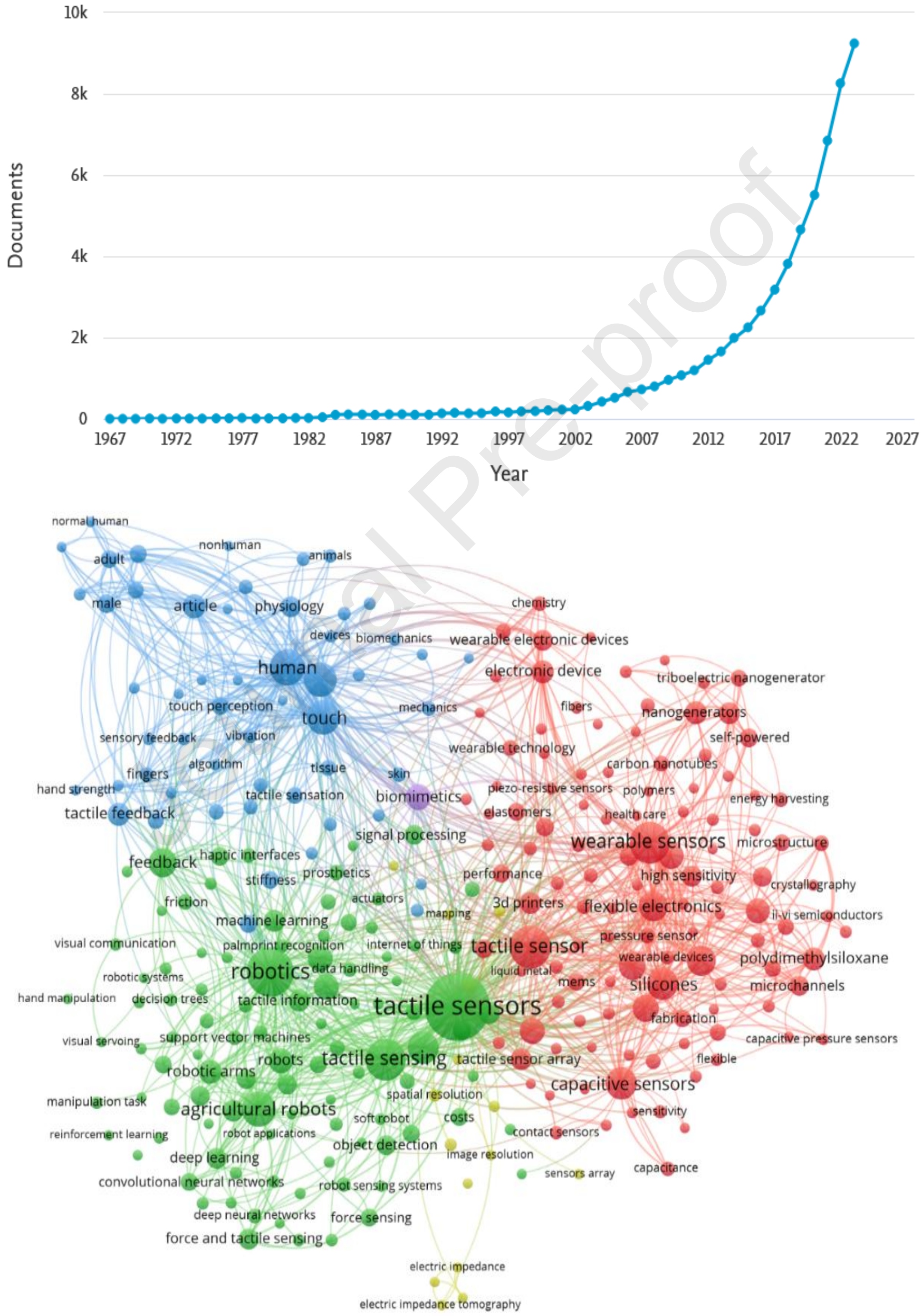

Fig. 1. (a) Number of published articles in the field of tactile sensors (2010-2024). (b) Related topics to the field of tactile sensors based on commonly used keywords (Generated by VOS viewer software).

2. Methodology of conduction research

To systematically identify and evaluate the most relevant and recent studies in tactile sensing technologies for human–robot interaction, we followed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, using a structured and transparent approach to article selection. Literature was retrieved from three major databases IEEE Xplore (n = 1,454), Scopus (n = 2,450), and Web of Science (WOS) (n = 2,150) covering the publication period from 2018 to 2023. Keyword queries targeted combinations such as "tactile sensor," "electronic skin," "piezoresistive," "piezoelectric," "capacitive," and "human-robot interaction," filtered by relevant subject areas (engineering, physics, materials science, and computing) and English language. An initial total of 6,054 records was collected, from which 5,326 were automatically excluded due to duplication or irrelevance using filtering tools. After manual screening of 728 titles and abstracts, 671 studies were excluded for not meeting the scope or relevance criteria. Of the 57 full-text reports retrieved, 3 could not be accessed. The remaining 54 articles were reviewed for eligibility, and 25 were excluded 19 due to duplication and 6 for language limitations. Ultimately, 28 studies met all criteria and were included in the final review. The detailed selection workflow, including the number of records at each stage and the reasons for exclusion, is illustrated in the PRISMA 2020-compliant flow diagram (Fig, 2), generated using the PRISMA2020 R package and Shiny App for transparency and reproducibility (Neal R. Haddaway et al., 2022).

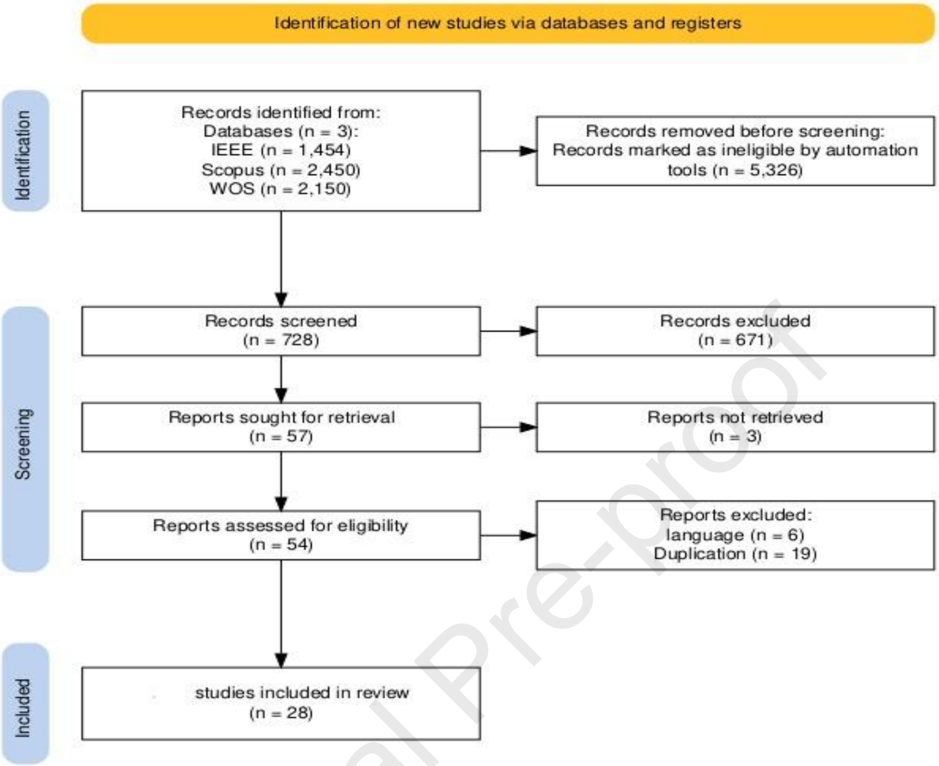

Fig.2. The Categorization and selection process.

3. Understanding the tactile system

To obtain touch information, the human tactile system relies on a diverse array of receptors, primarily mechanoreceptors, thermoreceptors, and nociceptor. Mechanoreceptors can sense vibration and pressure and are divided into four types, i) Meissner corpuscles, ii) Merkel cells, iii) Ruffini ends, and iv) Pacinian corpuscle (R.S. Johansson and G. Westling, 1984). For a detailed overview of their classification, functions, and locations, refer to Fig. 3 (a, b,c). These receptors exhibit diverse receptive fields, representing the body area to which a receptor responds, and they also display distinct rates of adaptation. Fast-adapting (FA) mechanoreceptors detect dynamic force changes and generate powerful signals during force application or removal (J Dargahi and S Najarian, 2004). Slow adapting (SA) mechanoreceptors, on the other hand, perceive static stresses and provide constant responses throughout extended stimulation. The number of mechanoreceptors varies throughout the body, ranging from roughly 241 cm^2 in the fingertips to 58 cm2 in the palm (R S Johansson and A B Vallbo, 1979; R.S. Dahiya et al., 2010), resulting in approximately 1 mm resolution in the fingertips (James C. Craig, Jayne M. Kisner, 1998; Robert W. Van Boven and Kenneth O. Johnson, 1994).

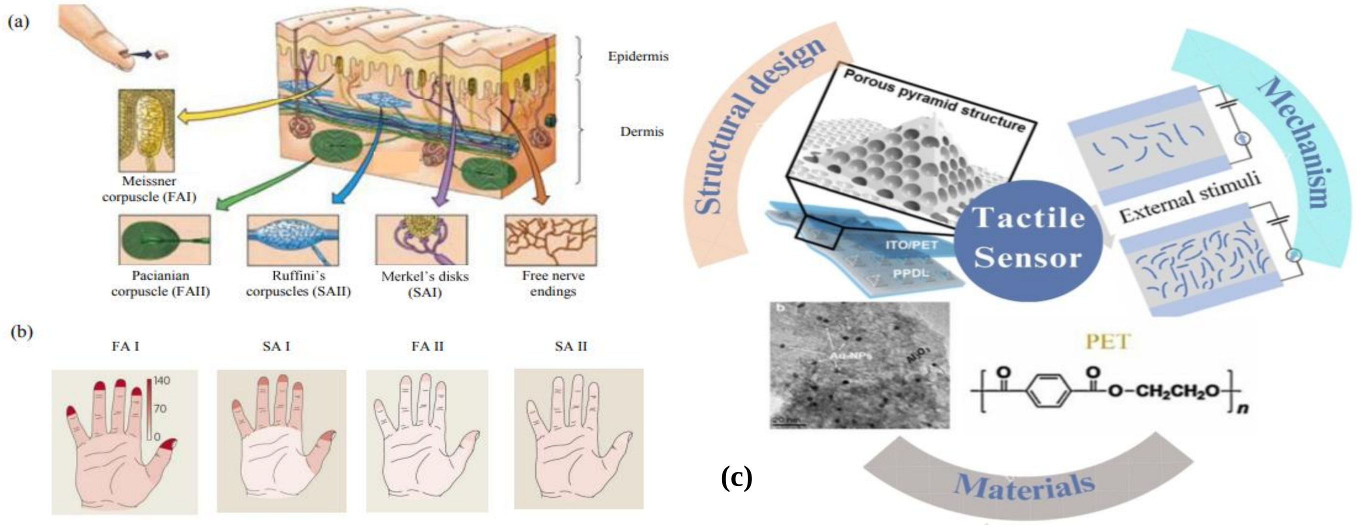

Fig. 3. Mechanoreceptors of human hairless skin. (a) structure and location. (b) receptor density (scale per Cm^2). Edited from (R.S. Johansson and G. Westling, 1984; R S Johansson and A B Vallbo, 1979). (c) Overview of Tactile sensors towards e-skin in terms of material selection, mechanism integration, structural design.

Human tactile data processing begins at individual receptors, where stimuli are transduced into neural signals (Roland Johansson and John Flanagan, 2009). The skin's nociceptor units, which are primarily responsible for pain perception, also respond to severe temperatures and, on occasion, mechanical stimulation. Signals from receptor groups undergo preliminary processing along neural pathways to the brain (Roland Johansson and Ingvars Birznieks, 2004), where they are ultimately interpreted (R.S. Dahiya et al., 2010; Roland Johansson and John Flanagan, 2009). This hierarchical processing minimizes cognitive load and enables rapid tactile perception to detect pressures greater than 10 kPa (Evan S. Dellon et al., 1992) with a temporal precision of 20-40 ms (James C. Craig and Xu Baihua, 1990), as well as vibrations at frequencies up to 800 Hz (J Dargahi and S Najarian, 2004).

Table 1.
Description of mechanoreceptors in human skin (Ravinder S. Dahiya et al., 2010).

	Adaptation Rate	**Spatial Accuracy (mm)**	**Stimuli Frequency (Hz)**	**Conduction Velocity (m/s)**	**Effective Stimuli**	**Sensory Function**
Meissner's Corpuscle	Fast	3-4	3-40	35-70	Temporal changes in skin deformation	Low frequency vibration &motion
Merkel Cells	Slow	0.5	0.4-3	40-65	Spatial deformation; sustained pressure; curvature, edge, corners	Pattern/form detection; texture perception; tactile flow perception
Ruffini Ends	Slow	7+	100-500+	35-70	Sustained downward pressure; lateral skin stretch; skin slip	Finger position; stable grasp; tangential force; motion direction
Pacinian Corpuscle	Fast	10+	40-500+	35-70	Temporal changes in the skin deformation	High-frequency vibration detection; tool use

Furthermore, Fig. 2(c) illustrates the key aspects of tactile sensors for e-skin applications, focusing on material selection, mechanism integration, and structural design. It highlights advanced structures like the porous pyramid, flexible materials such as PET, and conductive components like ITO and PPDL, demonstrating their role in enhancing sensitivity and functionality. The integration of external stimuli showcases the potential of tactile sensors to mimic human skin for applications in robotics, healthcare, and wearables. Additionally, Table 1 summarizes the characteristics of each of these receptors.

4. Literature review

Numerous research papers have explored the fundamental structure and techniques of tactile sensors, addressing various characteristics. However, an organized summary that provides an overview of the latest advancements in stretchable and elastic tactile sensor technology would be highly valuable (Ravinder S. Dahiya et al., 2010). Tactile sensors play a crucial role in detecting and/or measuring the force at a contact point. These sensors are vital for: i) Obtaining task-specific information, such as slip detection, and ii) Managing handling and operational commands, including grasping command parameters (D De Rossi, 1991). Table 2 presents general design guidelines for tactile sensors intended for use in humanoid robots.

Table 2
Critical characteristics to consider for the fabrication of tactile sensors to be realized on humanoid robots (Ravinder S. Dahiya et al., 2010; D De Rossi, 1991).

Frameworks	**Guidelines**
Force magnitude and direction	About 1000:1
Fabrication techniques	General mechanical assimilation, simple wire works, cost-effective

Shielding	Magnetic and electronic shielding
Transient changes	Both static and dynamic
Timing feedback	1ms for tactile [based on the size of array]
Data management	Preliminary processing to lower data to central unit
Power consumption	Energy Efficient
Detection surface	Acquiescent and durable
Sensor response	Steady, repetitive, small hysteresis
Spatial resolution between 2 sensing points	At fingertips = 1mm; On palm = 5mm
Array response	minimum or no crosstalk

A tactile sensor is an electronic device designed to capture data generated from physical interactions with its environment. This type of sensor typically utilizes a naturally elastic foam rubber material that deforms under external pressure (Husam A. Neamah and Al-Gburi Mousa, 2024; A. Wisitsoraat et al., 2007; Lucia Beccai et al., 2005). By integrating a camera with computer vision, the foam-based setup is transformed into an accurate software-driven tactile sensor. The software processes this data to determine the force distribution and contact points across the sensor's surface. Such sensors provide robots with critical information about the physical characteristics of their surroundings, with the sense of touch being a vital parameter. Tactile sensors are required to measure geometric and dynamic properties, such as contact force and torque. Based on specific modulation criteria, tactile sensors can be categorized into four primary types: i) Piezoresistive (Lucia Beccai et al., 2005), ii) Piezoelectric (Kohei Motoo et al., 2007; G.M. Krishna and K. Rajanna, 2004), iii) Capacitive (T Salo et al., 2006), iv) Opto-electric (Jin-Seok Heo et al., 2006). Advances in mechanical design, including the geometry and material properties of sensors, have significantly enhanced their functionality. These sensors are essential for tasks such as securely grasping and manipulating objects without slippage and for enabling responsive operation in dynamic and complex environments. For an artificial tactile sensor to emulate human touch effectively, it should be capable of measuring both geometric and dynamic attributes, including contact forces, torque, and spatial details about the contact surfaces. In 1982, Harmon introduced the first set of guidelines for designing touch sensors, creating a framework that continues to be widely referenced by researchers. These guidelines are broad and adaptable, depending on specific requirements, but they are not definitive. Various touch sensor templates employing capacitive, piezoresistive, piezoelectric, magnetic, and optoelectronic technologies have been developed based on these principles (Leon D. Harmon, 1982; Ang Ke et al., 2019). Tactile sensing plays a pivotal role in enabling robotic arms to perform autonomous handling and grasping tasks. However, developing a practical and cost-effective tactile sensor for artificial hands remains a significant challenge. Key factors to consider when designing such sensors include high electrical resistivity, high spatial resolution (with a larger number of pixels), minimal hysteresis, broad frequency response, reliable performance, and memory effect. Traditional tactile sensors consist of multiple sensing elements, known as taxels, which are typically positioned on the fingertips of an end effector or manipulator. Many sensors utilize fiber Bragg grating (FBG) technology, while diffusion sensors incorporate foam as a diffusion medium. To evaluate the performance of these sensors, a deformable elastic layer is often placed over the taxels, serving as a medium to transmit force and torque. Taxels also provide critical information about the size and location of the contact surface between the sensor and the object (Philipp Beckerle, 2021). Table 3 highlights the key characteristics of various types of tactile sensors.

Table 3
Comparison between different tactile sensor categories (D De Rossi, 1991).

Transduction Technique	Modulated Criterion	Advantages	Disadvantages	Typical layout examples	Sensor material	Structure of sensor
Piezoresistive	Variation of resistance	Less prone to noise; Elastic; Enhanced gripping property; Easy fabrication and designing techniques; can be modified for certain measurement levels	Hysteresis low switching frequency; Minimum detecting range, limited to pressure detection or imaging	Pressure sensors; Strain sensors (Yoshihiro Hasegawa et al., 2004; M. C. Hsieh et al., 2002; Ming Chun Hsieh et al., 2001; Chih-Chieh Wen and Weileun Fang, 2008)	Conductive Polymer composites	Micro electromechanical systems
Piezoelectric	Polarization	High-frequency response; Good choice for dynamic applications, mechanically flexible; Minimum weights and slim films are feasible; mechanically durable and chemically resistant	Not suitable for static measurement; Inelastic; Needs charge amplifier; Slow sensor output	Pressure sensors; Strain sensors (Chunyan Li et al., 2008; Mohammad Ameen Qasaimeh et al., 2009; S Sokhanvar et al., 2007; Yoshihiro Tanaka et al., 2007),	Piezo/ Pyroelectric	Flexible printed circuit boards
Capacitive	Variation of capacitance	High-frequency response; better image resolution; High dynamic range; Temperature independent;	Sensitive to noise; Comparatively complex circuitry; Crosstalk effect between sensory elements.	Pressure sensors; Strain sensors (Cheng-Ting Ko et al., 2006; Arridh Shashank et al.,	Carbon Nanotubes (CNT)	Plastic MEMS

		Application area is large; small size; Simple structural design and fabrication techniques		2009; Ding-zhong Tan et al., 2008)		
Opto-electric	Variation of light intensity	Better detection range; Durability; High spatial resolution; Maximum repeatability	Large size; Non-contact sensing	Pressure sensors (Masahiro Ohka et al., 2008; M. Ohka et al., 2008; K. Weiss and H. Worn, 2005)	Force detecting resistor	Silicon transistor

4.1. Piezoresistive tactile sensors

Piezoresistive tactile sensors use a pressure-sensitive element with a varying electrical resistance that measures pressure when stretched (Luxian Wang et al., 2016). The working idea of a piezoresistive-based tactile sensor is that conductivity changes when external pressure is applied. Fig. 4 illustrates the working principle of piezoresistive tactile sensors (Harry Rolnick, 1930).

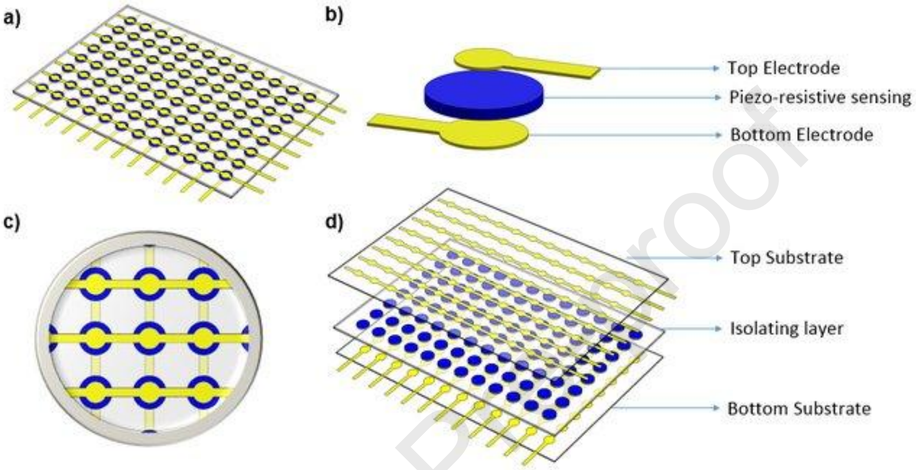

Fig. 4. Schematic diagram of the piezo resistive tactile sensor array (a) The complete design; (b) Single-cell view; (c) Plan zoomed view; (d) Sensor components view (Harry Rolnick, 1930).

Nanocomponents and doped silicon cantilever beams are the most common approaches for selecting a sensitive element. They also have the highest detection capability, as well as simple signal processing. Resistance can be defined as in Equation (1).

$$R = \rho \frac{L}{A} \tag{1}$$

Where ρ is resistivity, L & A is length and area cross-section of conductor, in strain type sensors the variation of resistance is given as in Equation (2).

$$\Delta R \ / \ R \ = (1 + 2v)\varepsilon + \ \Delta\rho \ / \ \rho \tag{2}$$

Where v & ε are Poisson's ratio, strain respectively, variation of this resistance depends on geometry and resistivity (Thomas W. Tombler et al., 2000). Piezoresistive properties can also be created with the variation of construction in energy band, which were detected in graphene, carbon nanotubes (Thomas W. Tombler et al., 2000), and silicon (Gen-Ichiro Kinoshita et al., 1975). Foam or conductive elastomer sensors are straightforward in design but come with several limitations, including: i) A wide range of nonlinear time constants; ii) Variations in time constants observed during force application versus force release; iii) Highly nonlinear force-resistance characteristics in elastomer-based sensors; and iv) Poor long-term stability due to the material's tendency to deform over time. Despite these challenges, sensors made from elastomers remain widely favored for their simplicity in construction and ease of interface design. Based on the piezoresistive technique, Raibert and his colleagues created a 6x8 tactile sensor array in 1984 (M. Raibert, 1984). The sensor array had a spatial resolution of 0.6 mm. With a sensitivity of 0.32mV/kPa and a spatial resolution of 1mm, the 4x4 piezoresistive tactile array was developed by Liu and his coworkers in 1993 (Litian Liu et al., 1993). A recent 4x4 piezoresistive tactile sensor with a sensitivity of 12.1 kPa/1 was created by Sun and his coworkers (Qi-Jun Sun et al., 2019).

4.2. Piezoelectric tactile sensors

The piezoelectric effect refers to the generation of electric polarization in piezoelectric materials when subjected to mechanical force. Materials that produce electrical charges under applied force or pressure are known as piezoelectric materials. On the other hand, piezoresistive sensors offer notable advantages, including rapid fabrication, high sensitivity, a broad measurement range, and a straightforward structure see Fig. 5 (a-h). Additionally, piezoresistive tactile sensors exhibit low susceptibility to noise, making them well-suited for array configurations with minimal field interaction or crosstalk between adjacent units (Pinyo Puangmali et al., 2008). However, these sensors have certain limitations. Their resistance is highly sensitive to temperature changes, and hysteresis is a common issue, leading to a restricted frequency response. Moreover, their linear error increases significantly under large deformations, limiting their application in environments with variable conditions (Husam A. Neamah and Al-Gburi Mousa, 2024; Mohsin I. Tiwana et al., 2012), (Sung-Ho Shin et al., 2019). According to Wolfenbüttel and Regtien (M.R. Wolffenbuttel and P.P.L. Regtien, 1991), and Beebe, Hsieh, et al. (David J. Beebe et al., 1995), piezoresistive tactile sensing is extensively utilized in developing silicon-based tactile sensors and deploying Micro-Electro-Mechanical Systems (MEMS). Interlink Electronics Inc. developed Force Sensing Resistors (FSRs) based on this technology, which are commonly used in joysticks and shape and position recognition devices. Stressing piezoresistive tactile sensors affects the material's band gap, leading to significant changes in carrier mobility, density, and resistivity (Charles S. Smith, 1954). This piezo-resistivity effect occurs in materials like graphene, silicon, and carbon nanotubes due to changes in the energy band structure (Thomas W. Tombler et al., 2000; T. Toriyama and S. Sugiyama, 2002; Sang-Hoon Bae et al., 2013). For instance, a silicon-based piezoresistive sensor embedded in a soft fingertip showed high-accuracy measurements for both longitudinal and shear stresses (Van Anh Ho et al., 2009).

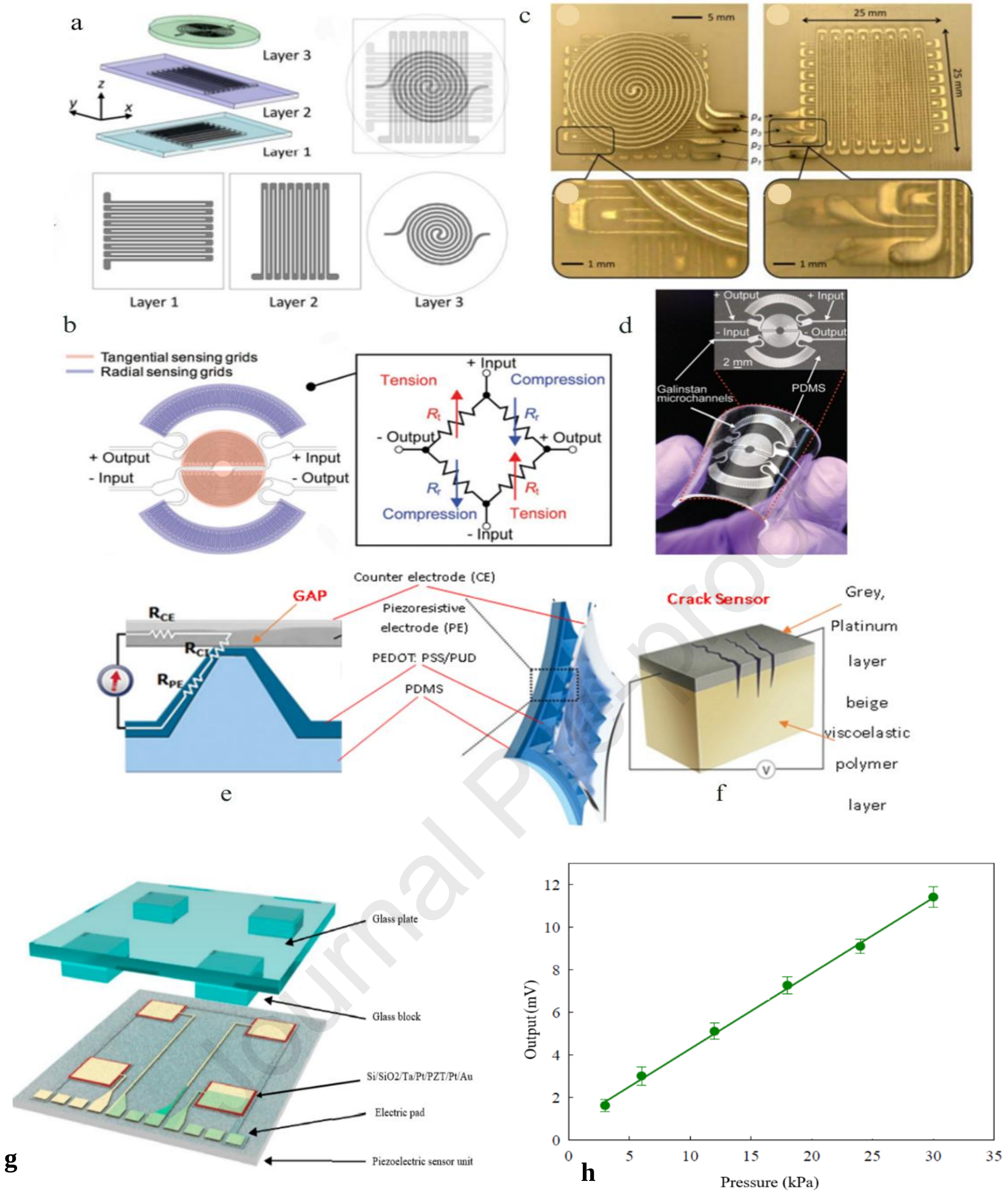

Fig. 5. (a) Sketch of three soft sensor coating made of silicone elastic embedded with microchannels: Exploded and Assembled view for Each sensor layer design, Adopted (Yong-Lae Park et al., 2011). (b) An analogous Wheatstone bridge circuit is created by the film sensor's schematic design and its corresponding circuit schematic, Adopted (Yuji Gao et al., 2017). (c) Plain prototype, The multi-layered soft artificial skin sensor with embedded with a liquid metal, eutectic gallium-indium (EGaIn) microchannels Adopted (Yong-Lae Park et al., 2011). (d) Visual prototype of a completed microfluidic film sensor designed and fabricated based on embedded Galinstan microchannels with 70 μm width and 70 μm height, Adopted (Yuji Gao et al., 2017). (e) Circuit diagram for a stretchable resistive pressure sensor that uses a micro pyramid array and a conductive elastomeric composite to determine the sensor's sensing principle (Chwee-Lin Choong et al., 2014). (f) A measurement scheme and schematic drawings of an ultra-mechanosensitive nanoscale crack junction-based sensor. Beige, viscoelastic polymer layer; grey, platinum layer (Daeshik Kang et al., 2014). (g) Main components of a piezoelectric tactile sensor unit (Junwoo Lee et al., 2014). (h) Electrical response for piezo electric tactile sensor Vs. the applied pressure on each unit (Junwoo Lee et al., 2014).

Recent research on piezoresistive sensors focuses on two key areas: developing flexible, self-healing composite materials with exceptional sensitivity (Jui-Chi Lin et al., 2023), and designing micro-structured, flexible sensors enhanced by micro- and nanoengineering techniques, incorporating both artificial and bionic microstructures (Zhenjin Xu et al., 2023). Materials such as 0D meta nanoparticles, 1D carbon nanotubes (CNTs), eco-elastic polymers (Songjia Han et al., 2019), cotton (Soonjae Pyo et al., 2019), PDMS (Soonjae Pyo et al., 2014), metal nanowires (NW) (Weibing Zhong et al., 2018), MXene, reduced graphene oxide (rGO) (Meng Zhu et al., 2020; Bowen Zhu et al., 2014), and polyester (Hongbo Dai and Erik T. Thostenson, 2019) are commonly used.

Alternative strategies like crack propagation in thin films and tunneling phenomena have been explored for high sensitivity (Tingting Yang et al., 2016), (Ho-Hsiu Chou et al., 2015). Materials with channel cracks or gap morphologies demonstrate exceptional sensitivity, whether the cracks are located between electrodes and sensing elements (Chwee-Lin Choong et al., 2014) or within the sensing material see Fig. 4 (e-f) (Daeshik Kang et al., 2014). Additionally, the sensor design depicted in Fig. 4(h) produced a linear response over the pressure ranges of 3 kPa to 30 kPa, and the output voltage was linearly proportional to the applied pressures between 1.8 mV and 11 mV. Tactile sensors based on piezoelectricity have improved stability, sensitivity, signal-to-noise ratio, and frequency response (Shuhai Liu et al., 2017). PVDF, a piezoelectric sensor material, is an ideal composition material for surface identification because it has exceptional qualities such as high sensitivity, high deformability, high-frequency response, and low permittivity. A lot of research about PVDF films focuses exclusively on wide frequency response for surface texture, Although PVDF sensors are often used for low-frequency motion monitoring, this characteristic can be advantageous in specific applications, such as tracking human motion with nanofiber PVDF. These sensors convert pressure into electricity through mechanical and electrical components. The resistance changes in piezoelectric touch sensors are determined by the voltage potential generated by the deformation of the crystal lattice, with sensitivity depending on the crystal structure. Crosstalk in piezoelectric tactile sensors can be minimized by employing a discrete array of sensing elements. During the piezoelectric effect, dipoles within the material create internal polarization under applied pressure. This may convert the mechanical field into an electrical field. In comparison with other sensors, piezoelectric technology sensors consume low power and have higher sensitivity. Maita et al. (Francesco Maita et al., 2015) fabricated a tactile sensor based on the piezoelectric effect that consisted of a poly (vinylidene fluoride-co-trifluoro ethylene) [PVDF-TrFE] capacitor regarding an extension gate configuration having sensitivity 430Mv/n.

With sensitivity and spatial resolution of 5.2Mv/gm and 0.07mm, respectively, Polla and his coworkers created an 8x8 Piezoelectric tactile sensor array(D.L. Polla et al., 1985). 2020 saw the creation by Zhu of a 4x4 piezo/thermoelectric tactile sensor with 109.4 μVK^{-1} sensitivity(Pengcheng Zhu et al., 2020). Kolesar and Dyson described an 8x8 Piezoelectric tactile sensor array based on CMOS & PVDF film, with MOSFET amplifiers added on chip and covering 100mm2area(E.S. Kolesar et al., 1996). Incorporating piezoelectric ZnO nanostructure, Wang et al. have created and manufactured a variety of nanosensors, piezotronic gadgets, and nanogenerators. By bonding nanowire to the skin of PDMS, they reported a single ZnO cable flexible strain sensor that had good sensitivity with such a GF of range to 1250, high stability, and quick reaction (Peng Wang et al., 2021).

4.3. Capacitive tactile sensors

Capacitors consist of two conductive plates and an insulating (dielectric) material between them (K. Suzuki et al., 1988). Numerically Capacitance is expressed as in Equation (3).

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \qquad (3)$$

Where *A* is the overlapping area of two electrodes, ε_o is the permittivity of vacuum, ε_r is relative permittivity and *d* is the distance between two electrodes. Almost all researchers found variations in *A* and *d* to calculate the force/pressure applied to the sensor. A general solution, according to current research, is to create a flexible dielectric layer to increase the sensitivity of touch sensors based on capacitive technology. Polydimethylsiloxane (PDMS) stands out among the compositional materials studied thus far. With living cells and human tissues, PDMS is reported to have better flexibility and biomedical consent. As a result, PDMS performs better in capacitive touch sensors as a thin-layers dielectric material.

Moreover, soft dielectric gap fillers are essential components in capacitive tactile sensors, directly impacting their sensitivity, hysteresis, and mechanical compliance. These materials often elastomers, gels, or liquids deform under applied pressure, modulating the sensor's capacitance. Recent advances have focused on modeling their complex electromechanical behavior to optimize performance. Researchers developed a nonlinear viscoelastic finite element model to simulate time-dependent responses in soft dielectrics, improving prediction accuracy for dynamic sensing conditions (Omar Akram Saleh Alwazzan et al., 2025). Authors. employed a physics-informed neural network to model pressure-capacitance responses, enabling efficient design tuning(Nima Ahmadi et al., 2024). Researchers, introduced a multiscale data-driven model linking microstructural properties to macroscopic sensor behavior (Omar Akram Saleh Alwazzan et al.). Complementing these efforts, authors. proposed an analytical framework based on strain energy functions that accounts for electromechanical coupling and nonlinear deformation (Samira Valizadeh et al., 2024). Together, these approaches offer vital tools for advancing high-performance, stretchable tactile sensors through integrated material and design optimization.

An appropriate design for a high-resolution sensor must consider the following: i) Compacted size of taxels; ii) The capacity and the variation in its value upon the application of force, which allows utilizing polymer-based material (dielectrics with high permittivity); iii) High sensitivity.

Capacitance variations can be measured using different circuit designs, depending on the desired output type. Some common DC output voltage configurations include: i) An electric current generator, which charges the capacitor for a limited duration; ii) An oscillator, where the capacitance value is linked to its operating frequency (Cheng-Ting Ko et al., 2006), followed by a frequency-to-voltage converter; and iii) A Wheatstone bridge combined with an instrumentation amplifier and a peak detector. Suzuki (K. Suzuki et al., 1988) developed a 32x32 capacitive-based tactile sensor array in 1988 with a 0.5mm spatial resolution and 0.4Pf/g sensitivity. A 16x16 capacitive tactile sensor array with a focus on sensitivity and spatial resolution was created in 1997 by De Souza and his colleagues, and it achieved 100 N sensitivity and 500 dpi spatial resolution (R.J. De Souza and K.D. Wise, 1997). Wang last year (2021) (Peng Wang et al., 2021) modeled a 6x6 touch sensor with a sensitivity 9.62kPa. Fig. 6(a) shows the typical construction of a capacitive tactile sensor developed by Ji et al. (Zhangping Ji et al., 2016). Fig. 6(b) shows capacitive tactile sensor response characteristics as per a test performed by Yuan et al. (Dandan Yuan et al., 2021).

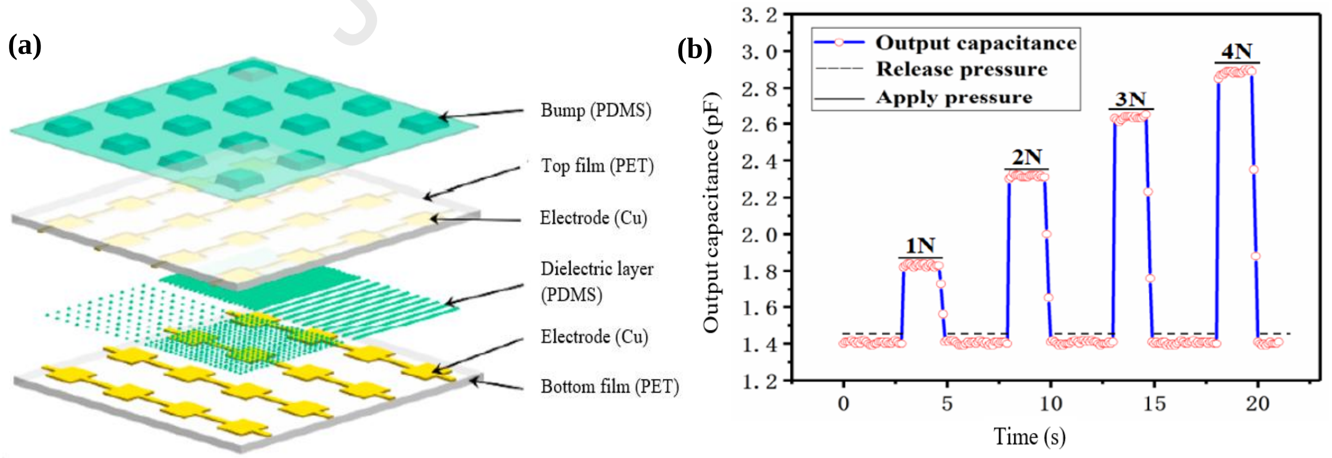

Fig. 6. (a) Typical construction of capacitive tactile sensor (Zhangping Ji et al., 2016). (b) an example of capacitive tactile sensor capacitance output vs. applied pressure considering response time and rebound time (Dandan Yuan et al., 2021)..

4.4. Optoelectronic Tactile sensors

The working principles of optical sensors are categorized into intrinsic and extrinsic types. Intrinsic sensors modify the polarization, phase, or intensity of transmitted light under applied force without disturbing the optical pathway, except when external forces interact with external light in the main pathway. Extrinsic sensors, on the other hand, are based on intensity measurements and are widely used due to their simplicity in manufacturing, data acquisition, and signal processing. The tactile properties of optical sensors are determined by analyzing variations in the input and output light. Bragg fiber (FBG) materials are particularly popular for these sensors due to the electromagnetic properties of light. The optical sensor's sensing method is based on light intensity modulation, Bragg Fibre Grafting, and interferometric device sensing. Stretchability, rapid reaction, lightness, and chemical inactivity are all features of an optical tactile sensor. As an example of how foam works in tactile sensing technology, urethane foam features a hollow whose dimensions fluctuate depending on the external force applied. And this force generates a change in dispersed energy density, which we can detect and utilize to recreate the amplitude of the exerted force. LED transistors and four phototransistors are used to measure the deformation of a flexible dome, and the deformation is then calculated analytically based on the vertical force applied to the dome. The force/touch sensor is based on a thorough investigation using finite element (FE) modeling. Optical sensors are resistant to electromagnetic interference, which makes them a good match for MRI and can be used in conjunction with an MIS control device. Due to bending losses caused by fiber routing, optical fiber-based sensors are expensive and difficult to construct into compound robotic compositions (such as anthropomorphic hands). By Saad and colleagues, an optical tactile sensor based on a birefringent generation that relies on a linear correlation between external force and phase lead has been described. By placing column-shaped tabs over a sheet of silicon rubber, Ohka and colleagues have developed an optically based tactile sensor(Masahiro Ohka et al., 2008). Tabs of varying sizes can be squeezed and replaced in three different directions, and tiny cones underneath the sheet are twisted to return the force that was applied. Fig. 7 shows a novel graphene-based optical waveguide tactile sensor developed by Kim et al. (Jin Tae Kim et al., 2018) along with its behavior according to dynamic mechanical force.

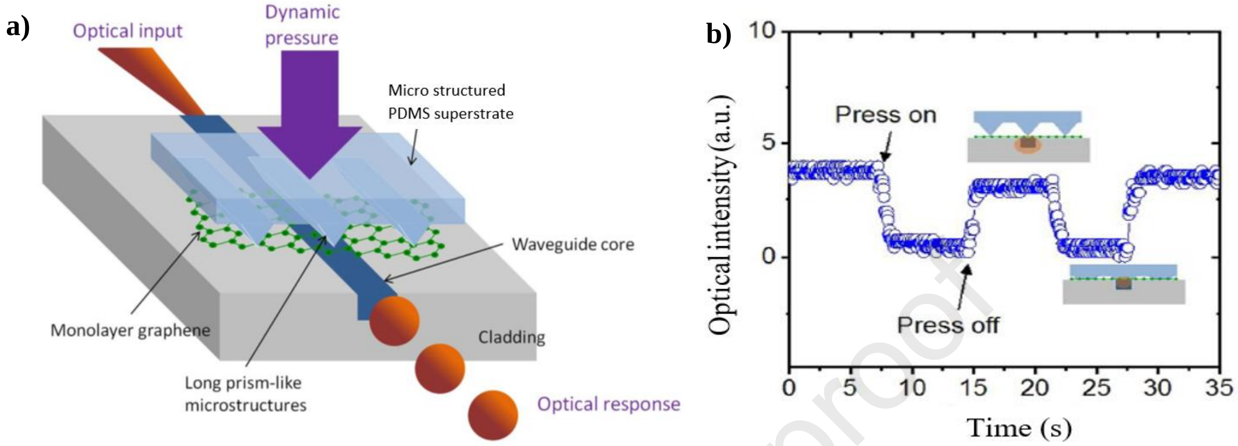

Fig. 7. (a) Overview of a graphene-based tactile optical waveguide sensor. An elastomeric PDMS superstrate with prism-like microstructures was integrated onto the graphene-optical waveguide platform. By adjusting the lateral deformation area, the waveguide core-graphene-PDMS interface and graphene's light absorption were mechanically tunable, even with a lower refractive index in the superstrate. The microstructures were fabricated using an anisotropic Si wafer wet etching process. (Jin Tae Kim et al., 2018). (b) The mechanical-to-optical sensor's temporal behavior in response to dynamic mechanical force (Jin Tae Kim et al., 2018).

5. Related Works in Tactile Sensing Technology

In 1969, Pfeiffer et al. demonstrated that touch sensors could improve prosthetic support by developing experimental equipment capable of detecting the presence of force, though not its magnitude (E. A. Pfeiffer et al., 1969). Around the same time, Stojiljkovic and Clot incorporated a series of transducers to create an artificial skin capable of measuring rigidity (Z. Stojiljkovic and J. Clot, 1977). In 1975 Kinoshita et al. (Gen-Ichiro Kinoshita et al., 1975) utilized sensing arrays of Piezoelectric effect to fabricate visible-tactile interdependent structure and construct these arrays on a robotic hand. Efforts in the 1970s set down the foundation of tactile sensing technology. The results of tactile sensing research were logically basic, however, at the end of this century, it was identified as a subject area that had the capability to solve engineering complications related with robotic commands.

Resistive materials of the 1980s were simple, inexpensive, heat resistant, and easy to produce, but they had a hysteresis problem and a limited dynamic range. With piezoresistive sensors, silicon technology functioned well. However, most of these sensors were rigid, uniform, and smooth. In 1984, Raibert and Tanner developed a touch sensor based on conductive rubber and metal electrodes (M. Raibert, 1984).

In the 90's stretchability and flexibility capability of material developed new scopes (M. Inaba et al., 1996; J. C. Lötters et al., 1997). The main use of tactile sensing that was focused on in this decade was minimally invasive surgery (MIS). To control the patient's condition, surgery needs both eyesight and contact (Gregory Tholey et al., 2005). Ohtsuka et al. developed a sensor featuring a rounded end tip, frequency counter, filter, and a piezoelectric-based transducer (Toshiya Ohtsuka et al., 1995). According to Lee and Nicholls (M.H Lee and H.R Nicholls, 1999), tactile sensors hold significant potential in three key areas: surgical operations, social (Husam A. Neamah et al., 2024; Husam A. Neamah et al., 2024; Kornél Katona et al., 2024) and rehabilitation robotics (Husam Almusawi and Géza Husi, 2021; A. H. AbdulKareem et al., 2018; Husam Almusawi et al., 2019), and agriculture and food production. The flexibility and softness of these sensors can enhance the accurate identification of soft tissues during surgery. Advances in computing and data processing have enabled researchers to revisit previously incomplete work, leading to numerous experiments aimed at improving the tactile response in minimally invasive surgery (MIS), particularly focusing on force sensing. King et al. (C.-H. King et al., 2009) developed haptic feedback on the robot's end-effector, allowing surgeons to detect the application of force to the gripper. The bulk of the accessories was ill-fitting, putting pressure on the area and preventing it from healing. Valdastri et al. (P. Valdastri et al., 2005) created a silicon-based three-axis force sensor that could calculate the socket fitting degree, improve the shape and aesthetics, and reduce skin injury. There was also a lack of response from the prosthetics technology. To address this issue, a number of models, such as Sabolich's sensational limb (Scott Sabolich, 2021), have been designed to increase the feedback on prosthetic technology. The fundamental goal of the twenty-first century was to replicate the complex functions of human skin, which included not only pressure detection but also humidity, stiffness, temperature, self-healing, etc. (Darryl P. J. Cotton et al., 2009; Akira Kimoto et al., 2010; Peer A. Schmidt et al., 2006; S. R. White et al., 2001; J. Yuji and K. Shida, 2000).

Multiple gadgets, such as wearable Flexible Hybrid Electronics (WFHE), have been fabricated as a result of developments in combining all physical and virtual devices within technology and soft materials for health maintenance of public and individual machine networks. WFHEs were found to be mechanically easy to alter the shape, elasticity, and stretchable electronic equipment that was sturdily linked with the body of the surface, according to Lim et al. (Hyo-Ryoung Lim et al., 2020).

Moreover, tactile sensors are increasingly critical in medical robotics, where precision and safety are paramount. In robotic-assisted surgery, systems such as the da Vinci 5 have begun integrating force feedback modules to allow surgeons to perceive applied forces, improving tissue handling and reducing accidental damage during minimally invasive procedures. A recent systematic review reported that tactile-enhanced RMIS systems improve transparency and reduce cognitive load for surgeons, though challenges remain in sensor miniaturization and data fusion. Additional studies have shown that prosthetic hands equipped with pressure sensors and vibrotactile actuators significantly improve grip control and the ability to distinguish object texture, thereby closing the sensory loop in artificial limbs (Luke Osborn et al., 2014).

In addition, wearable electrophysiological sensors could detect bioelectric impulses without penetrating the skin. WFHE advancements improve the performance of integrated artificial skin-appearing sensory devices. Table 4 below shows the related works related to tactile sensors addressing the utilized approach, resulting in force/pressure sensitivity, force/pressure ratio, and spatial resolution.

Table 4
Summarized table of Related works.

Author	Sensing Technique	Force/ Pressure Sensitivity	No. of Sensing Element	Force/Pressure ratio	Spatial Resolution [mm]
Raibert (M. Raibert, 1984)	Resistive	-	6x8	-	0.6
Polla et al. (D.L. Polla et al., 1985)	Piezoelectric	5.2mV/gm	8x8	2^{+}	0.07
Suzuki (K. Suzuki et al., 1988)	Capacitive	0.4pF/g	32x32	0.01^{+}	0.5
Cheung and Lumelsky (E. Cheung and V.J. Lumelsky, 1989)	Optical	-	16	-	-
Sugiyama et al. (Susumu Sugiyama et al., 1990)	Piezoresistive	0.02mV/kPa	32x32	-	0.25
Domenici and De Rossi (Claudio Domenici and Danilo De Rossi, 1992)	Piezoelectric	-	6x7	-	2.5
Liu et al. (Litian Liu et al., 1993)	Piezoresistive	0.032mV/kPa	4x4	200*	1
Chu et al. (Chung-tse Chu et al., 1996)	Capacitive	0.32pF/g [shf]	3x3	0.01^{+}	2.2
Gray and Fearing (B.L. Gray and R.S. Fearing, 1996)	Capacitive	20Mn	8x8	$1.0*10^{-4+}$	0.1
Kolesar et al. (E.S. Kolesar et al., 1996)	Piezoelectric	-	8x8	$0.008\text{-}1.35^{+}$	0.7
De Souza and Wise (R.J. De Souza and K.D. Wise, 1997)	Capacitive	100μN	16x16	-	500dpi
Um et al. (D. Um et al., 1998)	Optical	-	1000	-	25
Kane et al. (B.J. Kane et al., 2000)	Piezoresistive	1.59mV/kPa	64x64	35*	0.3
Leineweber et al. (Michael Leineweber et al., 2000)	Capacitive	13.5mV/kPa	8x1	100-300*	0.24
Castelli (F. Castelli, 2002)	Capacitive	-	8x8	120*	>2
Hellard (Greg Hellard, 2002)	Optical	-	4x4	-	>1
Wen et al. (Zhiyu Wen et al., 2003)	Field Emission	30.1mV/kPa	8x8	150*	1
Choi (Sung-Jin Choi et al., 2005)	Resistive & Piezoresistive	-	24	2^{+}	1
Ohka et al. (Masahiro Ohka et al., 2006)	Optical	1mN	-	2^{+}	2
Schmidt et al. (Peer A. Schmidt et al., 2006)	FSR & Capacitive	5mN	1 static 16 dynamic.	$0.05\text{-}10^{+} < 0.01^{+}$	-
Someya et al. (Takao Someya et al., 2005)	Piezoresistive	0.5-1V/N	6x6	$0.021\text{-}0.176^{+}$	0.42
Dahiya et al. (R.S. Dahiya et al., 2009)	Piezoelectric	0.5V/N	32	5*	1
Someya et al. (Takao Someya et al., 2004)	FSR	-	32x32	30*	2.54
Engel et al. (Jonathan Engel et al., 2005)	Resistive	-	25	-	5
Shan et al. (Jian Him Shan et al., 2005)	Piezoresistive	34mV/N [shf]	4x4	2^{+}	10

Heo et al. (Jin-Seok Heo et al., 2006)	Optical	1Mn	3x3	5N		5
Kim et al. (K. Kim et al., 2006)	Strain Gauge	0.25V/N [shf]	4x4	0.6^+		2.5
Ohmura (Yasuhiro Ohmura, 2007)	Optical	-	8x4	-		30
Maggiali et al. (Marco Maggiali et al., 2008)	Capacitive	-	12	-		10
Mukai et al. (T. Mukai et al., 2008)	Piezoresistive	-	8x8	128		18
Kim et al. (Kunnyun Kim et al., 2006)	Strain gauge	4.2	4x4	0-2		1.8
Choi et al. (Charina Choi et al., 2010)	strain gauge	3	4x4	0-0.8		-
Sohgawa et al. (M. Sohgawa et al., 2009)	Piezoresistive	15.7	3x3	0-0.13		1
Lee et al. (Insook Lee et al., 2008)	Capacitive	1.1	8x8	0-0.01		2.75
Ho et al. (Van Anh Ho et al., 2009)	Piezoresistive	2.2	-	0-0.5		-
Noda et al. (Kentaro Noda et al., 2006)	Piezoresistive	0.5	-	0-4		-
Noda et al. (K. Noda et al., 2009)	Piezoresistive	0.1	-	0.05-3		-
Beccai et al. (Lucia Beccai et al., 2008)	Piezoresistive	0.3	-	0-6	0-8	-
Wang et al. (Jin Wang et al., 2009)	Cond. Polymer	1.7	-	0-0.4		-
Kim 2009 (Kunnyun Kim et al., 2009)	Strain gauge	-	32x32	0-1		2
Engel et al. (Jonathan Engel et al., 2003)	Strain gauge	-	10x10	-		0.4
Zhang (Yuhua Zhang, 2010)	Strain gauge	-	n.s.	0-7		-
Yu et al. (S.-L. Yu et al., 2008)	Cond. Polymer	-	32x32	0-30kPa		1.9
Alirezaei et al. (Hassan Alirezaei et al., 2007)	Res-EIT	-	n.s.	0-150kPa		10
Cheng 2009 (M.-Y. Cheng et al., 2009)	Cond. Elastomer	-	8x8	0-650kPa		3
Someya et al. (Takao Someya et al., 2005)	Cond. Elastomer	-	12x12	0-1		4
Wettels et al. (Nicholas Wettels et al., 2008)	Cond. Fluid	-	n.s.	0.01-40		2
Hasegawa et al. (Yoshihiro Hasegawa et al., 2008)	Optical	-	4x4	0-0.3		2.6
Chorley et al. (Craig Chorley et al., 2009)	Optical	-	n.s.	0.05-0.5		5
Mannsfeld et al. (Stefan C. B. Mannsfeld et al., 2010)	OFET	-	8x8	0-2(2-18)kPa		2
Heo et al. (Jin-Seok Heo et al., 2008)	Optical	-	-	0-10		-
Sato et al. (Seichi Sato et al., 2008)	Optical	-	-	0.2-2		5
Chen et al. (Chien-Chun Chen et al., 2012)	Capacitive	14%/kPa	4x4	$2^+/20*$		-

Dobrzynka (Jagoda Anna Dobrzynska, 2013)	Capacitive	2.4%/kPa[nf],0.028%/kPa [shf]	2x2	140*	-
Tee and Ouyang (Benjamin C. K. Tee and Jianyong Ouyang, 2018)	Capacitive	-	13x10	10*	-
Charalambides et al. (Alexi Charalambides et al., 2015)	Capacitive	190mN[nf] 50mN[shf]	2x2	8 + [nf] , 2+ [shf]	-
Liang et al. (Guanhao Liang et al., 2015)	Capacitive	58%.3/N[x] 57%/N[y]	4x4	0.5+[x, y] [z]	-
Rana et al. (Axaykumar Rana et al., 2016)	Capacitive	-	3x4	15^{+}	-
Noda et al. (Kentaro Noda et al., 2012)	Piezoresistive	0.17%/kPa	1	-1.8-18*	-
Liu et al. (Xinchuan Liu et al., 2013)	Piezoresistive	23%/kPa	1	6.67*	-
Kilaru et al. (Rohit Kilaru et al., 2013)	Piezoresistive	8.05%/N	1	-	-
Pyo et al. (Soonjae Pyo et al., 2014)	Piezoresistive	6.67%/N[nf] 86.7%/N[shf]	2x2	2^{+}/163*	-
Seminara et al. (Lucia Seminara et al., 2013)	Piezoelectric	-	12	8^{+}	-
Maita et al. (Francesco Maita et al., 2015)	Piezoelectric	430mV/N	1	2^{+}	-
Sim et al. (Minkyung Sim et al., 2017)	Piezoelectric	-	3x3	275*	-
Liu et al. (Shuhai Liu et al., 2017)	Piezoelectric	-	2x2	2^{+}	-
Xie et al. (Hui Xie et al., 2012)	Optical	-	3x3	-	-
Ahmadi (Roozbeh Ahmadi, 2012)	Optical	-	1	4^{+}	-
Massaro et al. (Alessandro Massaro et al., 2013)	Optical	-	1	3.9^{+}	-
Fujiwara et al. (Eric Fujiwara et al., 2017)	Optical	0.08N	1	0.5^{+}	-
Wattanasarn et al. (S. Wattanasarn et al., 2012)	Magnetic	0.68mV/N	1	2.5^{+}	-
Alfadhel and Kosel (Ahmed Alfadhel and Jürgen Kosel, 2015)	Magnetic	856mΩ/kPa	1	0.85^{+}	-
Xi et al. (Kailun Xi et al., 2015)	Capacitive	o.23V/N	3X3	-	7
Sun et al. (Xuguang Sun et al., 2019)	Piezoresistive	12.1kPa^{-1}	4x4	-	-
Zhu et al. (Pengcheng Zhu et al., 2020)	Piezo/Thermoelectric	109.4µVK^{1}	4x4	100Pa-20.3kPa	-
Wang (Peng Wang et al., 2021)	Capacitive	9.62kPa	6x6	-	-

5.1. Criterions for an efficient tactile sensor

Several attempts have been made to develop novel tactile sensor technologies to accommodate varied operations. The materials are chosen and the construction design has a critical influence in completing key tasks and other vital activities. Numerous tactile sensors are made of novel composite materials and structural designs that have resulted in excellent sensory system performance. An efficient tactile sensor can be determined upon five main parameters as shown in Fig. 8.

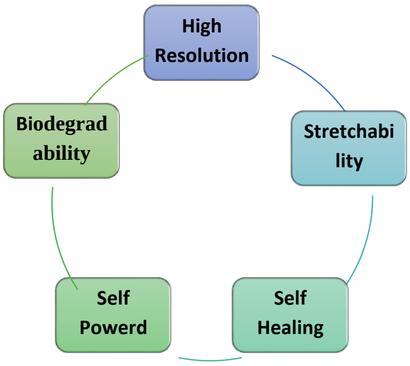

Fig. 8. Parameters to achieve a highly efficient tactile sensor.

5.1.1. High Resolution

Robots with high-resolution tactile sensors can distinguish the direction and location of objects, allowing them to execute more versatile actions (Zhong Lin Wang, 2010). The establishment of piezotronics and piezo-phototropic technology certified tactile sensors with high resolution. High-resolution enables touch sensors to detect effectively the texture of rigid objects in an environment of low visibility. This ability is required for the utilization of tactile sensors in electronic skins, image processing, and other related operations. Although, the normal piezoresistive or capacitive technology sensors have yet a restricted resolution range in millimeters. Excitingly, piezotronics technology has been used to improve the resolution capability. The technique of piezotronics is based on the polarization of non-moving ions in a crystal. Due to the nature of piezoelectric polarity potential, it is the outcome of the coupling action, which affects the local imbalance contacts at various sites of the material. The principle of the piezoelectric effect voltage-gate transistor differs from that of traditional field-effect transistors in that it is achieved between the metal-semiconductor contact interface by unbalanced contact features of voltage-induced ion polarization charge carrier and modulation behavior to enhance the touch sensors resolution by piezoelectric effect (Wenzhuo Wu et al., 2013).

5.1.2. Stretchability

Stretchability enhances the resemblance of tactile sensors to human skin and broadens their application scope. In nature, most animals possess tactile organs to sense parameters like temperature, roughness, and humidity. For stretchable tactile sensors, composite conductive materials, intrinsically stretchable conductors, and elastomers are employed to improve their stretchability (Sukjoon Hong et al., 2015; Debao Zhou and Haopeng Wang, 2013). Hou et al. developed a tactile sensor based on an electrode structure incorporating argentum nanofibers (AgNFs) and raw silk fiber (silk fibroin) (Chen Hou et al., 2019), while Sun et al. created an extensible electronic skin using prefabricated silver nanowires, where strength changed linearly with crack density over a 30% elongation range (Jiangman Sun et al., 2018).

Elasticity in tactile sensors can be achieved both at the structural and material levels. Early designs used fabricated structures to tolerate specific deformation within the fracture strain limits of composite materials. However, technological advancements now enable the use of naturally soft materials that are inherently stretchable, allowing reversible expansion and compression in response to applied force. For instance, Wang et al. fabricated an intrinsically polymer-based transistor array capable of operating at 100% stretchability, both horizontally and vertically relative to the direction of current transmission (Sihong Wang et al., 2018). The ability of polymer materials to stretch has sparked a slew of new tactile sensors research concepts. Geometrical configuration, a stretchable sensor with an island bridge design that can identify and evaluate multiple stimulations similar to the human somatosensory structure, is another method for achieving great stretchability. To create inherently stretchy material on an elastomeric substrate, two structural designs have been used: a) out-of-the-plane design and b) in-plane design. Polydimethylsiloxane (PDMS), Fluorosilicone and Eco flex, Dragon skin, and other silicon-based elastomers are utilized in stretchable sensors. A PCB (Printed Circuit) is typically used as a substrate above the rubber in an accessible stretchy tactile sensing solution. By lowering the parameters of electronic devices, components for multiplexing, signal processing, and other algorithmic measurements can be installed in the proximity of sensors (Ravinder S. Dahiya et al., 2013),(Zhiyuan Liu et al., 2018). Based on substrate structure, the force on the top of sensor can be calculated as in (4).

$$\varepsilon_{top} = \frac{(t_{sens} + t_{sub})}{2R} \frac{(1 + 2\eta + \chi\eta^2)}{(1 + \eta)(1 + \chi\eta)} \qquad (4)$$

where $\eta = t_{sens}/t_{sub}$, & $\chi = Y_{sens}/Y_{sub}$, which means force on top sensor decreased by increasing stretchability. Fig. 9 illustrates the bending of a stretchable tactile sensor (Sihong Wang et al., 2018; Ravinder S. Dahiya et al., 2013). Many scientists have worked to create high-performance flexible tactile sensors that mimic the micro- and nanostructures of living organisms (Haihang Wang et al., 2021). A tactile sensor, for instance, was created by Guo and colleagues using an electrode made of silk fibroin and Argentum nanofibers (Ag NFs). The silk fibroin film was extremely stretchable (more than 60%) (Wenxi Guo et al., 2015). Bao and colleagues created a transistor array out of a stretchable polymer. The device could function normally at 100% stretch, either parallel or perpendicular to the current transmission direction.

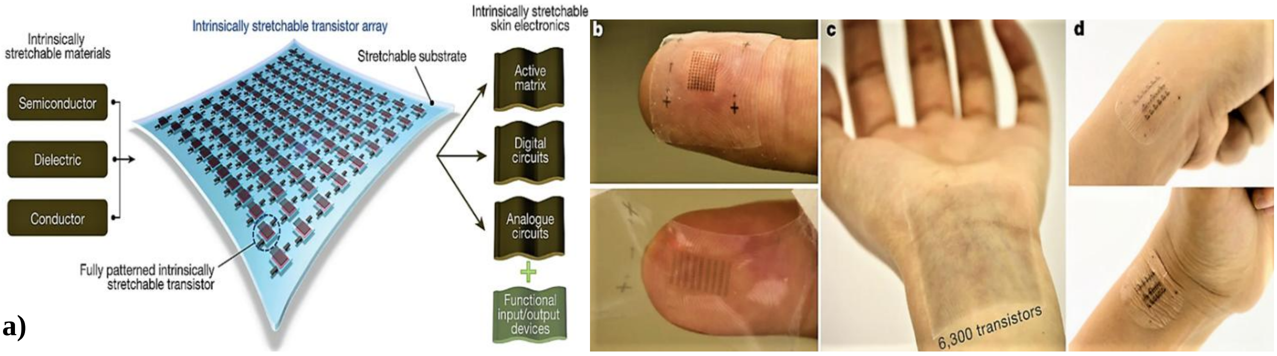

Fig. 9. (a) A three-dimensional view of an intrinsically flexible transistor array, the core component of skin electronics. (b) A fingertip array consisting of 108 flexible transistors, achieving a remarkable device density of 347 transistors/cm². (c) A large-scale array of 6,300 intrinsically flexible transistors, covering an area of approximately 4.4 × 4.4 cm², applied to a human wrist. (d) Intrinsically flexible circuits, representing a model for advanced skin electronics applications, seamlessly integrated onto a twisted human wrist (Sihong Wang et al., 2018; Wenjing Fan et al., 2020).

Pan et al. used conductive polymer materials to create a resistive pressure sensor with a hollow sphere structure. The pressure sensor has a sensitivity of up to 133.1 kPa^{-1} in the range of less than 30 Pa (Lijia Pan et al., 2014). Mu and colleagues created a flexible resistive-based force sensor capable of detecting forces in multiple directions (Chunhong Mu et al., 2018).In addition, Fan et al. demonstrated a self-powered cellulose-fiber-based TENG System with features like industrial bunch weaving, reuse, machine-washing resistance, max. sensitivity sensing, and wearing ease (Jizhuang Fan et al., 2020). Lorenzo Jamone et al. developed a tactile sensor with high sensitivity, low hysteresis, and good repeatability which calculates the normal external applied force.0.05 and N and 0.01N are the lowest detected force for fingertips and the phalangeal model respectively; the particular values are related to the state of art for the tactile sensors which are integrated into the robotic hand.

In addition, emerging materials like hydrogels and eutectic gallium-indium (EGaIn) are transforming tactile sensing for human-robot interaction by offering exceptional softness, stretchability, and biocompatibility. Hydrogels, with their high water content and ionic conductivity, mimic the mechanical properties of human tissue and have been used in soft, transparent, and self-healing sensors capable of detecting pressure, strain, and temperature (Antonio López-Díaz et al., 2024; Hritwick Banerjee et al., 2018; Honghong Wang et al., 2025). Recent developments integrate hydrogels with machine learning for enhanced signal interpretation and have shown promise in biomedical applications like wearable devices and surgical tools (Shuyu Wang and Zhaojia Sun, 2023). Similarly, EGaIn, a room-temperature liquid metal, is being embedded in elastomers or microfluidic channels to form highly deformable and conductive circuits. These systems provide precise pressure and strain sensing, with some designs also enabling temperature detection (Sen Chen et al., 2023; Yancheng Wang et al., 2021). EGaIn-based sensors support the creation of soft robotic systems with real-time feedback for safe, adaptive interaction (Weiqi Cheng et al., 2024). Together, hydrogels and EGaIn present a new frontier in multifunctional tactile sensors that closely replicate the behavior of natural skin.

5.1.3. Self-Healing

Human skin possesses the remarkable ability to heal and restore itself after external injury (Marek W. Urban, 2009), a feature that an ideal tactile sensor should replicate. A self-healing property significantly extends the lifespan of devices by enabling recovery from damage. Effective self-healing sensors must restore their functionality at room temperature through the reintegration of dynamic molecular bonds. These bonds, primarily covalent and non-covalent supramolecular linkages, enable mechanical recovery (Ying-Li Rao et al., 2016). Sun et al. introduced dynamic imine molecular bonds as reversible curing sites in PDMS chains (Jiangman Sun et al., 2018). By incorporating bis(imine)-terminated PDMS and 1,3,5-triformylbenzene, they created a polymeric cross-link that splits upon damage and restores via the Schiff reaction. Conductive materials such as a dispersed silver nanowire (Ag NW) lattice thin film and PEDOT film were employed, designed on a pre-stretched PDMS base to form a wavy pattern. However, the Ag-PEDOT film required additional curing via H-PDMS melting to restore electrical connectivity. Non-covalent supramolecular bonds, including metal-ligand, hydrogen bonding, π-π bonds, and host-guest complexes, offer another approach to self-healing (Ying Yang and Marek W. Urban, 2013). In such systems, weak hydrogen bonds form the foundation for healing, where mechanical injuries partially disrupt these bonds, enabling passive curing through reconnection. Sui et al. developed a conductive bionic hydrogel combining polyacrylamide (PAM) and sodium alginate (SA) nanofiber networks, mimicking the elasticity, stretchability, and sensitivity of natural skin (Chen Zhang et al., 2019). Additionally, PVA-borax hydrogel has emerged as a cost-effective candidate for self-healing, stretchable, and compliant electronic skin. Liu et al. enhanced this material by integrating pre-polymerized polydopamine (PDA) into a PVA-borax hydrogel system, improving its plasticity, stretchability, re-shapability, and elastic modulus (Zhiyuan Liu et al., 2018). The self-healing efficiency of the hydrogel structure was assessed through recovery of the storage modulus (G′) under strain sweeps from 0.1% to 100% and back to 0.1% at 0.1 Hz (Zhouyue Lei and Peiyi Wu, 2018).

$$\text{Self - Healing Efficiency} = G'A/G'B \tag{5}$$

Where G′A = storage modulus of strain sweeps from 100% to 0.1% at the strain of 0.1%; G′B = storage modulus of the strain sweeps from 0.1% to 100% at the strain of 0.1% (The test sample is the PC/rGO/PVA-1 hydrogel). Thuruthel et al.(Thomas George Thuruthel et al., 2021) developed a self-healing tactile sensor with self-healing material based on telechelic polyurethane with ureidopyrimidone end groups. The main structure and self-healing process are illustrated in Fig. 10 (Thomas George Thuruthel et al., 2021).

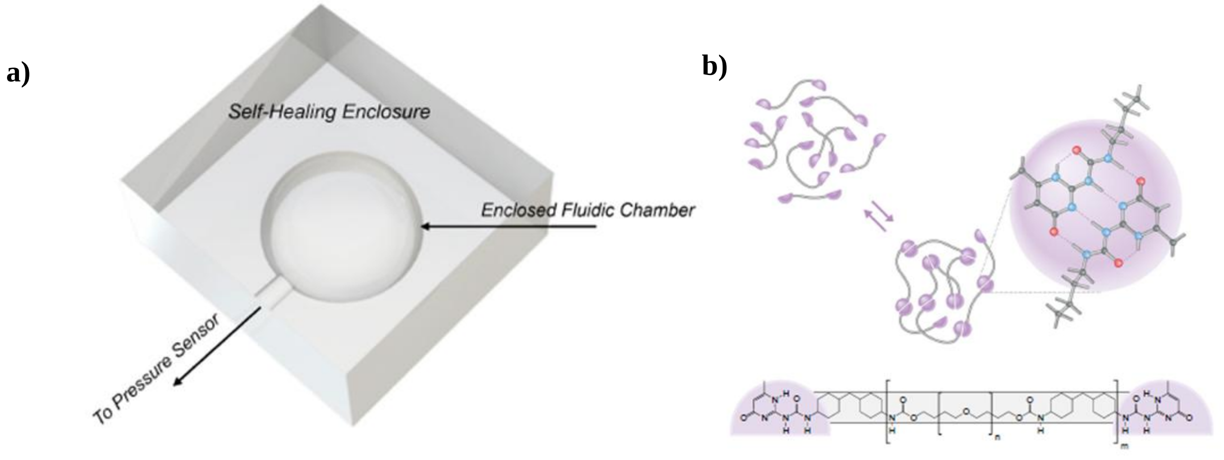

Fig. 10. (a) Design of the self-healing tactile sensor. (b) Together with the molecular structure, reversible hydrogen-bonding arrays are accountable for the supramolecular polymer's self-healing (Thomas George Thuruthel et al., 2021).

5.1.4. Self-Powered Capability

Wireless devices enable real-time, on-site monitoring and detection but still require a power source (Zhong Lin Wang and Jinhui Song, 2006). Ideally, these devices should be self-powered, eliminating reliance on batteries. The human body provides various energy sources, such as motion or position (e.g., exercise, muscle bending), sound waves (vibration energy), chemical components (e.g., glucose), and body fluids (e.g., blood circulation). However, the challenge lies in efficiently converting these energy sources into electrical energy. Harnessing such energy could significantly reduce the size of integrated optoelectronic nano systems (Ruixuan Yi et al., 2022), (Gengfeng Zheng et al., 2005), and resonators (X. D. Bai et al., 2003). In the future, energy harvested from nature and converted into electricity will be essential for tactile sensors (Wenxi Guo et al., 2015). Research on natural energy harvesting focuses on four main areas: i) Solar cells, which capture solar energy through photovoltaic technology; ii) Thermoelectric technology, which transforms thermal energy into electricity; iii) Piezoelectric technology, first demonstrated in 2006 by Wang and Song with their PENG design using ZnO nanowires; and iv) Triboelectric technology, where triboelectric nanogenerators (TENGs) convert mechanical energy into electrical energy (Zhong Lin Wang et al., 2012). Among well-known one-dimensional (1D) nanomaterials, ZnO stands out due to its unique properties: i) Its semiconducting and piezoelectric characteristics form the foundation for electromechanical interfaces in sensors and transducers; ii) It is biocompatible and bio-safe, suitable for biomedical applications with minimal toxicity; iii) ZnO facilitates the creation of various nanostructures, such as nanowires (NWs), nanobelts (NBs), nanosprings (Xiang Yang Kong and Zhong Lin Wang, 2003), nanorings, nanobows, and nanohelices (Pu Xian Gao et al., 2005). Fig. 11(a,b) depicts energy harvesting method and a self-powered tactile sensor designed by Wu et al. (Chaoxing Wu et al., 2020).

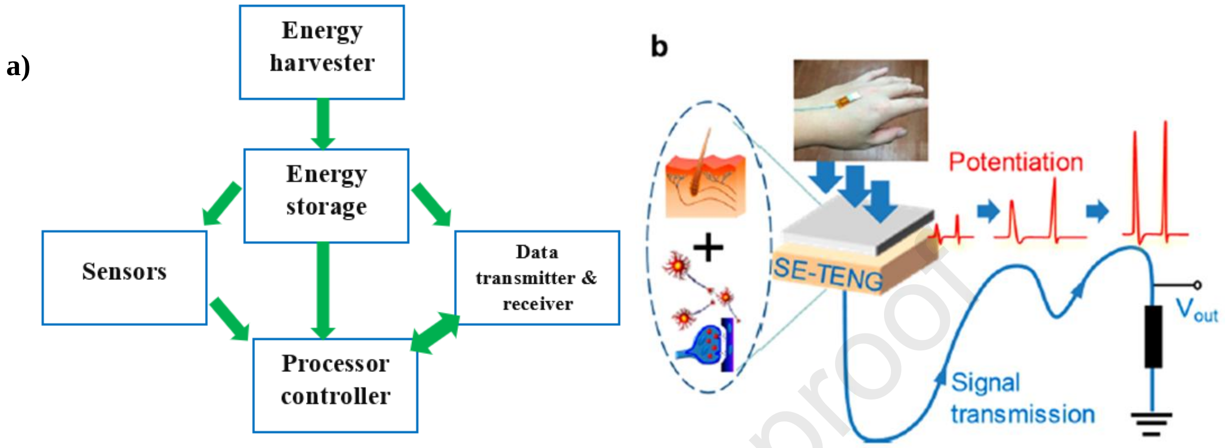

Fig. 11. (a) Energy harvester, energy storage, sensors, data processor, controller, data transmitter, and receiver are the five modules that make up the integrated self-powered system's schematic diagram. (b) The gadget has a single-electrode-based triboelectric nanogenerator as its configuration (SE-TENG).

Moreover, Fig. 11(b) The device can actively produce pressure-triggered electric signals thanks to the use of nanogenerator technology, which eliminates the need for an external power source (Chaoxing Wu et al., 2020).

The TENG was created by Wang et al. in 2012, and in subsequent years, it has been used in numerous power supplies and wearable sensors. Many studies on self-powered sensor techniques have been carried out to collect energy from the surroundings. Examples include solar cells for collecting solar energy with the help of the photovoltaic effect, thermal harvesters for collecting thermal energy based on thermoelectric effect, TENGs [triboelectric nanogenerators], and PENGs [piezoelectric nano-generators] for collecting mechanical energy with the help of triboelectric effect and piezoelectric effect respectively. With these power supplies, mechanical energy is observed as the main obtainable and practical power in daily routine because it is a universal source of energy that can be spotted at any moment & everywhere, as opposed to solar energy, which relies on the weather or season. Wang and Song created the first piezoelectric effect-based PENG in 2006, which can collect mechanical energy and transform that into electricity. Ma et al. (Ye Ma et al., 2016) developed a self-powered installed triboelectric sensor that can yield regular tracking of various pathological and physiological signs. Guo et al. reported the fabrication of a self-powered acoustic sensor for use as an exterior hearing aid in intelligent robotic applications (Wenxi Guo et al., 2015). Shaoxing Wu et al (Chaoxing Wu et al., 2020) demonstrated triboelectric nanogenerator-based intelligent neuromorphic tactile sensors with self-powered pressure sensing and key neuromorphic system features. These sensors can perform synapse assistance and potentiation, as well as memory & forgetting.

5.1.5. Biodegradability

Healthcare professionals can monitor various health issues, such as arrhythmia and bradycardia, through wireless communication using mobile and sensor systems.

With the growing emphasis on environmentally responsible technologies, tactile sensor research is increasingly embracing sustainable design principles. Biodegradable polymers such as polylactic acid (PLA), cellulose, chitosan, and starch-based hydrogels have emerged as promising materials for eco-friendly electronic skins, offering both mechanical compliance and environmental degradability (Huacui Xiang et al., 2022; Zhiqiang Zhai et al., 2022). These materials not only reduce long-term e-waste but also support biomedical applications where temporary sensor deployment is advantageous. Additionally, energy-efficient designs such as self-powered tactile sensors based on triboelectric nanogenerators (TENGs) are gaining traction (Ting Lei et al., 2017). These systems convert ambient mechanical energy like pressure, vibration, or motion into electrical signals, enabling real-time sensing without the need for external power sources (Ling-Feng Liu et al., 2024; Yajun Mi et al., 2022). The integration of such green technologies aligns with current trends in sustainable electronics and is expected to play a pivotal role in future wearable and implantable sensor systems.

Biodegradability in medical devices eliminates the need for secondary surgeries, advancing treatment technologies and improving stability (Victor Shnayder et al., 2005). Biodegradable tactile sensors can be fabricated using silicon nanofilms or inorganic films (Suk-Won Hwang et al., 2012). ZnO is particularly advantageous due to its high piezoelectric output, transparency to certain wavelengths, and excellent electron mobility (Kazuhiro Miyamoto et al., 2004), which make it suitable for applications ranging from films to wires, rods, and sensing devices (Min-Hua Zhao et al., 2004). Additionally, ZnO demonstrates good biocompatibility, making it safe for integration inside or outside the human body (Zhou Li et al., 2008). ZnO-based electronic devices can dissolve in fluids or water, offering an alternative to silicon and organic semiconductors, such as π-bonded molecules or polymers, for creating electronics and sensors. These devices hold promise in fields like energy recovery, light emission, and more. Other key materials include magnesium (Mg) for electrodes, magnesium oxide (MgO) for dielectrics, and silk fiber films for substrates and packaging. The manufacturing of organic electronics using these materials is environmentally friendly. For example, Wang et al. developed a biodegradable triboelectric nanogenerator (BN-TENG) based on natural materials to assist in treating diseased hearts (Zhong Lin Wang et al., 2012). Yihua Gao and colleagues use a hybrid 3-Dimensional design based on ultra-light & super-elastic MXene/reduced graphene oxide aerogel to fabricate a Piezoresistive based tactile sensor with a sensitivity of 22.56 kPa^{-1} and the limit sensation was 10 Pa. Bao's group demonstrated a completely biocompatible and disintegrable polymer of semiconductor material for transistors thin-film. The polymer is made up of reversible bonds of imine group and construction blocks which can be decomposed easily in a mildly acidic environment. In addition, biocompatible & disintegrable artificial-complementary metal-oxide-semiconductor (CMOS) stretchable circuits are signified. These stretchable integrated circuits are ultra-light weight (~2g/m2), ultrathin [<1 μm] under minimum functional voltage (4 V), suggesting potential functions for these semiconducting disintegrable polymers with less cost, transient electronics with ultra-light weight, and biocompatible (Ting Lei et al., 2017). Fig. 12 below shows the structure of a plant-based biodegradable capacitive tactile sensor developed by Elsayes et al. (Ahmed Elsayes et al., 2020).

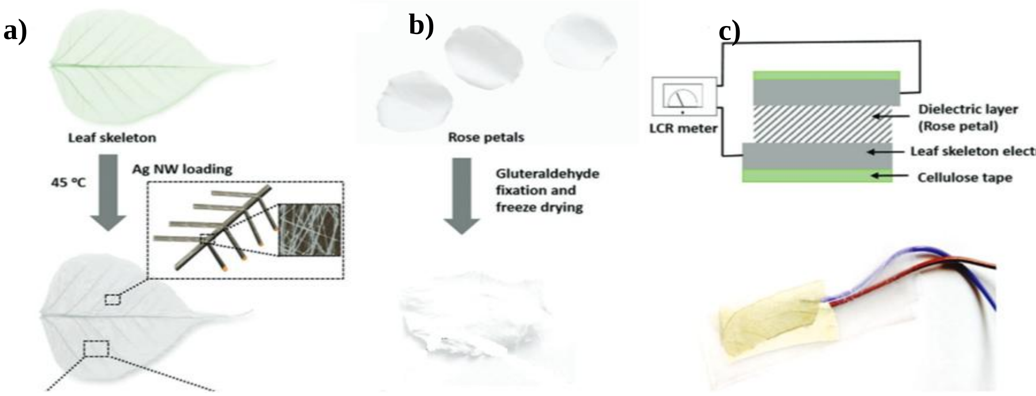

Fig. 12. (a) Ag NW is loaded into a leaf skeleton. (b) The dielectric layer is a freeze-dried rose petal. (c) A dielectric rose petal layer is sandwiched between two leaf electrodes to create a capacitive tactile pressure sensor, with cellulose tape acting as the sealing agent (Ahmed Elsayes et al., 2020).

To achieve biodegradability of tactile sensors for intelligent systems, conjugated polymers have been developed. Because of the good stretchability, easy fabrication process, and extremely high carrier mobilities, conjugated polymers are observed as an applicant for FETs [field-effect transistors]. Table 5 summarizes the current applications of tactile sensors used in diverse arenas.5

Table 5
Shows the applications that utilize tactile sensors in different fields (Cheng Chi et al., 2018; Javad Dargahi and Siamak Najarian, 2005).

Application Fields	Robotics Field	Biomedical Field	Sports Field	Agricultural Field	Aerospace & Automobile Field	Consumer service Field
Utilization and operational areas	Ready to command or manipulate the object. Aided/Rescue robots. Service robots [215, Remotely controlled robots.	Remotely robotics operations Analytical and Diagnostic Equipment Recovery/rehabilitation medication. Orthodontic Concern of Patients. Gait examination technique Minimally Invasive Surgery Equipment's	Position examination Sports teaching	Professional robots like for fruit harvesting, For fertilizer/manure sprayer	Security Map reading connection for mobile service guidelines Velocity amendment system Analytical equipment Equipment for protection	Health miniatures for example toothbrushes Aided robots for aged people Fabrics & clothing
Obstacles in design	Biased and categorization algorithm. repetition, abrasion-resistant, broad dynamic range Transformation, designated output over a broad range of temperatures Maximum frequency feedback.	Bioabsorbable. Strongly hold out against pasteurization operation price, because of the biodegradable capability Without wiring network, Consumption of Energy Maximum output feedback. Electric-cutaneous response procedure Secure and Trustworthy Uncomplicated	Acquiescent & specialized sensors. Longevity Wire network & energy restrictions Without wiring network	Flexibility to unordered situations. Poison-free & Sensitive free manufacturing Disinfection & dirt free. Secure for food grasping Proficient and expert motion. Gently handling sensitive objects Undetected operational fields	Equipment-based sensor structure Undiscovered operational fields Secure and accurate Strongly hold out against normal, shear, and tensile forces	Customer consent Abrasion-resistant & genuine price, therefore, it can be utilized in broad areas

6. Challenges and Future Directions

Numerous promising sensors have been outlined in the literature, and up to this point, single tactile sensors with various transduction techniques have received adequate research. There are comparatively more studies on single tactile sensors with novel materials and new designs than the tactile detecting system. Some proposed sensors have performance levels that exceeded the capabilities of human senses. Even though, custom-designed sensing arrays and systems remain urgently needed, owing to a lack of focus on robustness, which has been the most significant impediment to practical application scenarios. The vast majority of reported tactile sensors are extremely sensitive to factors in the working environment, including temperature, humidity, and unanticipated collisions. Another important consideration in tactile sensing arrays is consistency. While increasing the number of sensing units, calibrating each unit each time the array is used becomes extremely time-consuming. As a result, each element, including the response of pressure curve and response zero-load, should be consistent. Furthermore, the tactile array should be consistent over thousands of iterations. Most tactile sensors currently do not fulfill these requirements. Single sensors with a wide range of transduction operating features have been satisfactorily explored up to this point, and a wide range of tactile sensors have been defined in the literature. Stretchable sensors, according to Buchem et al. (Ilona Buchem et al., 2019), are a rapidly expanding trend in pressure and strain sensors. Furthermore, Han and his co-workers. exhibited the pioneering stretchable sensor and offered a future evolution based on a market survey and useful work (Su-Ying Han et al., 2017).

One of the persistent challenges in tactile sensor development is the lack of standardized testing protocols for evaluating key performance parameters such as sensitivity, hysteresis, response time, dynamic range, durability, and drift. This lack of uniformity not only hinders meaningful comparison between different sensor designs but also limits reproducibility and benchmarking across research groups. Several studies have highlighted the variability in measurement conditions such as loading methods, indentation geometry, and environmental factors which significantly affect reported performance metrics (Han Zhao et al., 2023; Zhen-Pei Wang et al., 2023). To address this, researchers have proposed frameworks for mechanical and electrical benchmarking using standardized phantoms and robotic platforms, aiming to simulate realistic use-case conditions. Furthermore, recent collaborative efforts such as the IEEE Tactile Standards Working Group (P2863) are actively defining performance evaluation protocols for tactile sensing systems in robotics and haptics. Adoption of such standards would accelerate technology transfer by ensuring comparability, transparency, and reliability critical elements for medical, industrial, and wearable sensor applications.

Moreover, as tactile sensing systems scale up in complexity and area such as in full-body robotic skins or smart prosthetics traditional wired architectures pose limitations in terms of weight, flexibility, and integration. Wireless tactile sensor networks (WTSNs) have emerged as a scalable alternative, enabling distributed sensing through modular, low-power nodes that communicate over protocols such as BLE, ZigBee, or custom RF interfaces. These systems allow for seamless integration over large, deformable surfaces without compromising signal integrity or mechanical compliance. Notable implementations include soft wireless skins capable of detecting pressure and temperature for humanoid robots, with real-time data streamed to central processors (Lin Zhang et al., 2024), and flexible sensor arrays using NFC and energy harvesting to achieve battery-free wireless operation (Gaoqiang Zhang et al., 2023). WTSNs also facilitate modular design and fault tolerance, essential for applications like prosthetic limbs, rehabilitation suits, and soft robotics. Addressing wireless data synchronization, latency, and energy management will be key to enabling next-generation large-area, intelligent tactile surfaces.

Tactile technology is a mature subject for future development and research due to the growing aging population, developments in prosthetics technology, increasing demand for commercial and domestic touch-based accessories, and the utilization of robotic surgery in healthcare facilities. Advances in novel materials, microstructure, and nanostructure have the potential to significantly increase sensor performance. On the other hand, artificial intelligence tactile device has made great progress in advanced applications such as behavior research and configuration recognition. Tactile sensing arrays' possible applications might be expanded still further, particularly in robotics and medical treatment. Robotic applications have advanced significantly in recent years as a result of the tremendous advancements in artificial intelligence (AI). Robots are becoming more intelligent and anthropomorphic. The blending of tactile and visual sensations is one of many research areas that place more emphasis on the interaction of fundamental sensory systems.

Moreover, neuromorphic tactile systems emulate the biological somatosensory process by encoding tactile stimuli into spikes using spiking neural networks (SNNs), enabling low-latency and energy-efficient processing suitable for embedded robotics. For example, NeuroTac combines a compliant skin and event-based camera to classify edge orientations using unsupervised SNNs(Fraser L. A. Macdonald et al., 2022). Iskarous et al. demonstrated a neuromorphic model robust to variations in scanning speed and pressure for dynamic texture classification (Mark M. Iskarous et al., 2025). On the hardware side, Fang et al. developed iontronic neuromorphic sensors using stretchable transistors that mimic synaptic plasticity for real-time touch memory (Shilei Dai et al., 2023), while Shen et al. introduced a hybrid triboelectric–capacitive sensor capable of spatiotemporal encoding(Zhixue Li and Hongwei Sun, 2023). Oddo et al. simulated a full spiking tactile pathway from mechanoreceptors to cortex for texture sensing tasks (Adel Parvizi-Fard et al., 2021). With neuromorphic chips like Intel's Loihi, these systems are being deployed in prosthetics, robotic skins, and wearable devices to enable intelligent, adaptive tactile perception (Dmitry Ivanov et al., 2022).

While triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs) offer exciting paths toward self-powered tactile sensors, several practical limitations curb their current applicability in robotics. TENGs often exhibit high output impedance, which hinders efficient energy transfer and power delivery, and show strong sensitivity to humidity, resulting in inconsistent performance in varied environments, as demonstrated by Fu et al. (Shaoke Fu et al., 2023; Zhan Shi et al., 2024). Their limited durability and device degradation over time present additional concerns for long-term use (Jun Zhao and Yijun Shi, 2023). PENGs, while reliable for dynamic energy harvesting, may also be limited by material fatigue and stability issues under prolonged mechanical loading, which challenges their longevity in repetitive robotic motions (Zhong Lin Wang et al., 2012; Ting Lei et al., 2017; Jun Zhao and Yijun Shi, 2023). These factors suggest that although TENG and PENG technologies are promising, further optimization is essential before they can be widely adopted in robust, long-term robotic applications.

For illustration, tactile sensing and visual details are needed together for robotic grasps, a fundamental but important research topic. Currently, the majority of studies focus on visual information for grasp location and object detection, followed by tactile feedback for object capture confirmation. More integration of tactile and visual information is possible, going beyond simply catching an object. The texture, hardness, etc. of an object could be felt using tactile sensors. Robots may be able to understand objects they come in contact with more thoroughly than humans do by combining shape and color information from visual sensors. Tactile sensors are primarily used in the medical area by surgical robot clips, which are attached to people's bodies and used to monitor physiological signals by assessing the degree of lesions and hardening of the contacted tissues. To meet the demands of more complex surgery, tactile sensors must be smaller and more sensitive. To measure blood vessel contraction tension during bypass surgery, for instance, cardiologists need tactile sensors.

7. Conclusion

In this article, we have briefly reviewed the operational procedures of tactile sensors and research-based characterization for various applications based on piezoresistive, capacitance, piezoelectric, and optoelectronic technologies. The current scope is to develop innovative materials and creative techniques to upgrade the continuous advancement in enhancing sensor functions. In particular, the fundamental characteristics of the sensors, such as flexibility, high spatial resolution, stretchability, self-healing, self-powered, and biodegradability Industries have increased their demand for and consumption of tactile sensory technologies. As shown in Fig. 1, it has been amply demonstrated in prior research publications. Similarly, research tasks in this field have increased. Problems with the tactile sensor, such as its incapability to operate without an external power source, limit the practical use of wearable technology. The ability to detect a process without an external power source has thus been established as a self-powered characteristic. Basic components for complex applications in humanoid robots and biomedicine include stretchability, transparency, and self-healing. As a result, structural design, Nano/macro designs of surface contacts, and novel materials should be improved and consolidated to achieve exceptional performance. The improvement of techniques is aided by the development and ongoing research in the tactile sensory system for a variety of applications, including the biomedical and industrial fields.

This paper provides a general overview of human tactile systems and the evolution of tactile sensors since the 1970s. We illustrate cutting-edge design trends using a range of transduction mechanisms, such as capacitive, piezo-resistive, inductive, and optical sensors. Furthermore, the benefits and drawbacks of the aforementioned mechanisms are discussed. CNT-based Nano composites are a great replacement for achieving the versatility of human skin. Their reduced cost and simple manufacturing techniques, such as digital printing, make them ideal for massive industrial production. Recent reviews indicate that capacitive and piezoresistive tactile sensors dominate current robotic applications due to their lower cost, straightforward fabrication, high sensitivity, and scalability, while piezoelectric, optical, and inductive sensors remain less commonly adopted and are often limited to niche or experimental uses. For example, comprehensive surveys of tactile sensing technologies highlight the widespread utilization of capacitive and piezoresistive sensors in robotic systems, contrasting with the relatively limited implementation of piezoelectric, optical, and inductive types because of integration challenges and higher costs (Cheng Chi et al., 2018; Jie Jin et al., 2023). These findings collectively suggest that piezoelectric, optical, and inductive tactile sensors, while technologically significant, are not yet the preferred options for mainstream robotic applications. Additionally, the use cases for tactile sensor arrays in robotics and medical assistance could be expanded. The use of tactile feedback to establish closed-loop control systems and the combination of visual and tactile details both are showing promise and meaningful suggestions for further studies. Stretchable tactile sensors' development was accelerated by polymer materials with inherent stretchability. The development of biomimetic and bioinspired robotics, synaptic prostheses, involves converting equipment (for surgical intervention, endoscopy, rehabilitative services, and additional help), and anthropomorphic robotics are all being facilitated by synthetic approaches. The artificial tactile sensing device must address three key challenges in each of these application areas.

1. creation of functional and serviceable robotic and automation system;
2. a clearer understanding of the techniques used by various biological systems;
3. successful connections to natural systems.

MEMS are captivating for biomedical applications, especially because they can be customized for specific physical and chemical characteristics at the micrometer and nanostructure sizes. BioMEMS, which combines biological and composite ingredients, would enable long-term Vivo detecting and a higher level of biocompatibility for the sensor. The recent growth in fusing biological components and micromachined devices could lead to the creation of fully integrated MEMS-based equipment ready to replace biological systems in the human body. However, in the past, most MEMS devices were built on rigid substrates, whereas versatile and complied structures will be needed to imitate and examine biological systems, as well as for improved bio integration. The competency and potential of triboelectric nanogenerators in intelligent sporting activities, safety, touch control, and information retrieval have received much interest in artificial intelligence technologies like machine learning, big data computation, and cloud-based services, which necessitate a large number of sensors and a multifaceted sensor network

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Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose. We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

Data availability

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Advancing Mechanoreceptor Sensing Technologies: A Strategic Review of Recent Innovations and Trends

Highlights

- Mechanoreceptor sensors reviewed for enhanced sensitivity and flexibility.
- Innovations in piezoresistive, capacitive, and piezoelectric tactile sensors.
- Address challenges in scalability, durability, and cost-effectiveness of sensors.
- Integration of tactile sensors with AI for self-learning and improved decision-making.
- Applications span robotics, medical diagnostics, and consumer electronics.

Dear Editor-in-Chief,

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

Thank you for your consideration of this manuscript.

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