Tactile Sensors for Advanced Intelligent Systems

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With the capability of completing a task or achieving a goal in an uncertain environment while simultaneously having the characteristics of adaptability, self-optimization, self-diagnostics, and self-maintenance, intelligent systems have witnessed extraordinary progress in recent years. These advances involve robotics, artificial intelligence and machine learning, automation, human–machine interfaces, the Internet of Things, control theory and control systems, smart and responsive materials, intelligent sensing systems, and programmed self-assembly. As an active technology conveying mechanical stimuli to a wide range of electrical and optical signals, tactile sensors are essential elements of intelligent systems and have accelerated the emergence of advanced intelligent systems by enabling the accurate recognition and safe interaction of humans and machines, smart sensing of control systems, precise control of robotics, and synergistic work of artificial intelligent systems. Herein, the recent advances of tactile sensors for advanced intelligent systems are reviewed, emphasizing these with the working principles of piezoresistance, resistance, capacitance, piezoelectricity, triboelectricity, and optics. Representative examples of their applications in advanced intelligent systems, such as robotics, human–machine interfaces, and artificial intelligence, are explored. The remaining challenges and perspectives in this emerging field are also discussed.

1. Introduction

As reported by the World Economic Forum, a fourth industrial revolution is currently taking place. Emerging technological breakthroughs in intelligent systems, such as the Internet of Things, artificial intelligence (AI), automation, robotics, human–machine interfaces (HMIs), control theory and control systems, quantum computing, machine learning, and smart sensing systems, promise to radically modify our future and the way we perceive our society.[1–7] With an integrated network of sensors, processors, and actuators, advanced intelligent systems (AIS) are capable of responding to stimuli, gathering and analyzing data, actuation, adaptability, and self-diagnostics and self-maintenance.[8–10] As an indispensable component of AIS, versatile sensors, including vision, tactile, taste, olfaction, and hearing have been developed and demonstrated.[11] Compared to other methods, tactile sensors have recently emerged because they can sense the geometry, texture, presence, and position of touched objects, as well as any additional relevant information, such as force, strain, shear, flexion, torsion, and vibration, thus enabling the accurate recognition and safe interaction of human and machine, the smart sensing of control systems, the precise control of robotics, and the synergistic work of artificial intelligent systems (Figure 1).

Tactile sensors are generally composed of pressure and strain sensors, which are able to convey mechanical stimuli to a wide range of electrical (voltage, resistivity, capacity, current, etc.) and optical signals based on enormous transduction mechanisms, including piezoresistive, resistive, capacitive, piezoelectric, triboelectric, optical, pyroelectric, magnetic, inductive, ultrasonic, and resonant.[12–20] Through a conjunction of materials innovation and
layout designs, researchers have been pursuing the development of
tactile sensors that can mimic human skin, which can synchronously
sense and distinguish diverse stimuli, such as the normal
pressure, lateral strain, shear, flexion, torsion, and vibration, all
simultaneously from a complex environment, with the attributes of
a large-scale, high spatial resolution, high sensitivity, fast
response, stretchability, life-time stability, and self-healing.[21–26]

This article intends to provide an overview on the state-of-the-art
of tactile sensors toward AIS, concentrating on the working
principles of piezoresist ance, resistance, capacitance, piezoelec-
tricity, triboelectricity, and optics. Novel materials and structure
strategies toward the performance improvement of tactile sen-
sors are discussed for each type. The applications of tactile
sensors in AIS, including robotics, HMIs, and AI are discussed.
Challenges and further research directions are proposed as well.
This review is expected to be a good tutorial for related
researchers.

2. Overview of the Working Mechanisms

Despite the variety of technical strategies currently implemented
to create a tactile sensor, here we only highlight the more com-
mon, or according to us, more promising strategies for practical
application. Their working mechanisms are shown in Figure 2,
corresponding to piezoresistive, resistive, capacitive, piezoelec-
tric, triboelectric, and optical mechanisms.

2.1. Piezoresistive

Piezoresistive tactile sensors transduce mechanical stimuli into a
change in the resistance, which typically depends on two main
mechanisms that are determined by the equation of resistance

\[ R = \frac{\rho L}{A} \]  

(1)

where \( \rho \) is the resistivity, and \( L \) and \( A \) are the length and cross-
sectional area of the resistor, respectively. The first mechanism is
determined by the change in the geometry (\( L \) and \( A \)) of the resis-
tor, where \( L \) increases and \( A \) decreases due to the Poisson effect
upon stretch.\[27\] The second one is based on the change in \( \rho \),
which can be caused by a dynamic percolation (Figure 2a)\[28\]
or quantum tunneling\[26\] of the conductive fillers in an insulating
polymer matrix, or a change in the energy band structure of a
semiconductor, such as Si\[30\] carbon nanotubes (CNTs),\[31\] or
graphene.\[32\] Piezoresistive tactile sensors generally require less
electronics since a change in resistance can easily be quantified
and they are therefore easy to manufacture and integrate. In addi-
tion, they are less susceptible to noise, so they work well in array
configurations with less cross-talk or field interactions between
adjacent units. However, the piezoresistive tactile sensors gener-
ally suffer from hysteresis and therefore have unfortunate
frequency response characteristics.

2.2. Resistive

Resistive tactile sensors utilize the change in the contact resis-
tance between two conductors under the applied force, which
generally occurs in an interlocked microstructure (Figure 2b)\[33\]
a woven textile structure,\[34\] or a micro-cracked metal thin film on
a soft substrate.\[35\] The dependence of the contact resistance \( R_c \)
on the applied force \( F \) is determined by

\[ R_c \propto F^{-\frac{1}{2}} \]  

(2)

which enables a high sensitivity at a low pressure and a broad
working range of the sensor.\[36\] Resistive tactile sensors generally
have a good dynamic response, a high sensitivity, and a tunable
working range. However, they are typically accompanied with an
undesirable drift and hysteresis.
Figure 1. Tactile sensors for AIS. a) Triboelectric pressure sensor. Reproduced with permission.[243] Copyright 2012, American Chemical Society. b) Capacitive pressure sensor based on transparent elastic films of CNTs. Reproduced with permission.[34] Copyright 2011, Nature Publishing Group. c) Optical pressure sensor based on mechanoluminescence materials. Reproduced with permission.[64] Copyright 2015, Wiley-VCH. d) Piezoelectric pressure sensor based on ZnO nanowire array. Reproduced with permission.[215] Copyright 2015, American Association for the Advancement of Science. e) Resistive strain sensor based on micro-cracked metal thin film. Reproduced with permission.[130] Copyright 2014, Nature Publishing Group. f) Optical pressure sensor based on GaN/ZnO p–n junction LED. Reproduced with permission.[264] Copyright 2013, Nature Publishing Group. g) Resistive pressure sensor based on interlocked microdome arrays of CNT/PDMS mixture. Reproduced with permission.[90] Copyright 2014, American Chemical Society. h) Smart glasses integrated with triboelectric pressure sensor. Reproduced with permission.[264] Copyright 2017, American Association for the Advancement of Science. i) Micro-cracked strain sensor for speech-pattern recognition. Reproduced with permission.[264] Copyright 2014, Nature Publishing Group. j) Intrinsically stretchable pressure sensor for skin electronics. Reproduced with permission.[264] Copyright 2018, Nature Publishing Group. k) Scalable tactile glove-based resistive pressure sensor. Reproduced with permission.[264] Copyright 2019, Nature Publishing Group. l) Epidermal electronic integrated with strain sensor. Reproduced with permission.[264] Copyright 2011, American Association for the Advancement of Science. m) Resistive pressure sensor for artificial afferent nerve. Reproduced with permission.[264] Copyright 2018, American Association for the Advancement of Science. n) Tactile glove based on microfluidic liquid metal. Reproduced with permission.[264] Copyright 2017, Wiley-VCH.

Figure 2. Working mechanisms of the tactile sensors. a) Piezoresistive. b) Resistive. c) Capacitive. d) Piezoelectric. e) Triboelectric. f) Optical.
2.3. Capacitive

Capacitive tactile sensors consist of a dielectric material sandwiched by two electrodes, which convey the mechanical stimuli into a change in capacitance (Figure 2c). For capacitors with a parallel plate structure, the capacitance ($C$) can be given as

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$ \hspace{1cm} (3)

where $\varepsilon_0$ is the permittivity of free space, $\varepsilon_r$ is the relative permittivity of the dielectric material, and $A$ and $d$ are the overlapping area and the distance between the two electrodes, respectively. $A$ and $d$ are sensitive to external mechanical stimuli and therefore can be used for tactile sensing, in which $A$ is typically used to measure the shear forces and strains, and $d$ is commonly used to measure the normal ones.\(^{[37,38]}\) $\varepsilon_r$ can be tuned by embedded fillers\(^{[39]}\) or specially designed microstructures\(^{[40,41]}\) to enhance the sensitivity and response speed. Capacitive tactile sensors generally exhibit an excellent frequency response, a large dynamic range, and a high spatial resolution. However, the high spatial resolution sacrifices the signal-to-noise ratio of the sensor because $C$ is proportional to the pixel size of $A$.\(^{[42]}\) Meanwhile, the capacitive tactile sensors are more susceptible to noise compared with the resistive ones due to the field interaction and fringing capacitance, and thus require relatively sophisticated electronics for filtering.\(^{[43]}\)

2.4. Piezoelectric

Piezoelectric tactile sensors are based on the piezoelectric effect, where a piezoelectric potential is generated by mechanically deforming the piezoelectric materials (Figure 2d). The piezoelectric effect can arise either from the displacement of the cations' and anions' center in materials with a non-centrosymmetric crystal structure, such as lead zirconate titanate (PZT),\(^{[44]}\) zinc oxide (ZnO),\(^{[45]}\) cadmium sulfide (CdS),\(^{[46]}\) aluminum nitride (AlN),\(^{[47]}\) and gallium nitride (GaN),\(^{[48]}\) or from the alignment of the permanent dipole moment inside the materials, such as polyvinylidene fluoride (PVDF),\(^{[49]}\) after a poling process. The ability of the piezoelectric materials to convert the mechanical loads into a piezoelectric potential is facilitated by utilizing the piezoelectric constant of $d_{33}$.\(^{[50]}\) Inorganic materials, such as PZT, ZnO, CdS, AlN, and GaN, generally possess a high $d_{33}$ and are thus sensitive to applied loads. However, the high Young’s modulus limits their applications in soft tactile sensors. PVDF is intrinsically flexible but has a low $d_{33}$. A combination of inorganic piezoelectric materials and a polymer matrix has been attempted to achieve a trade-off between the dielectric and mechanical properties.\(^{[51]}\) The piezoelectric tactile sensors exhibit an excellent high-frequency response due to the instantaneous generation of a piezoelectric potential upon deformation, making them an ideal candidate for the vibration measurements. However, they are unable to measure static deformations due to their large internal resistance.\(^{[21]}\) Moreover, piezoelectric materials are also pyroelectric, so concerns on the temperature sensitivity of the piezoelectric tactile sensors are therefore necessary.

2.5. Triboelectric

As an effective mechanical-to-electrical conversion mechanism, the triboelectric effect has been extensively investigated for self-powered tactile sensors, in which triboelectric charges are generated between two different contact materials by the coupling of contact electrification and electrostatic induction.\(^{[52,53]}\) In detail, when two materials with different triboelectric polarities contact with one another, charges transfer between the two material surfaces is promoted due to the triboelectric effect, leading to the formation of opposite charges on each side of the surfaces (step i shown in Figure 2e). When the two surfaces are separated, compensating charges are built up on the top and bottom electrodes due to electrostatic induction (step ii shown in Figure 2e). This induction promotes the current flow from the positive to the negative sides of the materials through an external circuit until the accumulated charges are neutralized and balanced on all sides of the electrodes (step iii shown in Figure 2e). Similarly, when the two different charged materials are brought closer to one another, the current flows from the negative to positive sides of the materials (step iv shown in Figure 2e).\(^{[54]}\) Consequently, the cyclic contact and separation between the two materials drive the output current flow back and forth between the positive and negative electrodes, endowing the self-powered sense of the normal forces.

Except for the vertical-contact-separation mode, the triboelectric tactile sensors can also work in the lateral-sliding mode, single-electrode mode, or free-standing-triboelectric-layer mode, as determined by their device architectures.\(^{[15,55,56]}\) The basic structure of the lateral-sliding sensor is similar to the vertical-contact-separation structure, where the relative sliding movement of the triboelectric layers is in a parallel direction to enable the signal’s output, thus allowing it to sense shear forces.\(^{[57]}\) A single-electrode sensor generally contains a grounded bottom electrode and relies on the electrons to transfer between the electrode and the ground to convert mechanical stimuli (could be normal forces or shear forces) into electrical signals.\(^{[58,59]}\) The free-standing-triboelectric-layer sensor typically consists of a pair of symmetric electrodes with a freely moving triboelectric layer between them, in which triboelectric charging takes place between the moving electrodes and the triboelectric layer, inducing the charges to flow between the electrodes due to the asymmetric charge distribution.\(^{[60]}\) This mode can sense both the normal forces and the shear forces.

2.6. Optical

Optical tactile sensors include several different approaches, all of which use light in some way, such as light phase, the propagation path, reflection, wavelength, polarization, color, and intensity. They are usually divided into two types: index- and camera-based sensors. The former uses the properties of optical reflection, propagation, etc., for tactile sensing.\(^{[61–63]}\) For example, the wavelength of a light beam transiting in an optical fiber can be shifted by an applied strain due to the change in the grating parameter (Figure 2f).\(^{[63]}\) The latter monitors the changes in light intensity or the color of the device when interacting with the applied force via a charge coupled device (CCD) or complementary metal oxide.
semiconductor (CMOS) camera, which is also our focus herein because it is suitable for the high spatial resolution of tactile imaging.\cite{64,65} For example, the change in light intensity of mechanoluminescence materials such as manganese-doped zinc sulfide under an applied pressure can be recorded via a digital camera for real-time tactile sensing.\cite{64} Optical tactile sensors are immune to common lower frequency electromagnetic interference generated by electrical systems, and usually have a high spatial resolution and wide frequency response range. However, they suffer from integration complexity and medium power consumption.\cite{66}

### 3. Materials and Structures toward Tactile Sensors

Generically speaking, tactile sensors consist of a tactile-sensitive component that produces a signal in response to mechanical stimuli. Two strategies have emerged for the development of a tactile-sensitive component: 1) the utilization of novel materials that intrinsically convert mechanical stimuli into optical or electrical signals; or 2) the layout designs of a structural unit that generates a signal upon deformations. Here both strategies are highlighted, aimed at the advancements of tactile sensors based on various working principles.

#### 3.1. Piezoresistive Tactile Sensors

With advances in the ease of fabrication and the abundance of constituent materials, conductive composites have become integral building blocks for the piezoresistive tactile sensors. The conductive composites are composed of conductive fillers embedded into insulated polymer matrices via blending,\cite{67} in situ formation,\cite{68} and ion implantation.\cite{69} A myriad of fillers have been exploited in the development of conductive composites, ranging from 0D nanoparticles (NPs) such as carbon black,\cite{70} Au NPs,\cite{69} and Ag NPs,\cite{68} to 1D nanowires (NWs) or nanotubes (NTs) such as Ag NWs,\cite{71} Au NWs,\cite{72} and CNTs,\cite{67} to 2D nanosheets such as graphene,\cite{73} Au flake,\cite{74} and Mxene.\cite{75} Polydimethylsiloxane (PDMS) is the most commonly used polymer matrix.\cite{76} Other matrices include Ecoflex,\cite{77} polyurethane (PU),\cite{78} polyvinyl alcohol (PVA),\cite{79} and hydrogel.\cite{80} The conductive composites work as tactile sensors based on the dynamic percolation or quantum tunneling of the fillers. In the former, the conductivity of the composites depends on the volume fraction of the fillers and is determined by percolation theory\cite{81}

\[
\sigma = \sigma_0 (V_f - V_c)^\alpha
\]

where \(\sigma\) is the conductivity of the composite, \(\sigma_0\) is a scaling factor proportional to the conductivity of the fillers, \(s\) is the conductivity exponent, \(V_f\) is the volume fraction of the filler, and \(V_c\) is the percolation threshold.\cite{82} As the composite is compressed or stretched, the conductivity of the composites increases or decreases because of the relatively increased or reduced \(V_f\), providing an electrical response to the pressure and strain.\cite{83,84}

**Figure 3a** shows a pressure sensor enabled by the dynamic percolation of nickel microparticles embedded in a supramolecular organic polymer.\cite{88} This sensor inversely responds to the applied flexion and tactile forces and is self-healing; it is capable of restoring 90% of the conductivity after 15 s and 100% of the mechanical properties 10 min after rupture.\cite{89} For the case of quantum tunneling, the fillers inside the matrix never come into contact with one another. The composites present an insulating electric behavior in the absence of any applied pressure, and show an exponential decrease in the resistance when the compression is attributed to the reduced thickness of the insulating layer between the fillers.\cite{29,89} The shape and morphology of the fillers play a pivotal role in the possibility of tunneling, which prefers a high aspect ratio and protuberances.\cite{29} An ultrasensitive pressure sensor has been demonstrated based on the giant tunneling effect of the CNTs/PDMS interlocked microdome arrays (Figure 3b).\cite{90} The tunneling mechanism and the interlocked construction enable the device to have an extreme resistance-switching behavior \((R_{OF}/R_{ON} \approx 10^4)\), high sensitivity \((−15.1 \text{ kPa}^{-1}, \approx 0.2 \text{ Pa minimum detection})\), and rapid response/relaxation times \((\approx 0.04 \text{ s})\).\cite{90}

Another approach for conductive composites toward a tactile sensor is the integration with a field-effect transistor (FET or OFET), in which the composites could be coupled into the source-drain electrode in series.\cite{91–94} The FET responds to mechanical stimuli with the reduced source-drain resistance. For example, pressure images have been taken by a flexible OFET integrated with pressure-sensitive rubber composed of PDMS and graphite particles (Figure 3c).\cite{95} The device contains a 32 × 32 array of pressure-sensitive pixels with an effective area of \(8 \times 8 \text{ cm}^2\), corresponding to a spatial resolution of 10 dpi (dots per inch).\cite{95} Compared to sensors based on pure composites, sensors relying on FET integrated with composites exhibit a higher sensitivity and much less crosstalk between pixels due to their perfect functionalities of signal transduction and amplification.\cite{95}

There have recently been a variety of liquid materials, such as liquid metals\cite{27,96,97} and ionic liquids\cite{98–100} that have been adopted into piezoresistive tactile sensors due to their intrinsic combination of conductivity and deformation. They are typically embedded in fluidic micro-channels of elastomers such as PDMS,\cite{101} Ecoflex,\cite{102} and block copolymers,\cite{103} and respond to mechanical stimuli due to changes in their geometry. These emerging materials demonstrate special functionality that is preferable for some particular applications. For example, a microfluidic tactile diaphragm pressure sensor based on embedded Galinstan micro-channels has been demonstrated, which is capable of operating in the range of 20–50 °C due to its Wheatstone bridge design (Figure 3d).\cite{104} The sensor can resolve sub-50 Pa changes in pressure with sub-100 Pa detection limits, a response time of 90 ms and a sensitivity of 0.0835 kPa\(^{-1}\). As an example of potential applications, a tactile glove with multiple embedded sensors is demonstrated providing comprehensive tactile feedback of a human hand when touching or holding objects.\cite{104}

With an intrinsic piezoresistive effect, various semiconductors such as Si,\cite{109} CNTs,\cite{110} graphene,\cite{111} α-In\(_2\)S\(_3\),\cite{112} MoS\(_2\),\cite{106,107} VO\(_2\),\cite{108} and PtSe\(_2\)\cite{109} have also been brought into piezoresistive tactile sensors, enabled by a change in energy band structures upon deformation. For example, a strain sensor with an ultrathin profile has been reported by the conjunction of MoS\(_2\) and graphene, in which the MoS\(_2\) strain gauge dominates the resistance change upon strain (Figure 3e).\cite{110} The device exhibits excellent
mechanical flexibility, a high gauge factor \( \text{GF} = (\Delta R/R_0)/\varepsilon \), where \( \Delta R/R_0 \) is the relative resistance change corresponding to the strain of \( \varepsilon \) under both compressive and tensile strains, good uniformity and optical transparency. The device is endowed with a conformal attachment on human skin, therefore the pressure mapping is transferred on the fingertip.\(^{[107]}\) Other unconventional materials have also been used to demonstrate piezoresistive tactile sensors, such as ZnO NW/polystyrene hybrid film,\(^{[110]}\) carbonized crepe paper,\(^{[111]}\) metal–organic framework,\(^{[112]}\) staircase-like Au NWs,\(^{[77]}\) and SiC film.\(^{[113]}\)

The unique properties and functionalities of these materials enable the versatile applications of tactile sensors. Conventional composite-based piezoresistive sensors often show poor sensitivity due to their limited deformability. One approach to this issue is to introduce porous structures into piezoresistive materials. Examples include graphene/PU sponge,\(^{[114]}\) reduced graphene oxide foam,\(^{[115]}\) conductive polymer containing hollow-sphere microstructure,\(^{[116]}\) graphene...
nanocomposite foam,[117,118] carbonized nano-sponge/silicone composite,[119] and carbon nanofiber aerogel.[120] Control in the pore morphology has also been demonstrated by using a reverse micelle solution.[121] However, the Poisson effect in these materials, where stretch materials expand in the longitudinal direction but compress transversely, intrinsically limit their sensitivity due to the Poisson compression squeezing active materials together.[122] Recently, an auxetic CNTs/PU foam with a negative Poisson ratio has been demonstrated, in which the PU foam is triaxially compressed to generate the re-entrant structure and then dipped into the CNTs suspension (Figure 3f).[123] Compared with a conventional foam sensor, the auxetic foam sensor with a Poisson’s ratio of −0.5 demonstrates a 300% improvement in sensitivity and the gauge factor increases by as much as 500%.[123]

3.2. Resistive Tactile Sensors

With the aforementioned power-law dependence of $R_\infty \propto F^{-1/2}$, resistive tactile sensors have been extensively investigated due to their high sensitivity and the large working range enabled by the dynamic contact mechanism.[21] A typical example is a tactile sensor with interlocked microstructures inspired by the human skin. In human skin, there is an intermediate ridge with interlocked microstructures at the epidermal–dermal interface, which acts as a magnifying lever for the transmission of tactile stimuli to the mechanoreceptors and simultaneously enhances the tactile acuity of mechanoreceptors (Figure 4a).[124,125] Inspired by this, a series of resistive tactile sensors based on different interlocked materials, such as metal-coated nanofibers,[126] graphene films,[127] conductive polymers,[128] and indium tin oxide (ITO) nanosprings[133] have been reported, contributing to the sensitive detections and differentiations of various mechanical stimuli. An exemplary sensor assembled with two interlocked arrays of Pt-coated polymeric nanofibers supported on thin PDMS substrates is shown in Figure 4b.[126] The sensor responds to mechanical stimuli by the change in the interconnection degree of the interlocked fibers, enabling the detection and recognition of pressure, shear force, and torsion, with detection limits of 5 Pa, 0.001, and 0.0002 N, respectively.[126] However, the proposed sensor has a limited capability in response to high-frequency dynamic stimuli. To deal with this issue, a sensor consisting of an interlocked hierarchical structure of ZnO NWs decorated PDMS micropillars has been demonstrated, in which the interlocked PDMS micropillars dominate the detections of the static pressure based on the resistive mechanism and the interlocked ZnO NWs contributes to the dynamic sensing based on the piezoelectric effect.[129]

Another approach inspired by nature for resistive tactile sensors is a micro-cracked metal thin film. The slit organs of a spider consist of approximately parallel crack-shaped sensory lyriforms, as shown in the upper-left panel of Figure 4c, endowing the ultra-sensitive monitoring of vibrations in the spider web.[130] Inspired by this, an ultrasensitive resistive tactile sensor with a micro-cracked Pt metal layer of 20 nm deposited on the PU acrylate substrate has been demonstrated.[130] The device exhibits a high gauge factor of over 2000 at a strain range of 0%–2% (upper-middle panel of Figure 4c), which is orders of magnitude higher than that of piezoresistive devices.[107,131] The ultrahigh sensitivity is attributed to the dynamic contact process of the micro-cracked metal layer under the applied strains, as shown in the bottom panel of Figure 4c.[130] The nearly cut-through micro-cracks have inherent asperity and zip-like crack edges (upper-right panel of Figure 4c). Under applied strains, the separation of adjacent metal segments induces a significant increase in the resistance, yet reconnections occur in the zip-like crack edges driven by Poisson forces to simultaneously decrease the resistance. This concomitant process results in a sensitive increase in the total resistance and simultaneously avoids device fracture in the working range.[130] A series of materials, such as graphene,[132,133] Au,[134] ITO,[135,136] and graphene[137,138] with a similar layout for tactile sensors have also been reported, enabling different sensing ranges and use cases. In addition, enhancements in the sensitivity of micro-cracked strain sensors by controlling the crack geometry have been demonstrated.[139,140] The gauge factor can increase up to 16 000 at a strain range of 0%–10% by the guide formation of straight micro-cracks.[140]

The idea of using textiles for resistive tactile sensors is intuitive, as they are naturally compressible and indispensable for human life.[141–143] The textile tactile sensors are woven out of conductive fibers or yarns, in which the $R_\infty$ between the fibers or yarns changes with the applied mechanical stimuli. Fibers and yarns can be inherently sensitive to mechanical stimuli or modified to be sensitive by applying a coating layer of sensing materials.[144–147] For example, the interlacing of graphene microribbons has led to a large gauge factor of 500 at a 2% strain, which is attributed to the textile geometrical conformation of graphene (Figure 4d).[146] Meanwhile, the stretchability of the graphene textile could be tailored to be over 40% by adjusting the graphene growth parameters and adopting an oblique angle direction for simultaneously stretching.[146] The incorporation of PDMS/carbon black composites coating on stretchable silver electrodes render the simultaneous map and quantify various mechanical stresses induced by normal pressure, lateral strain, and flexion (Figure 4e).[147]

Recently, the shape factor has been used to bestow the sensing properties of resistive tactile sensors.[148,149] The shape factor is a measure of the effect the shape of an elastomer has on its compressibility in response to an external pressure, which is defined by the ratio of the area in the compression (e.g., the pyramid’s peak) to the total unloaded surface that is free to expand (the four triangular walls of the pyramid).[150] Constructions with shape factor considerations for resistive tactile sensors typically consist of a microstructured elastomer coated with conductive materials and attached to a planar counter electrode. A representative example is shown in Figure 4f, in which the PDMS with micro-sized pyramids are coated by a conductive polymer layer composed of poly(3,4-ethylenedioxythiophene–poly(styrenesulfonate) (PEDOT:PSS) and an aqueous PU dispersion.[150] If a counter electrode is attached to the microstructured electrode under an external pressure, a potential difference between them will occur, which induces an electrical current flow through the contact area. The device can be operated at a voltage as low as 0.2 V, and exhibit a pressure sensitivity of 10.3 kPa$^{-1}$ and a detection limitation of 23 Pa when stretched by 40%.[150] Other
Figure 4. Resistive tactile sensors. a) Interlocked epidermal–dermal layer of human skin. Reproduced with permission. Copyright 2014, American Chemical Society. b) Resistive tactile sensor composed of interlocked Pt-coating polymeric nanofibers supported on thin PDMS substrates for detections and differentiations of pressure, shear force, and torsion. Reproduced with permission. Copyright 2012, Nature Publishing Group. c) Resistive tactile sensor based on micro-cracked metal thin film inspired by the spider’s slit organ and the proposed working mechanism of the sensor. Reproduced with permission. Copyright 2014, Nature Publishing Group. d) Resistive tactile sensor based on woven graphene microribbons. Reproduced with permission. Copyright 2015, American Chemical Society. e) Textile resistive tactile sensor for the simultaneous mapping and quantification of various mechanical stresses induced by normal pressure, lateral strain, and flexion. Reproduced with permission. Copyright 2016, Wiley-VCH. f) Resistive tactile sensor with the shape factor design, in which the PDMS with microsized pyramids are coated by a layer of PEDOT:PSS/PU and attached to a counter electrode. Reproduced with permission. Copyright 2014, Wiley-VCH.
3.3. Capacitive Tactile Sensors

Finding a correlation between the pressure and electrical capacitance is another way of constructing tactile sensors. One of the most straightforward approaches to capacitive tactile sensors is to directly use an elastomer as the dielectric layer sandwiched between two electrodes, and dielectric elastomers sandwiched by metal film electrodes representative initial attempts\(^{157–159}\). However, metal film electrodes suffer from a fairly good mechanical compliance when being deformed. To target this issue, CNTs\(^{160,161}\) and metal NWs\(^{162–164}\) percolated networks have been adopted as the electrodes to enable the sensor deformability. Figure 5a shows a stretchable and transparent capacitive tactile sensor based on stretchable spring-like CNTs film electrodes separated by a dielectric layer of Ecoflex, which shows linear responses to the pressure of up to 1 kPa and a strain of up to 50%\(^{165}\). Unfortunately, the sensor shows a poor pressure detection limitation of \(\approx 50\ kPa\) and a low pressure sensitivity on the order of \(10^{-4}\ kPa^{-1}\), attributed to the high viscoelasticity and limited compressibility of the dielectric layer.\(^{166}\) The control of micro- and nano-structures in the dielectric layers has been extensively investigated to improve their viscoelastic behavior and compressibility, and therefore to enhance the sensitivity of the sensors.\(^{165–169}\)

The introduction of foam structures into the dielectric materials are representative of the primary examples\(^{167–171}\). The foams in the dielectric layer could be an open-cell or closed-cell, in which the open-cell foams have connected pores to allow gases to easily pass through them from one pore to the other, whereas closed-cell foams have closed pores. Both of them enhance the sensitivity of the sensor because of the large volume fraction of empty spaces within the dielectric layers, rendering a large compressibility and improved viscoelastic behavior. For example, a highly sensitive capacitive pressure sensor based on open-cell PDMS have been developed (left panel of Figure 5b), performing an extremely low-pressure detection of 2.42 Pa, a high sensitivity of 0.63 kPa\(^{-1}\), a fast response time of \(\approx 40\) ms, and a good stability of over loading–unloading of 10 000 cycles.\(^{166}\) The resulting pressure sensors can be fabricated into multi-pixel arrays, endowing the real-time tactile sensing of the object’s motion (right panel of Figure 5b).\(^{165}\) In addition, PDMS foam combined with an air gap as the dielectric layer of a capacitive tactile sensor has been demonstrated, as shown in Figure 5c.\(^{166}\) The unique device architecture enables the detection, differentiation, and even energy-harvest of various mechanical stimuli, such as the normal force, stretch and bend, as well as a maximum pressure sensitivity of 1.5 kPa\(^{-1}\) in the working region of \(< 1\ kPa\).\(^{166}\)

Constructing the microstructures on the surfaces of the dielectric layers contributes to another design strategy in enhancing the sensitivity of capacitive tactile sensors. Assisted by a designed wafer mold, PDMS dielectric layers with various microstructures, such as pyramids, microlines, microrods, and hemispheres have been demonstrated for capacitive tactile sensors.\(^{173–176}\) For example, sensors with a pyramidal PDMS dielectric layer present a sensitivity improvement of \(\approx 30\) times when compared with unstructured ones (Figure 5d).\(^{176}\) The microstructured sensors show minimal hysteresis and can reliably detect the placement or removal of an ultra-small weight such as a blue bottle fly, corresponding to a pressure detection of 3 Pa.\(^{176}\) The dependences of the shape factor and spacing of the pyramidal microstructures on the sensitivity have been investigated as well, enabling device-tailored sensitivities and thus dexterous applications.\(^{177}\) Furthermore, the integration of a microstructured PDMS dielectric layer with OFET has been proposed for a significant enhancement in sensitivity.\(^{178}\) For example, high-mobility semiconducting polysilindigobithiophene-siloxane in a monolithic transistor design with a microstructured PDMS as the dielectric layer has been reported (Figure 5e), rendering the subthreshold operation of the device and therefore the amplification of changes in the capacitance upon deformations.\(^{167}\) The device presents an impressive sensitivity of 8.4 kPa\(^{-1}\), a fast response time of 10 ms, a high stability of over 15 000 cycles, and a low power consumption of 1 mW.\(^{167}\)

Recently, the microstructured elastomer layer has been used in the interlocked capacitive tactile sensor for the detection and discrimination of normal and tangential forces (Figure 5f).\(^{179}\) A PU layer with pyramidal microstructures coated by CNTs is used as the top layer of the device, and the bottom layer consists of a 2D array of molded PU/CNTs hills inspired by the spinosum layer of human skin. Between them an intermediate thin film dielectric layer of polyhydroxybutyrate-polyhydroxyvalerate (PHB-PHV) is used to ensure the electrical insulation of the capacitive sensors. Benefiting from the hierarchical architecture, the device is capable of measuring and discriminating in the real-time normal force, shear forces, and tilt forces (a combination of normal and shear forces), enabling the tactile feedback and precise control of a robot arm for various tasks, such as grasping a red berry.\(^{179}\)

Additional features such as self-healing and biodegradation in capacitive tactile sensors have also been achieved by utilizing novel materials.\(^{180–184}\) A self-healing polymer was designed by the combination of dynamic metal-coordinated bonds (β-diketone–europium interaction) and hydrogen bonds in a separated multiphase network, which can undergo self-healing with an efficiency of 98% after 48 h at 25 °C, without the need for any external stimuli.\(^{180}\) Sequentially, a self-healing capacitive tactile sensor was fabricated by using the polymer as the dielectric layer and a composite composed of this polymer and silver flakes as the electrodes, which can recover to their original sensing level after scratching and healing for \(\approx 40\) s.\(^{180}\) An all-biodegradable capacitive tactile sensor with biodegradable poly(glycerol sebacate) as the dielectric layers sandwiched by the Fe-Mg electrodes supported on a PHB-PHV substrate has also been reported, which enables various potential in vivo applications, such as the wireless monitoring of blood flow.\(^{182,183}\)

3.4. Piezoelectric Tactile Sensors

Through the conjunction of inherent flexibility, ease of processing and large sensitive areas, piezoelectric polymers have been...
Figure 5. Capacitive tactile sensors. a) Stretchable and transparent capacitive tactile sensor based on the stretchable spring-like CNTs film electrodes separated by a dielectric layer of Ecoflex, which shows linear responses to pressures of up to 1 MPa and a strain of up to 50%. Reproduced with permission.[38] Copyright 2011, Nature Publishing Group. b) Highly sensitive capacitive pressure sensors based on the dielectric layer of open-cell PDMS, enabling the real-time tactile sensing of the object motions. Reproduced with permission.[165] Copyright 2016, Wiley-VCH. c) PDMS foam combined with an air gap as the dielectric layer for capacitive tactile sensor, enabling the detection, differentiation, and even energy-harvesting of various mechanical stimuli, such as the normal force, stretching, and bending. Reproduced with permission.[166] Copyright 2014, Wiley-VCH. d) The pyramidal PDMS for a capacitive tactile sensor, which presents a sensitivity improvement of ≈30 times when compared with an unstructured one. Reproduced with permission.[176] Copyright 2010, Nature Publishing Group. e) Integration of microstructured PDMS dielectric layer with high-mobility semiconducting polyisodiobithiophene-siloxane in a monolithic transistor design for tactile sensing. Reproduced with permission.[167] Copyright 2013, Nature Publishing Group. f) A hierarchically patterned, interlocked capacitive tactile sensor for the real-time detection and discrimination of normal and tangential forces. Reproduced with permission.[179] Copyright 2018, American Association for the Advancement of Science.
emerging for tactile sensors.[185–190] Current state-of-the-art tactile sensors based on piezoelectric polymers mainly rely on thin-film geometries, among which PVDF and its derivatives are especially popular due to their plastic behavior, making them suitable for high-throughput processing based on molding, casting, drawing, and spinning.[191,192] However, an electrical poling process is generally necessary for these materials to create maximum polarization and then an achievement of good sensing performance, leading to accessional steps and constrained engineering designs.[193,194] Recently, advances in nanofabrication have been reported to optimize the piezoelectric response of the piezoelectric polymers, in which the near- and far-field electromspun methods are used to produce piezoelectric polymer nanofibers.[195] The associated extensional forces and electric fields during the electrospinning process can naturally pole the nanofibers, consequently enhancing the piezoelectric property.[196] Furthermore, aligned arrays of the piezoelectric material that consists of sheets of electrospun nanofibers of polyvinylidene-fluoride-co-trifluoroethylene (PVDF-co-CTFE) have been shown (inset in Figure 6a), offering a maximum current of 40 mA and a voltage of 1.5 V under simple bending conditions.[200] Flexible pressure sensors built simply by establishing electrical contacts to the ends of the aligned fibers show ultra-high sensitivity, even at an exceptionally small pressure value of 0.1 Pa (Figure 6a). The sensor can respond to both compressive and bending forces, and allow for various modes of sensing, such as acceleration, vibration, and orientation by the alternative device architectures.[200]

Despite the advances in piezoelectric polymers, their low piezoelectric constants constrain the realization of tactile sensors with high profiles. Diverse inorganic piezoelectric materials have been proposed to solve this problem, which simultaneously reserve the mechanical balance of the devices through specific form factors, such as nanoribbons,[201–204] nanofibers,[205] NWs,[206–207] nanosheets,[208–210] and nanospheres.[211,212] One recently reported example involves nanoscale ribbons of PZT formed on an Si/SiO2 wafer using a sol–gel process.[213] It is then released by undercut etching of the sacrificial interfacial layer of SiO2 to allow transfer printing onto a thin, flexible polyimide substrate.[214] The flexible pressure sensor consists of an array of square elements of PZT nanoribbons collectively connected to the gate electrode of an adjacent transistor (left panel of Figure 6b), which renders the amplified pressure detections with an ultrahigh sensitivity of ≈0.005 Pa and a fast response time of ≈0.1 ms.[214] The ultrathin profile (a thickness of less 30 μm) enables the device to have conformal lamination on the skin and therefore the continuous monitoring of pressure transients associated with arterial blood flow (right panel of Figure 6b).[214] Another example is a strain-gated piezotronic transistor array based on patterned ZnO NWs on a flexible polymer substrate prepared by combining the hydrothermal method with state-of-the-art microfabrication techniques (right panel of Figure 6c).[215] The basic structure of the piezotronic transistor only consists of ZnO NWs that are in contact with the source/drain electrodes, in which the charge carrier transport is modulated by the piezoelectric potential created in ZnO upon stress (middle panel of Figure 6c). The device has an impressive pixel density of 92 × 92 cm−1, which can be applied to taxel-addressable, self-powered, and high-resolution tactile imaging (right panel of Figure 6c).[213]

Recently, piezoelectricity has been observed in 2D atomically thin materials, such as hexagonal boron nitride,[216,217] graphene,[218,219] group-III monochalcogenides,[220] group-IV monochalcogenides,[221] and transition metal dichalcogenides (TMDs).[222,223] For instance, the first experimental demonstration of the piezoelectric effect in an atomically thin MoS2 is shown in Figure 6d, in which only the MoS2 flakes with an odd number of atomic layers produce piezoelectric outputs when strained.[224] The single monolayer flake can generate a peak output of 15 mV and 20 pA under a 0.53% strain, corresponding to a power density of 2 mW m−2 and a mechanical-to-electrical energy conversion efficiency of 5.08%.[224] Moreover, a single crystal of Sm-doped Pb(Mg1/3Nb2/3)O3-PbTiO3 with giant piezoelectricity has been demonstrated, showing extremely high piezoelectric constants ranging from 3400 to 4100 pC N−1 (Figure 6e).[225] The giant piezoelectric properties arise from the enhanced local structural heterogeneity induced by the Sm3+ dopants, and the variation of the piezoelectric constant is less than 20% over the as-grown crystal boule, exhibiting good property uniformity.[225] All of these achievements in material innovations show the promise of contracting a self-powered tactile sensor with very fancy performances, such as a thickness of a few atom layers, thus enabling diverse and handy applications.

3.5. Triboelectric Tactile Sensors

Tactile sensors based on the triboelectric effect have been emerging since being demonstrated in 2012 because they solve the issue of power consumption for the sensing unit.[226] A mountain of commercial materials, including plastics, rubbers, elastomers, and metals have been applied to the construction of triboelectric tactile sensors, enabling them forms of diversity and wide working ranges.[227] A general concern on the selection of active materials that rub with one another is the difference in their electron affinities. Electron affinities determine a material’s likelihood of gaining an electron, and their difference dominates the charges transport during the contact and separation process of active materials, and therefore the triboelectric output.[228] One ordering of such electron affinities for commonly used materials of triboelectric tactile sensors is shown in Figure 7a, guiding the selection of the materials for triboelectric tactile sensors.[229] Recently, diverse functional materials, such as hydrogel,[230,231] ionic liquid,[232–234] ionogel,[235] liquid metal,[236] and conductive composites,[237] have also been adopted to triboelectric tactile sensors to achieve such various functional characterizations as stretchability,[231] self-healing,[238] transparency,[235] waterproof,[239] shape memory,[240] and biocompatibility.[241,242] For example, a stretchable and transparent triboelectric tactile sensor has been demonstrated by hybridizing elastomer and ionic hydrogel as the electrification layer and electrode, respectively.[241] The device can respond to a wide range of pressures from several to over 100 kPa with a maximum sensitivity of 0.013 kPa−1, and exhibits an average transmittance of 96.2% for visible light as well as a stretchability of 1160% (Figure 7b).[231]
In regard to structure designs, surface micropatterns of triboelectric materials utilizing microstructures\textsuperscript{[243-245]} or NWs\textsuperscript{[246,247]} and hierarchical structures between contact materials by interlocking\textsuperscript{[248,249]} or bulk spacers\textsuperscript{[250,251]} can effectively boost the triboelectric effect between rubbed materials by enlarging the contact area and the change in the separation distance, thereby elevating the sensitivity and working range of the tactile sensors. For instance, triboelectric tactile sensors composed of microstructured PDMS and ITO/PET can achieve a maximum voltage of 18 V and a current of 0.7 μA under a tiny strain of 0.13%, enabling the self-powered and sensitive detections of a water droplet (8 mg, \( \approx 3.6 \text{ Pa in contact pressure} \)) and a falling feather (20 mg, \( \approx 0.4 \text{ Pa in contact pressure} \)), as shown in Figure 7c.\textsuperscript{[243]} The device shows an ultralow detection limit of \( \approx 13 \text{ mPa} \) and a wide dynamic detection range from 0.33 to 10 Hz.\textsuperscript{[243]} An interlocked triboelectric tactile sensor with a single-electrode mode has also been demonstrated that is capable of detecting both normal...
pressures of up to 1.5 MPa with a sensitivity of $\approx 51.43 \text{kPa V}^{-1}$ and tangential forces ranging from 0.5 to 40 N with a maximum sensitivity of 2.5 N V$^{-1}$. Meanwhile, the directions of applied tangential forces can also be clearly distinguished by using a four-partitioned electrode structure. 

Significant progress has been witnessed in the array of triboelectric tactile sensors toward tactile imaging. An initial example is the simple integration of $6 \times 6$ triboelectric tactile units into a common electrode, which is capable of detecting both normal pressure and tangential forces. 

**Figure 7.** Triboelectric tactile sensors. a) One ordering of electron affinities for commonly used materials of triboelectric tactile sensors. Reproduced with permission. $^{[229]}$ Copyright 2017, American Institute of Physics. b) A stretchable and transparent triboelectric tactile sensor by hybridizing the elastomer and ionic hydrogel as the electrification layer and electrode, respectively. Reproduced with permission. $^{[231]}$ Copyright 2017, American Association for the Advancement of Science. c) A triboelectric tactile sensor composed of microstructured PDMS and ITO/poly(ethylene terephthalate) (PET), enabling self-powered and sensitive detections of a falling feather (20 mg, $\approx 0.4$ Pa in contact pressure). Reproduced with permission. $^{[243]}$ Copyright 2012, American Chemical Society. d) An interlocked triboelectric tactile sensor with a single-electrode mode, which is capable of detecting both normal pressure and tangential forces. Reproduced with permission. $^{[249]}$ Copyright 2018, Wiley-VCH. e) A self-powered, pressure-sensitive triboelectric tactile sensor array based on a single-electrode mode for high-resolution tactile mapping in real time. Reproduced with permission. $^{[257]}$ Copyright 2016, Wiley-VCH.
Spatial resolution of imaging is low due to the large size of the units, which are limited by their vertical-contact-separation working mode. The single-electrode mode has been proposed to solve this issue, in which the spatial resolution depends on the size of each electrode patch that can be significantly shrunk using microfabrication techniques. Figure 7e shows a self-powered triboelectric tactile sensor array based on the single-electrode mode, in which the micropatterned PDMS serves as the electrification layer and is connected to the bottom electrode via vertical interconnect accesses to simplify the electrode layout.\textsuperscript{[257]} The device consists of 16 × 16 tactile units and can map tactile stimuli in real time with a spatial resolution of 5 dpi and a pressure sensitivity of 0.06 kPa\textsuperscript{-1}.\textsuperscript{[257]}

### 3.6. Optical Tactile Sensors

Compared with electrical methods, the visualization of tactile stimuli using optical methods has many appealing attributes, such as avoiding stray capacitances and thermal noises, subduing wiring complexity and crosstalk, and most importantly, allowing for a high spatial resolution of tactile imaging.\textsuperscript{[258]} A wide variety of configurations have been demonstrated for optical tactile imaging either by the integration of pressure sensors and electroluminescence devices,\textsuperscript{[259–262]} in conjunction with the electroluminescence and tunneling effect\textsuperscript{[263]} by combining p–n junction light-emitting diodes (LEDs) with the piezo-phototronic effect,\textsuperscript{[264]} or by incorporating electrochromic devices with the piezotronic effect.\textsuperscript{[265]} For example, a user-interactive optical tactile sensor has been reported by utilizing organic light-emitting diode (OLED) arrays with the anode and cathode of each OLED pixel connected to a thin-film transistor and a pressure-sensitive rubber, respectively (Figure 8a).\textsuperscript{[259]} The as-fabricated OLEDs are turned on locally where the surface is touched, and the emission intensity quantifies the magnitude of the applied pressure. The device can not only spatially map the applied pressure but can also provide an instant visual response with red, green, and blue emissions.\textsuperscript{[259]} Unfortunately, the spatial resolution demonstrated here, at a level of millimeter order, is far from the one in the skin of the human finger (≈40 μm).\textsuperscript{[266]} By a conjunction of electroluminescence and the tunneling effect, an optical tactile sensor with a resolution on par with the human finger skin has been demonstrated.\textsuperscript{[263]}

The device consists of a five-nanoparticle-monolayer structures separated by dielectric layers constructed on a transparent ITO electrode using the well-known layer-by-layer self-assembly technique, as shown in the upper-left panel of Figure 8b. The CdS nanoparticle layer emits visible light at a wavelength of 580 nm under a bias, and the emission intensity can be enhanced by the applied pressure due to the enhanced electrons tunneling both in the dielectric layer and the nanoparticle monolayers, which are caused by the thinning of the dielectric layer and the compacting of the nanoparticles. The device exhibits a high resolution of ≈40 μm, permitting the coin fine structure to be mapped (Figure 8b).\textsuperscript{[263]}

Despite the achievements in high resolution, the random emission sites put in a barrier for achieving taxel-addressable tactile imaging. Patterned electroluminescent arrays composed of aligned n-ZnO NW/p-GaN LED pixels have been demonstrated to provide an approach to this issue (left panel of Figure 8c).\textsuperscript{[264]}

In this system, the emission intensity of each pixel depends on the applied pressure due to the piezo-phototronic effect, which can be explained using the schematic band diagram shown in the middle panel of Figure 8c. A piezoelectric potential is created in the ZnO NW upon pressure, resulting in a local dip in the band to temporarily trap holes near the GaN–ZnO interface, thereby increasing the carrier injection rate toward the junction region as well as the electrons-holes recombination rate. The device permits taxel-addressable tactile imaging with an unprecedented spatial resolution of 2.7 mm (right panel of Figure 8c).\textsuperscript{[264]}

However, the lack of flexibility due to the rigid sapphire substrate may limit its application. A laser lift-off technique has been applied to separate the GaN layer from the sapphire substrate, allowing for the subsequent transfer of GaN to a flexible substrate and then the fabrication of flexible n-ZnO NW/p-GaN LED arrays for tactile imaging.\textsuperscript{[267]} Another approach to flexibility is to replace the GaN with a p-type organic semiconductor. The flexible and patterned ZnO NW/PEDOT:PSS LED array has been demonstrated by spin-coating PEDOT:PSS on the top of the aligned ZnO NW array grown on a flexible substrate, enabling the pressure distribution to be mapped with a spatial resolution of 7 μm.\textsuperscript{[268]} The piezo-phototronic effect has also been applied in other light-emitting systems, such as n-ZnO NW/p-Si LED,\textsuperscript{[269]} ZnO NW/OLED,\textsuperscript{[270]} InGaN/GaN multiple quantum wells,\textsuperscript{[271]} and CdS NW/PEDOT:PSS LED\textsuperscript{[272]} for high-resolution tactile imaging.

Recently, mechanochromic materials, including intrinsic such as mechanoluminescence materials,\textsuperscript{[64,273–276]} or extrinsic such as photonic hydrogels,\textsuperscript{[277]} photonic aerogels,\textsuperscript{[278]} and photonic celluloses\textsuperscript{[279–281]} have been proposed for optical tactile imaging. For instance, a flexible optical tactile sensor composed of manganese-doped zinc sulfide (ZnS:Mn) embedded in thermoplastic ethylene–vinyl acetate copolymer has been demonstrated, as shown in the left panel of Figure 8d.\textsuperscript{[64]} As one of the mechanoluminescence materials, ZnS:Mn enables the direct conversion of mechanical stimuli into optical signals, with the corresponding mechanism detailed in the middle panel of Figure 8d. The piezoelectric potential generated within ZnS upon strain induces a tilt in the conduction and valence bands, detraping the bound electrons in defect states near the conduction band edge. The detrapped electrons transit to holes in the valence band, leading to an energy release by non-radioactive recombination. The released energy blue-shifts the outer shell electrons of Mn\textsuperscript{2+} ions from 6A\textsubscript{1} to 4T\textsubscript{1}, and photo emission occurs when the excited electrons fall back to the 6A\textsubscript{1} state.\textsuperscript{[64]} The device permits dynamic pressure mapping with a temporal response of 10 ms and a spatial resolution of less than 100 μm, enabling such prospectiv applications in AIS as electric signatory (right panel of Figure 8d).\textsuperscript{[64]}

Furthermore, the coupling of the triboelectric effect into mechanoluminescence materials has been demonstrated, contributing to the optical and electrical dual-mode pressure sensing within the full dynamic range.\textsuperscript{[282]} Photonic hydroxypropyl celluloses respond to mechanical stimuli by exhibiting iridescent colors due to Bragg reflections, in which the changes in the helical pitch of mesophase hydroxypropyl celluloses upon the strain alter the diffraction wavelength.\textsuperscript{[279]} An ultra-adaptive optical pressure sensor based
Figure 8. Optical tactile sensors. a) Pressure visualization enabled by an OLED array with the anode and cathode connected to a thin-film transistor and a pressure-sensitive rubber, respectively. Reproduced with permission.[259] Copyright 2013, Nature Publishing Group. b) Optical tactile sensor for tactile imaging with a resolution on par with the skin of the human finger by conjunction of electroluminescence and the tunneling effect. Reproduced with permission.[263] Copyright 2006, American Association for the Advancement of Science. c) Patterned electroluminescent arrays composed of aligned n-ZnO NW/p-GaN LED pixels for taxel-addressable tactile imaging with an unprecedented spatial resolution of 2.7 mm. Reproduced with permission.[264] Copyright 2013, Nature Publishing Group. d) Mechanoluminescence materials for dynamic pressure mapping. Reproduced with permission.[64] Copyright 2015, Wiley-VCH. e) An ultra-adaptive optical pressure sensor based on photonic hydroxypropyl celluloses for pressure detection and strain mapping during human motions. Reproduced with permission.[279] Copyright 2019, Wiley-VCH.
on hydroxypropyl celluloses is demonstrated, exhibiting a wide pressure response ranging from 0 to 30 kPa, which can be used as photonic skin for strain mapping during human motion (Figure 8e).\(^{[279]}\)

4. Tactile Sensors for Advanced Intelligent Systems

Benefitting from all the aforementioned achievements, tactile sensors significantly boost advances in various intelligent systems, ranging from robotics, AI, to HMIs. Here, representative examples in these areas are highlighted, focusing on the dedications of the built-in tactile sensors.

4.1. Robotics

One promising avenue toward the increased dexterity and adaptability in robots is to provide them with tactile senses. Targeting this, electric skins enabled by advances in various tactile sensors have been presented to allow for the safe and precise operation of robots in unknown, uncertain, and cluttered environments.\(^{[283,284]}\) Tactile gloves composed of PDMS/CNTs composite represents the first example, which permit the detection of both normal and shear forces by the resistive and capacitive approaches, respectively (Figure 9a).\(^{[285]}\) A robotic gripper equipped with a tactile glove and a feedback on will hold the object tighter when a downward-pointing shear force induced by the addition of a mass is detected; otherwise, the object is dropped off.\(^{[285]}\) However, the mechanical compliance of the device hinders its seamless integration with the robots. Epidermal electric skins based on conductive polymers\(^{[286]}\) or layout designs\(^{[8,287]}\) have been proposed to solve this problem. For example, smart prosthetics instrumented with ultraslim strain, pressure, and temperature sensors network, enabled by the single crystalline silicon nanoribbons with serpentine/self-similar layouts, allows for diverse manipulations of the prosthetics, such as keyboard tapping and ball grasping (Figure 9b).\(^{[287]}\) Despite these advances in robotic hands, achieving dexterity on par with the human hand is still a challenge due to the limited understanding of the tactile feedback involved in the human grasp. Very recently, a tactile glove combined with emerging machine-learning tools has been attempted to study the mechanics of how humans grasp objects.\(^{[288]}\) The tactile glove consists of 584 piezoresistive sensors distributed on the palm, enabling a record of a large-scale tactile dataset with 135 000 frames, each covering the full hand, while interacting with 26 different objects (Figure 9c). These datasets reveal the signatures of how the human hand manipulates objects, thereby aiding the future design of prosthetics, robot grasping tools, and human–robot interactions.\(^{[288]}\)

4.2. Artificial Intelligence

AI is among the primary driving force for the development of tactile sensors, in which tactile sensors endow cognitive functions and then learning capability to machines. However, the integration of tactile sensors in AI is still in its infancy due to the immaturity of coupling signals to terminals, a function similar to nerves in human. Very recently, attempts to create artificial nerves by the conjunction of sensing, transmitting, and processing components have begun.\(^{[289–292]}\) A representative example is shown in Figure 10, in which the resistive pressure sensors are integrated with ring oscillators and synaptic transistors, corresponding to mechanoreceptors, nerve fibers, and the synapses of a human, respectively.\(^{[293]}\) The responses of resistive pressure sensors to external stimuli are converted into action-potential-like voltage pulses through the ring oscillators and then are integrated and converted into postsynaptic currents by the synaptic transistors. The artificial nerve can be subsequently used to interface with biological efferent nerves in a detached cockroach leg, leading to the actuation of the tibial extensor muscle in the leg.\(^{[293]}\)

4.3. Human–Machine Interfaces

Significant progress has been witnessed in tactile sensors for HMIs, related embodiments including smart keyboards\(^{[294]}\), touch screens,\(^{[295,296]}\) voice recognition systems,\(^{[297–299]}\) robotics control,\(^{[247,300–303]}\) and smart home control systems.\(^{[304]}\) Selectively, a self-powered non-mechanical-punching keyboard enabled by a single-electrode triboelectric tactile sensor can not only sensitively trigger a wireless alarm system once gentle finger tapping occurs but also trace and record typed content by detecting both the dynamic time intervals between and during the inputting of letters and the force used for each typing action (Figure 11a).\(^{[294]}\) Such features hold promise for use in a smart security system that can realize detection, alert, recording, and identification.\(^{[294]}\) A smart home control system composed of a single-electrode triboelectric tactile sensor with ordinary glasses as the framework has also been reported, which can successfully trigger home appliances, such as lamps, fans, and the doorbell (Figure 11b).\(^{[304]}\) Furthermore, a hand-free typing system via an eye blink can be implemented as well by the conjunction of a wireless transceiver module, in which a virtual cursor shifts periodically on a virtual keyboard, and executes the click action when the eye blink is detected.\(^{[304]}\) The control of a robot arm for various motions enabled by a piezoelectric tactile sensor with a multilayer of graphene heterostructures has been demonstrated (Figure 11c).\(^{[300]}\) The electrical signals responding to various motions of the human wrist, such as relaxing, bending, and pressing, are transmitted to a computer via a data-acquisition board, and then are analyzed and distinguished to deliver appropriate commands to the robot arm. A doll can be grasped and lifted by the robot arm with human control.\(^{[300]}\)

5. Conclusion and Outlook

This review, which is far from exhaustive, aims to provide a glance at state-of-the-art tactile sensors for AIS. Tactile sensors enabled by different mechanisms, including piezoresistive, resistive, capacitive, piezoelectric, triboelectric, and optical are summarized, together with material innovations and layout designs for performance enhancements.
Figure 9. Tactile sensors for robotics. a) Tactile glove composed of PDMS/CNTs composite permits the adaptive object grasp of robotic hand. Reproduced with permission. Copyright 2017, Wiley-VCH. b) Smart prosthetics instrumented with ultrathin strain, pressure, and temperature sensors network, enabled by single crystalline silicon nanoribbons with serpentine/self-similar layouts, allows for the diverse manipulations of prosthetics, such as keyboard tapping and ball grasping. Reproduced with permission. Copyright 2014, Nature Publishing Group. c) Learning the signatures of the human grasp using a scalable tactile glove. Reproduced with permission. Copyright 2019, Nature Publishing Group.
Representative contributions of tactile sensors for AIS are highlighted as well.

As in any research area, there is still much work to be done on intelligent systems before they are ready for the marketplace. In the case of tactile sensors, each type has pros and cons and a trade-off between performances is still necessary. Additional attributes, such as stretchability, transparency, self-healing, biocompatibility, biodegradability, as well as integrated sensing of tactile, temperature, humidity, and even pain are also essential for mimicking human skin and therefore allowing for dexterity in robotics. Combined material innovations and structure designs will definitely offer continuous opportunities in this regard. Data transmission and processing represent another bottleneck. Wireless data transmission would be ideal because it avoids wiring complexity. However, the transmission speed and distance may be limited. Data from all taxels need to be differentiated and integrated, providing comprehensive information for actuations. However, sometimes not all the data are meaningful, and hence selection and filtering are necessary to reject redundant data. The latest progresses in software engineering such as cloud computing, big data analysis, and machine learning have been proposed to target these issues, in which suitable algorithms and mathematical calibrations hold promise for maximal precision and optimal efficiency. Finally, the integration of the sensing, processing, and probably actuating modules at the systematic level with synergies of reasonability, reliability, economy, and high efficiency remain unresolved, requiring strong interdisciplinary efforts to address them.

Figure 10. Tactile sensors toward AI. The artificial nerve consists of three components: a pressure sensor, an organic ring oscillator, and a synaptic transistor, corresponding to the mechanoreceptor, nerve fiber, and synapse, respectively. The artificial nerve can be used to interface with biological efferent nerves in a detached cockroach leg, leading to the actuation of the tibial extensor muscle in the leg. Reproduced with permission. Copyright 2018, American Association for the Advancement of Science.
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Conflict of Interest

The authors declare no conflict of interest.

Keywords

human–machine interfaces, intelligent systems, robotics, soft electronics, tactile sensors

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