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SOFT ROBOTICS (M SPENKO, SECTION EDITOR)

Soft Tactile Sensing Skins for Robotics

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Abstract

Purpose of Review Soft electronic skins (E-skins) capable of tactile pressure sensing have the potential to endow robotic systems with many of the same somatosensory properties of natural human skin. In this progress report, we review recent progress in creating soft tactile pressure sensing skins to give robots a sense of touch that resembles human skin sensing.

Recent Findings For soft tactile pressure sensing skins, researchers have focused on five main sensing principles: (1) resistive; (2) capacitive; (3) magnetic; (4) barometric; and (5) optical. The combination of these traditional sensing techniques, along with the use of soft materials such as liquid metal and magnetic elastomers, has improved the perception capabilities and mechanical characteristics of artificial skin. In addition, the implementation of artificial intelligence and machine learning algorithms for data processing give robotic systems with these soft sensing skins an enhanced sense of touch.

Summary E-skins for tactile sensing have a central role in a range of robotic applications, from haptics and teleoperation to bio-inspired soft robots. For many of these applications, E-skins must be soft, thin, flexible, stretchable, and lightweight so that they can be mounted on a robot, incorporated into clothing, or placed on human skin without interfering with mobility or contact mechanics. Significant research has been conducted on sensing techniques that can allow a robot to achieve a sense of human touch, with important progress being made in force feedback sensing, texture recognition, and spatial acuity. We begin by covering principles of tactile sensing in humans, robotics, and human-machine interaction. This is followed by an overview of soft material transducers capable of pressure and force sensing. This includes resistive, capacitive, magnetic, barometric, and optical sensing techniques. We close with a summary of emerging trends in sensor design and implementations for applications in robotics.

Keywords Tactile sensing · Soft electronics · Soft robotics · Conductive elastomers · Liquid metal · Magnetic elastomers

Introduction

Tactile perception in robotics plays a crucial role in helping machines perceive their environment and interact with objects. While cameras, optical and photonic detectors, machine vision, and other non-contact modes of sensing also have a critical role, many robotic systems increasingly require the ability to directly measure reaction forces and stimuli. This ability is key to detecting contact with surfaces, manipulating objects, and safely interacting with humans [1]. This is especially true in emerging domains like human-machine interaction, wearable robotics, and bio-inspired soft robotics, where robotic systems must be engineered from materials that must either mimic or physically interact with soft human tissue.

While there have been promising developments in tactile sensor technologies over recent years [2–5], many of these are rigid or bulky and do not meet the desired mechanical characteristics of artificial skin. Progress in electronic skins (E-skins) for robot sensing increasingly relies on the development of soft tactile sensors that are constructed from soft, thin, flexible, stretchable, and lightweight materials. These soft sensors represent an emerging class of technologies [6] that have the potential to dramatically improve the ability of robots to possess the physical properties and somatosensory functionalities of natural human tissue. Such technologies possess characteristics that

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make them ideally suited as artificial skin with adequate elasticity to conform to multiple surfaces and sufficient mechanical compliance to make them safe and comfortable for physical human-robot interaction [3, 7].

In this progress report, we present an overview of recent developments in soft material architectures that function as pressure transducers for measuring contact, force, and surface pressure. While robot sensing is a rich domain that covers various aspects of mechatronics, computer vision, control, state estimation, and machine learning, we will primarily focus on the mechanics and physics of soft sensors and the mechanisms by which mechanical load is translated into electronic measurements. The first section covers an overview of tactile sensing, from natural human sensing to current practices in robotic touch. The second section introduces a selection of mechanisms that have been recently popular in soft robotic sensing: resistive, capacitive, magnetic, barometric, and optical-based sensors. In the last section, we summarize the current trends and direction in the development of flexible soft tactile sensors. This article is intended to be a progress report and update on recent developments and current trends in soft tactile pressure sensing and is not meant as a comprehensive review of E-skins or robotic sensing. For a more complete overview, the reader should refer to more comprehensive review articles in the literature (e.g., [8–12]).

Overview of Tactile Sensing

The sense of touch was the first of the human senses to develop [13], enabling the ability to sense temperature, textures, identify shapes, give force feedback [14, 15], and communicate [16]. To be able to accomplish these tasks, human skin possesses thousands of receptors distributed throughout the body that can be classified as thermoreceptors (temperature sensing), nociceptors (pain/damage identification), and mechanoreceptors (mechanical stimuli) [17–19]. Together, these receptors combine to form a complex sensorial architecture.

Mechanoreceptors, i.e., mechanoreceptive afferent neurons, perceive mechanical stimuli, giving the body the ability to identify shapes, textures, object compliance, force perception, and spatial acuity. Mechanoreceptors receive a mechanical stimulus input and output this information in the form of an action potential. This information is then transmitted to the brain through nerves [6, 8]. Replicating the properties of mechanoreceptors has been a research goal in the fields of robotic manipulation, human-robot interaction, and wearable robotics. For robotic sensing skins, the mechanical input stimulus is converted into a change in electrical or magnetic signals through a number of modes. These modes include changes in resistance, capacitance, dielectric constant, magnetic field, or light intensity [20]. These raw data along with the material properties of the sensing mode are then used to output usable information for feedback.

For robotic manipulation, grasping force control is especially important for avoiding slippage and/or damage to the object being held [21]. For slip detection, tactile feedback has been the main sensory function used as discussed in [2], while force feedback has been widely explored for grasping, as described in [21, 22]. Wearable robotic systems also make use of tactile sensors, mainly for haptic interfaces for teleoperated robots or virtual reality platforms [23–26]. In these applications, tactile sensors are combined with haptic actuators and feedback control to give the user the perception of touch, tactile feel, or mechanical contact [27].

In the field of human-robot interaction (HRI), computer vision [28, 29] and speech recognition [30–32] are most commonly used as the primary modes of sensing and interaction. However, there has been a recognition of human touch and tactile HRI as an important mode of physical interaction [33]. Different technologies have been developed to give robots tactile sensing capabilities of touch, each of them trying to accomplish the following tasks: detect contact with an object by measuring static and dynamic forces; measure the magnitude and direction of contact forces for stable grasp; identify the location and change in relative position of contact points during object manipulation; detect forces tangential to the contact point in order to monitor slip; identify force variation associated with the material properties of objects, such as their stiffness, elasticity, and surface texture.

Soft Tactile Sensors

Since the last decade, there has been tremendous progress in creating soft tactile sensors using a variety of materials and transduction mechanisms. Here, we will review efforts that utilize popular approaches that exploit changes in electrical resistance, capacitance, magnetic field, changes in barometric pressure, and optical transmission/reflection in response to mechanical loading.

Resistive Sensing Skins

Among the various techniques for soft sensing robotic skins, resistive-based sensors have been especially popular. One approach is to embed a soft polymer with channels or cavities of a conductive fluid. When external force or pressure is applied, the fluid is squeezed and its electrical resistance increases (Fig. 1a). This principle has been used

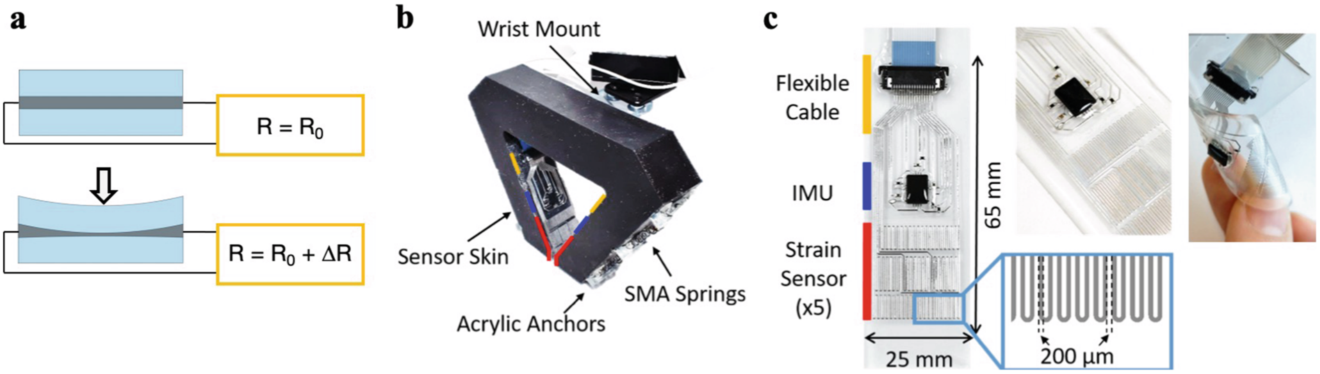

Fig. 1 Resistive LM sensing skins: **a** The pressure sensors are composed of serpentine traces of eutectic gallium-indium (EGaIn) LM alloy. Applied pressure causes the cross-sectional area of the channel to decrease and the electrical resistance to increase [34]. **b** Soft robot gripper with an elastic sensing skin for detecting contact and lift of objects (adapted from Ref. [35] with permission, copyright IEEE, 2019). **c** The skin is composed of five liquid metal (LM) pressure sensors and a 9-axis inertial measurement unit (IMU) that is connected to an external microcontroller using stretchable LM circuitry (adapted from Ref. [35] with permission, copyright IEEE, 2019)

for both ionic fluids [36–38] and gallium-based liquid metal (LM) alloy [34]. Such sensors have been discussed in a variety of review papers that focus on LM and soft microfluidics, such as [39] and [40], respectively. One recent example of a robotic implementation that utilizes a resistive LM-based tactile sensor is presented in Fig. 1b and c [35]. This robotic skin utilizes a high density of serpentine microfluidic LM channels for contact detection and grasp classification. To further improve the sensitivity and dynamic range of these sensors, researchers have examined the influence of channel cross-section geometry on electromechanical response [41], and have also explored the inclusion of microspheres within the cross section in order to increase both sensitivity and linearity of these soft sensors [42].

Another popular approach involves the use of piezoresistive materials placed between overlapping arrays of electrodes. As pressure is applied, the material is squeezed and alters the electrical resistance between the overlapping electrodes. Piezoresistive inks are especially popular and have been used in commercial piezoresistive pressure arrays, like those produced by Tekscan, Inc. Other methods include the use of foams [44–46], piezoelectric materials [47, 48], conductive hydrogel microspheres [49], and carbon nanotubes [50]. For example, a piezoresistive tactile sensor based on a hierarchical pressure-peak effect is described in [51]. With this approach, a wide detection range and a high sensitivity are achieved for detecting different pressure stimuli like foot pressure, respiration, and pulse and finger heart rate.

Figure 2a–c present a piezoresistive-based sensing glove in which 548 pressure sensors are incorporated in the palm and fingers [43]. The glove is capable of object detection and achieves pressure sensing through the piezoresistive response of a force-sensitive film that is placed between an overlapping array of conductive threads. Piezoelectric pressure sensors have also been demonstrated for haptic feedback. By using the change in piezoelectric resistance of a soft sensing skin, the current is varied through a coil below the skin. This current induces a force on a magnet that actuates upward or downward on the piezoresistive skin, giving haptic feedback to the body [52].

There has also been progress on combining fluid-based resistive sensing with other sensing mechanisms to decouple various modes of mechanical deformation induced by compression, bending, and stretching. The sensor presented in Fig. 3a and b incorporates resistive sensing using a channel of ionically conductive fluid that is bounded by films of conductive fabric [53]. When the sensor is stretched or compressed under pressure, such deformation leads to changes in electrical resistance of either the ionic channel or conductive fabric walls.

The selection of soft resistive tactile skins discussed in this section is by no means exhaustive and represent only a small portion of recent advancements in soft robotic sensing. For a more complete overview, the interested reader should refer to review papers by Chortos et al. [8] and Yang et al. [11].

Capacitive Sensing Skins

Capacitive sensing represents another popular approach to create soft tactile sensing skins [60–62]. These are typically composed of measuring the change in capacitance between two overlapping electrodes that are separated by a dielectric elastomer [63] or air gap [64]. Spin-coated iontronic films have also been used as the dielectric material, showing the potential for high sensitivity sensing at pressures below 1.5 kPa (Fig. 4a and b) [54]. Such capacitance change is induced by an applied pressure that deforms the electrodes and causes the gap to decrease and/or the overlapping area

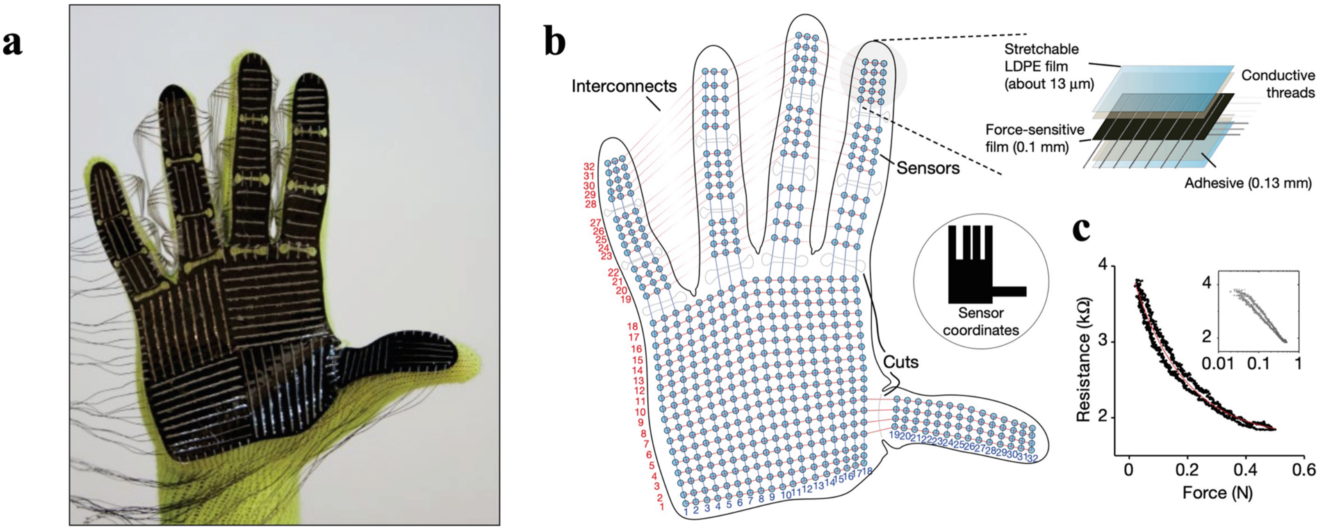

Fig. 2 Piezoresistive sensing skin: **a** sensorized glove for grasp detection. **b** The glove is composed of 548 piezoresistive sensing nodes placed between overlapping arrays of conductive thread. **c** When force is applied, the resistance between the orthogonal conductive threads decreases (adapted from Ref. [43] with permission, copyright Springer Nature, 2019)

to increase [65]. One work used a conductive hydrogel as the electrodes with an elastomer and ZnS embedded dielectric center layer. Not only did this skin exhibit a change in capacitance when loaded with pressure, but also acted as a hyperelastic light-emitting capacitor (HLEC), mimicking the color-changing nature of an octopus (Fig. 4c and d) [55]. Researchers have also fabricated electrodes with carbon nanofibers or graphene nanoplatelets suspended in a polymer [66], along with liquid metal embedded in Ecoflex elastomer [67]. Foams embedded with LM alloys have also been used as soft dielectric materials for capacitive tactile sensing [56].

In addition to contact forces and surface pressure, capacitive transducers are also capable of detecting proximity. Such sensors rely on the conductivity of the non-contacting object, such as a human finger, which functions as a counter electrode. One recent study uses electrical capacitance tomography for detecting motion of objects that are in close proximity to or in contact with an array of electrodes [68]. A separate study characterized the proximity performance of a soft capacitive sensor produced using polymer drop on demand (DOD) ink-jet printing [69]. The sensor was capable of non-contact proximity detection at a distance of up to 60 mm.

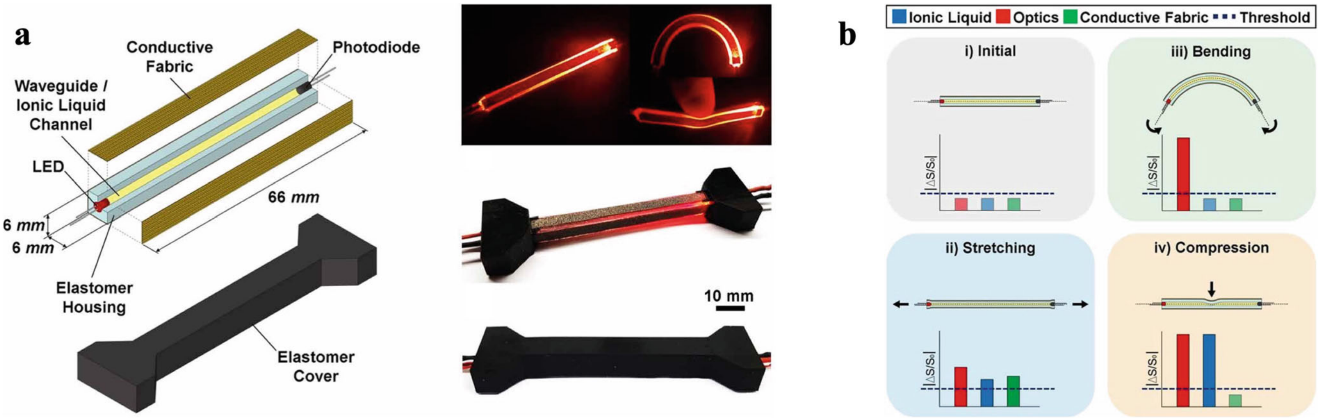

Fig. 3 Resistive multimodal sensing skin: **a** soft sensor capable of multimodal deformation sensing using piezoresistivity and photonics. Resistive stretch and pressure sensing are accomplished using a combination of ionically conductive fluidics and a piezoresistive conductive fabric (adapted from Ref. [53] with permission, copyright American Association for the Advancement of Science, 2020). **b** The sensor is able to independently sense stretching, bending, and pressure through relative changes in the signal output of the piezoresistive and photonic materials (adapted from Ref. [53] with permission, copyright American Association for the Advancement of Science, 2020)

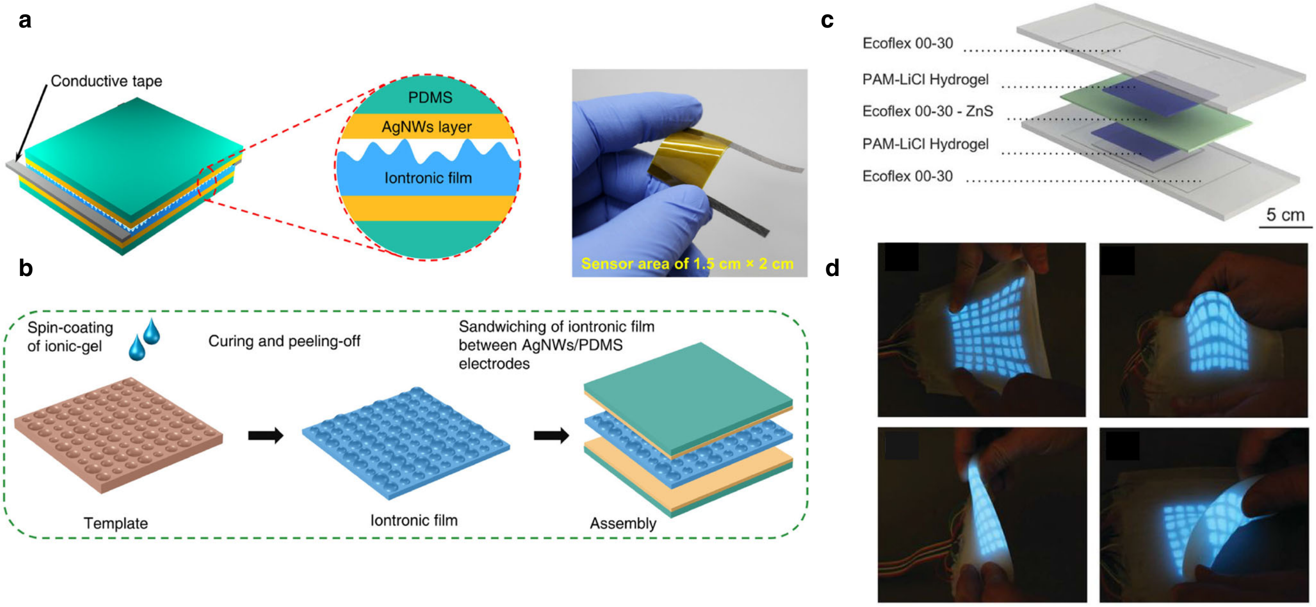

Fig. 4 Capacitive sensing skins: **a** soft parallel plate capacitive sensor made of an iontronic film dielectric layer with silver nanowire electrodes encased in polydimethylsiloxane (PDMS). This design allows for an extreme sensitivity of 131.5 kPa^{-1} for a low-pressure range of <1.5 kPa (adapted from Ref. [54] with permission, copyright American Chemical Society, 2018). **b** Method for sensor fabrication (adapted from Ref. [54] with permission, copyright American Chemical Society, 2018). **c** Layup of a soft optical-capacitive sensor. The sensor is composed of hydrogel electrodes and a ZnS phosphor-doped dielectric elastomer layer that change capacitance and luminescence when a potential difference is applied and the sensor is deformed (adapted from Ref. [55] with permission, copyright American Association for the Advancement of Science, 2016). **d** Images of the optical-capacitive sensing skin showing the skin's ability to deform and change light intensity in response to bending and stretching (adapted from Ref. [55] with permission, copyright American Association for the Advancement of Science, 2016)

Magnetic Sensing Skins

An emerging trend in soft tactile sensing is to embed elastomers with a dispersion of magnetized microparticles. When pressure is applied, the elastomer deforms and the microparticles move and rotate, causing the internal magnetic field to change. This change in magnetic field is monitored by a magnetometer that is placed either within the elastomer or in close proximity. Such an approach to tactile sensing was introduced by Hellebrekers et al. [57] and has also been studied by several other research groups [58, 71]. Because the elastomer can be embedded with a high concentration of magnetic particles, tactile sensing can be achieved over continuous rather than discrete nodes. Converting the raw magnetic field data to determine the location and intensity of applied surface pressure requires data-driven techniques based on machining learning [72]. Using a quadratic discrimination analysis, one study was able to distinguish between 25 grid locations in a 15-mm^2 area with a $>98\%$ accuracy (Fig. 5a–c) [57].

Recent studies have demonstrated the use of magnetic tactile skins for both localization and force feedback in robot grasping tasks [73], as well as facial motion tracking for quadriplegic individuals (Fig. 5d) [58, 70]. Related efforts have also explored the development of magnetic-based sensors in which pressure is monitored by tracking changes in magnetic field coupling between electromagnetic coils [74–76]. Another class of magnetosensitive skins are based on changes in magnetic fields within the environment. Such sensors are described in more detail in a recent review paper by Canon Bermudez et al. [77].

Optical Sensing Skins

Optical sensors can identify pressure variations due to changes in the intensity of light as it travels through the material. These sensors are based on a light source, a modulator, transmitter, and a photosensitive element for light detention such as a camera or photodiode [81]. Figure 6a shows the Gelsight sensor, which is composed of a digital camera covered with an elastomer that is coated with a reflective film [78]. When pressure is applied, the elastomer deforms and the surface tractions are estimated by displacements in the surface of the elastomer that are detected by the camera.

Optical sensors have also been engineered with soft polymers functioning as the transmission medium. Elastic deformation causes a change in the refractive index of the

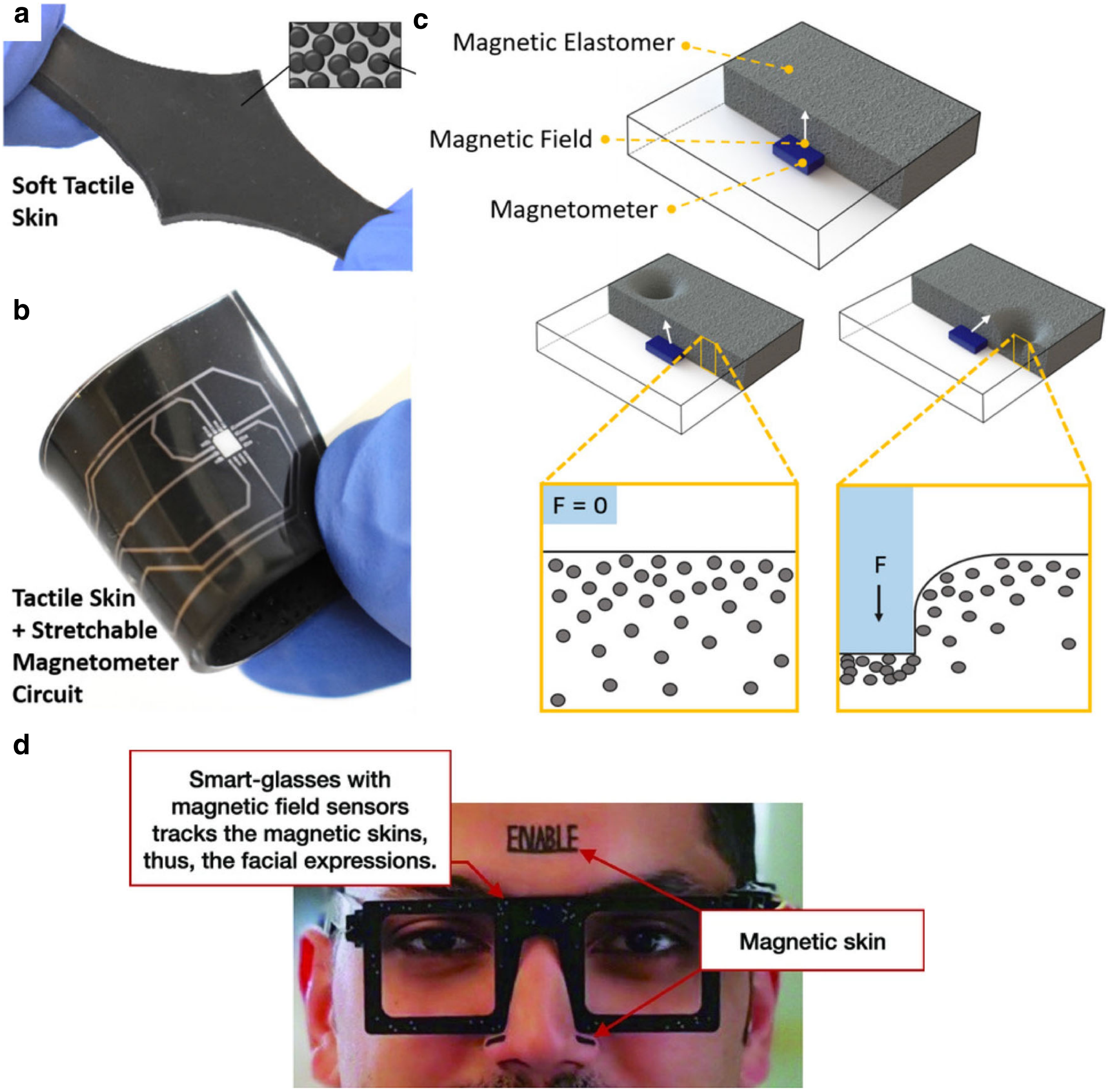

Fig. 5 Magnetic sensing skins: **a** image of magnetic particle embedded elastomer (1:1 weight ratio) under deformation (adapted from Ref. [57], under CC-BY License). **b** Image highlighting deformable circuitry and 3-axis magnetometer for detecting changes in the magnetic field when pressure is applied to the surface (adapted from Ref. [57], under CC-BY License). **c** Diagram of the sensing mechanism, highlighting how the change in magnetic particle configuration, when an external force is applied, varies the magnetic field detected by the magnetometer (adapted from Ref. [57], under CC-BY License). **d** Image of magnetic skin attached to the nose and forehead. These skins can be fabricated in various shapes dependent on the application and are made from magnetic powder (NdFeB) embedded in Ecoflex. Magnetic field sensors mounted to glasses pick up small movements for individuals with spinal cord injuries (adapted from Ref. [70] with permission, copyright John Wiley & Sons, 2020)

polymer or fiber optic cable, resulting in a relationship between strain and light intensity [53, 82–84]. These flexible sensors offer low susceptability to electromagnetic interference and a fast response [18]. Image processing has also been used for contact detection by the use of visual markers on compliant elastomeric surfaces and miniaturized

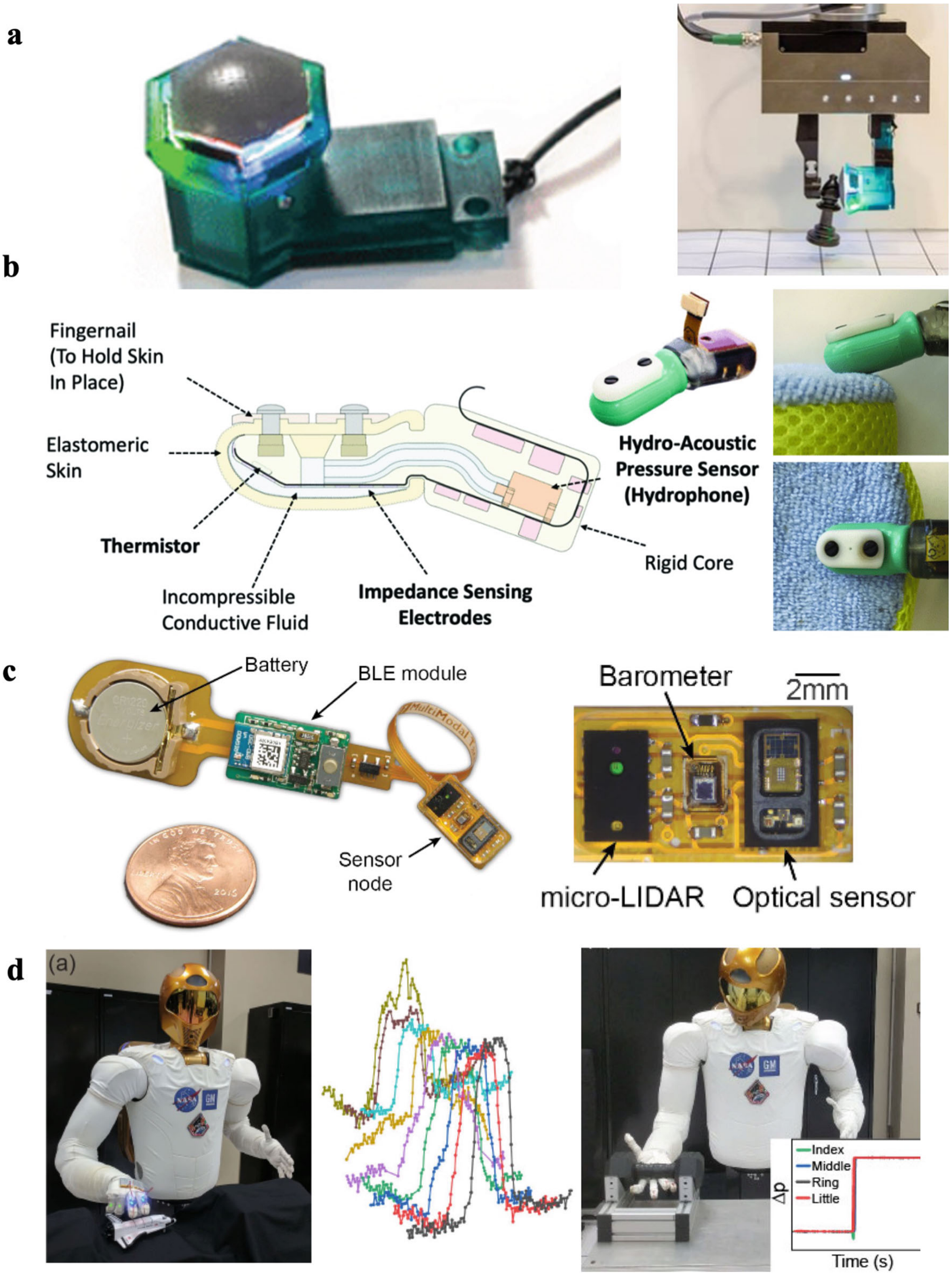

Fig. 6 Optical and barometric sensing: **a** The Gelsight sensor is composed of a digital camera covered with an elastomer that is coated with a reflective film. When pressure is applied, the elastomer deforms and the surface tractions are estimated by the displacement of the elastomer surface detected by the camera (adapted from Ref. [78], under CC-BY license). **b** The SynTouch ® BioTac® tactile sensor measures contact forces and vibration using a variety of sensing modalities. This includes a barometric sensor encased within an elastomer-sealed fluidic medium to measure surface pressure (adapted from Ref. [79] with permission, copyright IEEE, 2020). **c** Combined photonic and barometric sensing incorporated into a sticker-like flexible circuit (adapted from Ref. [80] with permission, copyright IEEE, 2020). **d** The circuit is mounted to the fingertips of the NASA Robonaut 2 humanoid robot and used for object scanning and force/contact detection (adapted from Ref. [80] with permission, copyright IEEE, 2020)

cameras in order to detect the position change in the markers and process this information into contact force magnitudes [80, 85, 86].

Barometric Sensing Skins

The use of barometric monitoring in hydraulic or pneumatic circuits as a means for tactile sensing has a long history of use in robotic manipulation [17]. Sensing pressure within a working fluid offers a high-frequency response, and is ideal for vibration propagation [22], thus allowing texture recognition and slippage detection. It is also increasingly common to create pressure sensing skins composed of a microelectromechanical barometric sensor that is backfilled with a soft elastomer like silicone rubber [59, 80, 87]. This approach is used in commercial pressure sensors like the TakkTile sensor from RightHand Robotics, Inc., and the BioTac sensor from SynTouch. Referring to Fig. 6b, the BioTac sensor incorporates various sensing modalities for measuring surface tractions and vibrations [79]. This includes a miniaturized barometric sensor that is embedded within an elastomer-sealed fluidic medium to measure internal hydrostatic pressure that is generated by contact forces.

In general, the use of soft pneumatic sensing chambers enables the ability to achieve mechanical properties (flexibility, compliance, elasticity) and reliable sensor properties that are compatible with human-machine interfaces [88, 89]. Moreover, there has been exciting progress in combining barometric sensing with other sensing modalities. In addition to the SynTouch BioTac, multimodal sensing with an integrated barometric chip has also been recently demonstrated with the wireless sensing sticker reported in [80]. Referring to Fig. 6c, the sticker contains a MEMS-based barometric sensor along with a time-of-flight and photonic sensing chip for proximity detection and shape scanning. The circuit is mounted to the fingertips of the NASA Robonaut 2 humanoid robot and used for object scanning and force/contact detection (Fig. 6d). As with the TakkTile sensor, the barometric chip used in this implementation is sealed in a soft elastomer and measures surface tractions by detecting changes in the hydrostatic pressure of the elastomer.

Trends and Future Outlook

Achieving the sensory capabilities and mechanical properties of human skin remains an important goal in robotics and soft materials engineering. In addition to the methods and papers reviewed here (Table 1), there continues to be new mechanisms for detecting force and pressure using soft

Table 1 Comparison chart of selected robotic sensing skins described in the text

Sensing modality	Dynamic range	Bandwith	Material properties	Highlights	Ref.
Capacitive	14 kPa	40 ms	40% strain, elastomer based	Proximity sensing	[69]
Capacitive and resistive	110 kPa	33 ms for 5.4-kPa loading and 19 ms for unloading	Elastomer-based foam with nickle microparticles and Young's modulus of 0.79 MPa	Self-healing and proximity sensing	[90]
Magnetic	0.14–2.4 N	50 Hz	Elastomer and magnetic particle–based skin	High-resolution sensing	[57]
Resistive and optical	292 kPa	N/A	50% max strain, fabricated with elastomer cover, conductive fabric, and ionic microfluidic channel with a waveguide	Multimodal	[53]
Resistive	0.04–600 kPa	<60 ms	Elastomer-based skin	High-pressure range	[51]
Barometric	140 kPa	100 Hz	Flex-PCB holding BMP388 MEMS covered with a 3-mm silicon rubber. Shore hardness of 13A	High resolution and sensitivity. Good linearity and low hysteresis	[59]
Optical	>0.05 N	30 Hz	0.145-MPa Neo Hookean Elastomer over a rigid camera and LEDs for photometric stereo	High resolution for spatial acuity and texture sensing	[78]

materials. For example, recent studies have also begun to examine tactile sensing using the triboelectric effect [91–93]. Moreover, progress is not limited to new materials and transduction mechanisms. Advancements in this field also depend on further progress in the use of machine learning for mapping a soft sensor's raw data into accurate measurements of pressure intensity and location [94–99].

Another recent direction in the field is to create soft tactile sensing skins that are resistant to mechanical damage and are self-healing. Self-healing robotic skins have been explored in a variety of recent studies [90, 100, 101]. Such technologies have the potential to enable robotic systems to be more resilient and reduce the need for manual maintenance and intervention.

Coupled with this has been progress in the development of robot skins that are capable of damage detection [102, 103]. Rather than measure force or pressure, these sensing skins can detect puncture, tearing, or other mechanical damage that might threaten the robot's material integrity.

Lastly, future efforts should focus on the further development of multimodal sensing skins that combine pressure and force detection with other modes of sensing and imaging. This includes elastically deformable robot skins that merge tactile sensing with sensing for proprioception, physiological monitoring, and vision. While there has already been promising work in this domain [35, 53, 104–106], there remain rich opportunities for further progress.

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Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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