8 Biomimetic Skin

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8.1 Introduction

Replicating the fundamental characteristics of biological organs to develop their artificial equivalents and using them in robotic platforms is an area that is attracting significant interest through topics such as soft robotics; electronic skin, or eskin; and bionic limbs (Dahiya 2019; Dahiya, Akinwande et al. 2019; Dahiya, Yogeswaran et al. 2019; Soni and Dahiya 2020). The interest in this field is also fueled by the new and emerging applications of robots in areas such as smart factories and ambient assisted living, where safe and intelligent human-robot interaction is necessary. For robotic systems to move from industrial environments to home and urban or social areas, it is critical for them to have human-skin-like capabilities in order to enable safe human and robot interaction (Argall and Billard 2010; Dahiya et al. 2013). Robotic systems need to function close to humans for this to be achieved; therefore, the equivalents of human organs are needed for robots. Pacemakers and cochlear implants are some of the artificial organs developed in the past. The successful commercialization of some of the bionic organs such as electronic noses and ears and bionic eyes has encouraged researchers to explore more artificial organs—for example, eskin or tactile skin. This progress is also supported by technological advances in soft and flexible electronics (Gupta, Navaraj, et al. 2018; Núñez, Manjakkal, and Dahiya 2019), which could allow tactile skin to conform to curved surfaces (Hammock et al. 2013; Dahiya, Yogeswaran, et al. 2019); artificial muscles (Roche et al. 2014); and computation including artificial intelligence (AI; Decherchi et al. 2011; Luo et al. 2017; Navaraj et al. 2017). However, current advances still fall short of leading us to the functionalities offered by human skin. A deeper look at the sensory mechanisms in the human body shows the importance of the "sense of touch" in wide-ranging tasks such as the assessment of various properties of real-world objects and their handling. The size, shape, texture, temperature, surface roughness, hardness, softness, curvature, and more can all be assessed by touching. To determine such parameters, the human skin has different types of receptors that are distributed nonuniformly throughout the body, as discussed in the next section (Dahiya, Metta et al. 2009; Dahiya and Valle 2013; Dahiya, Mittendorfer et al. 2013; Yogeswaran, Dang et al. 2015). These receptors are embedded at different depths in the soft skin. It is challenging to realize an artificial skin with this level of complexity, especially when soft electronics technology is still at an early stage of development. Furthermore, the sensing feature of skin is intimately connected with computation, actuation, and energy (Soni and Dahiya 2020). An eskin with tightly coupled sensing, actuation, computation, and energy devices over a large area will be hugely beneficial for robotics as well as other emerging areas such as autonomous vehicles, tactile internet (Simsek et al. 2016), and augmented/virtual reality in which intelligent interaction is desired. This chapter focuses on a new perspective related to eskin or tactile skin and presents some case studies. Section 8.1 presents a new approach for obtaining sensorized complex structures such as robotic or prosthetic hands. The advanced multimaterial, three-dimensional (3D) printing approach and the innovative designs used to realize the robotic hand with embedded sensors, actuators, and electronics are presented in section 8.3. Section 8.4 presents another case study in which different types of transducers (piezoelectric and capacitive) have been stacked to obtain the FA (fast-adapting) and SA (slow-adapting) receptors' equivalents of the human skin. The presented sensor stack is expected to allow eskin to detect both static and dynamic tactile or contact events. Furthermore, the machine-learning approach has been used to demonstrate the texture-detection capability of the presented sensor stack. Last, section 8.5 describes a new soft sensor device with a tightly coupled touch sensor and actuator. Altogether, these case studies show how eskin research is advancing toward tightly coupled sensing, actuation, and computation.

8.2 Tactile Sensing

The human skin is the largest organ of the human body. It comprises multiple mechanoreceptors, classified into two major categories (FAs and SAs) based on their response (table 8.1). The FA mechanoreceptors (Meissner's corpuscles and Pacinian corpuscles) are responsible for the detection of dynamic contact force/pressure applied to the human skin. They respond to slippage, to high-frequency vibration, and to the onset and offset of stimulation. On the other hand, SA mechanoreceptors (Merkel cells and Ruffini corpuscles) detect roughness, stretch, and static stimulation on the skin. Furthermore, the fingerprint patterns and the interlocked microstructures of the human skin enhance the perception of fine texture by amplifying the vibrotactile signals during surface exploration (figure 8.1). In general, these cutaneous mechanoreceptors of the human body provide the necessary tactile information to manipulate objects with extreme accuracy (see chapter 6)

The artificial skin (eskin) was developed to mimic human skin through a combination of different materials, structures, and technologies. One of its earliest uses was in 1985,

Table 8.1
Classification of various mechanoreceptors

Classification	Pacinian corpuscle	Ruffini corpuscle	Merkel cells	Meissner's corpuscle
Adaptation rate	Fast	Slow	Slow	Fast
Effective stimuli	Temporal change in skin morphology	Vertical force detection, slippage	Spatial deformation, curvatures, edges	Temporal change in skin morphology
Sensory function	High-frequency vibration	Position, grasp, motion	Pattern detection, perception, texture	Low-frequency vibration, grip control

Source: Adapted from Dahiya 2010.

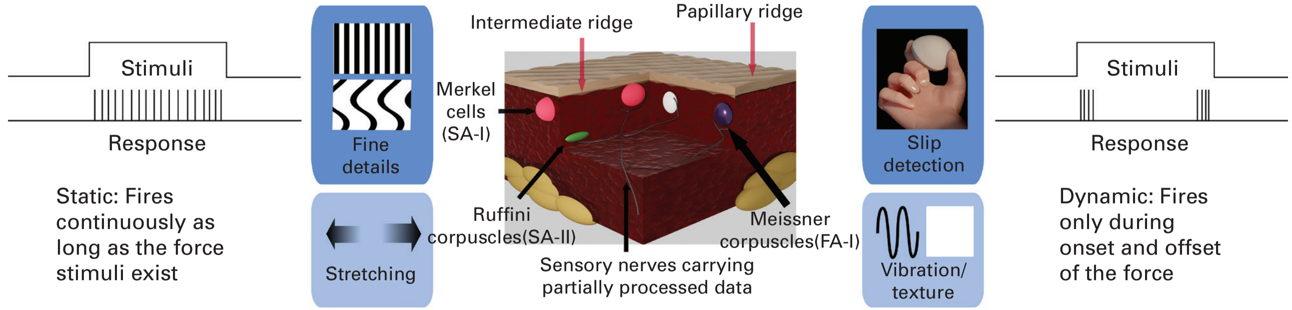

Figure 8.1
The MRs in the glabrous human skin that enable the tactile sensation. The SA MRs (*left*) respond with continuous spikes during the static stimuli, and the FA MRs (*right*) respond with spikes during the transition or the dynamic part of the stimuli.

when a flexible array with a resolution of 5 cm was attached on a robotic arm for sensing proximity (Hammock et al. 2013). Since then the nature of eskin has not changed much, as most of the eskins share similar sensors and readout characteristics along with their morphologies (Navaraj et al. 2017; Yogeswaran et al. 2018; Núñez, Manjakkal, and Dahiya 2019). Generally, they have a base substrate (bendable/stretchable) on top of which the sensing element/s (capacitive, resistive, piezoelectric, and so on) are developed. Usually, an encapsulation layer is added on top of the sensing structure to reduce the possibility of wear and tear. These devices can be bendable in order to conform to the surface of a robot's rigid body to equip them with more advanced humanlike tactile-sensing capabilities (Kappassov, Corrales, and Perdereau 2015; Yogeswaran et al. 2015; Núñez et al. 2017).

8.3 Robotic Hands with Intrinsic Tactile Sensing

Intrinsic or tightly integrated sensing, actuation, and computation elements, all embedded in 3D structures, will underpin the advances in the next generation of smart and complex systems such as humanoid robots with the capabilities to carry out cognitive tasks (Ntagios et al. 2020). The human skin is densely packed with different types of mechanoreceptors (as described in section 8.1) that support humans' ability to carry out cognitive tasks by enabling them to understand and rapidly respond to the constantly changing environment. As humans interact with the environment, the touch stimuli from these tightly coupled receptors are constantly being processed, interpreted, and stored by the brain followed by swift action from the concerned effector in response to the stimulus (Bear, Connors, and Paradiso 2020). This real-time, closed-loop interaction enables humans to respond using not only the immediate stream of information from the receptors but also the previously stored information. So for robots to be autonomous and able to carry out cognitive tasks, eskin should be able to acquire, process, and store information from the environment in a closed-loop fashion through tightly coupled sensors, actuators, and computation elements. This will enable a fast, real-time response and adaptation of the robot to its dynamic environment.

There have been some attempts toward bestowing robots with humanlike dexterity through artificial muscles, large-area eskins, computing devices, and so on, but these robots often fail to execute intricate tasks that are easily conducted by humans (Viteckova, Kutilek, and Jirina 2013; Siegwart et al. 2011). The reason is that current arrangements do not explore the synergistic working of sensors, actuation, and computation to the same degree as humans. The eskins developed nowadays have some human-skin-like features, but their surface mounting comes with the challenge of wear and tear during frequent use. These issues arise from the way they are deployed on the surface of robotic bodies. The sensors need to be in direct contact with objects and often have limited protection from extreme forces and/or sharp edges. Another common problem is routing the vast amount of wires in eSkin devices to the computing unit. This often results in a potential hazard when operating a robotic system. Some of these challenges can be alleviated by embedding the sensing elements in the core structure of robots.

Additive manufacturing, or 3D printing, as it is more commonly known, has emerged over the last few decades and could offer new solutions for developing robotic parts with embedded sensors (see section 2.1). The process is based on a build sequence in which the structure is constructed from the layer-by-layer deposition of materials. As an additive method (as opposed to a subtractive technique such as milling), 3D printing provides an ability to obtain complex 3D structures with arbitrary shapes and more geometric freedom when taking the build process into consideration. If today's single-materials-based, 3D-printing approach can be adapted to incorporate the simultaneous printing of multiple materials (e.g., plastic and metal) then there is potential for the manufacturing of "smart" objects with enhanced functionalities and with embedded sensing/electronic components (Nassar et al. 2018). This is an exciting approach for robotics because different sensing and actuating materials can be embedded into a robot's body as part of the build process. The printing of various conducting materials, along with typical plastic or polymers to create complex 3D structures, will allow the efficient use of 3D space inside these structures. The open-source nature of most fused deposition modeling (FDM) printers and their accompanying software also lends itself to widespread modifications to the printers in various ways, such as incorporating multiple printing heads, printing novel materials, and adjusting the print settings to suit a desired custom application. This being said, there are some limitations, particularly with regard to the print resolution. Nozzle diameters, build volumes, relatively slow fabrication speeds for mass production, material properties, and lack of adjustability during fabrication are some of the limiting factors of this technology. Researchers are currently working toward improving these machines via integrating other fabrication mechanisms, feedback controls, and AI (Sitthi-Amorn et al. 2015; Skylar-Scott et al. 2019). Nonetheless, the overwhelming benefits of printing rigid structural materials, soft materials, conductive inks, and sensing and actuating elements all in one fabrication method for robots in arbitrary shapes is an avenue that will spur the research in coming years.

Recent work (Ntagios et al. 2020) in which innovative hand design has been used along with multimaterial 3D printing is a good example of this approach. A 3D-printed soft capacitive sensor and associated readout electronics (e.g., a capacitance to digital converter chip on a small PCB) were embedded into the 3D-printed robotic hand (Ntagios et al. 2020). At first a five-finger 3D-printed hand was designed to have embedded actuators for movement of each of the fingers. The design consisted of multimaterial 3D printing by a modified 3D printer mounted with multiple hot ends with different materials. The hand's design was segmented into three sections: bottom, middle, and top (figure 8.2*a*). The top and bottom sections were printed with polylactic acid (PLA), a well-known 3D-printing material, and the middle part was printed with flexible thermoplastic polyurethane (TPU). In between the sections, a thin layer of acrylonitrile butadiene styrene (ABS) was printed to increase the adhesion between the sections. In this way, the entire hand was fabricated in one continuous print without the need for assembly or support material. This arrangement of materials utilized the rigidity of the PLA and ABS and the elasticity of TPU to achieve flexion of the finger joints. The hand is an underactuated and self-adapting mechanical end effector without any complex mechanical parts. This is an attractive approach to mechanical design because it achieves multiple requirements of robotic end effectors, minimizing the postprocessing and assembly time, in contrast with the more common production of robotic end effectors that utilize fabrication techniques such as machining, molding, and/or laser cutting to produce the parts of the system and are often required to implement extremely complex driving mechanisms to animate the hand (Weiner et al. 2020). Most robotic hands, especially the commercial ones, are fabricated with completely rigid materials, resulting in a massive amount of parts needing to be fabricated and assembled (Belter et al. 2013).

Further, a similar methodology was used to produce fingertips with an embedded capacitive sensor and embedded readout electronics (figure 8.2*b*). The fingertip had a simple design to enable the fabrication of the aforementioned system (figure 8.2*c*). The architecture of the phalanx imitated the structure of the human finger, with a rigid interior (bone), soft tissue, and skin. The pattern of the sensor mimicked this morphology, with a rigid PLA base and conductive and dielectric material encapsulated between the rigid PLA and the top surface made of TPU. In the core of the rigid PLA structure lay the embedded electronics. The fabrication of this part was performed in steps, the first being the printing of PLA up to the level of the two pull-up resistors, which are needed to implement the interintegrated circuit (I2C) protocol for the integrated circuit (IC) chip meant to read the capacitance variations. The subsequent steps involved the placement of resistors and the direct ink writing (DIW) of a custom-made graphite ink for interconnects. After the ink dried, a second section of PLA was printed on top until the designated area housing the PCB was mounted with a capacitance-to-digital converter IC. The PCB was placed on top, followed by further printing until complete encapsulation was reached. In the study three conductive materials, silver adhesive paste, conductive PLA, and custom-made graphite-based ink, and two dielectric materials, Ecoflex and TPU, were explored to create the capacitive sensor. Other studies have printed silicone rubber materials as part of their transducers, and they have concluded that softer materials such as Ecoflex reduce the hysteresis of the transducer (Tomo et al. 2018). Five variations of the sensor were created with a combination of these materials:

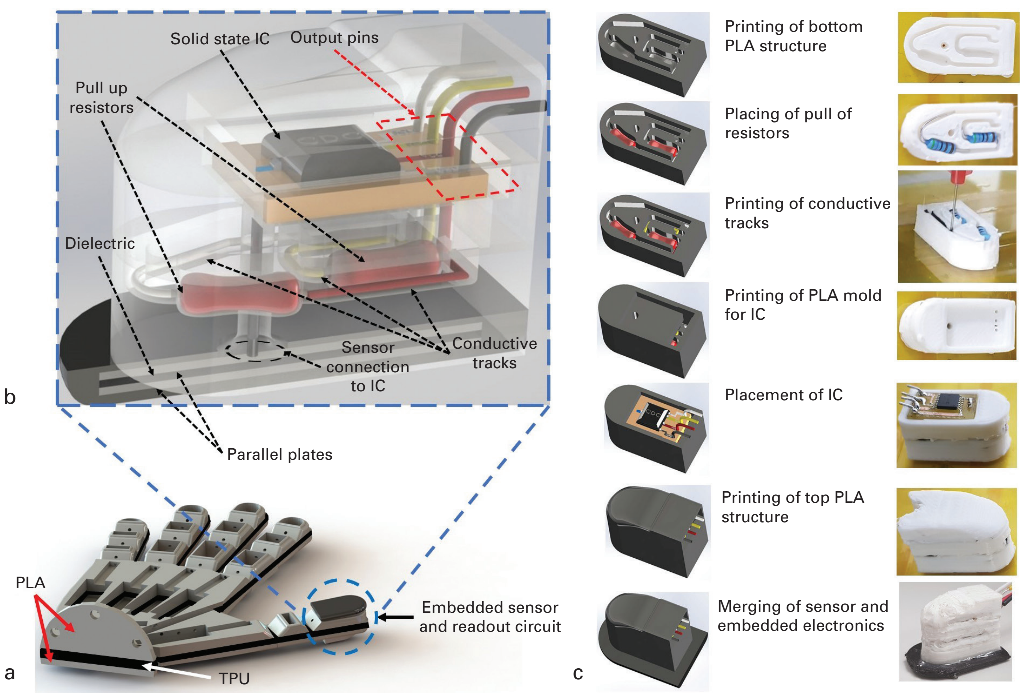

Figure 8.2
The 3D-printed hand with intrinsic tactile sensing. (a) CAD design of the hand with the smart sensing phalanx that has a soft capacitive touch sensor and an embedded readout circuit. (b) CAD design of the interior structure of the phalanx. (c) Fabrication steps for the 3D-printed phalanx.

Ecoflex-silver, TPU-silver, Ecoflex-graphite, TPU-graphite, and Ecoflex-TPU. All sensor variations were fabricated using the customized 3D printer. The conductive PLA and the TPU were deposited with fused deposition modeling (FDM) technique, and the Ecoflex was drop casted. The graphite ink was printed with direct ink writing (DIW) technique, and the silver paint was brushed, but similar techniques can also be used with the silver.

The Ecoflex-silver variation showed superior performance (figure 8.3) and a stable and repeatable response in static and dynamic conditions with a minor hysteresis effect. The superiority of the Ecoflex dielectric and the silver paste electrodes over the other devices was due to the materials' properties. The adhesion of the Ecoflex and the silver paint was found to be the strongest with respect to other samples. The silver paste, which is known to develop cracks, did not do so in the embedded configuration. This arrangement of materials and the interactions between them demonstrate an alternative approach toward sensor endurance. The embedding of sensing elements inside flexible elastomers provides the required protection to the sensing elements, thus increasing the duration of the use phase of the sensing modules and preventing costly repairs.

In recent years, a number of similar studies have been initiated that attempt to utilize this technology. Previously, most 3D-printed sensors were fabricated using the direct ink method (Muth et al. 2014). These methods were most commonly used for soft robotics and eskin-type approaches (Truby et al. 2019). Recently, more studies are using FDM techniques as well (Kaur and Kim 2019).

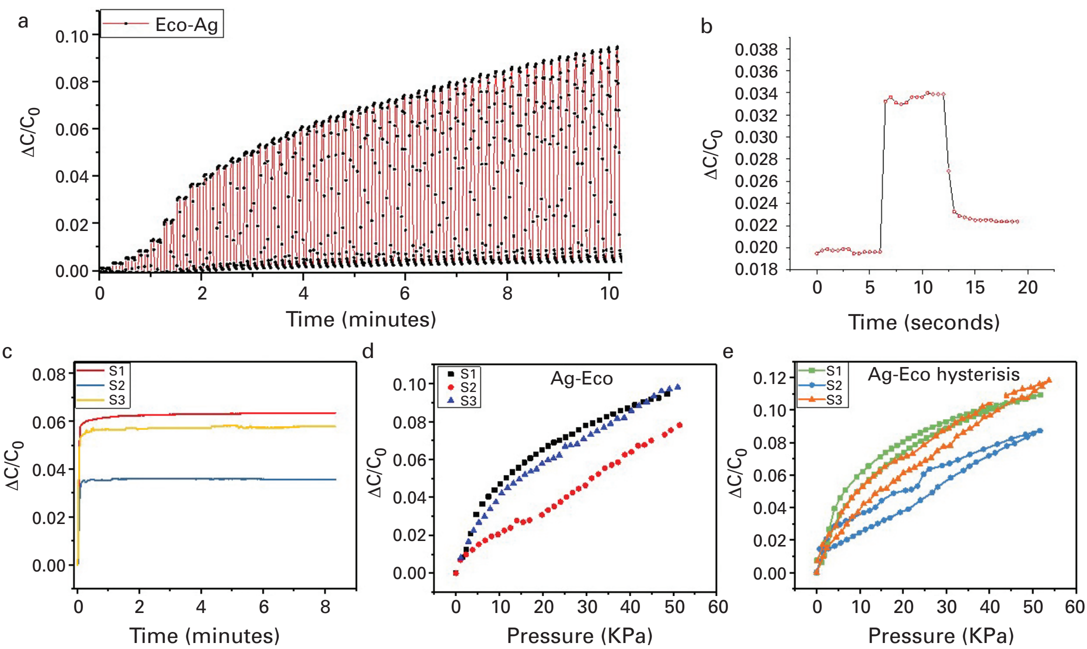

Figure 8.3
(a) Dynamic response of one of the Eco-Ag sensing devices over time with increasing pressure. (b) Relative change in capacitance of the Eco-Ag sensing device with respect to time during one of the loading-unloading cycles. (c) Response of all three sensors under constant load. (d) Relative change in capacitance with increasing pressure. (e) Hysteresis curve of the tested devices.

Obtaining complex smart structures with intrinsic sensing, actuation, and computing is the way to progress to the next era of autonomous robotic systems. The tightly integrated sensing within the 3D-printed structures could pave the way for a new generation of truly smart systems that can change their appearance and shape autonomously. In comparison with state-of-the art robotic or prosthetic hands, this approach could lead to robust and affordable hands with more functionalities. Furthermore, the multimaterial 3D-printing methodology offers efficient use of 3D space through embedded components.

8.4 Tactile Sensor with Piezoelectric/Capacitive Stack

The dynamic and static force feedback from the skin is central to humans for daily tasks. As mentioned in 8.1, human skin contains both FA and SA mechanoreceptors. However, most of the tactile sensors reported in the literature provide either static or dynamic pressure (Yousef, Boukallel, and Althoefer 2011; Jamone et al. 2015; Kaur and Kim 2019). The spatiotemporal detection of tactile stimuli is important for texture recognition (Yousef, Boukallel, and Althoefer 2011; Dahiya et al. 2013), and for this purpose it is necessary for eskin to have the ability to detect both static and dynamic contacts. To address this issue, scientists have recently developed a new touch sensor—a stack of piezoelectric and capacitive sensors. This allows the measurement of both static and dynamic stimuli, and with the use of machine-learning or artificial intelligence (AI) tools, we can explore further cognitive skills such as detecting the texture of a curved surface (Navaraj and Dahiya 2019). This highly sensitive, capacitive-piezoelectric, flexible sensing skin with fingerprint-like patterns was formed to detect and discriminate between spatiotemporal tactile stimuli, including static and dynamic pressures and textures.

Multifunctional sensors that provide information about static and dynamic events are vital for the autonomy and dexterity of robots. In this study, to compensate for the inability of the piezoelectric sensor to perform static sensing, an integrated capacitive sensor was introduced. Thus, a capacitive-piezoelectric sensor stack was formed to mimic human skin's SA and FA mechanoreceptors (figure 8.4). The sensor was encapsulated within the 3D-printed distal phalanx of the index finger, using fingertip patterns from TPU. This pattern enhanced the detection capability of the system to identify surface roughness. This is a significant leap forward, as most of the surface roughness systems developed prior to this work have relied heavily on large area arrays (Drimus et al. 2014; Lee, Kukreja, and Thakor 2017).

The tactile sensor had a floating electrode-based capacitive structure in tandem with a piezoelectric structure. The sensor utilized two soft elastomers with low and high Young's modulus. This arrangement enabled high sensitivity at low pressures, due to the softer elastomer, without saturating at higher pressures, due to the high Young's modulus elastomer. At static pressure, the elastomers compressed, and the floating electrode moved closer to the signal and ground electrodes (figure 8.4). The sensor stack was integrated into the distal phalange of the index finger of a 3D-printed prosthetic/robotic hand. The sensing device was covered with fingerprint ridges made from TPU polymer 3D-printed filament. The ridges were positioned in a staggered fashion to provide robust protection, in a way similar to human skin.

Early studies in this field have implemented classifiers with tactile sensors utilizing Fourier transform wavelets. Researchers have concluded that a change in texture over time

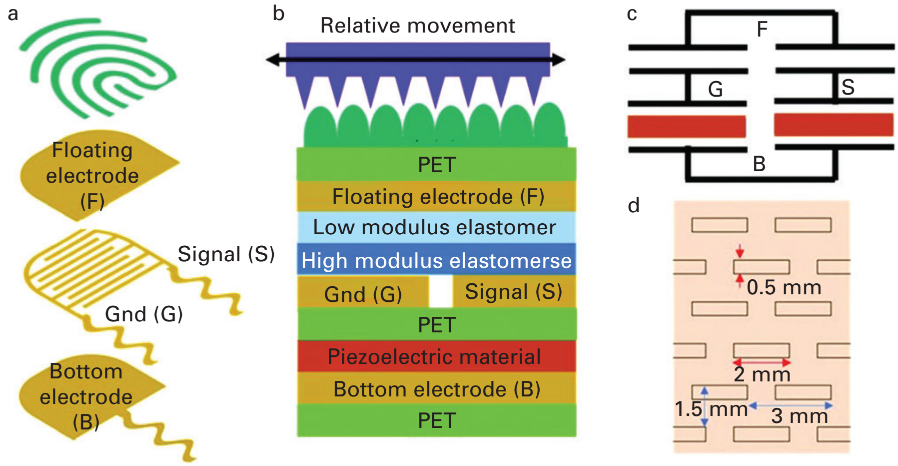

Figure 8.4
(a) Schematic illustration of the biomimetic sensory stack. (b) The layers in the sensory stack, with fingerprint ridges shown at the top. (c) An equivalent diagram of the biomimetic sensory stack. (d) The dimensions of the designed fingerprint ridges realized via 3D printing using NinjaFlex.

is an important factor between surfaces with irregular textures. A short-term Fourier transform could be used to explore more irregular surfaces (Jamali and Sammut 2011).

In Navaraj and Dahiya (2019), a biologically plausible wavelet transform was used to encode the sensor's output into spike trains based on a leaky integrated-and-fire (LIF) model. The spikes were classified with a tempotron classifier using a biological observed spike timing-dependent plasticity (STDP) mechanism learning algorithm. With this approach nonplanar texture surfaces can be classified, unlike prior works. This was made possible with a six-degrees-of-freedom robotic arm that maintained constant static pressure on the surface of the object. The data were fed to a wavelet-based processing algorithm, using the Gabor wavelet transform (GWT) instead of the common Fourier transform. This approach offers localization in time and frequency domain, and at the same time wavelet transform appears to be a more plausible approach in biological systems. To further prove the point, the results were also presented using short-time Fourier transform (STFT) with a window size of one hundred samples. After the GWT transform, the data were encoded into latency-coded spike trains, as this is the assumed reason why biological systems have such a fast response to dynamic stimuli. An LIF model was used for the spike model, while the amplitude represented how fast the spike was elicited within the time span. This work was tested to prove whether textures can be perceived with a single biomimetic sensory stack. To prove the truthfulness of the above statement, hook-and-loop fasteners were used as textures for binary classification. The classification was conducted using both planar and nonplanar surfaces to remove possible biases. One hundred planar scans, fifty concave and fifty convex, were recorded, with each scan comprising both hook and loop textures. Training data consisted of 160 randomly selected samples for the neural network and 40 for testing.

Figures 8.5*a–d* show the system's response and easily demonstrate that the loops produced higher amplitude signals than the hooks due to loops interacting more with the fingertip patterns. In the training error over the number of epochs, it is also clear that the

GWT approach to texture recognition is superior to the traditional STFT method. The STFT-based approach has an accuracy of 95.3 percent, while the GWT-based approach offers 99.45 percent accuracy for the same window of time (figure 8.5*e*). In conclusion, the output of the sensory stack under a closed-loop system was able to classify textures with a maximum accuracy of 99.45 percent, which also demonstrated the possibility that a single sensory stack may be sufficient for texture classification.

8.5 Integrated Sensing and Actuation Technology

This section examines the research focused on integrating sensors and actuators for an advanced eSkin. To utilize the full potential of robots, it is important to enable them to interact with dexterity and cognitive capabilities, as well as learn from their resulting interaction with the environment. The purposeful employment of a robot's environment is proposed in the context of developmental robotics in section 6.3. Future robots should be able to deal with the uncertainty of the natural environment by continually learning, reasoning, and sharing their knowledge. As previously discussed in section 8.2, eskin is one of the effective approaches that researchers have used to achieve this. However, existing robots are mostly equipped with eskin having only sensing capabilities. As mentioned in

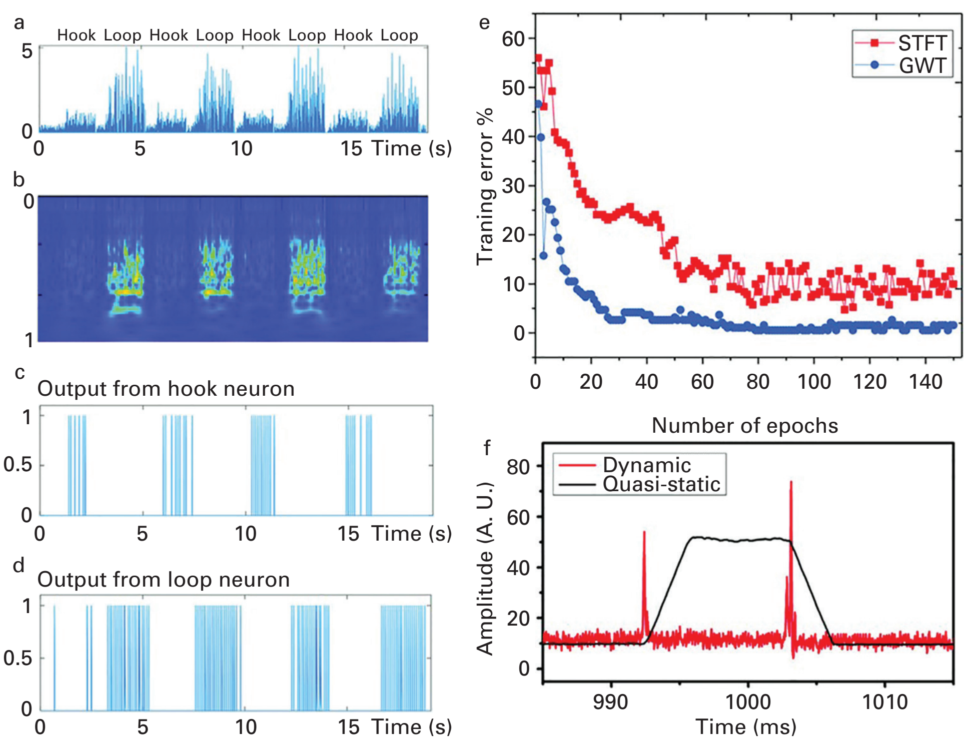

Figure 8.5
(a) A typical recorded signal from the dynamic scan. (b) Gabor wavelet scalogram. (c, d) Output from the tempotron classifier neuron corresponding to the (c) hook and (d) loop. (e) Training error versus number of epochs comparing STFT and GWT-based features. (f) Plot of the wirelessly transmitted live data acquired via the rqt plot of the ROS package.

section 8.2, researchers have designed tactile sensors for eskin using various material (Yogeswaran et al. 2015) structures (Mannsfeld et al. 2010; Gong et al. 2014; Wang et al. 2014), morphologies (Dahiya and Gori 2010; Navaraj et al. 2017; Navaraj and Dahiya 2019), and transduction methods (Dahiya et al. 2011; Adami et al. 2012; Dahiya and Valle 2013; Khan et al. 2015; Gupta, Shakthivel, et al. 2018; Gupta, Yogeswaran, et al. 2018; Hannah et al. 2018; Kawasetsu et al. 2018; Yogeswaran et al. 2018), with some mimicking the human skin's features, such as fingertip-like patterns on the surface and integrated static and dynamic sensors (Navaraj and Dahiya 2019). However, the complexity of eskin goes beyond just integrating various types of touch sensors on flexible substrates (Núñez et al. 2017).

Seamless integration of both sensing and actuation capabilities will improve the granularity of haptic information inherent in the next generation of eskin (Dahiya et al. 2019), enabling a substantial contribution to AI systems. Robots donned in such eskin will have humanlike dexterity, cognitive skills, and physical abilities, as they will be able to learn from their environment via rich and diverse information. In this context, some studies have explored adding sensing capabilities to different types of actuators to obtain information regarding the degree of displacement produced during actuation. These actuators include electromagnetic (Andò and Marletta 2016; Do et al. 2018), pneumatic (Yeo et al. 2016), and electroactive polymers (EAPs; Nakamura and Kawakami 2019) with different operating principles and materials (Chen et al. 2019). Unlike electromagnetic actuators and ionic EAPs (Asaka et al. 2013), the majority are unable to provide bidirectional actuation, vibrotactile feedback, or a high level of displacement due to limitations in the actuation principle and/or materials used (Biswas and Visell 2019). Further, the majority of the actuators with integrated sensing functions are manufactured either on paper (Phan et al. 2017; Amjadi and Sitti 2018) or with EAPs (Jung, Kim, and Choi 2008) that require relatively high voltages (~150 V per micrometer displacement; Yeo et al. 2016). Electromagnetic actuators are capable of providing high displacement (up to 1 mm and a high force ~5 mN/mm^2 at 5 V; Guo et al. 2018; Noguchi, Nagai, and Kawamura 2018) as well as bidirectional actuation (Bintoro et al. 2005) and vibrotactile feedback (Do et al. 2018) at different frequencies (⇐1 Hz and >500 Hz). In particular, bidirectional actuation is advantageous in the manipulation of the direction of actuation, as it provides options for controlled multidirectional displacement (Cho and Ahn 2002). In the effort to make electromagnetic actuators intrinsically soft and wearable, the field of magnetoelectronics has also been rapidly gaining attention (Hellebrekers, Kroemer, and Majidi 2019). In this case, flexible magnets and elastomers mixed with ferromagnetic materials are harnessed for the purpose of actuation (Almansouri et al. 2019; Hintze et al. 2014). However, electromagnetic actuators have so far been those most employed for actuation purposes (Said et al. 2016; Paknahad and Tahmasebipour 2019), with primary applications in micropumps (Said et al. 2018) and tactile displays (Zárate and Shea 2016). By integrating sensing capabilities in electromagnetic actuators, multidirectional actuation capability and excellent controllability could be adequately harnessed to advance applications in the realization of soft eskin with both sensing and haptic feedback capabilities.

Electromagnetic actuators (EMAs) function by converting magnetic energy into mechanical energy and are generally governed by three fundamental laws: the Lorentz law, Faraday's law, and the Biot-Savart law (Gomis-Bellmunt and Campanile 2009). Actuation in

EMAs occurs through the interaction of the magnetic field (produced by a current through a coil) with a permanent magnet and/or a ferromagnetic material (Kawasetsu et al. 2018). This interaction produces either a repulsive or an attractive force applied directly to a membrane or plunger, thereby causing displacement. This repulsive or attractive force is utilized to achieve the repulsion and attraction of soft membranes of the eskin. Principally, electromagnetic actuation occurs by means of two main circuits: 1) the electrical circuit that establishes the current and voltages and 2) the magnetic circuit that establishes the magnetic field strength and flux. The current I produces the controllable magnetic field $\vec{H}$, while the magnetic field produces the magnetic flux ø and the magnetic flux density $\vec{B}$ (equation 8.1).

$$\vec{B} = \mu_r \mu_0 \vec{H}, \tag{8.1}$$

where μ_r = relative permeability of the material, μ_o = permeability of the vacuum, and the magnetic constant = $4\pi \times 10^{-7} H$.

The addition of intrinsic sensing to electromagnetic actuators is advantageous, as mentioned in section 8.3 and shown in research (Ozioko, Navaraj, et al. 2018; Ozioko, Hersh, and Dahiya 2018, 2019; Ozioko, Karipoth, et al. 2021). Figure 8.6*a* shows this principle and the device structure composed of a tactile sensing (piezoresistive) layer integrated on top of a permanent magnet that is part of a flexible electromagnetic, coil-based actuator. The device can detect contact force via the piezoresistive layer and simultaneously produce a proportional actuation using the electromagnetic actuator. Figure 8.6*a* shows the device before actuation, while figure 8.6*b* and figure 8.6*c* show the device during different actuation modes. During actuation, the top layer is attracted to or repelled by the coil, as shown in figure 8.6*b* and figure 8.6*c* respectively, in accordance with the electromagnetic principle previously described in this section. In each case, there are two possible states, the vibration state and the nonvibration state, depending on the direction of the supplied current. When a constant current is supplied, the device operates in a nonvibration state. The vibration state occurs when the pulsating current of a given frequency is supplied through the coil. This makes it possible to control the speed, movement, and direction of the top layer via the manipulation of the magnitude and direction of the supplied current. Hence, eskin with this feature can be controllably tuned as required.

Figure 8.7 shows a more detailed operating principle of the device. The two main modules of the device (sensing and actuation) are controlled by the sensing and actuation module, respectively. Figure 8.7*a* shows the soft, piezoresistive sensing layer. This sensing layer could be realized using any soft sensing layer, but in this case a graphite ink was encapsulated using Sil-Poxy™. When an external force is applied to the sensing layer, the particles of graphite move closer to one another from distance *d1* and *d2* to $d1 + \Delta d1$ and $d2 + \Delta d2$, respectively. This creates a closer conducting network that causes a reduction in resistance of the material from R (figure 8.7*a1*) to $R + \Delta R$ (figure 8.7*a2*). Figure 8.7*c* shows what happens when external pressure is applied to the sensing layer. In this case, a change in resistance (ΔR) occurs as read by the sensing control module. This resistance shift causes a change in current (ΔI) flowing through the spiral coil that is driven by the actuation control module. This change in current in turn causes a proportional change in the magnetic field produced by the spiral coil that leads to a change in the force of actuation. This change in actuation force causes the top layer to move away from the coil due to repulsion or closer to the coil due to attraction. Therefore, this device takes advantage

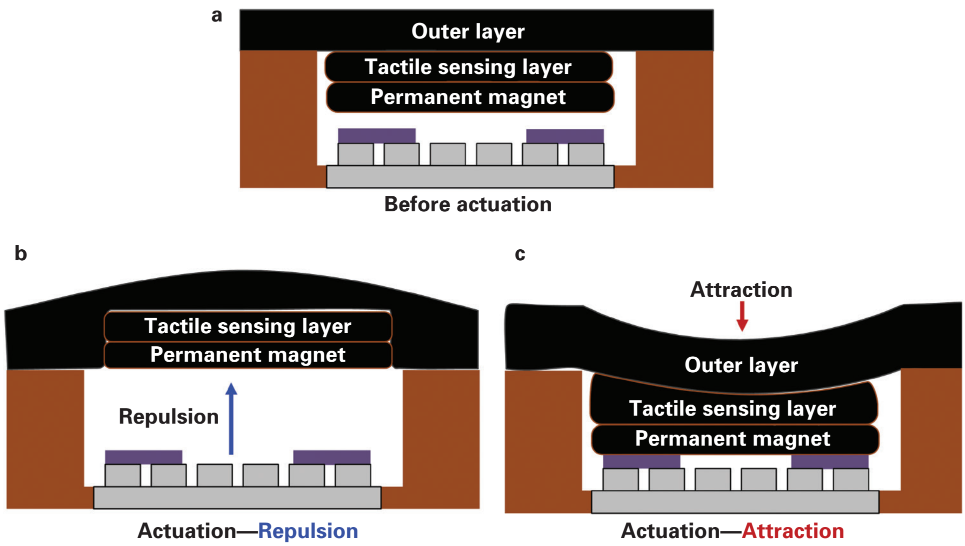

Figure 8.6
Actuation modes. (a) Before actuation. (b) Repulsion mechanism. (c) Attraction mechanism.

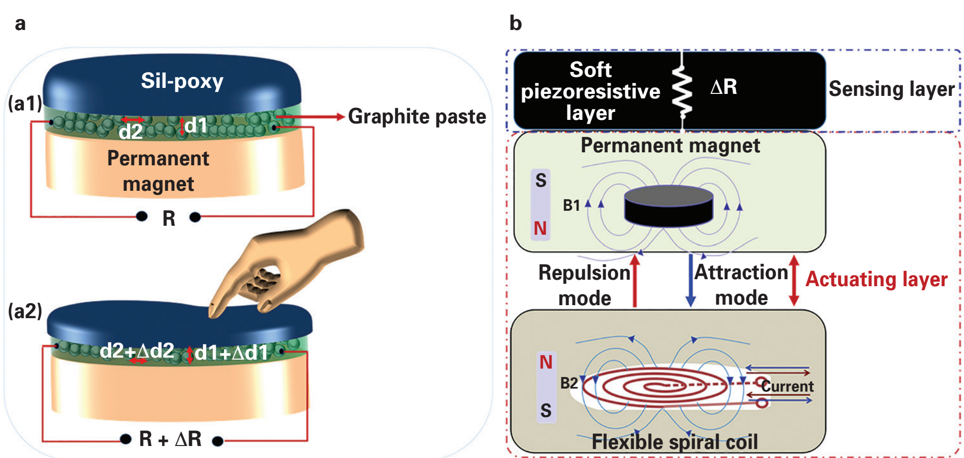

Figure 8.7
(a) The structure and principle of the piezoresistive layer. (b) The structure and principle of the actuation layer.

of the sensing ability of the piezoresistive layer and the magnetic interaction between the coil and the permanent magnet to produce simultaneous sensing and actuation. Additionally, the sensing and actuation could be independently controlled using digital logic gates and a microcontroller programmed with corresponding algorithms.

Figure 8.8 shows the response of the sensing layer of the integrated device alone as well as that of simultaneous sensing and actuation. This result illustrates that the self-controllability characteristic of the integrated device makes the concept advantageous for use in future tunable eskin, enabling controllability and the extraction of richer information. Future applications could explore embedding this integrated device in a robotic fingertip to control its stiffness for improved grasping of objects.

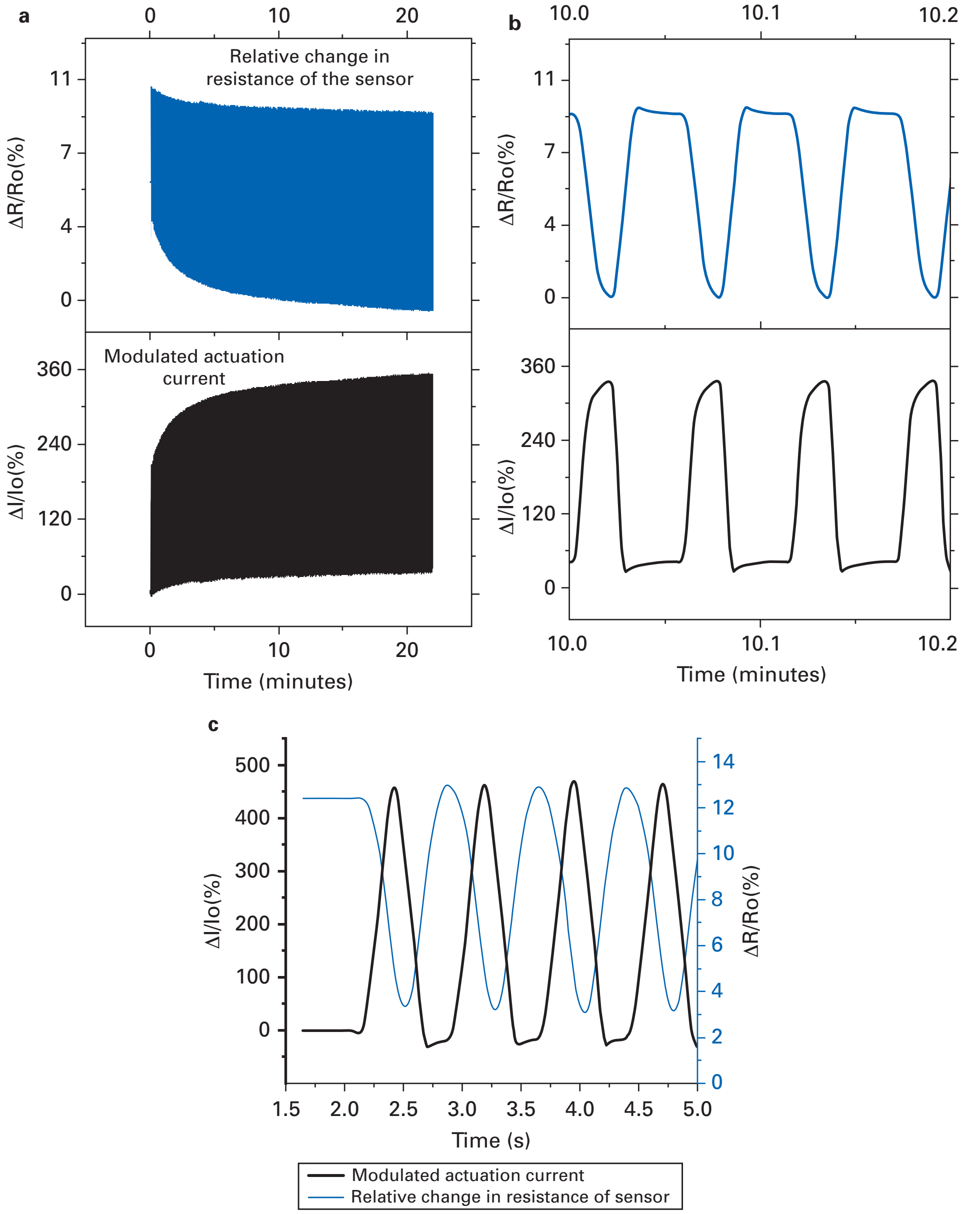

Figure 8.8
(a) Output of sensing layer and the modulated current through the actuating coil during simultaneous sensing and actuation at approximately 0.25 Hz for approximately twenty-two minutes. (b) Zoom-in of figure 8.8*a* demonstrating that as the resistance decreases, the current through the actuator increases. It also shows the stability of the device for approximately twenty-two minutes of continuous use. (c) Change in current and resistance during simultaneous sensing and actuation at 1 Hz.

8.6 Conclusion

This chapter presented the current state and development of tactile sensing and actuation technologies in robotic skin along with new approaches toward biomimetic and bioinspired tactile sensing and computing. Current fabrication techniques and their limitations and drawbacks were discussed. The growth of 3D printing and the advantages it provides were examined, as well as how this new technology can enhance current tactile and actuation systems. The two tactile sensor structures presented in sections 8.3 and 8.4 do in many ways mimic human skin's functionality. The 3D-printed hand with intrinsic tactile sensing discussed in section 8.2 has the embedded actuation, capacitive sensors in the distal phalanges, and embedded electronics capable of reading the capacitive value and transmitting the digital information to the microcontroller. In this way the wear and tear issue of eskin is alleviated, along with the wiring complexity issue. The biomimetic tactile sensor presented in section 8.3 uses a sensory stack to simultaneously measure dynamic and static conditions. Data from sensors were fed into a neural network that could classify two textured surfaces with an extreme accuracy rate of 99.45 percent. In the study, a comparison between the commonly used short-time Fourier transform and a biomimetic Gabor wavelet transform was performed to explore the superior system. The piezoresistive sensor with integrated actuation presented in section 8.5 can provide vibrotactile feedback. Devices such as these have the potential to advance soft robotics by allowing such robots to "squeeze" while continuing to sense ambient conditions.

In general, the case studies presented show how eskin research is advancing toward tightly coupled sensing, actuation, and computation. The key cognitive skills needed to advance robot capabilities include memory, decision-making, action understanding, and prediction. The technologies discussed in this chapter open opportunities for achieving these skills by allowing robots to effectively sense their environment and process, store, and use the obtained information to respond to their dynamic environment. This can have a significant impact on human-robot interaction—for instance, humans are able to extract important information from tactile stimuli that depends not only on the underlying touch characteristics but also on the context of the touch, culture, and emotions of the individuals who are communicating. So enabling robots not only to sense tactile information but also to understand the intended meaning of touch has great potential to advance robot cognition as well as human-robot interaction.

Additional Reading and Resources

- This edited volume provides a complete overview of tactile sensing in humans. It includes definitions and classification. It also classifies all transduction methods to realize tactile sensors and materials. Dahiya, Ravinder S., and Maurizio Valle. 2013. *Robotic Tactile Sensing: Technologies and System*. Berlin: Springer Science and Business Media.
- A compact volume conveying a great deal of information on sensing and actuation. This volume provides information on sensing for broad variety of stimuli. Extensive description is given to robot motion, both for soft and rigid robots, tackling some control algorithms. Siciliano, Bruno, and Oussama Khatib, eds. 2016. *Springer Handbook of Robotics*. Berlin: Springer.

• A special issue presenting the latest work on flexible electronics and eskin. Dahiya, Ravinder, Deji Akinwande, and Joseph S. Chang. 2019. "Flexible Electronic Skin: From Humanoids to Humans." Special Issue, *Proceedings of the IEEE* 107 (10): 2011–2015.

• Basic knowledge of different types of tactile-sensing mechanisms for nonexperts. Explains the different stimuli and basic circuitry used for reading the outputs: https://www.elprocus.com/tactile-sensor-types-and-its-working/.

• BEST (Bendable Electronics and Sensing Technologies) YouTube channel, containing robotic/prosthetic videos with tactile sensing, 3D printing, and more: https://www.youtube.com/channel/UCOOdG132wFmWSTPPBUARAvA/.

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