Printed Strain Sensors for On-Skin Electronics

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On-skin electronics have drawn extensive attention as they revolutionize many aspects of healthcare, motion tracking, rehabilitation, robotics, human–machine interaction, among others. Flexible and stretchable strain sensors represent one of the most explored devices for on-skin electronics. Many printing techniques have recently emerged showing great promises for manufacturing strain sensors. Herein, it is aimed to provide a timely survey of recent advancements in printed strain sensors for on-skin electronics. This review starts with an overview of sensing mechanisms for printed strain sensors, followed by a review of various printing techniques employed in fabricating these sensors. The materials, structures, and printing processes of representative strain sensors are discussed in detail for each printing method. Finally, potential applications of printed flexible and stretchable strain sensors are presented focusing on three areas: healthcare, sports performance monitoring, and human–machine interfaces. The review concludes with a discussion of challenges and opportunities for future research.

1. Introduction

Skin is the largest organ of the human body and possesses rich information regarding health conditions and body activities.1] On-skin electronics that can be directly attached to the skin are quickly emerging and have found broad applications such as disease diagnosis, sports performance tracking, rehabilitation, and human–machine interaction.2] In particular, key biological information such as body motion, facial expression, heart rate, respiration rate, phonation, swallowing, and many others can be accessed from the mechanical deformation of the skin.3] Skin-attachable strain sensors capable of detecting skin deformations are therefore one of the most explored devices for on-skin electronics.4]–]6] Skin-attachable strain sensors are particularly promising since they meet the stringent requirements mentioned above. Inorganic nanomaterials have been extensively explored as sensing elements due to their large surface area, extraordinary material properties, good mechanical compliance compared with their bulk counterparts, and compatibility with a variety of manufacturing methods.7] To build up strain sensors, sensing materials are typically patterned on polymeric substrates that can help the sensors achieve the desired flexibility, stretchability, durability, and human friendliness.8]

Strain sensors for on-skin electronics can be fabricated using a variety of methods, including drop casting, spin coating, spray coating, liquid phase mixing, chemical synthesis methods, vacuum filtration and transfer, micromolding, thin-film deposition, and photolithography.9]–]18] Printing provides a versatile approach for strain sensor manufacturing with several salient features. Printing strain sensors requires a lesser number of steps and manual labor. Sensor structures can be easily customized based on a predesigned CAD file and it is easier to achieve desired structures in high resolution than strain sensors fabricated by coating methods, micromolding, liquid phase mixing, and chemical synthesis methods.19] Compared with coating techniques, printing methods dramatically reduce material waste. While strain sensors fabricated by vacuum filtration and transfer often suffer from defects introduced during the transfer process, with printing techniques, strain sensors can be directly patterned on diverse planar substrates and even non-planar substrates with high dimensional accuracy.20] In comparison to deposition and photolithography, printing methods eliminate the need for clean room facilities.21]–]23] Printing techniques provide a convenient, economical, and versatile method to fabricate strain sensors for on-skin electronics.24]–]28]
This review aims to provide a timely survey at the intersection of skin-mountable strain sensors and printed electronics. The review is organized as follows: Sensing mechanisms employed in printed sensors are introduced in Section 2. In Section 3, various printing techniques and printed flexible and stretchable strain sensors are presented. In Section 4, the applications of printed strain sensors in healthcare, sports performance monitoring, and human–machine interfaces are reviewed. In the last section (Section 5), challenges and outlooks in this emerging field are discussed. Interested readers are referred to recent reviews on strain sensors for aspects that are not covered in this review. 

2. Strain Sensing Mechanisms

Various strain sensing mechanisms have been adopted for flexible and stretchable strain sensors, including capacitive, resistive, piezoelectric, triboelectric, and optical. For printed skin-attachable strain sensors, capacitive, resistive, and piezoelectric mechanisms are mostly used. Materials, internal micro-/nanostructures, and manufacturing methods are important factors that can influence the response of strain sensors. Conventional thin-foil strain gauges are typically based on geometrical changes, material piezoresistive effects, or piezoelectric effects. With the development of highly stretchable strain sensors, new sensing mechanisms are proposed, including crack propagation, disconnection, and tunneling effect. These sensing mechanisms are mainly based on resistance changes caused by strain-induced changes in micro/nanostructures. In this section, we will review these three sensing mechanisms for printed strain sensors (Figure 2).

2.1. Capacitive Effect

Strain sensors based on capacitive effects are basically deformable capacitors. Under tensile strain, the length in the strain direction increases while the cross-sectional area decreases due to the Poisson effect. The geometrical deformation under strain leads to the change in the capacitance. The initial capacitance of capacitive strain sensors is given by
\[
C = \varepsilon_0 \varepsilon_r \frac{lw}{d} \tag{1}
\]

where \(l\), \(w\), and \(d\) are the length, width, and thickness of the dielectric layer, respectively. \(\varepsilon_0\) and \(\varepsilon_r\) are the dielectric constant of the vacuum and the dielectric layer, respectively. We assume that the electrode and the dielectric layer have the same Poisson’s ratio (\(\nu\)). When a tensile strain \(\varepsilon\) is applied, the length of the capacitor increases to 
\[
(1 + \varepsilon)l,
\]
while the width and thickness contract to 
\[
\left(\frac{1}{1 + \nu \varepsilon}\right)w \quad \text{and} \quad \left(\frac{1}{1 + \nu \varepsilon}\right)d,
\]
respectively. The capacitance under a tensile strain is thus expressed by
\[
C' = \varepsilon_0 \varepsilon_r \frac{(1 + \varepsilon)l(1 - \varepsilon)w}{(1 - \nu \varepsilon)d} = (1 + \varepsilon)C \tag{2}
\]

Therefore, the theoretical gauge factor (GF), defined as the ratio of the relative resistance change to the applied strain, is given by
\[
GF = \frac{\Delta C}{C} = \frac{C' - C}{Ce} = 1 \tag{3}
\]

It is clear that the capacitance change is a linear function of the applied strain \(\varepsilon\) and the theoretical GF for a capacitive strain sensor is 1. Capacitive strain sensors typically adopt the parallel-plate structure where a dielectric material is sandwiched between two layers of electrodes placed in parallel.\(^{2,31-35}\) Core-shell structures are alternative architectures for capacitive strain sensors,\(^{36}\) where the cross-section is divided into four layers, from the inside to the outside are conductive layer, dielectric layer, conductive layer, and encapsulating layer. Coplanar structures where electrodes and dielectric component are in the same layer is developed to improve the dynamic strain sensing ability of the strain sensor because fringing capacitances play a vital role in coplanar capacitors.\(^{37,38}\) For printed skin-attachable capacitive strain sensors, electrodes are commonly made of conductive and deformable composites, in which conductive materials can be Ag nanoparticles (AgNPs), Ag nanowires (AgNWs), carbon nanotubes (CNTs), carbon black (CB), graphene, and graphene oxide (GO). Elastomers, such as Ecobex and polydimethylsiloxane (PDMS), are highly suitable for the dielectric layer.\(^{8,14}\)

As predicted from Equation (3), capacitive strain sensors typically exhibit low sensitivity, high linearity, and negligible hysteresis. In contrast, resistive strain sensors (discussed in Section 2.2) typically show high sensitivity but suffer from large nonlinearity and hysteresis.\(^{18}\)

### 2.2. Resistive Effect

It is well-known that electrical resistance is a function of material electrical resistivity \(\rho\), cross-sectional area \(A\), and length \(l\)
\[
R = \rho \frac{l}{A} \tag{4}
\]

The GF for a resistive strain sensor can be expressed by\(^{39}\)
\[
GF = \frac{\Delta R}{R} = (1 + 2\nu) + \frac{\Delta \rho / \rho}{\varepsilon} \tag{5}
\]

where \(\Delta R\) and \(R\) present changes in resistance and the initial resistance, respectively. \(\varepsilon\) is the applied strain and \(\nu\) is the Poisson’s ratio. \(\Delta \rho\) and \(\rho\) are changes in resistivity and the initial resistivity, respectively. The former part \((1 + 2\nu)\) represents resistance changes due to geometrical deformations and the latter part \((\Delta \rho / \rho) / \varepsilon\) represents strain-induced changes in the intrinsic material resistivity. Metal- and carbon-based materials have been widely used to build up resistive strain sensors.\(^{16,40-43}\) The materials are either deposited on top of elastomeric substrates
or embedded in an elastomeric matrix to form resistive sensing parts.

For conventional strain gauges, the main contributions of resistance changes are from the geometrical effect and the change in the intrinsic material resistivity. However, for highly flexible and stretchable resistive strain sensors, contributions of these two factors to the overall changes in resistance are low.\[^{17}\]

Instead, resistance changes can mainly be attributed to the strain-induced changes in micro/nanostructures that alter the number of conductive pathways.\[^{8}\]

For example, relatively brittle thin films of CNTs or metal NPs can be coated on the top surface of polymers or fibers.\[^{44,45}\]

Upon stretching, microcracks are generated and the density and volume of microcracks increase with the applied strain. As a result, the number of conductive pathways decreases, and the resistance increases tremendously as a function of the tensile strain.

Similarly, “disconnection” represents another resistive sensing mechanism for stretchable strain sensors, especially for nanomaterial-based sensors. Sensing materials, such as AgNWs, ZnO NWs, CNTs, and graphene, slide against each other under the applied strain as a result of their network structure.\[^{40,46–50}\]

The disconnection (sliding) decreases the overlapped area in the sensing material, reduces the number of conductive pathways, and therefore increases the overall resistance. Disconnection and reconnection processes determine the electromechanical response of strain sensors. When adjacent conductive materials continually slide until a small gap is generated, electrons can pass through the nonconductive barrier between the adjacent conductors.\[^{51}\]

Tunneling effects represent another sensing mechanism for resistive strain sensors.\[^{32}\]

The resistance induced by the tunneling effect is given by

\[
R_{\text{tunnel}} = \frac{V}{A J} = \frac{h^2 d}{A \varepsilon^2 \sqrt{2m} \lambda} \exp\left(\frac{4\pi d \sqrt{2m}}{h}\right)
\]  

where \(V\) represents the electrical potential, \(A\) is the cross-sectional area of the conductor, \(J\) is the tunneling current density, \(h\) is the Planck’s constant, \(d\) represents the distance between two adjacent conductors, \(\varepsilon\) is the single electron charge, \(m\) is the mass of electrons, and \(\lambda\) denotes the height of the energy barrier of the nonconductive barrier. Strain sensors based on the tunneling effect are mainly made of entangled carbon and Ag-based nanomaterials, where entangled materials tend to unfold upon stretching.\[^{53–55}\]

Accordingly, changes in the distance between adjacent materials lead to the changes in \(R_{\text{tunnel}}\).

Printed skin-attachable resistive strain sensors often adopt coplanar structures where electrodes and the sensing element are in the same layer.\[^{56–60}\]

Various piezoresistive materials, such as AgNWs, AgNPs, graphene, CNTs, CB, MXene, poly(3,4-ethylendioxythiophene):polystyrene sulfonate (PEDOT:PSS), and aliphatic urethane diacylates (AUD) are printed directly onto substrates as the sensing part. To increase the initial resistance and resistance change in a fixed area, these materials are often patterned into zigzag, ring, diamond, and fractal-inspired patterns.\[^{44,57,61–64}\]

### 2.3. Piezoelectric Effect

Piezoelectric strain sensors are made of piezoelectric materials that can convert mechanical stimuli into electrical outputs.\[^{65–68}\]

Electrical dipole moments are generated due to the deformation of noncentrosymmetric crystal structures or porous electrets that contain long-lasting charges in the pores.\[^{69,70}\]

Many piezoelectric materials, such as ZnO NWs, poly(ethylene oxide-co-trifluoroethylene) (PVDF-TrFE), have been used to develop flexible and stretchable strain sensors.\[^{70–72}\]

Piezoelectric strain sensors possess high GF, fast response, and low power consumption.\[^{73}\]

However, there are several limitations of piezoelectric strain sensors for on-skin electronics, including relatively poor flexibility/stretchability and low-strain sensing range.\[^{67}\]

Flexible and stretchable strain sensors based on piezoelectric effects are not as common as those based on capacitive effects or resistive effects.\[^{8}\]

The zigzag pattern is used for piezoelectric strain sensing to enhance the output signal of the strain sensor.\[^{74}\]

### 3. Printing Techniques for Skin-Attachable Flexible and Stretchable Strain Sensors

Printing techniques can be categorized into contact printing techniques and noncontact printing techniques.\[^{75}\]

Screen printing and gravure printing are contact printing techniques. Materials jetting, materials extrusion, and vat photopolymerization, which belong to noncontact printing techniques, are commonly used for manufacturing strain sensors for on-skin electronics.\[^{76,77}\]

Comparison of each printing technique in terms of resolution, key features, and limitations is summarized in Table 1. Table 2 presents examples of printed flexible and stretchable strain sensors.

#### 3.1. Contact Printing Techniques

In contact printing techniques, the ink is printed on substrates through a prepatterned part that is in contact with the substrates.\[^{20,78}\]

Contact printing techniques provide a reliable approach to print strain sensors with high throughput and controlled performance.\[^{79}\]

#### 3.1.1. Screen Printing

A screen printing process typically involves four components: ink, squeegee, screen (patterned stencil), and substrate (Figure 3a).\[^{79,80}\]

The screen is initially a stencil that can have different mesh sizes. Before printing, openings of the screen are selectively blocked such that only the unblocked areas let the ink pass through. This way, the patterned stencil defines the final patterning of the printed devices.\[^{79}\]

During printing, inks are squeezed onto the substrate through the screen by a squeegee. When the screen is being pulled off from the substrate, the ink undergoes four stages: 1) the initial state of the ink, 2) extension of the ink, 3) formation of the ink into filament structure, and 4) rupture of filament structure (Figure 3b).\[^{79}\]

The quality of printed structures is highly dependent on the size of...
the filament structure because the uneven areas caused by the rupture of the filament structure become bigger as the size of the filament structure becomes bigger. The resolution of screen printing (40–150 µm) is primarily determined by the geometry and open area of the mesh, the ink, and the substrate. The ideal ink for screen printing should be pseudoplastic, and the ink should exhibit decreasing viscosity under the shear stress without viscoelasticity and thixotropy. These properties can minimize the formation of filament structures and prevent the ink from slumping down to the side. Viscosity, yield stress, and surface tension of the ink also affect printability. Typically, low viscosity (ranges from 0.5 to 5 Pa s), high yield stress, and high surface tension are required when preparing the ink. The ink typically consists of fillers, binders, and solvents. By optimizing the composition of the ink, desired ink properties mentioned above can be acquired. Various materials have been employed as fillers for screen-printing of strain sensors, including AgNPs, AgNWs, Ag flakes, andCNTs. Thermoplastic polyurethane (TPU), polyvinylidene fluoride (PVDF), and Nafion are commonly used as binders. Dimethylformamide (DMF), tetrahydrofuran (THF), n-methyl-2-pyrrolidone (NMP), and deionized (DI) water are often used as the solvent. These materials are commonly printed on substrates such as PDMS, polyimide (PI), polyurethane (PU), polyethylene terephthalate (PET), and Ecoflex.

Screen printing is a low-cost printing technique to fabricate large-area strain sensors. In view of this, a resistive strain sensor was prepared using the screen printing method. The screen-printable ink was composed of core-shell structures of Ag coated-polystyrene spheres (PS) fillers and PDMS matrix. Under tensile strain, the distance between adjacent conductive fillers changed, resulting in the resistance change due to the tunneling effect. The strain sensor showed a wide sensing range (>80%), high sensitivity (GFs of 17.5, 6.0, and 78.6 for the strain ranges of 0–10%, 10–60%, and 60–80%, respectively, and excellent conductivity (1.65 × 10^4 S m^-1). In another work, polyvinyl chloride (PVC) and CB composites were screen-printed onto the PI substrate coated with a silver layer. The strain sensor was able to detect both the tensile and compressive bending based on the cracking mechanism. Upon tensile or compressive bending, the gap of cracks increased or decreased, accompanied by the increase or decrease in the resistance. The GF for tensile bending was found to be as high as 741 (Figure 3d). The GF for compressive bending was 1563 and 47 for low and high strain regions, respectively (Figure 3e).

3.1.2. Gravure Printing

Gravure printing utilizes the direct transfer of functional inks through the physical contact of engraved structures with a substrate. It offers several distinct features when used to fabricate electronics with functional materials—high-throughput, high-resolution, and good compatibility with roll-to-roll processes. The schematic of gravure printing is shown in Figure 4a. In a typical printing cycle, the desired patterns are engraved on the surface of the printing roller. Then the ink is applied by rotating the printing roller in an ink reservoir and the excess ink is removed by moving the printing roller against a doctor blade. By placing the printable substrate between the printing roller and the impression roller, the patterns in the engraved printing roller are transferred to the substrate. Instead of using a printing roller, which is a cylinder, the setup can be modified to use a flat engraved template to transfer the patterns to the substrate, as shown in Figure 4b. The printability of the ink is determined by the rheological properties, including the surface tension γ and viscosity η. Along with the printing speed U, the capillary number (Ca) is defined to evaluate the printing fidelity:

\[
Ca = \frac{\eta U}{\gamma}
\]

High Ca results in ink residues in the nonengraved area, while low Ca leads to dragging-out of the pattern from the engraved
| Printing techniques | Sensing mechanisms | Materials Printed | Printed components | Applications | References |
|---------------------|--------------------|-------------------|-------------------|-------------|------------|
| Screen printing     | Resistive          | AgNPs/PU          | Sensing part      | Sports performance monitoring | [44]       |
|                     | Resistive          | Ag/silicone elastomer | Sensing part     | Healthcare, sports performance monitoring | [56]       |
|                     | Resistive          | Ag, SBS, CB/PDMS  | Sensing part      | Healthcare, sports performance monitoring, human–machine interfaces | [59]       |
|                     | Resistive          | Ag microflakes/textile | Sensing part  | Human–machine interfaces | [83]       |
|                     | Resistive          | AgNWs/textile     | Sensing part      | Sports performance monitoring | [83]       |
|                     | Resistive          | CNTs/cotton composite fabric | Sensing part | Sports performance monitoring | [84]       |
|                     | Resistive          | CNTs/PDMS/paper   | Sensing part      | Sports performance monitoring | [189]      |
|                     | Resistive          | PDMS-based CPNs   | Sensing part      | – | [190]      |
|                     | Resistive          | AgNWs-Ag flake/TPU | Sensing part     | – | [191]      |
|                     | Capacitive         | AgNWs/Ecoflex     | Electrodes        | Healthcare, human–machine interfaces | [2]        |
|                     | Resistive          | AgNWs/PDMS       | Electrodes        | Human–machine interfaces | [86]       |
|                     | Resistive          | AgNP-CNT/PDMS     | Sensing part      | Human–machine interfaces | [192]      |
|                     | Resistive          | AgNP-CNT/silicone rubber | Fully 3D-printed | – | [87]       |
|                     | Resistive          | AgNP-CNT/PET      | Fully 3D-printed  | Human–machine interfaces | [88]       |
| Gravure printing    | Resistive          | Active carbon/PET | Sensing part      | Sports performance monitoring, human–machine interfaces | [193]      |
|                     | Resistive          | CNTs/polymeric substrate | Sensing part | – | [112]      |
|                     | Resistive          | Graphene aerogel/PET | Sensing part | Sports performance monitoring | [113]      |
|                     | Resistive          | AgNPs/PDMS       | Sensing part      | – | [114]      |
|                     | Capacitive         | Ag/PET fiber      | Electrodes        | – | [115]      |
|                     | Capacitive         | CPDMS/PDMS       | Electrodes        | Sports performance monitoring | [33]       |
|                     | Resistive          | AuNPs/PDMS       | Sensing part      | Sports performance monitoring | [194]      |
|                     | Resistive          | CNTs/PDMS        | Sensing part      | Healthcare | [195]      |
|                     | Resistive          | VisJet composites | Sensing part      | – | [196]      |
| Inkjet printing     | Resistive          | PEDOT: PSS/PDMS  | Sensing part      | Human–machine interfaces | [197]      |
|                     | Resistive          | AgNP/TPU         | Sensing part      | Sports performance monitoring | [130]      |
| EHD printing        | Resistive          | AgNPs with organic stabilizer/PET | Sensing part | Healthcare, sports performance monitoring | [198]      |
| Aerosol Jet printing| Resistive          | AgNWs/PMMA       | Sensing part      | Sports performance monitoring | [57]       |
|                     | Resistive          | Carbon-based ink/Ecoflex | Sensing Part | Human–machine interfaces | [61]       |
|                     | Resistive          | NH$_2$-MWCNT-RGO/SIS | Sensing part | Sports performance monitoring | [199]      |
|                     | Resistive          | Gallium-indium alloy/Elastomers | Fully 3D-printed | Human–machine interfaces | [200]      |
|                     | Resistive          | k-carrageenan and AAm DN pre-gel | Sensing part | Sports performance monitoring | [201]      |
|                     | Resistive          | AgNPs/PUA        | Sensing part      | Sports performance monitoring | [202]      |
|                     | Resistive          | TOCNF$_2$-Ti$_3$C$_2$ Mxene | Sensing part | – | [63]       |
|                     | Resistive          | AgNW-TPU/textile | Sensing part      | Sports performance monitoring, human–machine interfaces | [203]      |
|                     | Resistive          | EGO-PDMS/SU-8 epoxy | Sensing part | Sports performance monitoring | [145]      |
|                     | Resistive          | AgNWs/PDMS       | Sensing part      | Sports performance monitoring | [62]       |
|                     | Capacitive         | Glycerol-NaCl-PEG | Fully 3D-printed | Sports performance monitoring, human–machine interfaces | [36]       |
| FDM                 | Resistive          | PVDF              | Sensing part      | – | [74]       |
|                     | Resistive          | CNTs-TPU         | Fully 3D-printed  | Sports performance monitoring | [51]       |
|                     | Resistive          | Ga-In-Sn-Ni particles | Sensing part | – | [204]      |
|                     | Resistive          | Graphene-PLA-TPU | Fully 3D-printed  | Sports performance monitoring, human–machine interfaces | [58]       |
|                     | Resistive          | CNTs-AgNP-TPU    | Sensing part      | Sports performance monitoring | [205]      |
|                     | Resistive          | CNTs/silicone rubber | Sensing part | Human–machine interfaces | [206]      |
|                     | Capacitive         | CNTs/PDMS        | Electrodes        | – | [37]       |
cells. When Ca ≈ 1, the printing performance is optimal. The printing performance can be adjusted by tuning the ink properties and the printing speed. For example, three graphene inks with different viscosities were developed to print dots and continuous lines. It was found that the ink with lower viscosity spread severely after printing (Figure 4c) and the printed dots tended to have empty centers (Figure 4d). Furthermore, the lower viscosity of the ink would lead to ink residues, which were extended to a tail under the effect of blading. The suitable viscosity of the ink for gravure printing is in the range of 0.1–1 Pa s.

The surface status of the printing roller with engraved cells is of great significance to the printing performance. Electromechanical processes and photolithography/etching processes can be used to fabricate engraved patterns with a feature size of several micrometers. To solve the problem of possible ink residues on the nonengraved area, selective surface modification of the printing roller was developed. A thin silicon wafer was patterned using the conventional photolithography process. The nonpatterned surface of the wafer was modified to be hydrophobic with a water contact angle of 110°, and the engraved cell surface was coated with Ni with a water contact angle of 30°, as illustrated in Figure 4e. The high contrast in the wettability led to the easy constraint of the ink in the engraved cells without spreading to the nonpatterned area, even without blading.

Sajid et al., developed a flexible resistive strain sensor using a micro-gravure roll-to-roll printing system. The ink was composed of activated carbon as conductive fillers and PVDF as the binder. Moreover, a protecting layer of polyvinyl acetate (PVAc) was applied on the surface of printed sensors to improve the long-term stability. The resistance increased 60% when the sensor was bent to 120° in the tensile direction and decreased 40% when bent to 120° in the compressive direction. The most significant benefit of the roll-to-roll gravure printing is the high

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Table 2. Continued.

| Printing techniques | Sensing mechanisms | Materials Printed components | Applications | References |
|---------------------|--------------------|------------------------------|--------------|------------|
| STL                 | Resistive          | RS-F2-FLGR-02 Microchannels  | Sports performance monitoring | [159]      |
| DLP                 | Resistive          | CNTs-Hydrogel Fully 3D-printed | Sports performance monitoring | [60]       |
| DLP                 | Capacitive         | PAAm-PEGDA Electrodes        | Sports performance monitoring | [34]       |
| DLP                 | Capacitive         | CNTs-Photocurable resin      | Electrodes   | –          |
| DLP                 | Resistive          | Flexible resin (Formlabs)    | Fully 3D-printed | Human–machine interfaces |

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Figure 3. a) Schematic illustration of a screen printing process. b) Four stages of the ink when the mesh was pulled off from the substrate. Adapted with permission. Copyright 2021, The Authors, published by American Chemical Society. c) Images and schematics of the screen-printed strain sensor under different mechanical stimuli. The resistance changes of the screen-printed strain sensor as a function of strain upon d) tensile bending and e) compressive bending. Adapted with permission. Copyright 2020, IOP Publishing.
throughput and rapid fabrication. Park et al., applied this strategy to print commercial Ag paste on PET substrates with high production speed up to 10 m min\(^{-1}\) using an industrial roll-to-roll production system, as illustrated in Figure 4f.\(^{[100]}\) The printed serpentine electrode was then used as a strain sensor (Figure 4g). The sensor showed comparable GF and linearity to commercial strain sensors, both in bending and tensile test.

3.2. Noncontact Printing Techniques

Noncontact printing techniques involve nozzles to dispense inks onto the substrate and/or laser to cure inks on the substrate.\(^{[20]}\) Materials jetting, materials extrusion, and vat photopolymerization techniques used for printing skin-attachable strain sensors are introduced in this section.

3.2.1. Materials Jetting

In materials jetting, inks are jetted through a nozzle onto substrates layer by layer to create required structures.\(^{[77]}\) Various materials jetting techniques are employed for printing flexible and stretchable strain sensors, such as inkjet printing, electrohydrodynamic (EHD) printing, and aerosol jet printing.

_Inkjet Printing:_ During an inkjet printing process, droplets of ink are directly deposited on the substrate through a jetting head which is followed by a solidification process such as evaporation of the solvent, polymerization of the ink, and vitrification.\(^{[15,19,75,101]}\) The resolution of inkjet printing can be as low as tens of micrometers.\(^{[15,102]}\) A number of parameters can influence the process of generating droplets, including the Reynolds number, \(N_{\text{Re}} = \frac{v\alpha\rho}{\eta}\), Weber number, \(N_{\text{We}} = \frac{v^2\alpha\rho}{\gamma}\), velocity \((v)\), radius of the printing orifice \((\alpha)\), density \((\rho)\), viscosity \((\eta)\), and surface tension \((\gamma)\).\(^{[102–106]}\) The printing behavior of the ink is determined by the inverse \((Z)\) of the Ohnesorge number\(^{[15,107–110]}\)

\[
Z = \frac{N_{\text{Re}}}{\sqrt{N_{\text{We}}}} = \frac{\sqrt{\alpha\rho\gamma}}{\eta} \tag{8}
\]

Z of a printable ink typically ranges from 4 to 14.\(^{[109,110]}\) If \(Z\) is too small (<4), the droplet filament is too long to be printed and it will take a long time to generate a droplet.\(^{[106]}\) When \(Z\) is larger than 14, the ejected ink cannot form a single droplet.\(^{[106]}\)
The viscosity of the ink used in inkjet printing can range from 0.005 to 0.02 Pa s. Carbon-based ink (e.g., CNT and graphene), Ag-based ink (e.g., AgNPs), and polymer-based ink (e.g., PDMS) are often used in inkjet printing of either resistive or capacitive strain sensors.

Inkjet printing can be divided into two categories: continuous inkjet printing (Figure 5a) and drop-on-demand inkjet printing (Figure 5b). In continuous inkjet printing, the ink is jetted continuously through the jetting head. Droplets are charged to control the position of the deposited droplets. The desired droplets are deposited precisely onto the substrate, while undesired droplets are deflected by the electric field to a container to be recycled. Continuous inkjet printing can achieve a relatively high printing rate (greater than 10 m s⁻¹).

Figure 5c shows a strain sensor manufactured by continuous inkjet printing which is compatible with roll-to-roll manufacturing. During the continuous inkjet printing, the AgNPs based ink was injected onto a polyethylene naphthalate (PEN) substrate, followed by flashligh sintering. The resistance of the strain sensor changed based on the strain-induced geometrical deformation. Since temperature can also affect the geometry of the strain sensor, the sensor can also be used for temperature sensing.

In drop-on-demand inkjet printing, droplets are generated only when required. When the pressure pulse is increased beyond the threshold value in the nozzle, a droplet is jetted. Two basic approaches are typically used to generate the pressure pulse: thermal actuation based on heating-induced bubbles and piezoelectric actuation based on the piezoelectric effect.

The resolution of the drop-on-demand inkjet printing is better than that of continuous inkjet printing. This printing mode can also reduce material waste and damages to the substrate. As a result, drop-on-demand inkjet printing is widely used for printing stretchable strain sensors. Figure 5d,e demonstrates the drop-on-demand inkjet printing of graphene/ZnO composites for strain sensing components. Disconnection and cracking mechanisms are responsible for the change of resistance under strain. Roughness (r) of the substrate affects the initiation and propagation of cracks and therefore is essential to the stretchability of the strain sensor. Figure 5d shows that under different roughness, the stretchability of the sensor varied from 10.5% to 30%. The increase of resistance within 5% tensile strain was mainly attributed to the decrease of the overlapped area of graphene flakes. Beyond 5% tensile strain, the cracking of the film was the dominant mechanism. The strain sensor is promising in human motion detection due to its large strain sensing range and high stability.

**EHD Printing:** Compared with conventional inkjet printing where the ink is pushed out by the thermal or acoustic energy, the EHD printing applies an extra electric field between the nozzle and the substrate that can help pull out the ink from the nozzle, as shown in Figure 6a. At the critical state, the introduced electrostatic force balances the gravitational force and the surface tension force of the ink. Ions in the ink accumulate near the surface of the meniscus due to the electric field.
The meniscus is deformed into a conical shape, i.e., the so-called Taylor cone. There are generally five components in a typical EHD printing system: ink supply system, power supply system, motion system, visualization system, and control system. By controlling the applied voltage, printing can be achieved on both conductive and insulating substrates.\textsuperscript{[111]} The frequency of jetting can be determined by the voltage and offset height using the following equation\textsuperscript{[75]}

\[ f = K \left( \frac{V}{h} \right)^{\frac{1}{2}} \]  

(9)

where \( f \) is the frequency of jetting, \( K \) is a constant depending on the ink, \( V \) is the voltage, and \( h \) represents the offset height. The relationship between jetting mode, electric field strength, and flow rate is shown in Figure 6b.\textsuperscript{[75]} When both the flow rate and electric field strength are in a proper range, a continuous stream of ink can be formed, which is called cone-jet mode.\textsuperscript{[123]} The cone-jet mode is the most commonly used in EHD printing.

There are two aspects to consider when selecting the ink for EHD printing: printability of the ink and spreading of the ink after being transferred to the substrate. Printability of the ink can be improved by balancing the fluidic properties of the ink (i.e., surface tension, viscosity, and density) and electric properties, such as conductivity and dipole moment.\textsuperscript{[124]} Large surface tension (>50 mN m\(^{-1}\)) will reduce printability.\textsuperscript{[124]} The high viscosity of the ink can ensure the stability of the printing process, nevertheless, reduce the printing resolution.\textsuperscript{[125]} The viscosity of the ink typically ranges from 1 to 10 Pa s.\textsuperscript{[111]} The higher the conductivity and viscosity of the ink, the smaller the Reynolds number is needed to ensure the printability of the ink.\textsuperscript{[124]} However, when the ink has relatively high conductivity, it can be challenging to achieve good printability due to the possible discharge caused by the electrical field between the nozzle and the substrate.\textsuperscript{[126]} Spreading of the ink can be controlled by modifying the hydrophilic-lipophilic properties between the ink and the substrate.\textsuperscript{[75,125]} Nanomaterials, such as AgNWs and CNTs, and conductive polymers, such as PEDOT:PSS and polycaprolactone/poly(acrylic acid) (PCL/PAA), are commonly used to develop the ink.\textsuperscript{[127]} For instance, proper surface modifications allow for printing of the AgNW based ink on a PDMS substrate with high-resolution and complex patterns.\textsuperscript{[127,128]} The PDMS substrate initially exhibited poor wettability with the ink. With proper surface treatment either by polydopamine or UV/ozone, the wettability between the ink and the PDMS can be enhanced (Figure 6c) to achieve tunable printing performance.

Lead zirconate titanate (PZT) films are the most commonly used sensing materials for piezoelectric strain sensors.\textsuperscript{[129]} Conventional manufacturing methods (i.e., sputtering and chemical vapor deposition), are time-consuming and require complex processes to pattern films with feature sizes smaller than 100 \( \mu \)m.\textsuperscript{[129]} EHD printing with high resolution and tunable printing performance offers a new way of fabricating PZT-based strain sensors. To demonstrate this, Wang et al., employed the EHD printing technique to fabricate microstructural PZT thick films that served as sensing materials for piezoelectric strain sensors.\textsuperscript{[129]} The additive manufacturing process is desirable for one-step deposition without a further material removal process. Figure 6d compares the ink prepared from PZT NPs before and after ball milling. Figure 6e shows the microstructural PZT thick film before and after printing. The additive manufacturing process is desirable for one-step deposition without a further material removal process. Figure 6f,g shows the SEM images of the EHD-printed PZT traces. The PZT ink before and after ball milling. The cross-sectional image of the printed PZT microstructural pattern shows the EHD-printed PZT traces. d–g Reproduced with permission.© 2021, Elsevier.

![Figure 6. Comparison between a) conventional inkjet printing and b) EHD printing. c) The dynamic contact angles of (i) pristine PDMS, (ii) dopamine-treated PDMS, and (iii) UV/ozone-treated PDMS surfaces. Reproduced with permission.\textsuperscript{[122]} Copyright 2021, American Chemical Society. d) PZT ink before (left) and after (right) ball milling. e) The cross-sectional image of the printed PZT microstructural pattern. f,g) SEM images showing the EHD-printed PZT traces. d–g) Reproduced with permission.© 2021, Elsevier.](image-url)
the printing of uniform and thick PZT traces with high resolution (Figure 6d–g).

Thanks to the focusing effect of the electric field, the droplets and the lateral variation of printed patterns using EHD are relatively small. Hence, EHD printing can achieve high resolution in the range from 240 to 5 μm.[19] Another advantage of EHD printing compared to inkjet printing is that EHD printing can be compatible with high viscosity ink because the power generated by the electric field is larger than the thermal actuation and piezoelectric actuation.[110] However, the height of the printed structure is limited because of electrostatic repulsion.[76] EHD printing also suffers from low printing speed. To improve the printing speed of EHD printing, Khan et al., modified the EHD printing system to have five nozzles for simultaneous printing.[130] High-resolution conductive traces can be printed onto prestrained TPU substrates with high speed and high throughput, leading to the facile manufacturing of strain sensors.

**Aerosol Jet Printing**: Aerosol jet printing employs a focused aerosol spray to print complex structures (Figure 7a).[131–133] During aerosol jet printing, the ink is atomized by a pneumatic or ultrasonic atomizer to generate droplets. Then droplets are transported to a deposition head by a carrier gas such as N₂ or He. Finally, these droplets mix with a third gas flow (sheath gas) and form a narrow and high-speed stream.[131] Focusing ratio (FR), defined as the sheath gas flow rate to the carrier gas flow rate, plays a vital role in controlling the aspect ratio of printed structures.[134] The width and thickness of the printed line can vary significantly for different FRs. Therefore, the printed structure will be ill-defined if the FR is out of the suitable range.[132,134]

Another important factor that determines the printed structure is ink properties.[135] Aerosol jet printing is capable of printing inks with a viscosity ranging from 0.001 to 1 Pa·s.[75,135] The particle size of the ink should be less than 1 μm to prevent the nozzle from clogging.[136] The distribution of particle sizes should be narrow.[116] The boiling point of the ink also needs to be controlled to ensure that the ink does not evaporate before being delivered onto the substrate.[135,136] Due to the long distance between the nozzle and substrate, the ink can be printed onto a nonplanar substrate.[137,138] Compared with inkjet printing which ejects a single droplet, aerosol jet printing ejects tremendous droplets with diameters ranging from 1 to 5 μm.[139] Owing to the high resolution, a miniaturized strain sensor can be printed (Figure 7b).[57] PI ink and AgNW ink were printed layer by layer to form a sandwiched structure where the AgNW sensing layer was sandwiched between two PI layers (Figure 7c). Using aerosol jet printing, the dimension and number of printed passes were controlled precisely. The strain sensor was based on the disconnection mechanism. The resistance varied largely as a function of strain and the GF could reach 13 for the strain range between 175% and 200% (Figure 7d). The strain sensor was demonstrated in detecting the pulse rate and joint movements.

**3.2.2. Materials Extrusion**

DIW and FDM are extrusion-based printing methods. During the printing process, inks are extruded onto the substrate by pressure.[75]

**DIW**: During a DIW process, air pressure is used to directly extrude materials onto substrates through a nozzle (Figure 8a). Either inks with low viscosity or inks exhibiting reduced viscosity at the increasing shear rate (shear-thinning materials) can be printed by DIW.[29,140] Postprocessing methods such as UV sintering and thermal curing are required to solidify printed
structures. Printed structures based on low-viscosity materials, however, need to be postprocessed rapidly layer by layer. As a result, shear-thinning materials are more commonly used in DIW and the printed structures can achieve a high aspect ratio. The viscosity of the ink for DIW ranges from 10 to $10^5 \text{ Pa s}$ at different shear rates.\cite{ref141-143} Fillers, binders, additives, and solvents are essential ink components for DIW. Carbon-based materials (e.g., CB, CNTs, graphene), metal-based materials (e.g., AgNPs and AgNWs), Mxenes, and conductive hydrogels are commonly used as fillers.\cite{ref29} Binders, such as silicone rubber and TPU, facilitate the uniform dispersion of fillers in the ink.\cite{ref141-143} To improve the rheological properties of the ink for DIW, additives and solvents can be added to the ink.\cite{ref144} As an example of preparing inks with suitable viscosity, the electrochemically derived graphene oxide (EGO) aqueous suspension was mixed with the PDMS submicrobead sediment (Figure 8b,c).\cite{ref145} The ink achieved a shear-thinning thixotropic fluid behavior and thereby can be extruded from a nozzle with a diameter of 50 \( \mu \)m. The viscosity of the ink can vary from 48.3 Pa s under the shear rate of 0.881 \text{s}^{-1} to 1242 Pa s under 0.009 \text{s}^{-1}. A resistive strain sensor was printed with this ink by DIW. Upon stretching of the strain sensor, the deformation of the PDMS matrix caused sliding of EGO sheets, which increased the resistance based on the disconnection mechanism. The strain sensor possessed an approximately linear response to the strain with a GF of 20.0 \($/\%$\) up to 40% tensile strain.

Printing speed plays an important role when DIW is used to print ink containing conductive materials because the liquid ejection time can affect the number of conductive pathways.\cite{ref62,142} As an example, resistive strain sensors based on ring and diamond shapes were fabricated by printing AgNW ink onto the hydroxylated Si wafer, followed by coating a 100 \( \mu \)m-thick PDMS layer (Figure 8d).\cite{ref62} As shown in Figure 8e, the resistance of the printed structure could vary from 3 to 13 \( \Omega \) when the printing speed changed from 1 to 9 mm s\(^{-1}\).
DIW is highly versatile and can be used to process a wide range of materials with a resolution as high as several micrometers.\textsuperscript{[135]} Taking the advantage of the wide choice of materials, a multicore–shell DIW has been used for fabricating strain sensors, where multiple inks were coextruded to construct multiple layered structures.\textsuperscript{[136]} The strain sensor employed a core–shell capacitor structure, in which the ionic conductive fluid of glycerol, sodium chloride, and polyethylene glycol (PEG) was used as the conductive layer, and modified silicone elastomer was used as the dielectric layer, as shown in Figure 8f. Upon stretching, both the resistance of the conductive layer and the capacitance of the core–shell strain sensor were changed (Figure 8g,h). The GF of the resulting strain sensor is 0.348 over a wide strain range of 250%, below the theoretical GF of capacitive strain sensors. The strain sensor can be readily attached on the joint (Figure 8i) to track large body motions.

**FDM:** During a typical FDM process, materials are molten or semimolten through a heated nozzle, deposited on substrates or fabrication platforms, then cooled down and solidified (Figure 9a).\textsuperscript{[146]} This process will cycle layer by layer to construct the required 3D structure. Materials with low melting temperatures are commonly used and processed into the form of filaments. For this reason, FDM is also known as fused filament fabrication.\textsuperscript{[147]} FDM is widely used for fabricating resistive, capacitive, and piezoelectric strain sensors (Table 1), either the sensing components or the entire sensors. For fully printed flexible and stretchable strain sensors, thermoplastic composites composed of conductive fillers (e.g., AgNPs, CNTs, CB, graphene) and thermoplastic matrix (e.g., PLA and TPU) are mostly used.\textsuperscript{[58,148–151]} Figure 9b illustrates an example of resistive strain sensors fabricated by FDM using the composite ink of CNTs and TPU.\textsuperscript{[51]} By introducing 1-pyrenecarboxylic (PCA) to the ink, the interaction between TPU and CNTs was enhanced so as the strain sensing performance. Based on the tunneling effect-induced changes in resistance, the strain sensor obtained very high GF (117 213), wide detectable strain range (up to 250%), and good stability (during 1000 loading and unloading cycles).

Despite its widespread applications for strain sensors, FDM suffers from several challenges. First of all, the resolution is limited due to the swelling of materials in the melting process.\textsuperscript{[152]} The typical resolution of FDM is 100–150 μm.\textsuperscript{[154]} Moreover, the strength of printed structures is relatively low due to shrinkage, residual stress, and voids generated during the layer-by-layer solidification process.\textsuperscript{[154]} Furthermore, the requirement that materials must be manufactured into a feedstock filament with a certain diameter poses a limit to the choice of materials for FDM.\textsuperscript{[154]} To realize desired properties in the printed structures, optimization in material selection and printing parameters such as nozzle diameter, build orientation, and printing speed is required.\textsuperscript{[154,155]} FDM can be customized for different materials to achieve desired properties. For instance, FDM assisted with electric poling processes can improve the degree of alignment and therefore the piezoelectric behavior of printed piezoelectric materials.\textsuperscript{[74]} Figure 9c demonstrates piezoelectric strain sensors printed using this FDM setup.\textsuperscript{[74]} The electric poling facilitates dipole alignment and the transformation from the α phase to the β phase to enable piezoelectricity in the printed PVDF structures. Under cyclic bending, the printed strain sensor (Figure 9d) showed an output current of ±1.5 nA and a charge of 12.0 nC (Figure 9e), illustrating the capability to detect dynamic stimuli.

In addition to printing strain sensing components, FDM was also employed to print 3D sacrificial molds for fabricating porous silicone-based strain sensors.\textsuperscript{[156]} Silicone rubber was cast onto the printed acrylonitrile butadiene styrene (ABS) mold followed...
by dissolving the mold to prepare a porous silicone rubber. Surface-deposited graphene (SDG) strain sensors, shown in Figure 10a, were obtained by dip-coating graphene onto the porous silicone rubber. Alternatively, another type of strain sensor (surface-embedded graphene [SEG] sensors), shown in Figure 10b, was obtained by dip-coating graphene onto the mold, casting silicone rubber, and then dissolving the sacrificial mold. These two types of strain sensors showed different performances. Figure 10c shows that the SEG sensors of which resistance merely changed in 12 months, achieving high stability because the sensing materials were embedded on the surface. Humidity could hardly affect the sensitivity of the SEG sensor, owing to the fact that the hydrophobic silicone rubber surface could prevent water molecules from reaching the conductive network (Figure 10d). Both types of strain sensors showed good durability during over 400 cycles of stretching and releasing.

3.2.3. Vat Photopolymerization

Vat photopolymerization represents 3D printing techniques where liquid photosensitive resins are selectively cured using the laser to fabricate desired structures. In this section, stereolithography (STL) and digital light processing (DLP) techniques used for printing skin-attachable strain sensors are reviewed.

STL: STL (Figure 11a) is one of the most mature 3D vat photopolymerization techniques. During the printing process, the laser (typically 355 nm) scans the surface of liquid resins to solidify the resin. The platform then moves downward and the next layer of resin will be solidified. The desired structure is printed layer by layer with a resolution as low as 6.5 μm.

Materials for STL consist of photocurable resins, corresponding crosslinkers, and catalysts. Materials are cured based on two mechanisms, cationic photocuring and radical polymerization. During cationic photocuring, protonic acids are produced by the laser beam to catalyze the polymerization and cure the resin. In radical polymerization, photoinitiators could generate free radicals to polymerize prepolymers and monomers. The viscosity of the resin should be low, typically ranging from 0.1 to 10 Pa s.

For flexible and stretchable strain sensors, STL can be utilized to print microchannels for strain sensors, as shown in Figure 11b. The microchannel was created in the top layer of the strain sensor. Then sensing materials, Galinstan, was

Figure 10. Schematic illustrations of the a) porous SDG sensor and b) porous SEG sensor. Resistance changes of SDG and SEG strain sensors in response to c) shelf life and d) humidity changes. a–d) Adapted with permission. Copyright 2020, American Chemical Society.

Figure 11. a) Schematic illustration of STL. Reproduced under the terms of the CC-BY license. Copyright 2021, The Authors. Licensee MDPI. b) Fabrication process of the strain sensor made by STL and injection of Galinstan. Comparison of changes of resistance between 5 mm thick strain sensor and 3 mm thick strain sensor under c) tensile bending and d) compressive bending. (b–d) Reproduced with permission. Copyright 2019, American Chemical Society.
injected into the microchannel followed by attaching the electrodes and sealing the two ends. The performance of the strain sensor can be improved by increasing the thickness of the strain sensor. Because when tensile bending or compressive bending is applied to strain sensors, the deviation to the center and therefore the effective strain increases with increasing the thickness of the strain sensor. As shown in Figure 11c,d, changes of resistance for strain sensors with 5 mm thickness were larger than that of strain sensors with 3 mm thickness for both tensile and compressive bending.

DLP. Different from STL, where a laser beam is used to scan the liquid resin, in a DLP process, a projector (digital light processing unit) is used to cure a complete layer of liquid resins, as schematically illustrated in Figure 12. The wavelength of the laser used in DLP is usually 405 nm. The resolution of 35 μm was achieved using DLP 3D printing techniques. The choice of materials for DLP is limited to radical photosensitive resins because it is hard for cationic photocurable resins to be photopolymerized under 405 nm irradiation.

DLP was adopted to print multiple components in flexible and stretchable strain sensors, including electrodes for capacitive sensors, piezoresistive sensing elements for resistive sensors, and molds/skeletons for resistive sensors. DLP is an efficient way to print electrodes for stretchable capacitive strain sensors. In recent work, inks composed of acrylamide (AAm) monomer, poly(ethylene glycol) (PEGDA) oligomer, and MgCl₂ were printed as electrodes via DLP. The printed electrodes were sandwiched by three 3M very-high-bond (VHB) tapes to assemble the sensor (Figure 12b). The resulting capacitive strain sensor showed a linear gauge factor of 0.92 (Figure 12c) and high durability under over 5000 cycles of strain variation from 0% to 25% (Figure 12d).

For devices under repetitive deformations, such as strain sensors, it is beneficial to introduce self-healing capabilities. For this reason, composites of conductive carboxyl multiwalled carbon nanotubes (c-CNTs) and the photocurable N-acryloylmorpholine (ACMO) resin were DLP-printed to fabricate resistive strain sensors. When the broken sensor parts were put in contact, the broken hydrogen bonds would regenerate due to the interactions between carboxyl, carbonyl, amino groups, and water molecules. With the help of the self-healing ability, the strain sensor showed enhanced durability in response to repetitive stretching and releasing.

4. Applications

Printed flexible and stretchable strain sensors can be readily attached to the skin surface for detecting skin deformations associated with health conditions and body activities. High sensitivity is desired for detecting subtle deformations such as blood pulse, respiration, phonation, and facial expressions. Alternatively, large sensing range and stretchability are required for detecting large deformations such as finger flexing, wrist bending, and

![Figure 12.](image-url)
knee motions. In this section, we will highlight representative applications of printed flexible/stretchable strain sensors for on-skin electronics.

4.1. Healthcare

With on-skin electronics, critical health-related information can be accessed in a continuous and unobstructive way. Compared with hospital-based healthcare, wearable health monitoring at home settings offers a comfortable and cost-effective way to collect key information from daily activities. Continuous health monitoring provides new insights for disease diagnosis and treatment and has the great potential to reduce the personnel load and high cost in healthcare. As one of the most important skin-attachable sensors, strain sensors can detect either subtle or large deformations that are clinically relevant, such as pulse rate, respiration, swallowing, and joint motions (Figure 13a).\(^{[161–163]}\)

Pulse rate is one of the vital signs that reflect basic health conditions.\(^{[164]}\) Several chronic diseases, such as diabetes and arteriosclerosis, can induce the change of blood viscosity and thickening and hardening of arteries, and then, affect the pulse rate.\(^{[164]}\) Hence, continuous detection of pulse rate by strain

![Figure 13](image-url)
sensors can help diagnose and manage such chronic diseases.\textsuperscript{164} Another vital sign that is commonly monitored by strain sensors is respiration rate. Monitoring of respiration rate is important in the diagnosis of asthma, anemia, and other respiratory diseases.\textsuperscript{14} For example, a resistive strain sensor was fabricated by screen printing, where the ink was composed of Ag, polystyrene-block-polybutadiene-block-polystyrene copolymer (SBS), and CB.\textsuperscript{29} The sensor achieved high sensitivity (GF > 870) and a large strain sensing range of 100\% based on the cracking mechanism. High sensitivity is essential for detecting subtle skin deformations associated with pulse rate and respiration rate. Figure 13b shows the output signals when the sensor was attached to the wrist for pulse rate sensing. Similarly, Figure 13c presents strain signals related to the respiration/breath rate when the sensor was attached to the chest.

Some diseases such as Parkinson’s disease, epilepsy, stroke, and Tourette syndrome can lead to abnormal body motions such as tremors and loss of automatic movements.\textsuperscript{165} Continuous monitoring using skin-attachable strain sensors is therefore beneficial for the early diagnosis and management of such diseases. The Zhu group developed screen-printed capacitive strain sensors based on AgNW electrodes and Ecoflex dielectrics.\textsuperscript{12} Monitoring of Patellar reflex or knee-jerk was achieved by mounting stretchable strain sensors on the knee joint (Figure 13d) when the person was sitting with the lower leg relaxed naturally. A hammer was used to tap the patellar tendon ligament to evaluate the patellar reflex. The capacitance changes during a normal knee jerk, without the sign of absent or pendular knee jerk, are provided in Figure 13e. The lower leg first straightened involuntarily with a sudden decrease in the capacitance and then came to rest quickly accompanied by a quick decrease in the capacitance to the initial value. The amplitude and duration of the kicking motion are useful in the diagnosis of nervous system diseases such as tabes dorsalis, receptor damage, and hypotonia.\textsuperscript{166,167}

With a modified and softer AgNW-based capacitive strain sensor, the finger function of an individual with stroke was monitored by placing the sensor on the finger joint (Figure 13f).\textsuperscript{13} Bending the finger joint led to increased joint angle and therefore increased strain across the finger joint. The strain sensor showed sufficient resolution to capture the jerk motion of the finger joint for the individual with stroke (Figure 13g). The results were cross-validated against a commercial IR motion tracking camera that can track reflective markers attached to the finger. The correlation between the skin strain measured from the strain sensor and the joint angle from the motion camera was higher than 93\% at different joint oscillation speeds, illustrating the high accuracy of the skin-attachable strain sensors for tracking joint kinematics in clinical populations. Accurate sensing in a mechanically imperceivable manner is particularly important for people with reduced muscle strength.

Real-time tracking of phonation, chewing, and facial strain can assist in disease diagnosis and rehabilitation. Contrary to large deformations in human joints, the strain involved in these skin movements is much smaller. A screen-printed strain sensor based on the cracking mechanism was proposed for tracking such small deformations.\textsuperscript{154} The strain sensor can be used to detect facial movements and phonation due to its excellent sensitivity (GF > 10\textsuperscript{4}–10\textsuperscript{6}), low hysteresis (<20\%), low overshoot (<2.5\%), and good durability (>3000 repeated cycles). When the strain sensor was attached to the throat, the resistance changed corresponding to different behaviors such as swallowing, coughing, sniffing, and phonation (Figure 13h,i). Likewise, when the strain sensor was attached to the cheek and frontalis, various facial movements such as chewing, uplifting of the eyebrows, and looking down could be detected (Figure 13j). Decoding of facial kinetics (e.g., facial strains and phonation vibrations) with printed strain sensors also offers a novel strategy to develop nonverbal communication interfaces.\textsuperscript{158,160} Such interfaces can improve the communication capabilities for those with speech and voice disorders, and serve as a promising way for controlling smart machines through facial expressions and speech.\textsuperscript{170}

4.2. Sports Performance Monitoring

Real-time sports performance monitoring provides quantitative information to analyze whether the movements are standard and whether the physiological indicators are normal, which can improve training efficiency and avoid sports injuries.\textsuperscript{96} The most conventional convenient way to capture body motions is based on goniometers, protractors, and videography. Alternatively, several sensing technologies are adopted for motion detection, such as accelerometers, gyroscopes, and IR cameras (with reflective markers attached to the skin or clothing). In general, these methods are inaccurate, not in real-time, expensive, and might impede natural body movements. Skin-attachable strain sensors provide an accurate, real-time, and natural way of motion tracking without impeding body activities.\textsuperscript{171,172}

Printed flexible and stretchable strain sensors have been used for tracking various body motions ranging from finger flexing to wrist bending and knee motions. For instance, monitoring of wrist bending was demonstrated by attaching strain sensors (Figure 14a) to the wrist (Figure 14b).\textsuperscript{44} The strain sensor was fabricated by screen printing of AgNPs ink over a PU substrate. The resistive strain sensor was able to monitor the wrist bending based on the cracking mechanism. Bending the wrist caused an increase in the resistance and straightening the wrist led to the recovery of the resistance value. Various knee motions can be detected by attaching strain sensors across the knee (Figure 14c,d). Examples of such sensors include screen-printed capacitive sensors,\textsuperscript{21} screen-printed resistive sensors,\textsuperscript{24} and multicore–shell inkjet-printed capacitive sensors.\textsuperscript{166} Specifically, a resistive strain sensor was fabricated by DIW-printing of conductive silicone rubbers on a PDMS substrate.\textsuperscript{173} The knee motion could be tracked by measuring the strain introduced during knee bending (Figure 14e). The quantified body motions (e.g., angle, speed, acceleration) during sports or rehabilitation can help the users improve their postures, evaluate their athletic performance, and prevent injuries.\textsuperscript{14} Motion parameters may also be stored and then analyzed by coaches or therapists to improve the training quality and make informed decisions during rehabilitation.

4.3. Human–Machine Interfaces

Printed flexible and stretchable strain sensors are also explored to develop human–machine interfaces for controlling smart
machines (e.g., computers, robots, and prosthetics). Gesture and motion recognition are key enabling technologies for human–machine interfaces, which can be achieved either by directly mounting strain sensors on the skin surface or integrating strain sensors into hand-worn data gloves. Data gloves are effective bridges between motion data acquired from strain sensors and controlling of smart machines. Figure 15a presents a data glove with resistive strain sensors (Figure 15b) embedded inside, which was prepared by DIW of carbon-based conductive grease over an Ecoflex substrate. Since the output signal from strain sensors varied with different finger bending angles, strain sensors placed on each finger were able to capture the bending of individual fingers. This way, gesture recognition can be achieved using strain sensors (Figure 15c). Figure 15d illustrates another smart data glove that was constructed with strain sensors based on piezoresistive CB/PDMS composites. Enabled by gesture recognition, robots can be remotely controlled by fingers. The motion of human fingers was acquired from the data glove and wirelessly sent to the robotic finger. Then the robotic finger was able to mimic the motion of human fingers. The remote control of robotics can facilitate tasks in dangerous environments, such as rescue in earthquakes or accidents, and facilitate complicated tasks, such as surgical operations.

Printed flexible and stretchable strain sensors also have great potential as interactive human–computer interfaces for VR/AR applications and entertainment. The gesture identified with strain sensors can be used to control the avatar in the virtual environment. Compared with commonly adopted vision-based methods, activity recognition based on strain sensors has some advantages such as high accuracy, good portability, and low requirements for space and external bulky setups.

5. Conclusions
As we discussed in Section 4, with the rapid progress in advanced manufacturing, printed flexible and stretchable strain sensors have been explored for a broad range of applications, such as personal healthcare, sports performance monitoring, and human–machine interactions. Moving forward, challenges and opportunities coexist on the path toward widespread adoption of printed strain sensors for real-world applications, both in fundamental and applied aspects.

Owing to the development of deformable materials and structures, the mechanical properties of printed strain sensors have been improved to a level comparable to that of skin. For future research, more efforts are required to improve other aspects for on-skin applications. Though efforts have been made to improve the stability and some strain sensors can have stable outputs over hundreds of deformation cycles, improved stability should be achieved to meet the needs of daily activity tracking. To adapt to environmental changes in daily life, such as temperature, moisture, and sweat, strain sensors with high sensitivity to strain but negligible sensitivity to other stimuli are desirable. Most printed strain sensors are responsive to deformations in all directions. Strain responses along different axes are usually coupled due to the Poisson’s effect. To address the cross-sensitivity issue, efforts are ongoing to develop strain sensors that are responsive to strain in one direction only and develop multiaxial strain sensors that can effectively decouple strains in different directions.

As for printing technologies, high printing resolution is desired to obtain smaller strain sensors and a higher level of integration. Printing speed and throughput need to be improved for large-scale production. Combining printing techniques with
roll-to-roll processing is a promising way to achieve large-scale production.\[20\] As summarized in Table 1, each printing technique has advantages and disadvantages. A strain sensor system can include different materials; one printing method might be more suitable to print certain types of materials than other methods. It can be beneficial to combine different printing techniques to develop a multi-material printing platform, especially integrated with roll-to-roll processing for continuous production of flexible/stretchable sensor systems.\[20\] For example, a wider range of materials can be printed by combing different printing techniques.

For real-world applications, strategies for integrating strain sensors with other functional units with a small footprint are in demand.\[180\] Together with other sensors and components, such as electrochemical sensors for sweat analysis and vibrohaptic actuators for haptic feedback, the integrated wearable system will be able to provide more comprehensive information and interactive interfaces to facilitate disease diagnosis, rehabilitation process, and closed-loop control of robots/prosthetics.\[165\] In addition, improvements in form factors and the visual appearance of strain sensors will promote the transition from proof-of-concept prototypes to commercial products. To enhance user experience and protect user privacy, strain sensors that are mechanically and visually imperceptible are appealing for on-skin electronics too.\[183\] The research goal should move from mere sensor demonstration to the development of integrated, high performance, and human-friendly strain sensors. The goal will be achieved through continuous innovations in materials selection, structural design, and advanced manufacturing and integration.

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Conflict of Interest

The authors declare no conflict of interest.

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