Structural engineering is proved to be effective in improving both measurement sensitivity and range for flexible and stretchable strain sensors. Herein, the latest advancements in structural engineering strategies are summarized for the improvement of sensing performances of flexible and stretchable strain sensors. Porous structures, wrinkled structures, and overlapped structures can increase the sensing range significantly. High sensitivity of strain sensors can be achieved by crack structures in thin film and strain concentration structures in substrate. Strain sensors with hierarchical structures are able to have both high sensitivity and wide sensing range. Moreover, potential applications of flexible and stretchable strain sensors fabricated with engineered structures are presented. The study is concluded with analysis of challenges and future perspectives for structural engineering strategies.

1. Introduction

Recent progress in the development of flexible and stretchable sensors has promoted their applications in wearable devices, health monitoring, electronic skins, and so on. As an important element in the family of flexible and stretchable sensors, strain sensors have recently received tremendous attention. By converting physical deformation (especially large deformation) into electrical signals, stretchable strain sensors can be valuable for health monitoring, human movement detection, human–machine interfaces (HMI), and so on. As in the case of human movement detection, strain sensors must have high stretchability to match the maximum deformations of human body, especially elbows and knees (>55%). In addition, strain sensors also must have high sensitivity to detect subtle deformation of human body (usually less than 1% strain). However, conventional strain sensors based on metal and inorganic semiconductors have relatively low sensitivity and narrow sensing range. For instance, strain sensors based on the resistance change in metal foils were only able to detect strain under 0.2%, whereas polysilicon strain sensor only exhibited a gauge factor (GF) of 34 within 0.12% strain.

Resultantly, significant amount of research work has been undertaken to improve the sensing range and measurement sensitivity of flexible and stretchable strain sensors, with focus on sensing mechanisms, materials, and structural engineering. Among these sensors, piezoelectric and triboelectric strain sensors have high sensitivity and fast response due to high-speed charge transfer. However, large interference limits their applications in wearable devices. Capacitive strain sensors typically composed of a dielectric layer sandwiched between two electrodes have shown great potential in wearable and skin-mountable applications because of their simple readout circuit and relatively high performances of detecting dynamic loads. However, capacitive-type strain sensors have relatively low sensitivity. On the contrary, resistance-type flexible and stretchable strain sensors have been reported more widely than other types due to the advantages of cost-efficient fabrications, easy signal collections, and low interferences. In particular, structural engineering has been demonstrated as effective strategies for improving sensing range and sensitivity of resistance-type flexible and stretchable strain sensors.

This article aims to survey the structural engineering strategies developed recently for the enhancement of measurement range and sensitivity of flexible and stretchable strain sensors. The characteristics of structural design, preparation processes, improvement of sensing performances, and applications of those sensors are discussed in detail. First, the structure engineering strategies for improving sensing range, such as porous structures, wrinkled structures, and overlapped structures, are described. Afterward, structural designs for improving measurement sensitivity, such as cracking and strain concentration structure, are discussed, with focus on the working principles of structures and analysis of strain control mechanisms. Third, structural engineering approaches for improving both sensing range and sensitivity are reported, followed by the applications of those flexible and stretchable strain sensors. The discussion of challenges and future perspectives on structural engineering strategies for flexible and stretchable strain sensors are presented in the last section.
2. Structural Engineering for Improved Sensing Range

To enable applications for various scenarios mentioned earlier, the sensing ranges of flexible strain sensors have to be wide. Geometrically designed structure such as porous structures, wrinkled structures, and overlapped structures can significantly improve sensing range of strain sensors. The working mechanisms and preparation processes of these structures, as well as the effectiveness of those approaches, will be discussed in detail in this section.

2.1. Porous Structures

Compared with materials of continuous medium, porous structural materials have relatively low density, large specific surface area and large porosity. A large number of pores render the porous material easy to deform due to smaller elastic modulus. As porous materials show greater stretchability than materials of continuous medium, strain sensors based on porous structures naturally have a wide sensing range. In particular, sponge is a common porous material, mainly made of wood cellulose or foamed plastic polymer. Sponges are widely used in various industries because of simple and cost-effective manufacturing processes. As sponges are easy to obtain and have excellent flexibility, a large amount of research works on strain sensors based on commercial sponges have been reported recently. For example, Lu and co-workers fabricated a versatile strain sensor based on polyurethane (PU) sponge coated with carbon black (CB).[32] To deposit CB on the surface of PU sponge backbones and form cellular-like conductive networks, a commercial PU sponge was alternately dipped into oppositely charge CB suspensions (Figure 1a). During the detection of small compressive strain, the deformation of backbones introduced cracks on CB layers, increasing the resistance. As the strain increased, pores were further compressed and backbones started to contact with each other, which shortened the conductive paths and decreased the resistance. As shown in Figure 1b, the sensor exhibited wide sensing range (0.2–60% of compressive strain), excellent flexibility, and fast response times (<20 ms). Moreover, the resistance...
response maintained stable after over 50,000 cycles of strain loading–unloading cycles. Inspired by the microcrack sensing structures of spiders and the wing-locking sensing systems of beetles, Zhang and co-workers presented a flexible wearable strain sensor based on commercial PU sponges.[33] An in situ reduction process was utilized to deposit reduced graphene oxide (RGO) sheets onto the backbones of PU sponge. In addition, in situ chemical oxidative polymerization of conducting polymers was utilized to deposit conductive polyaniline nanohair (PANIH) arrays onto the RGO sheet layers. As the RGO sheet layers were fragile and cracks occurred even under small strain (0–10%), the strain sensor was able to detect tiny motion (27 Pa pressure, 0.2% strain). Under large strain (>20%), the contact of PANIH arrays increased conductive paths and shortened the length of conductive paths, which decreased the resistance. As the PU sponge had excellent compressibility, the strain sensor could be compressed to 80% strain (Figure 1c) and exhibited stable performance after 10,000 loading–unloading cycles. Meanwhile, the strain sensor demonstrated fast response time (22 ms) and recovery time (20 ms). The strain sensors mentioned earlier both utilized commercial PU sponges as substrate, thus the trends of resistance change under compressive strain were similar. In general, based on the magnitude of the applied strain, their resistance response curve could be divided into three stages. The formation and propagation of cracks on the conductive layer induced an increase in resistance upon small compressive strain (<10%). With increasing compressive strain, the appearance of backbone contact led to a decrease in resistance, whereas the crack was still expanding. As a result, the synergism of cracks and contact drove the resistance to decrease. As the strain further increased, the resistance response was principally determined by the increased contact areas of backbones, which exhibited more dramatic decrease than the second stage. In particular, sensing ranges of the second stage for these two strain sensors were 10–50% strain and 10–20% strain, respectively. The difference could be explained by the existence of PANIH arrays. As the contact of backbones was enhanced by PANIH arrays, the effect of cracks on resistance was shielded at small strains (≈20%). Although these strain sensors were demonstrated to have wide sensing ranges, the response curves of resistance to strain were nonmonotonous with negative and positive curvatures in different ranges, which hindered their practical applications.

As the resistances of above strain sensors exhibited apparently decrease at the second and third stages, the monotonicity of response curve was only hindered by the performances under small compressive strain. To obtain monotonous response of strain sensors based on PU sponges, Zeng and co-workers reported a high-performance strain sensor based on auxetic PU foam.[34] As shown in Figure 1d, the auxetic PU foam was fabricated by heating and cooling triaxial compressed conventional foam. The scanning electron microscopy (SEM) images showed that the pores of auxetic foam were concave polygonal (Figure 1e), whereas the pores of normal sponge were hexagonal. The reentrant cellular structure allowed the foam to expand (contract) in other axes under uniaxial tension (compression). Importantly, the auxetic foam strain sensor was able to detect both compressive and tensile strains. Under compressive strain, the increase in contact areas between backbones of auxetic foam led to the decrease in resistance. On the contrary, the generation and propagation of cracks on the conductive layer of auxetic foam increased the resistance under tensile strain. As a result, the strain sensors showed an ultrawide sensing range of 60% compressive strain to 80% tensile strain. In addition, as the auxetic foam was compressed in all three directions under uniaxial compressive strain, the increasing rate of contact areas between backbones of auxetic foam was larger than that of commercial sponges, leading to higher measurement sensitivity of strain sensors based on auxetic foam. Likewise, the triaxial expansion of auxetic foam under tensile strain exacerbated the generation and propagation of cracks, causing the auxetic foam sensor to be more sensitive during tension. Generally, the measurement sensitivity of strain sensors, termed as GF, is defined as

$$GF = \frac{\Delta R}{R_0 \times \epsilon}$$  \hspace{1cm} (1)

where $\epsilon$ represents the applied strain, $R_0$ represents the initial resistance of strain sensor, and $\Delta R$ is the resistance change between initial resistance and the resistance of strain sensor under $\epsilon$ strain. The auxetic foam sensor was demonstrated to have GFs of 1.45, 2.63, and 0.464 at 0–60% compressive strain, 0–30% tensile strain, and 30–80% tensile strain, respectively, whereas the GF of commercial foam was only 0.491 for the whole sensing range (Figure 1f). The comparable GF at 30–80% tensile strain could be explained by the disappearance of reentrant structures under large tensile strain. It is important that the response of the sensor to strain was monotonous for both compressive and tensile strain, which can be explained by the backbone structures of auxetic foam. The SEM images show that backbones of auxetic foam already had contact under 0% strain. Although cracks were generated and propagated upon small compressive strain, the increase in contact areas played a decisive role on resistance change, which made the resistance decrease monotonously. Under tensile strain, the combination of cracks and reduction of contact areas increased resistance monotonously.

Another method to fabricate strain sensors with porous structures is to synthesize porous substrate with desirable properties instead of adopting commercial sponges. As elastomers have great stretchability, porous materials utilizing elastomer as cell walls have improved stretchability, which endows strain sensors with wider sensing ranges. For example, thermal-induced phase separation (TIPS) technique was utilized to fabricate porous graphene/thermoplastic polyurethane (TPU) foams that showed excellent performances for strain detection.[35] In this approach, a mixture of conductive graphene and TPU pellets dissolved in dioxane was placed in freeze-drying vessel for phase separation and sublimation of ice crystal, leading to the formation of conductive graphene/TPU foam. As the TPU molecular chain contracted during ice crystal sublimation, there were a lot of small holes on the cell walls of the foam, which caused significant destruction of graphene conductive networks and the increase in resistance. As a result, the strain sensor had stable piezoresistive behavior for up to 90% strain and exhibited good recoverability and reproducibility after cyclic loading. The resistance response curve had two linear segments, which were 0–60% strain with a GF of 2.45 and 60–90% strain with a GF of 12.24. In particular, the two different linear response ranges could be explained by the corresponding stress–strain curve, as shown in Figure 1i. When the strain was less than 60%,
the stress showed a slow and proportional increase with strain. As the strain exceeded 60%, a densification region appeared. As the cell walls suffered more serious destruction in the densification region, the compression sensitivity was higher than that of low strain regions. As another example, a compression-molding and salt-leaching method was utilized to prepare carbon nanotube (CNT)/TPU composites with porous segregated conductive network.[14] NaCl particles, TPU powder, and CNT were ball-milled first, and then the composite powder was compression-molded into a film at 85 °C. As shown in Figure 1g, the dissolution of NaCl in deionized (DI) water formed porous structures. The SEM images showed that CNT localized at the cell walls to form conductive network. Moreover, the increasing pore concentration would reduce strength and elongation at break of the sensor, whereas the decrease in elongation at break hindered the further expansion of the sensing range. As a result, the sensor had wide sensing range of up to 950% tensile strain, and the sensing range decreased with the increasing pore concentration. In addition, the relative resistance change curve of the strain sensor with tensile strain was monotonous and nonlinear. Particularly, the sensor exhibited the maximum GF of 356.4 at 700–800% tensile strain (Figure 1h). Moreover, the strain sensor showed outstanding stability and durability during 5000 stretching–releasing cycles. As the remarkable performances of strain detection, the strain sensor was applied in wearable sensing systems for human motion detection, soft robots, HMI, and so forth.

In addition to strain sensors based on porous substrate, strain sensors based on porous conductive materials have also been reported recently. Due to the characteristics of lightweight, high porosity, large surface areas, and high conductivity, conductive aerogels have recently attracted a great deal of attention. Qiu et al. successfully fabricated a strain sensor based on polydimethylsiloxane (PDMS) and porous compressible graphene aerogel (CGA).[37] In contrast to strain sensors mentioned earlier, graphene was utilized as backbones and PDMS was coated on the cellular wall of CGA. A functionalization–lyophilization–microwave process was utilized to synthesize CGAs. Afterward, CGA was immersed into mixture solution of hexane and PDMS. After removing solvent at 120 °C, the PDMS was deposited on the surface of the cellular wall, forming the composite of PDMS/CGA. Compared with pure CGAs, the PDMS layers in the hybrid structure increased the mechanical properties of CGA and prevented the formation of cracks on the surface of CGA. Thus, the porous PDMS/CGA composite was able to maintain effective resistance under large compressive strain. As a result, the strain sensor could endure compressive strain up to 90% and demonstrated excellent repeatability. In addition, the strain sensor showed linear response in the range of 0–90% strain and had high electromechanical stability after repeated compression.

2.2. Wrinkled Structures

The mismatched deformation between surface functional materials and elastic substrate will induce wrinkles in the functional material layer. When detecting strain stimuli, the deformation of wrinkles can bear part of strain and postpone the failure of surface functional materials. Therefore, wrinkled structures can be adopted to increase stretchability of functional materials and extend the working range of strain sensors. The difference between thermal expansion coefficients of functional materials and elastomer substrate is usually utilized to introduce mismatched deformation and form wrinkles. For example, Khine and co-workers fabricated wearable strain sensors based on self-similar microsized wrinkled CNT thin film on Ecoflex films.[38] As shown in Figure 2a, the CNT film was sprayed on polystyrene (PS) using a spray gun followed by placing the sample into an oven set at 150 °C. As the oven temperature was higher than the glass transition temperature of PS, PS was melted and compressed in biaxial directions, whereas the thermal deformation of CNT thin film was very small. The mismatched deformation between PS and CNT film created wrinkles on the CNT film. After cooling to normal temperature, the wrinkled CNT films were transferred to Ecoflex to fabricate wrinkled CNT–Ecoflex (wCE) strain sensors. As Ecoflex has remarkable stretchability and the stretchability of fragile CNT films was improved by the wrinkled structure, wCE strain sensors exhibited an ultrawide sensing range up to 700% strain, whereas planar CNT films could be stretched to 12%.[38] In addition, the response curve of the relative resistance due to tensile strain could be simply divided into two regions. Under low strain range (0–400%) (Figure 2b), the decrease in contact areas between different wrinkles and reduction of effective conductive areas of single wrinkle slightly reduced the resistance, with GF of 0.65 (Figure 2c). For large strain range (400–700%), the wrinkles on CNT films disappeared, and the generation and propagation of cracks on CNT films increased the resistance sharply (GF = 48). Furthermore, the same group also presented a wrinkled platinum (wPt) strain sensor with tunable sensitivity and sensing range.[39] The tunable strain sensors were prepared by depositing Pt films of different thickness on elastomer substrate. As thinner metal films had better flexibility and ductility, the density of wrinkles decreased and the fracturing of Pt film increased as the thickness increased. As fewer wrinkles would weaken strain separation effect of wrinkled structures and the broken Pt film would increase the resistance during stretching, the strain sensor with thick Pt film had narrower sensing range and larger sensitivity than that of strain sensor with thin Pt film. As a result, the sensor with 5 nm wPt film demonstrated a wide detecting range with maximum strain as high as 185%, whereas 50 nm wPt film exhibited a relatively narrow detecting range only up to 95% strain. In addition, 50 nm wPt film displayed high GF of 27 at 95% strain, whereas 5 nm wPt film showed low GF of 9 at equivalent strain. However, compared with 2% sensing range of strain sensor based on Pt film without any structure, the sensor with 50 nm wPt film still showed a significantly improved sensing range, which confirmed the remarkable effect of wrinkled structures. In the meantime, the strain sensor also had great repeatability and stability with no obvious change and hysteresis in response curve during the test of 1000 cycles.

Another facile and scalable process for fabricating wrinkled structure is exploiting the mismatched stiffness between functional materials and elastomer substrate. The prestretching of elastomer substrate is also widely utilized to introduce wrinkles on the layers of functional materials. For instance, Shen and co-workers prepared a wrinkle-assisted crack microstructure yarn
strain sensor (WCMYSS) based on CNT ink and PU yarn. CNTs were coated on swollen PU yarn through ultrasonic treatment first, and then the CNT/PU yarn was uniformly and slowly prestretched to a constant strain. Due to the mismatch in Young’s modulus between CNTs and PU yarn, the CNTs layer would break during the prestretching process. After releasing the strain, retracted PU yarn would compress CNTs film and introduce wrinkles on CNTs layer. As the cracks could enhance the sensitivity and the wrinkles could expand the sensing range, WCMYSS was expected to have outstanding performances. Indeed, WCMYSS not only had ultralow limit of detection (0.1% strain) and excellent durability, but also exhibited a wide sensing range up to 200% strain. Different from the previous wrinkled strain sensors, the propagation of cracks on the CNTs layers of WCMYSS accelerated the increase in resistance, which caused high GF under small tensile strain. Under large strain, the wrinkled structure disappeared, and the further propagation of existing cracks and the formation of new cracks increased the resistance dramatically. As the WCMYSS had an average diameter of only 925 μm, it could be easily woven into clothes and showed great potential in wearable systems. Moreover, Liu and co-workers prepared core–shell fiber strain sensors with wrinkled structures. A Chinese brush pen was utilized to coat silver nanowires (AgNWs) ink on prestretched commercial PU fibers. After releasing the prestrain, the PU fiber compressed AgNWs film and formed multiscale wrinkled microstructures, as shown in Figure 2d. Due to high stretchability of PU fiber and AgNWs layers, the core–shell conductive fibers demonstrated high conductivity, durability, and a wide sensing range of up to 400% strain (Figure 2e). In addition, the conductivity of the strain sensor dramatically dropped linearly with the increased writing cycles, as more writing cycles contributed to thicker AgNWs layer. As a result, the conductive fiber with 100 writing cycles exhibited an initial resistivity of <10⁻¹⁵ Ω cm and a sensing range up to 417% tensile strain, whereas that of the conductive fiber with ten writing cycles were >10 Ω cm and 100%, as shown in Figure 2f.

2.3. Overlapped Structures

Generally, the measurement mechanism of most strain sensors with overlapped structures is based on the variation of contact areas. As an overlapped structure can promote the failure strain of strain sensors by enabling the areas of contact along increased length scale, the sensing range can be effectively enhanced and tuned by the overlapped areas. Due to the planar sheet nature, 2D materials such as graphene and MXene are widely used for the construction of overlapped structures. For example, Ren and co-workers fabricated a high-performance strain sensor based on overlapping graphene sheets. The RGO film on PDMS was prepared from graphene oxide (GO) film by laser scribing (Figure 3a). In addition, another PDMS layer covered the RGO layer to stabilize the structure and prevent the structure from mechanical damage. The SEM images showed that RGO was composed of many graphene sheets that had overlapped regions. Under small strain, the elongation of strain sensor led to the reduction of overlapped areas, which increased the resistance according to Ohm’s law, as shown in Figure 3a. Under large strain, as the overlapped areas disappeared, the expansion of the gap between different graphene sheets increased the resistance according to tunneling effect, leading...
to exponential increase in resistance. As a result, the graphene strain sensor based on overlapped structure exhibited a sensing range of 7.5%, about 5 times of the sensing range of strain sensors based on monolithic graphene. Furthermore, to enhance the sensing range, the same group presented another strain sensor based on overlapped graphene sheets and Ag nanoparticles (AgNPs). The preparation processes of graphene sheets were the same as earlier, whereas AgNPs were drop-coated on PDMS film by mixing with GO dispersion. After that, the AgNPs were evenly dispersed between graphene sheets and served as conductive bridges between graphene sheets. Compared with graphene strain sensors without AgNPs, the decrease in contact area between graphene sheets and AgNPs further increased the resistance at equivalent strain, enhancing the sensitivity. On the contrary, AgNPs postponed the generation of microcracks between graphene sheets and stabilized the propagation of microcracks, which broadened sensing range and increased the linearity of response under large strain. As a result, the graphene sensor with AgNPs exhibited improved sensing range of 14.5% and improved GF of 475. Moreover, Ma and co-workers demonstrated a high-performance strain sensor based on overlapped structures of graphene platelets (GnP). A simple and cost-effective method was utilized to prepare overlapped GnP based on commercial graphite. Worm-like GnP were pressed onto adhesive tapes to form overlapped structures and intimate contact between different platelets. After that, a layer of PDMS was prepared by spin coating and cured on GnP surface. As liquid PDMS had low viscosity and surface energy, it could diffuse into GnP film, to stabilize GnP and enhance its stretchability. As a result, the sensor exhibited remarkable stability and reproducibility with a sensing range of 25% strain, and a maximum GF of 152 was demonstrated. On the contrary, the sensing range of GnP on the adhesive tape was demonstrated to be only up to 12%, which was almost half of GnP on PDMS. The improved sensing range could be explained by the fact that PDMS was far more stretchable than the adhesive tape.

Since 1D materials (CNTs and metal NWs) have large aspect ratio, overlapped regions can be easily formed between different NWs or NTs. However, as the change in overlapped areas of 1D materials with random distribution is independent, the variation of different overlapped area under tensile strain usually leads to the fluctuation of the electrical resistance. Thus, 1D materials need to be aligned or arranged to prepare overlapped structures. For instance, Kim and co-workers presented a strain sensor based on overlapped CNT bundles. As shown in Figure 3c, the conductive layer of strain sensor was composed of vertically aligned CNT (VACNT) bundles arranged as fish scales. At first, VACNTs were synthesized by chemical vapor deposition. Then, a
roller attached with Ecoflex film rolled over VACNTs to transfer VACNTs onto elastomer film. It is noted that the rolling process dumped VACNTs and rendered VACNT bundle overlap with each other. Compared with strain sensors with overlapped structures of graphene sheets, the sensor shows an ultrawide sensing range of 145% strain (Figure 3d). This can be explained by the fact that the overlapped areas of VACNTs were larger than that of graphene sheets. In addition, the overlapped areas of VACNTs could be controlled by the distance of VACNTs and the length of VACNT. For certain distance, the larger length of VACNT leads to larger overlapping areas, wider sensing range, and higher sensitivity.

3. Structural Designs for Improved GF

The capture of low magnitude strain signals is critical for accurate perception of environmental stimuli and human intention for HMI. To improve the sensitivity of flexible and stretchable strain sensors for the detection of low strain, researchers have designed structures such as crack and strain concentration structures.

3.1. Crack Structures on Planar Surface

Spiders are able to sense extremely small variations of cobweb because of the crack-shaped slit organs near their leg joints. Due to high sensitivity of the biosensor system and the uncomplicated biological structure, diverse strain sensors simulating crack-shaped structure of spiders have been prepared. Generally, strain sensors with crack structures consist of flexible substrate and conductive thin films. And the opening and closing of cracks on conductive thin films will affect the resistance, allowing the sensors to detect strain stimulus. The crack structures can be divided into two types according to crack morphology: one is channel crack and the other is isolated microcrack. As the isolated microcracks do not penetrate through the entire width of the conductive thin films, straight conductive paths are divided into network of conductive paths. With the propagation of isolated microcracks, the length of conductive paths increases and the width of conductive paths decreases. As the conductive paths are not broken, the resistance is determined by Ohm’s law

\[
R = \frac{\rho \times L}{S}
\]

(2)

where \( L \) is the length of conductive path and \( S \) is the cross-sectional area of conductive path. As the strain increases, the resistance increases with the increase in \( L \) and decrease in \( S \). In contrast to isolated microcracks, channel cracks penetrate the entire width of conductive thin films and a fully expanded channel crack will cut off the conductive path, causing the resistance of strain sensor to be infinite. In addition, when the channel crack gap is in nanometer scale, the electrons with a lower energy than the barrier height have probability to flow across the gap, which is termed as tunneling effect. The resistance of conductive films when tunneling effect occurs is determined by the tunneling conduction model, which can be described as

\[
R = \frac{N}{S} \left[ \frac{8\pi hs}{3A}\gamma \right] \exp(\gamma s)
\]

(3)
\[
\gamma = 4\pi(2m\phi)^{1/2}/h
\]

(4)

where \( R \) represents the electrical resistance of strain sensor, \( N \) is the number of sheets within a conductive path, \( S \) is the number of conductive path, \( \hbar \) is Plank’s constant, \( s \) is the average gap of channel cracks, \( A \) is the effective cross-sectional area, \( m \) and \( e \) are the mass and charge of electron, respectively, and \( \Phi \) is the height of the energy barrier. As the increasing strain will increase the average gap \( s \), the resistance will increase exponentially according to model. However, the range of crack gap width for tunneling effect is very narrow. Once the tunneling effect disappears, the resistance becomes infinite. Thus, the resistance of strain sensor with channel crack will increase exponentially from a small value to infinite within a small strain range, indicating a very high sensitivity of the strain sensor. As for strain sensors with isolated microcracks, the applied strain is shared by a number of microcracks, resulting in small expansion of single microcracks. The increase rate of \( L \) and decrease rate of \( S \) are slow because of the small expansion of microcracks, indicating a poor sensitivity. Therefore, to fabricate strain sensor with high sensitivity, channel cracks should be prepared on the conductive layer of strain sensor. The strain sensors discussed below are all based on channel cracks.

Due to remarkable conductivity, excellent ductility, and simple preparation processes, metal films are the most common conductive layers for flexible strain sensors with channel cracks. For example, Kim and co-workers demonstrated a high sensitivity strain sensor that utilized Pt film as conductive layer and polyurethane acrylate (PUA) as substrate.\(^{[47]}\) The patterned Pt layer was deposited on the surface of PUA by a shadow mask using sputtering. After that, the sample was mechanically bent with various radii of curvature. Due to the poor stretchability of Pt film, channel cracks were introduced on the Pt film. In addition, the cracks extended into PUA substrate, resulting a small gap between matching crack edges even at 0% strain. Under small strain, although stretch in the axial direction disconnected the crack edges, the compression in the transverse direction reconnected them because of the zip-like morphology of channel cracks and the positive Poisson’s ratio of PUA. Therefore, the change in resistance under small strain still followed Ohm’s law. As the strain increased, the contact area reduced and the resistance increased slowly. Furthermore, when the distance between the top of crack edges was in nanometer scale and the other parts of crack edges were completely separated, the tunneling effect began to affect the resistance, resulting in an exponential increase in resistance. In this stage, slight increase in applied strain caused a sharp increase in resistance. As a result, the strain sensor was able to detect vibrations with amplitudes of \( \approx 10 \) nm and exhibited a GF of 2000 in 0–2% sensing range. Moreover, as different spider species have crack-shaped slit organs with different geometrical parameters, their sensing abilities are demonstrated to have different range of frequency and spectrum. To further evaluate the effect of the geometric factors of channel cracks, the same group prepared strain sensors with different crack depths.\(^{[48]}\) The preparation processes of PUA substrate and Pt film were the same as before. The initial cracks
were introduced by bending the sample with various radii of curvature, whereas additional tensile force was applied on both sides of sensor to obtain different crack depths (Figure 4a). The atomic force microscopy (AFM) results indicated that the crack depth was proportional to the magnitude of tensile force. As additional force was applied after the formation of initial cracks, the crack density and crack asperity were almost the same. Therefore, crack depth was the dominant factor affecting the crack gap under strain stimulus. As tunneling resistance increased exponentially with the increase in crack gap according to the aforementioned equation, strain sensors with large crack depth exhibited larger resistance change than that with small crack depth at equivalent strain, indicating higher sensitivity (Figure 4b). As a result, the GF increased with the increase in additional tensile force, and showed value of more than 16 000 with 10 N tensile force (Figure 4c). In addition to Pt, gold is another common conductive material for strain sensors with crack structures. For instance, Zhu and co-workers prepared a high sensitivity strain sensors based on gold thin film. \[49\] Electron beam evaporation was utilized to deposit gold thin film onto PDMS substrate, and then a prestretching process was applied to the gold/PDMS assembly to introduce channel cracks. As the elastic modulus of gold thin film was larger than that of PDMS, the deformation of gold film was less than that of PDMS during prestretching. Due to the poor adhesion of gold film, sliding occurred between gold film and PDMS substrate, leading to the overlap of edges of channel cracks after the release of prestretching. Therefore, as the strain was increased from 0%, the decrease in overlapped areas increased the resistance at first. When the overlapped area disappeared, tunneling effect began to drive the resistance to increase exponentially. Thus, the relative resistance response curve of the strain sensor could be divided into two regions. The resistance of first region was determined by the overlapping model that follows Ohm’s law, exhibiting low sensitivity. The resistance of second region was determined by the tunneling model, which exhibited a high sensitivity. In addition, as large prestretching strain introduced large slide, the overlapped areas of crack edges increased with prestretching strain. Strain sensors with small overlapped area were able to exhibit exponential response curve even at low strain, whereas those with large overlapped areas were not able to exhibit sharp increase in resistance until the overlapped areas disappeared. On the contrary, ultrasmall prestretching strain led to low crack density and small initial crack gap, which contributed to small resistance change. As a result, a prestretching strain of 10% was adopted to prepare the most sensitive gold film strain sensor, which possessed GFs as high as 200 (<0.5%), 1000 (0.5–0.7%), and greater than 5000 (0.7–1%).

Apart from metal film, other materials with outstanding conductivity and limited stretchability have also been utilized as conductive layers in channel crack strain sensors. For instance, Choi and co-workers prepared a highly sensitive strain sensor based on indium tin oxide (ITO). \[50\] The strain sensor was fabricated by depositing 600 nm ITO on 30 μm PET film. Channel cracks were introduced by stretching the films up to 2% strain. As ITO showed good adhesion with PET and poor ductility, the ITO film on PET exhibited flat surface without overlapped areas. In addition, due to the asperity of cracks and the compression on
transverse direction upon applied tensile strain, sides of crack edges were connected, retaining the conductivity of ITO film. As the strain increased, the increasing gap caused the disconnection of cracks and the appearance of tunneling effect, resulting in exponential increase in resistance. ITO strain sensor exhibited high sensitivity in 0–2% strain, similar as Pt crack strain sensors. Furthermore, the edges of cracks on ITO sensor had lower asperity than that of Pt sensor smoother edges, resulting in less side contact between crack edges, eventually leading to the earlier occurrence of tunneling effect and higher sensitivity. As a result, compared with 2000 GF at 2% of Pt sensor, the GF of ITO sensor was up to 4000 at 2%. Moreover, Liu and co-workers presented a strain sensor based on AgNWs/graphene hybrid particles.\(^{[31]}\) The layer of AgNWs and RGO hybrid particles (SGHPs) was prepared by filtering SGHPs mixture using poly(vinylidene fluoride) (PVDF) filter membranes, followed by casting of TPU above the membranes to form SGHPs/TPU composites, as shown in Figure 4d. After that, cracks were induced by prestretching the composite membranes. Due to weak interfacial reaction between hybrid particles and localization of strain, channel cracks were formed during prestretching process. Due to the buckling of SGHPs layer and different resilience between SGHPs layer and TPU, overlapped areas occurred on the surface upon releasing. When the applied strain was in the range of 0–0.3%, the resistance of SGHPs layer increased due to the decrease in overlapped areas. Due to the 1D AgNWs on the edges of SGHPs, the overlapped edges still had subtle line contact, whereas other parts without AgNWs remained separated. Therefore, resistance change in the strain sensor under 0.3–0.5% strain was determined by the coupling of wires contact and tunneling. When the applied strain was greater than 0.5%, the AgNWs on the edges were disconnected and the conductive pathways were broken. Thus, the resistance in this stage was only determined by tunneling effect between relatively close AgNWs, exhibiting high increasing rate of resistance. On the contrary, as large prestretching strain led to large overlap region, strain sensor with 10% prestretching strain was demonstrated to have the best sensitivity, as shown in Figure 4e. As a result, the strain sensor with 10% prestretching strain demonstrated GF as high as 20 (0–0.3%), 1000 (0.3–0.5%), and 4000 (0.5–1%), respectively (Figure 4f).

3.2. Strain Concentration Structures

As channel cracks on the conductive layer of strain sensors contribute to high sensitivity for detecting small strain, the generation and propagation of cracks play a decisive role on the sensitivity of strain sensor. Strain concentration structures on the substrate can control the location of cracks and accelerate the propagation of cracks, which are beneficial for improving sensitivity. Strain concentration structures divide the substrate surface into two parts: strain concentration regions and strain separation regions. As the strain on strain concentration regions is larger than applied strain due to the strain amplification effect, cracks are more likely to form and the crack gap is larger than that of strain sensors without structural design. Therefore, upon smaller strain, tunneling effect occurs on the surface of strain sensors with strain concentration structures, whereas the crack edges of strain sensor without structure still contact, leading to higher GF of former sensors. Due to simple design and excellent strain concentration effect, V-notch structure is a commonly adopted strain concentration structure. For example, Lin and co-workers presented a V-notch strains sensor with unprecedented sensitivity.\(^{[52]}\) PDMS was cast against the SU-8 mold which had V-notch pattern. After peeling PDMS from the SU-8 mold, 10 nm Cr and 40 nm Au were deposited on the surface of PDMS to form the strain sensor. The effective structure was the bridge region with opposing V-notch features which connected two pads. Due to strain concentration, the fracture spot of gold film preferentially appeared at the V-notch tip upon an ultrasmall tensile strain. Due to piezoresistive effect of gold film, the resistance increased slowly with the strain at the beginning of strain loading. After the appearance and propagation of the crack, the separated regions hindered the flow of electrons, causing the increase in resistance. Furthermore, due to fast expansion speed of the crack, tunneling effect appeared upon small strain and drove the resistance to increase exponentially. Therefore, the strain range from the appearance of tunneling effect to the disappearance was very narrow, resulting in a step-like response of resistance. As a result, the single-crack-activated strain sensor exhibited remarkable GFs of 300 (0–0.045%), 100 000 (0.045–0.08%), and 1.42e8 (0.08–0.0845%). Moreover, Ren and co-workers developed a high sensitivity strain sensor based on surface V-notch structured PDMS.\(^{[53]}\) Due to the ease to crack, PS was utilized to prepare the structure template of PDMS. The solvent-induced swelling method was utilized to fabricate V-notch arrays on the surface of PS. Then, double template transferring method was used to prepare PDMS film with V-notch arrays on the surface. After that, a 50 nm-thick gold film was deposited on the surface of PDMS by sputter coating, as shown in Figure 5a. Due to the strain concentration at the bottom of the V-notch, initial cracks were easily generated at gold surface. As the strain was increased, cracks propagated downward and the thickness of the gold layer was decreased sharply, resulting in an increase in resistance. Upon further strain, cracks propagated to the PDMS surface and the tunneling effect became the primary factor affecting the resistance, causing the exponential increase in resistance. In addition to tensile strain, the strain sensor was also able to detect compressive strain. Under compressive mode, the applied strain reduced the distance between two sides of the V-notch, resulting in an increase in the thickness of the gold layer (Figure 5a). In the beginning of compressive strain loading, due to the excellent strain concentration effect of V-notch, small applied strain could cause the gold layer to contact. As the strain was increased, the depth of V-notch decreased, resulting in the decrease in the concentration effect. Thus, the strain required for gold layer to contact became larger, which reduced the sensitivity. As a result, the strain sensor possessed GFs as high as 945.65 (0.1–5.5%) and 5888.59 (1.5–2%) under tensile mode, whereas under compressive mode, it exhibited GFs of 103.21 (0–0.4%) and 33.92 (0.4–1.2%). As baseline for comparison, the strain sensor without surface V-notch structure exhibited GFs of 832.55 (0–2%) in tensile mode and 46.53 (0–0.6%) during compression (Figure 5b).

Apart from V-notch structures, the island–bridge structure is another widely adopted strain concentration structure. As the island area is thicker than bridge area, certain applied strain will
lead to different local strains for cross-sectional areas of island and bridge regions. The mechanics model of island–bridge structure was built and described as:

\[
\varepsilon(l_{\text{island}} + l_{\text{bridge}}) = \varepsilon_{\text{island}} \times l_{\text{island}} + \varepsilon_{\text{base}} \times l_{\text{bridge}}
\]

(5)

\[
\sigma_{\text{island}} \times (h_{\text{trench}} + h_{\text{bridge}}) \times w = \sigma_{\text{base}} \times w \times h_{\text{bridge}}
\]

(6)

\[
\sigma_{\text{bridge}} = E \times \varepsilon_{\text{bridge}}
\]

(7)

\[
\sigma_{\text{island}} = E \times \varepsilon_{\text{island}}
\]

(8)

where \(l_{\text{island}}\) and \(l_{\text{bridge}}\) represent the length of island and bridge regions, respectively. \(h_{\text{bridge}}\) represents the thickness of bridge region, whereas \(h_{\text{trench}}\) is the thickness difference between island and bridge regions. \(\varepsilon\) represents the global strain of the model, whereas \(\varepsilon_{\text{bridge}}\) and \(\varepsilon_{\text{island}}\) represent the local strain. \(\sigma_{\text{bridge}}\) and \(\sigma_{\text{island}}\) represent the local stress. According to this model, local strain of island and bridge regions can be calculated as

\[
\varepsilon_{\text{island}} = \left(1 - \frac{h_{\text{bridge}}}{h_{\text{trench}}} \times \frac{l_{\text{island}}}{l_{\text{bridge}} + l_{\text{bridge}}} + 1\right) \times \varepsilon
\]

(9)

\[
\varepsilon_{\text{bridge}} = \left(1 + \frac{h_{\text{bridge}}}{h_{\text{trench}}} \times \frac{l_{\text{island}}}{l_{\text{bridge}} + l_{\text{bridge}}} \times \frac{h_{\text{bridge}}}{h_{\text{island}} + h_{\text{bridge}}}\right) \times \varepsilon
\]

(10)

According to the equations, the bridge region is in strain concentration state. Compared with conductive layer on substrate without any structure, cracks on conductive layer of bridge area tend to appear and propagate under smaller strain, leading to high sensitivity of strain sensors. For example, Chen and co-workers presented a fiber-shaped strain sensor with sensitivity enhanced by island–bridge structures.\(^{[54]}\) Due to Plateau–Rayleigh instability, beads formed automatically on the PDMS fibers after dipping with PDMS precursor. Then, Au was deposited on the fiber-bead structure to complete the fabrication of the strain sensor. As the gold film on the surface of fiber-bead structure had initial randomly distributed nano-effects, randomly distributed microcracks formed on both the beads and fibers during the first tensile strain cycle, dividing gold film into interconnected gold microislands. Furthermore, due to the diameter of beads is larger than that of fibers, beads could be regarded as islands while fiber regions between beads functioned as bridges, and strain concentration was induced on the fiber regions. Therefore, microcracks on fiber regions were longer and wider than those on beads. On the contrary, upon equivalent strain, the statistical analysis result exhibited that cracks on fiber with beads were longer than that of fiber without beads. As longer cracks cut off more conductive pathways, fiber with beads possessed larger resistance change, leading to higher sensitivity. As a result, the sensor of fiber with beads demonstrated GF of 42.3 for 0–120%, whereas GF of the fiber sensor without beads was only 9.8. In addition, as the effect of strain concentration increased with the thickness of island areas, local strain of fiber regions between large beads was larger than that of small beads, which resulted in wider and longer cracks on fiber regions between large beads. Thus, the fiber with large beads had higher sensitivity, and the GF of fiber with beads had a positive linear correlation with the bead diameter \((R^2 = 0.96)\). Moreover, Zhang and co-workers fabricated a strain sensor based on...
AgNWs@patterned PDMS using a simple and scalable method.\cite{cite}

As shown in Figure 5c, AgNWs solution was spin-coated on steel net-patterned PDMS substrate, followed by drying of AgNWs and prestretching of substrate. As the square plate arrays were thicker than the parallel concave line microstructures, the parallel concave lines could be considered as bridges, whereas the square plate arrays were regarded as islands. Under tensile strain, due to random distribution of AgNWs, microcracks were observed in square plate and parallel concave lines. The finite element method (FEM) simulation results confirmed that the parallel concave lines perpendicular to the strain had greater strain concentration, which played a decisive role in the resistance change in the strain sensor. In particular, strain concentration caused a larger deformation of the parallel concave lines than that of surface without structures, thus resulting in a sharper decrease in conductive path, leading to a higher sensitivity. The resistance change in the strain sensor was divided into two stages. Upon small strain, the strain concentration effect induced microcracks with wide gap and high density on the parallel concave lines, causing a decrease in conductive paths and an increase in resistance. As the strain increased, the initial conductive path was blocked, and electrons flowed through another longer conductive path, resulting in an increase in resistance. In addition, as AgNWs had large aspect ratio and PDMS had excellent stretchability, conductive networks still existed when the strain sensor endured large strain, indicating that the strain sensor had wide sensing range. As a result, the strain sensor exhibited an ultrahigh GF of 150 000 within 60% strain range, which was about 136 times larger than those of sensors without surface microstructures (Figure 5d).

4. Structure Engineering Beneficial for Both Sensing Range and Sensitivity

Although porous wrinkled and overlapped structures can extend the sensing range of strain sensor, these structures reduce the strain on conductive materials, postponing the disconnection of the electrical contacts, eventually resulting in lower GFs. On the contrary, crack and strain concentration structures can enable the breakage of electrical contacts upon low applied strain; however, these structures reduce the stretchability of the sensor, resulting in a low sensing range. Generally, the increase in GF will lead to decrease in sensing range, as the two indicators are seemingly contradictory. Nevertheless, researchers have developed hierarchical structures which can achieve both high sensitivity and wide sensing range, as shown in Figure 6.

Generally, hierarchical structures are composed of multilayer conductive materials or substrates. The presence of multilayer structures, either in conductive materials or substrate, leads to sequential breakage of electrical contacts in each layer, which causes the resistance to change rapidly throughout a wide strain range.
range, endowing the strain sensor with a high sensitivity and a wide sensing range. For example, Peng and co-workers presented a strain sensor with a hierarchical structure consisting of conductive Ag particles and long-range entangled CNTs.\cite{38} Through layer-by-layer (LBL) deposition, a strain-induced locking mechanism formed on the interface between Ag particles and CNT network. In the initial state, due to the fact that the conductivity of Ag is higher than that of CNTs, the conductive pathway was formed by the laminated Ag particles. When tensile strain was applied, the separation of Ag particles cut off the conductive pathways due to the weak electrical contacts between Ag particles and the large deformation mismatch between Ag particles and PDMS substrate, causing the increase in resistance. Moreover, the transverse compression by Poisson effect caused CNTs to permeate into Ag particles and formed special Ag-CNT sensing layer on the interface region. The CNTs in the Ag-CNT sensing layer functioned as conductive bridges which connected separated Ag particles and maintained the unobstructed conductive routes over a large tensile strain range. As the applied tensile strain increased, most of the electrical contacts between Ag particles were broken, the electronics flow paths mainly existed in the special Ag-CNT sensing layer. In addition, the increase in CNTs length connecting Ag particles and disconnection between Ag particles and CNTs resulted in rapid increase in electrical resistance. Compared with strain sensor based on pure Ag, CNTs in the hierarchical structure ensured effective resistance response upon a large strain and expanded the sensing range. On the contrary, compared with strain sensor based on pure CNTs, Ag particles in the structure broke the stable resistance of “bulky” CNT network and introduced rapid resistance change, causing high sensitivity for the whole sensing range. As a result, the strain sensor based on the structure could be stretched up to 120%, and exhibited a GF of 218.8 for 0–40% strain and 3990.8 for 40–120% strain. Likewise, Wang and co-workers designed a novel strain sensor based on conductive layers composed of PS/graphene conductive microspheres mingled freely with graphene nanosheets.\cite{39} A PS/GO suspension was dropped unidirectionally onto one side of the AuNW film and encapsulate the structure. When the applied tensile strain was below 30%, some electrical contacts between AgNWs were broken, causing an increase in electrical resistance. As the PUA nanofibers were able to sustain strain by the shape change in nanofiber network, nanofibers themselves were not critically stretched. When further tensile strain was applied, nanofibers were actually stretched and cracks were induced on the covered gold layer, resulting in a rapid increase in resistance. Therefore, the resistance response of the sensor to strain was divided into two stages. In the first stage (0–30%), the increase in resistance was mainly determined by the fracture of AgNW network. For the second stage (>30%), the generation and propagation of cracks on Au layer of the nanofibers were the dominating reason that increased the resistance. Due to the high sensitivity of crack sensing mechanism, the resistance at this stage increased dramatically. Compared with strain sensor based on pure AgNWs film, the addition of AuNWs not only ensured the effective response of the sensor under large strain, but also increased the sensitivity. As a result, the strain sensor based on AuNW–AgNW hybrid network could exhibit a wide sensing range of 0–90% and a high GF of 2370.

Hierarchical structures with multilayer substrates can induce different cracks on the conductive layer in different strain range. As the generation and propagation of cracks cause the dramatic increase in resistance, controlling the generation and propagation of cracks in specified strain range can extend the sensing range while maintaining measurement sensitivity. For example, Wang and co-workers fabricated an ultrasensitive and highly stretchable strain sensor based on hierarchical assembly of interfacial NWs which retarded penetrating cracking and increase the stretchability of metal thin film strain sensors.\cite{40} As shown in Figure 6c, due to the aggregation of PDMS NWs, micrometer-sized voids (MVs) existed between NW clusters and were distributed over the entire PDMS substrate. In addition, there were also nanovoids (NVs) between individual NWs within the clusters. The presence of MVs and NVs resulted in two-stage crack generation during tensile loading. When the applied strain was low, due to the strain concentration effect, cracks were first initiated at the bottom of MVs, which was the surface of underly-
Since the NW clusters were randomly distributed on the substrate, the MV-initiated cracks were not capable of cutting off conductive paths which maintained an effective resistance response of the sensor. When applied strain reached a critical threshold, the second-stage cracks were initiated from the NVs between individual NWs within the clusters. The propagation of NV-initiated cracks with the strain further increased the resistance. Compared with strain sensor with Pt film on a flat surface, the two stages of crack initiation retarded the occurrence of channel cracks, extending the sensing range while maintaining the sensitivity. As a result, the strain sensor was able to be stretched up to 130% and exhibited an ultrahigh GF of more than $10^7$ (Figure 6d).

5. Applications

Due to the stretchability and ease to form conformal contact with human skin, flexible and stretchable strain sensors have been typically adopted to measure physical and biomedical signals from human body, including biomedical monitoring,[9,10] detection of human motion,[11–13,62,63] and HMI.[14,15,64] Through structural engineering, strain sensors with high GF are advantageous in detecting subtle human motion of low strain and high frequency vibration (blinking, pulse, facial muscles movement, etc.). On the contrary, structural engineered stretchable strain sensors with wide sensing range can be utilized to monitor motion of large strain (joint flexion, finger motion, etc.).

5.1. Biomedical Monitoring

Due to the high GFs, structure-engineered strain sensors can detect slight vibration and tiny deformation induced by physiological signals, thus they can function as excellent health monitoring devices. Figure 7a shows pulse signals under normal and exercise conditions monitored by a strain sensor.[60] The sensor was attached to the wrist for pulse measurements. Due to high measurement sensitivity, the sensor could detect characteristics of the wrist pulse, including percussion, tidal, and diastolic waves, which could be applied for the diagnosis of heart disease. Figure 7b shows a strain sensor attached on the intercostal muscles for measuring chest wall displacement during respiration.[139] The contraction and relaxation of underlying inspiratory muscles will cause characteristic displacement of the intercostal muscles which can be detected by the strain sensor. Figure 7c,d shows the correlation of inspiration capacity (IC) and tidal volume (TV) measured by a spirometer and the strain sensor. The maximum inspiratory and expiratory cycles and the respiratory status in the following cycles of the subject were monitored by the sensor. During inhalation, the expansion of the chest cavity caused the strain sensor to be stretched, leading to the increase in resistance. According to measurements of the strain sensor, the subject’s vital capacity was 3500 mL and TV was 600 mL, both well within the expected physiological range.

Stretchable strain sensors have also been utilized for detecting small deformation of facial muscles. Four sensors attached on...
each side of the mouth and forehead could accurately distinguish five different facial expressions, including funny, smile, angry, sad, and laugh.\textsuperscript{[60]} As facial expressions can accurately reflect psychological activities, monitoring of facial expressions can be a useful tool for the diagnosis of Alzheimer’s disease, depression, and autism. Furthermore, as human vocalization is based on muscle movement and vibration, strain sensors attached on throat muscle can identify various pronunciation of words.\textsuperscript{[61]} The pronunciation of different words led to different resistance change in the strain sensor. The noninvasive and continuous measurements enabled by the strain sensor can be useful in the rehabilitation of people with damaged vocal cords.

5.2. Human Activities Monitoring

Flexible and stretchable strain sensors attached on human body are capable of monitoring different human activities. Figure 8 shows the relative change in resistance, while the strain sensor attached on joint areas was bent (finger, elbow, wrist, and knee). As shown in Figure 8a, the angle of finger bending was positively correlated with the relative change in resistance.\textsuperscript{[63]} Strain sensor attached on the wrist was easy to detect the bending motion of wrist joints\textsuperscript{[36]} (Figure 8b). Similarly, the relative change in resistance increases with the bending angle of the arm\textsuperscript{[46]} (Figure 8c). In addition, the strain sensor attached on the knee was capable of differentiating various knee-related movements, including marching on the spot, walking, running, jumping, and squatting\textsuperscript{[40]} (Figure 8d). On the contrary, strain sensor array could be utilized to measure foot pressure pattern at different gait phases.\textsuperscript{[144]} Barefoot pressure distributions of various gait phases, including neutral position, pronation, supination, plantarflexion, and dorsiflexion, were detected accurately. Monitoring of different gait phases is an essential evaluation tool for injury prevention, prosthetics, and orthotics design.

5.3. HMI

Flexible and stretchable strain sensor can also be used for HMI. Strain sensors can convert the deformation and vibration signals of human body or robots into electrical signals, which can be utilized as control signals for robotic actuations and closed-loop robotic operations. Shi et al. demonstrated wireless control of a robot movement by using a strain sensor.\textsuperscript{[145]} The first example was controlling the robot movement by stretching the strain sensor. The resistance change in the strain sensor was captured by a microcontroller (MCU) device, which sent a wireless signal to the robot computer once the resistance change exceeded threshold. After predefined time delay, the computer activated the robot’s servo control system and moved the robot toward the user. In another experiment, they demonstrated bending the wrist could also activate the robot’s motion as the resistance of the strain sensor on the wrist exceeded threshold.

Figure 8. Applications of flexible strain sensor for monitoring human activities. a) Relative resistance change in strain sensor for monitoring finger bending. Reproduced with permission.\textsuperscript{[61]} Copyright 2018, Wiley-VCH. b) Relative resistance change in strain sensor for monitoring wrist bending. Reproduced with permission.\textsuperscript{[36]} Copyright 2019, American Chemical Society. c) Relative resistance change in strain sensor for monitoring elbow bending. Reproduced with permission.\textsuperscript{[46]} Copyright 2019, Wiley-VCH. d) Relative resistance change in strain sensor attached on human knee under different movements. Reproduced with permission.\textsuperscript{[40]} Copyright 2019, American Chemical Society.
6. Conclusions and Perspectives

In conclusion, we have summarized various structure engineering strategies that are able to improve the sensitivity and sensing range of flexible and stretchable strain sensors. Porous structures, wrinkled structures, and overlapped structures can effectively improve the stretchability of strain sensors, but cannot improve measurement sensitivity. Crack structures and strain concentration structures are advantageous in enhancing sensitivity; however, they limit the sensing ranges of the sensor. Strain sensors with hierarchical structures presented so far can achieve wide sensing range and high sensitivity at particular strain range, while achieving superior sensitivity in the whole sensing range is still a great challenge, as shown in Figure 9. To overcome the limitation, continuous work on the development of sophisticated hierarchical structures is desirable. The combination of hierarchical structures and strain concentration structures may be an excellent strategy for improving the sensitivity of hierarchical structures under small strain.

In the meantime, most of the structures reported so far are prepared by the cast method based on templates, which is not suitable for fabrication of complex hierarchical structures. In contrast, new fabrication technologies, such as 3D printing, electrospinning, and laser microengineering, can be effective alternatives to fabricate high precision complex structures for flexible and stretchable strain sensors. For example, a stretchable sensor with a multimodulus architecture was fabricated by a full 3D printing process.\textsuperscript{[65]} Electrospinning was utilized to develop a flexible strain sensor with special 3D conductive network.\textsuperscript{[66]} Laser microengineering was used to prepare a series of microstructures on elastomers for modulating and enhancing the sensitivity of the sensors.\textsuperscript{[67]}

Another challenge is the integration of flexible and stretchable strain sensors with power supply, signal acquisition, and transmission modules. Conventional data acquisition and transmission method may induce complicated measuring circuits for sensor array, and the hard nature of the circuit compromises the wearability of the system. To date, there are several approaches that utilized flexible printed circuit board (FPCB) with integrated modules to collect and transmit the signal of sensor array to the terminal for processing.\textsuperscript{[68,69]} The integration scheme enhances the flexibility of the system; however, the materials and electronic components adopted are still in lack of stretchability and softness, leading to further demand of developing conformable integrated systems for measurements from human skin.

Although there are still challenges, with the continuous enthusiasm in the development of structural engineering strategies, we anticipated the continuous enhancements in the performances of flexible and stretchable strain sensors, and their actual applications in wearable healthcare, HMI, intelligent prosthesis, and assistive devices.

Acknowledgements

This work was supported by National Natural Science Foundation of China (grant nos. 51820105008 and 91648115). The authors also acknowledge the support from Flexible Electronics Research Center of HUST for providing experiment facility.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

biomedical monitoring, flexible electronics, human–machine interfaces, stretchable strain sensors, structural engineering
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