

Wearable and stretchable conductive polymer composites for strain sensors: How to design a superior one?

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ABSTRACT

Wearable and stretchable strain sensors have potential values in the fields of human motion and health monitoring, flexible electronics, and soft robotic skin. The wearable and stretchable strain sensors can be directly attached to human skin, providing visualized detection for human motions and personal healthcare. Conductive polymer composites (CPC) composed of conductive fillers and flexible polymers have the advantages of high stretchability, good flexibility, superior durability, which can be used to prepare flexible strain sensors with large working strain and outstanding sensitivity. This review has put forward a comprehensive summary on the fabrication methods, advanced mechanisms and strain sensing abilities of CPC strain sensors reported in recent years, especially the sensors with superior performance. Finally, the structural design, bionic function, integration technology and further application of CPC strain sensors are prospected.

1. Introduction

There is a growing demand for flexible electronic devices [1–4]. In particular, stretchable and wearable electronic devices are needed for multiple potential monitoring applications such as human health [5], body motion [6,7], rehabilitation and soft robotics [8–10]. Wearable strain sensors have attracted extensive attention because they can interact with the human body, reflect the health condition, and have long-term monitoring [11,12]. Wearable strain sensors can be attached to clothing or directly attached to human skin for human activity monitoring in real time [13–15]. In addition to high efficiency, the strain sensors must meet some requirements of lightweight, high stretchability, good flexibility, reliable durability, low power consumption and

biocompatibility [16,17]. These requirements are stringent for mechanically compliant and highly stretchable strain sensors for human skin [18,19].

It has been found that the conductivity of CPC varies with the change of inner conductive network of the polymer matrix [20,21]. When the CPC are stimulated by the external environment such as strain and temperature, the conductive network would be changed and the resistance would make a difference accordingly [22]. Therefore, flexible CPC can be used as multifunctional response sensors to monitor external intervention, illustrating great application potentials in human motion monitoring, fitness tracking and wearable interactive devices [23,24], as shown in Fig. 1a. According to the existing data on Web of Science, the research on CPC Strain Sensor has gone through 21 years (Fig. 1b)

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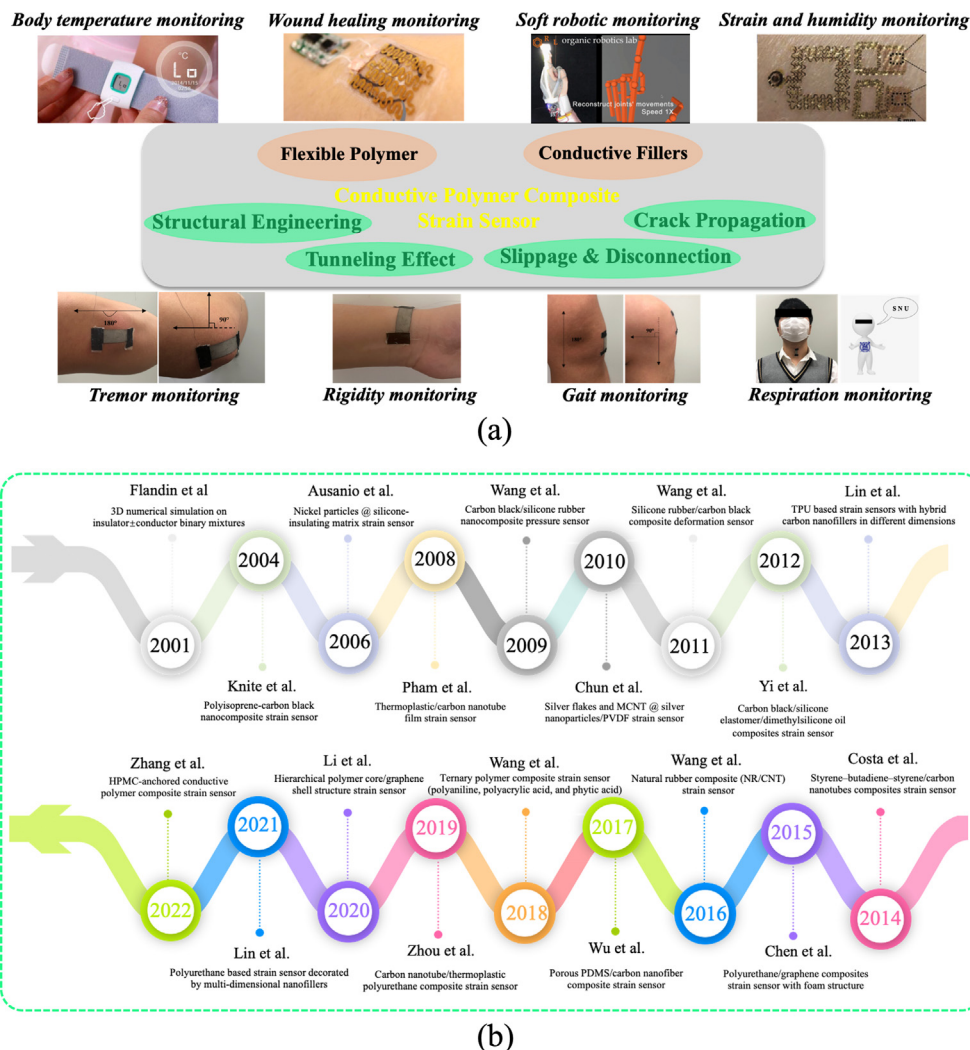


Fig. 1. (a) Wearable CPC strain sensors are promising in the field of human health detection, smart wound dressing and body motion monitoring [24]. (b) The developing timeline of CPC strain sensors [24–41]. Figure used with permission from Lin, L. et al. [24] Copyright © Elsevier, 2021.

[24–41]. From the proposal of basic research methods at the beginning to the updating of flexible polymer materials and conductive fillers, the research enthusiasm is rising year by year. Especially around 2014, the CPC strain sensors became more and more sophisticated in design and performance.

In this paper, the main manufacturing process, working mechanism and strain sensing performance of wearable and stretchable CPC strain sensors are summarized. The structure of this paper is as follows: Firstly, we summarize the typical CPC manufacturing technologies of novel functional conductive fillers and flexible polymer substrates, especially emphasizing the advantages of conductive nanofiber composites. Secondly, the mechanisms of strain sensing behavior are discussed. In particular, the structural engineering, disconnection, crack propagation and tunnelling effect between intrinsic conductive networks can be applied to strain sensing with high sensitivity. Thirdly, we hammer home the evaluations of the wearable and stretchable CPC strain sensors, including mechanical property, gauge factor, working strain, response time, durability and biocompatibility. Finally, the research status, challenge and outlook of the wearable CPC strain sensors are delivered.

2. Strain sensing mechanism

Compared with traditional mechanical sensors, flexible and stretchable CPC strain sensors have greater flexibility, which can adapt to

different working environments to a certain extent, and meet the deformation requirements of equipment and signal output [42]. The stretchable strain sensor responds to the applied strain by different mechanisms depending on the substrates, micro-structures, conductive networks, and manufacturing process [43]. Different from traditional mechanical sensors, mechanisms such as structural engineering, disconnection between conductive fillers, crack propagation and tunnelling effects are used to develop flexible, wearable and stretchable CPC strain sensors.

2.1. Structural engineering

On Oct. 10, 2000, the Royal Swedish Academy of Sciences decided to award the 2000 Nobel Prize in Chemistry to Alan Haig and Alan MacDiarmid of the United States and Hideki Shirakawa of Japan for their discoveries of conductive polymers [44,45]. Since then, more and more researchers have been engaged in the development of conductive polymers and CPC. In the field of healthcare, wearable devices have attracted more and more attention due to their advantages of intelligence, high sensitivity and wide working strain [46,47]. Traditional metals and semiconductors were widely used as the strain sensor preparation materials, which has been unable to meet the growing medical and health demands, because of their poor biocompatibility, non-portability, inaccurate monitoring and other shortcomings. To tackle the obstacles, it is promising to develop wearable and stretchable CPC strain sensors that

are flexible, low-cost, highly sensitive and easily to manufacture.

2.1.1. Blend doping

CPC are ideal choices for preparing wearable strain sensors due to their advantages of light weight, high conductivity, controllable conductive network and handy manufacturing [48]. One of the traditional methods for preparing CPC is conductive polymer modification, which is usually not used as the basic materials for strain sensors. The common approach is to mix conductive nanofillers directly into molten polymers, such as carbon nanotubes, graphene and metal nanoparticles, through blend doping [49]. Conductive nanofillers usually have very high surface energy, and are difficult to achieve great dispersion effect in molten polymer substrates, which tend to aggregate, negatively declining the mechanical property and conductivity of CPC. In addition, CPC generally exhibit low conductivity, as most nanofillers are wrapped by polymers, which greatly impede electron transport, due to their insulating properties. In addition to the direct doping of conductive nanofillers in the molten polymer substrates, CPC strain sensors can also be fabricated by permeating the elastomer polymer solution in the pre-constructed conductive network. CPC strain sensors prepared by blend doping usually have good strain sensing performance, but their applications in wearable strain sensors are severely limited due to the weak biocompatibility, poor air permeability and hard structure with large thickness.

2.1.2. Surface modification

To effectively avoid the increasing thresholds, decreasing conductivity, and improve the controllability and sensitivity of conductive networks, researchers have put forward the selective modification of

conductive nanofillers on the surfaces of flexible polymer substrates, which contain the surfaces of polymer particles, fibers and membranes [20,50]. To some extent, the surface modifications of conductive nanofillers can avoid the hard issues of blend doping, which may cause

Table 1

Comparison of the strain sensing performance of CPC strain sensors extracted from literatures.

Polymer substrate	Conductive fillers	Working strain	Gauge factor	Ref.
PVA	PA	100–140%	3.44	[55]
Epoxy resin	CNTs	0.6–14%	6	[56]
PMVS	CNTAs/CB	0–60%	10	[57]
TPU	CB	0–20%	10.8	[58]
PDMS	CB	0–10%	15.75	[49]
PVA	SA/TA	180–200%	15.98	[59]
Aramid/PVA	Polyaniline	100–130%	39	[60]
TPU	Graphene pellets	50–100%	80	[61]
TPU	SWCNT/RGO	200–300%	114.7	[62]
PVA/gelatin	CB	0–18%	523	[63]
TPU	MWCNT	5–50%	5200	[64]
PA6/PVA	CB	0–40%	9706.9	[65]
OBC	CB	90–100%	1.40×10^4	[66]
TPU	CNT/AgNPs	200–250%	4.33×10^4	[67]
TPU	CNTs/GNP	150–250%	1.30×10^5	[68]
Fluoroelastomer	CNTs	85–100%	1.36×10^5	[69]
TPU	HPMC/AgNF	30–35%	2.8×10^7	[41]

(CB: carbon black; PA6: polyamide 6; PVA: poly (vinyl alcohol); CNTs: one-dimensional carbon nanotubes; MWCNT: multi-walled carbon nanotube; SA: sodium alginate; TA: tannic acid; OBC: olefin block copolymer; PA: phytic acid; PMVS: polymethylvinylsiloxane; SWCNT: single-walled carbon nanotube; RGO: reduced graphene oxide).

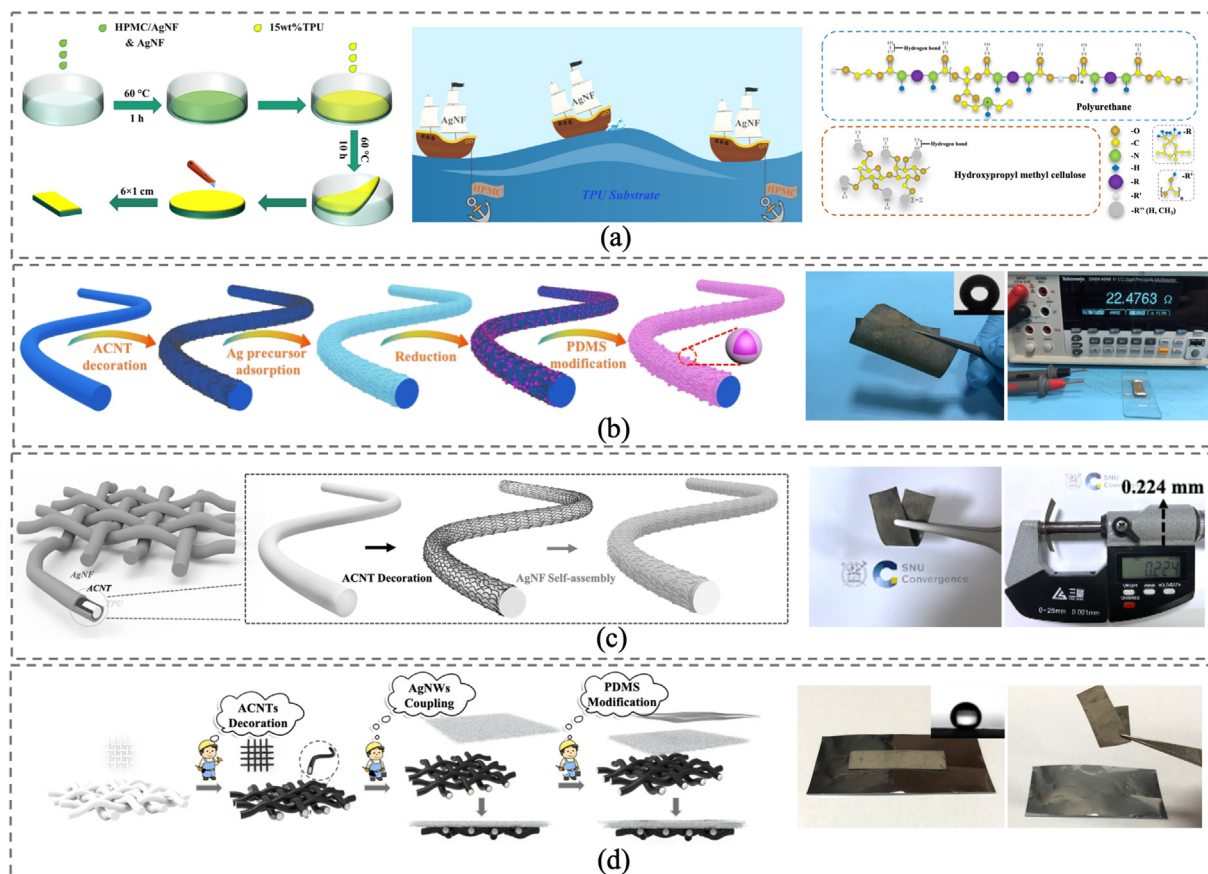


Fig. 2. Four design strategies of CPC strain sensors: (a) TPU/HPMC/AgNF [41], (b) TPU/ACNTs/AgNPs/PDMS [53], (c) TPU/ACNTs/AgNF [54], (d) TPU/ACNTs/AgNWs/PDMS [24]. (TPU: Thermoplastic Polyurethanes; ACNT: Acidified Carbon Nanotubes; AgNPs: Silver Nanoparticles; AgNF: Silver Nanoflowers; AgNWs: Silver Nanowires; PDMS: Polydimethylsiloxane; HPMC: Hydroxypropyl methyl cellulose) Figure used with permission from Lin, L. et al. [41] Copyright © Elsevier, 2022. Lin, L. et al. [53] Copyright © Elsevier, 2020. Zhang, W. et al. [54] Copyright © Wiley-VCH, 2021. Lin, L. et al. [24] Copyright © Elsevier, 2021.

agglomerations, blocking the inner conductive pathways. The commonly used surface modification method is to construct conductive network based on conductive ink by hot-pressing on the polymer substrate surface [51]. In addition, modification of activated functional groups and subsequent grafting of conductive nanofillers on substrate surface has become a focus of research (Fig. 2a). Here are some strain sensing performance comparisons of CPC with different manufacturing methods, as shown in Table 1.

Conductive nanofiber composites (CNC) are one kind of CPC. The initial preparation method of CNC is similar to blend doping, which is mainly obtained by electrospinning polymer solution containing conductive nanofillers [52]. The conductive nanofillers are distributed in the polymer nanofibers through the electrospinning process, which have similar disadvantages with CPC prepared by blend doping, leading to the agglomeration of conductive nanofillers. As an alternative, conductive nanofillers can be selectively modified on the polymer nanofiber surface. In our previous study, we proposed to modify acidified carbon nanotubes by ultrasonication and silver nanoparticles by in-situ reduction on the surface of nanofibers [53,54]. Further, CNC have superior stretchability, porous structure, air permeability and skin affinity, which are potential candidates for the advanced wearable CPC strain sensors (Fig. 2b–d) [53, 54].

2.2. Slippage & disconnection

In the conductive thin layers fabricated by conductive nanofillers, electrons can pass freely through the well-developed overlapping conductive network [70]. The stretching of conductive network causes some of the nanofillers that are in contact with each other to lose their contact area, reducing the conductive pathways and thus increasing the resistance. From a microscopic point of view, the disconnection of the thin-layer conductive network organized by conductive nanofillers under stretching is caused by the slippage of nanofillers due to the weak interfacial bonding between nanofillers and stretchable polymer substrates [71]. Recently, Jeong et al. put forward a stretchable CPC strain sensor with gold nanosheet (AuNS) and PDMS substrate, which has great durability due to hot-pressing fabrication [72]. While being stretched, the AuNS based strain sensor can maintain their contact without experiencing any severe mechanical strain or von Mises stress, as show in Fig. 3a. The slippage and disconnection mechanisms are usually used in the fabrication of ink-based CPC strain sensors, which are similar with stretchable electrodes and can form an effective contact with human body to detect dynamic signals.

2.3. Crack propagation

The brittle conductive networks outside the CPC are prone to stress-induced crack propagation, mainly in the stress concentrated area [74]. Currently, CPC strain sensors urgently need to achieve high sensitivity over a very large working strain. In general, cracks in the as-prepared materials are considered a sign of structural failure but constructing microcracked structures might be an effective way to achieve high sensitivity of CPC strain sensors. The researchers have been focusing on the design of the conductive networks and the protective coatings [51]. In addition, our group came up with an innovative structure design. One-dimensional and two-dimensional conductive nanofillers are often modified on polymer substrate surfaces by spraying and hot pressing [75]. The conductive network constructed by our group is based on the self-assembly of AgNWs and densely packed to form a quasi-two-dimensional conductive thin layer [24]. Because there still exists a large amount of AgNWs entangled together inside the gaps of nanofiber membrane, the external stress can realize the effective transfer to conductive network, which can maintain inner conductive pathways during large strains, achieving superior sensing performance (Fig. 3b). The advantage of using a dual conductive network is to maintain the overall conductivity of CPC under large strains. One-dimensional carbon

nanomaterials are generally not sensitive to strain, and the conductive nanofillers that are prone to cracks and disconnections during strain should be constructed, which would lead to a large resistance change. As shown in Fig. 3c, the single AgNWs conductive network would exist some bottleneck locations, which critically limited the conductivity during large strains, leading to the sharp but nonlinear increase of resistance signals [42]. From a typical work made by Li et al., the network structure of carbon paper in the PDMS is critical to the performance of the strain sensor. Under a strain-free condition, carbon fiber network with few disconnections exists in the PDMS matrix. As the carbon fiber is tougher than PDMS, when the composite sensor encounters some deformations, disconnections and cracks start to appear in the carbon fiber network because it sustains much larger stress. Further, these disconnections gradually expand with an increase of the applied strain, which causes a decrease in the conductive paths and thus an increase in sensor resistance (Fig. 3d). The relationships of $\Delta R/R_0$ with applied bending, tensile, and compressive strain are presented in Fig. 3e–g, respectively. Under strain deformation, the $\Delta R/R_0$ of the sensor increases continuously, and two linear regions with different slopes are seen in a typical $\Delta R/R_0$ -strain curve.

2.4. Tunneling effect

Transit of electrons through the insulating barrier is called tunneling, which means electrons can tunnel through the polymer thin layer. The tunneling effect is often used to explain the sensing mechanism of CPC strain sensors fabricated by blend doping. With the increase of the tunneling distance and the destruction of the conductive pathways, the resistance of CPC increases significantly during the stretching process [76]. On the contrary, the conductive fillers can return to the initial position during the recovery process to reduce the tunneling distance and restore the conductive pathways. Thereby reducing the resistance of CPC, which exhibits detectable signals.

3. How to evaluate a wearable strain sensor

Strain sensing performance of CPC strain sensors are evaluated by different parameters, such as mechanical property, gauge factor, working strain, response time, durability, biocompatibility etc. [77] These parameters are not the only determinant to performance of CPC strain sensors on the macro level, but more importantly, the unique design on the microstructure, which affects the strain sensing performance, additional functions and application potentials.

3.1. Mechanical property

Mechanical property is the basic performance of CPC strain sensors, which largely determines the durability and working strain of the sensors, affecting their application value [78]. The mechanical properties of CPC strain sensors are varied, among which the main ones are tensile and resilience. They depend on the types of polymer substrates, conductive fillers, inner structures, and manufacturing processes [79,80]. Generally, the mechanical properties of CPC prepared by blend doping are significantly poorer than that of polymer substrates. However, the mechanical properties of CPC prepared by surface modifications do not decrease obviously. Recently, Wang et al. reported the TPU/CB fibrous film strain sensor and detailed explained the stress-strain and sensing-strain curves [81]. Usually, tensile testing is evaluated on a universal test machine with the speed of 5 mm/min (Fig. 4a and b).

3.2. Gauge factor

Normally, researchers introduce the concept of gauge factor (GF) to express the sensitivity of strain sensors, and its calculation is $GF = (\Delta R/R_0)/\Delta\epsilon$, where ΔR represents the change of resistance and $\Delta\epsilon$ represents the working strain (Fig. 4c) [24,83]. It is noteworthy that the responsivity

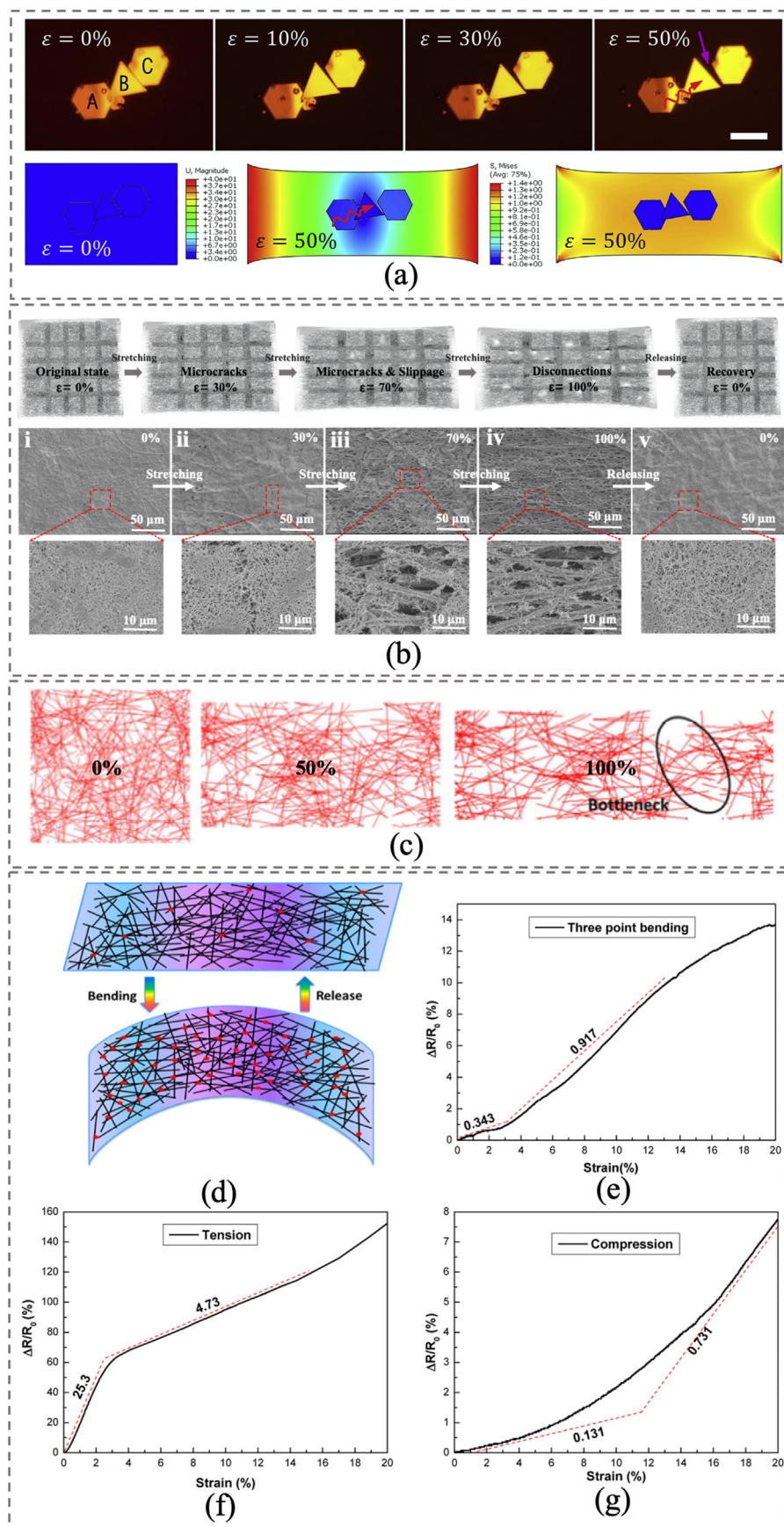


Fig. 3. Three typical stretching mechanisms: (a) Sequential microscope images and corresponding FEA results of percolated AuNSs under 0% and 50% mechanical strain [72]. (b) Schematic illustration of the sensing mechanism of the CPC strain sensor with double conductive networks of ACNTs and AgNWs [24]. (c) AgNWs network at different strains for a high resistance strain sensor [42]. (d) Schematic of the inner conductive network change in the Carbon Paper/PDMS composite during strain. Resistance changes of Carbon Paper/PDMS composite: (e) bending strain, (f) applied tensile strain and (g) compressive strain [73]. Figure used with permission from Jeong, S. et al. [72]. Copyright © Elsevier, 2020. Lin, L. et al. [24]. Copyright © Elsevier, 2021. Amjadi, M. et al. [42]. Copyright © Wiley-VCH, 2016. Li, Y. et al. [73]. Copyright © American Chemical Society, 2016.

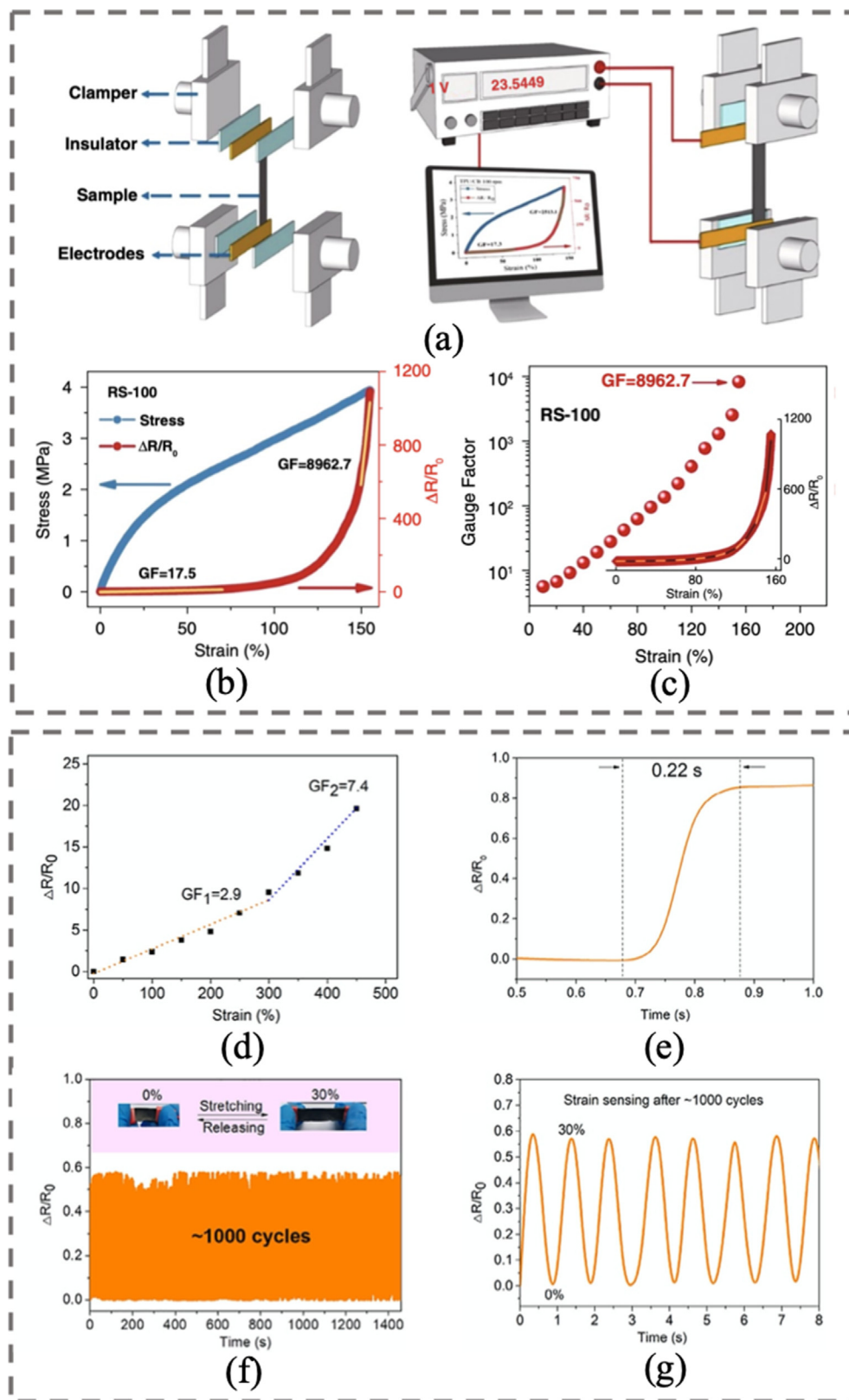


Fig. 4. Strain sensing performance regarding GF, working strain, response time, and durability. (a) Schematics of the tensile test clamping with a sample and the tensile testing machine coupled with a Pico ammeter. (b) The normalized change in tensile stress and electrical resistance ($\Delta R/R_0$) vs. strain. (c) GF of the sample [81]. (d) Resistance response of the CPC strain sensor to gradually increasing strain from 0 to 450% and its GFs. (e) Response time of the CPC strain sensor to high-speed tensile deformations. (f) Durability of the CPC strain sensor for more than 1000 cycles. (g) The reversible sensing performance of the CPC strain sensor after 1000 cycles [82]. Figure used with permission from Wang, X. et al. [81] Copyright © Springer Nature, 2021. Zhou, H. et al. [82] Copyright © Elsevier, 2021.

of the strain sensor is denoted by R/R_0 , where R and R_0 represent the transient resistance and the initial resistance [84]. For CPC strain sensors, it is normal to have more than two linear fitting curves due to the irregular change of conductive networks, which is mainly determined by the specificity of conductive fillers, so some strain sensors have different

GFs under different strains (Fig. 4d).

According to Tables 1 and 2, the GFs of CPC prepared by surface modification are much higher than that prepared by blend doping. With further and in-depth research, researchers are unable to be satisfied with the GFs of CPC strain sensors that are less than 100. It means that the

Table 2

Comparison of the strain sensing performance of TPU nanofiber membrane based CPC strain sensors extracted from literatures.

Polymer substrate	Conductive fillers	Working strain	Gauge factor	Durability	Ref.
TPU	CNTs	50–100%	0.339	700 cycles (0–50%)	[86]
TPU	Graphene	95–100%	5.9	600 cycles (0–50%)	[87]
TPU	PANI	0–110%	17.15	unmentioned	[88]
TPU	SWCNT	50–100%	33	unmentioned	[89]
TPU	rGO	10–100%	79	6000 cycles (0–50%)	[90]
TPU	CNY	0–2%	1700	300 cycles (0–2%)	[91]
TPU	ACNTs and AgNPs	20–70%	1.04×10^5	1000 cycles (0–70%)	[53]
TPU	AgNWs and ACNTs	38–100%	1.36×10^5	1000 cycles (0–70%)	[24]
TPU	rGO and AgNWs	84–100%	4.4×10^7	1000 cycles (0–10%)	[92]

(PANI: polyaniline; CNY: carbon/graphene composites nanofiber yarn).

sensitivity of strain sensors is still far from practical expectations, hence they create new innovations on the conductive networks constructed by the inner conductive fillers. The key to improving GF depends on the precise design of the conductive network [85]. The common practice now is to use conductive nanofillers to construct nano-conductive networks. We can not only design different nano-conductive networks, but also realize the leap-forward improvements of GF by using conductive nanofillers with different dimensions and different morphologies. Additionally, conductive nanofillers with different dimensions can be used to customize different flexible polymer substrates. Our research group has designed the TPU nanofiber membrane-based CPC strain sensor with dual conductive networks containing one-dimensional ACNTs network and zero-dimensional AgNPs network [53]. And the strain sensor possesses an extremely high GF of approximately 1.04×10^5 (with the strain from 20% to 70%), and they can be used to monitor both large and subtle joint movement. Table 2 lists the typical CPC strain sensors prepared by surface modification. We can clearly find that the CPC strain sensors using double conductive networks have a significant advantage in the sensing performance of high GF. Generally, the selection dual conductive networks of CPC strain sensors are complicated, mainly depends on the dimensional characteristics of conductive nanofillers. Commonly, 0-dimensional conductive nanoparticles, 1-dimensional conductive nanowires and 2-dimensional conductive nanosheets are used. The combination of conductive networks with different dimensions usually results in high GF and large working strain. Actually, the conductive network composed of small-dimensional nanofillers is extremely sensitive to strain, resulting in the disconnection of the conductive network, but the sustainable strain range of the deformation is extremely small, which easily leads to the insulation of the overall composite under large strain. On the contrary, the conductive networks composed of large-dimensional nanofillers can greatly make up for the shortcomings of the low-dimensional conductive network, especially their relative insensitivity to strain, which can maintain the overall conductivity of the CPC under large strain, so that the strain sensors would still have stable and detectable electrical signals (when the low-dimensional conductive network is completely destroyed by strain deformation).

3.3. Working strain

Working strain is broadly interpreted as the strain range under which the strain sensor produces a stable GF [93]. Crucial here is linearity, as the nonlinear curve can make the calibration difficult. Therefore, the preparation of structurally ordered nano-conductive networks will be more capable of adapting CPCs strain sensors to complex strain conditions [94]. Accordingly, Li et al. prepared a wearable CPC strain sensor

with two conductive networks through combined spray-coating of AgNW and GO [92]. The GFs at the strains of 50–84% and 84–100% are 1.0×10^6 and 4.4×10^7 , respectively. The disadvantage of this CPC strain sensor is that it has an extremely high GF only under large strains. If CPC strain sensors can achieve extremely high GF under both small strains and large strains, they would have broad sensing application prospects.

3.4. Hysteresis effect

Hysteresis effect means that the fatigue crack propagation rate will be greatly delayed if the stress in one cycle is too high when the crack member is subjected to alternating load [86]. Minimal hysteresis becomes important when the CPC strain sensor is under dynamic load, especially when they are used for flexible and wearable devices [42]. The large hysteresis may result in the irreversibility of the strain sensor under dynamic load. The hysteresis effect of CPC strain sensors is mainly caused by the viscoelastic properties of polymer and the interaction between the conductive nanofillers and polymer substrates [90]. The strong interfacial binding between soft conductive nanofillers and polymer substrates will provide better strain sensing performance. When the binding is weak, the conductive nanofillers slide in the polymer substrate at high tensile. However, they cannot quickly slide back to their original position after fully releasing the strain, resulting in high hysteresis effect. In contrast, the weak interface adhesions between rigid conductive nanofillers and polymer substrates are required for the nanofillers to fully return to its initial position upon release. This phenomenon must be paid attention to when designing the internal conductive networks of CPC strain sensor.

3.5. Response time

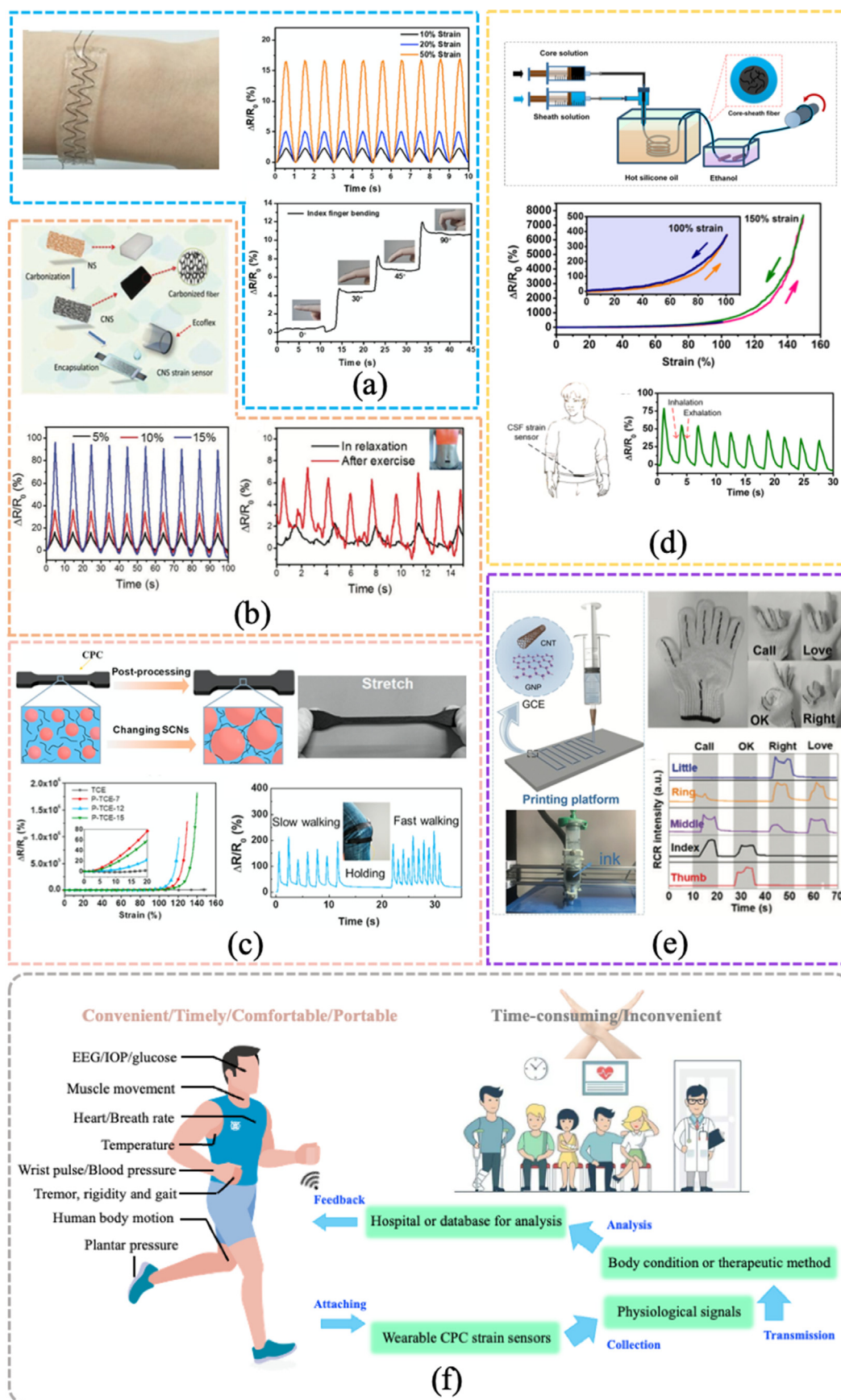
The response time reflects the time it takes for the signal output of the strain sensor to reach a steady state [95]. However, due to the viscoelasticity of CPC and the brittleness of the conductive network, most CPC strain sensors have different degrees of response delay [96]. The CPC strain sensors with carbon nanomaterials as conductive fillers usually have a faster response time, while the response time of CPC strain sensors with metal nanomaterials as conductive fillers is relatively longer, which is around 150 ms. Table 3 illustrates the comparison of the response time of PDMS based CPC strain sensors with different conductive nanofillers. Additionally, CPC strain sensors processed by blend doping exhibit relatively longer response time because of the friction force between conductive fillers and polymer substrate, resulting in a slow speed of stretching and releasing of the inner conductive networks [97]. For instance, Zhou et al. have designed a CPC strain sensor composed of hollow polyaniline spheres (HPS), poly(vinyl alcohol) (PVA) and phytic acid (PA) [82]. Upon high-speed deformations, the CPC strain sensor

Table 3

Comparison of the response time of PDMS based CPC strain sensors extracted from literatures.

Conductive polymer composite	Gauge factor	Response time (ms)	Ref.
PDMS/Graphene/CNTs	35	30	[98]
PDMS/CNTs nanopaper	2.21	50	[99]
PDMS/silicone rubber/CNTs/CBs	1.25	60	[100]
PDMS/Carbon fragments	62.8	60	[101]
PDMS/CNTs/AuNPs	70	60	[71]
PDMS/CNTs	87	65	[102]
PDMS/PU sponge/NiNPs/rGO	3360	100	[103]
PDMS/PAVG	10.28	112	[104]
PDMS/PU fiber/AgNWs	9557	120	[105]
PDMS/CNFs/GNPs	7.04	132	[106]
PDMS/rGO	18.5	145	[107]
PDMS/TPU fibers/Aligned rGO	593	160	[108]

(CNF: carbon nanofiber; GNPs: graphene nanoplates; NiNPs: nickel nanoparticles; PAVG: parallelly aligned vertical graphene).



(caption on next page)

Fig. 5. Wearable and biocompatible CPC strain sensors for human health monitoring. The strain sensing performances and body motion monitoring abilities of (a) Carbon nanotube (CNT) fiber/polyacrylamide (PAAm) hydrogel composite strain sensor [118], (b) Encapsulation of a carbonized nano-sponge (CNS) with silicone resin strain sensor [119], (c) Thermally expanded micro-spheres (TEM)/CNT/Ecoflex (TCE) composite strain sensor [120], (d) Elastomer-wrapped carbon nano-composite strain sensor, and e graphene nanoplatelet (GNP)/carbon nanotube (CNT)/silicone elastomer (GCE) fiber composite strain sensor [121]. (f) The advanced and biocompatible CPC strain sensing system would ensure a convenient and timely way for portable healthcare [122]. Figure used with permission from Yi, F. et al. [118] Copyright © Elsevier, 2020. Yu, X. et al. [119] Copyright © The Royal Society of Chemistry, 2017. Xue, S. et al. [120] Copyright © Elsevier, 2022. Tang, Z. et al. [121] Copyright © American Chemical Society, 2018. Zhu, W. et al. [122] Copyright © The Royal Society of Chemistry, 2022.

exhibit a long response time of 0.22 s, as shown in Fig. 4e.

3.6. Durability

Durability represents the reliability and repeatability of the strain sensor to long-term stretching-releasing cyclic tests [109]. Whether it can have steady electrical signal output, mechanical transfer and morphological stability are the criteria for evaluating a qualified CPC strain sensor [110]. Durability is even more important for wearable CPC strain sensors because they need to accommodate large, complex and dynamic strain deformations [111]. As shown in Fig. 4f and g, most reported CPC strain sensors exhibit outstanding durability and stability during more than 1000 stretching and releasing cycles.

3.7. Biocompatibility

Wearable strain sensors are usually attached to clothing or in direct contact with human skin to obtain relevant human signals (Fig. 5a–e). The preparation process of CPC strain sensors is relatively simple, but the strain sensing abilities have good and regular curves, which can be suitable for monitoring a variety of body movements. CPC strain sensors should be biocompatible because of their wearable properties and the demand for potentially clinical applications [112,113]. Biocompatibility is a broad biological concept, which can be more specific in the field of wearable devices [114,115]. Air permeability, comfort, skin affinity, no cytotoxicity, antibacterial property and no tissue adhesion are the biocompatibility required for wearable CPC strain sensors in the fields of human health monitoring and medical diagnosis [116,117]. If CPC strain sensors are developed that can accurately detect human health signals with superior biocompatibility, it would play a vital role in the innovation and promotion of modern medical diagnosis and treatment, greatly improving the development of intelligent health monitoring (Fig. 5f).

4. Conclusion

Wearable and stretchable CPC can be assembled into strain sensors and applied in human health monitoring and medical diagnosis fields. A superior CPC strain sensor should have outstanding GF, especially under small strains. Further, long-term durability is necessary for CPC strain sensor during cyclic strains. Many high-performance CPC strain sensors can be developed by improving the properties and structures of flexible polymer substrates and conductive fillers, which have large working strain, high GF, minimal hysteresis effect and reliable durability. Deeper research in the future is likely to focus on several directions, as shown below.

- 1) Stable and sensitive conductive networks can be achieved by optimizing conductive nanofillers to accurately design conductive pathways, which would ensure the sensitivity and linearity of the CPC strain sensors.
- 2) Stretchable and flexible polymer substrates should be further developed with good biocompatibility, low price, uniform structure and superior mechanical property.
- 3) Wearable and adhesive CPC strain sensors should be designed through bionic structures, avoiding the use of artificial glue, to improve the wearing comfort and skin affinity.

- 4) The self-powered CPC strain sensor with wireless transmission should be designed for practical applications. Current signal processing circuits in flexible and stretchable sensing systems rely partly or entirely on rigid silicon chips, resulting in unnecessary stress generation and local strain imbalances.

With the term of real applications, the continuous research and breakthroughs are essential to develop high performance CPC strain sensors for the advanced health monitoring system, which can improve the quality of our life.

Author contributions

L.L. and S.P. designed the Figure & Table, and wrote the manuscript under the supervision of W.Z., S.H.P and Y.P. Y.K. and M.B. prepared the Reference. J.L. and J.G. revised the manuscript. All authors reviewed the manuscript and provided corrections and comments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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