The stretchable carbon black-based strain fiber with a remarkable linearity in a wide sensing range

Hao Wang‡, Yang Yue‡, Wenze Zou†, Yang Pan† and Xiaogang Guo‡

‡Institute of Advanced Structure Technology, Beijing Institute of Technology, Beijing, Hebei, China; †School of Computer Science and Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu, China; ‡Xuteli School, Beijing Institute of Technology, Beijing, Hebei, China

ABSTRACT

Ascribed to its wide sensing range, high sensitivity, and low stiffness to match target objects with complex 3D shapes, the stretchable strain sensor has shown its promising applications in various fields, ranging from healthcare, bodynet, and intelligent traffic system, to the robotic system. This paper presents a low-cost and straightforward fabrication technology for the stretchable strain fiber with the combined attributes of a wide sensing range, exceptional linearity, and high durability. The hybrid composite consisting of carbon black and silicone is utilized as the functional material to respond to the external mechanical deformation due to the piezoresistive effect. To address the remarkable hysteresis of the CB-silicone composites, the latex tubes with excellent mechanical robustness and a considerable accessible tensile strain are introduced as the outer supporting components. After injecting the conductive CB-silicone composite into these tubes, the stretchable strain fibers are successfully prepared. Notably, the stretchable strain sensor exhibits linearity ($R^2 = 0.9854$) in a wide sensing range (0–400%) and remarkable durability even after the 2500 cycles under 100% tension. Additionally, the potential of this stretchable strain fiber as the wearable strain sensor and the real-time feedback is demonstrated by detecting the body motion and the expansion devices.

CONTACT
Xiaogang Guo ‣ guoxg@bit.edu.cn
Institute of Advanced Structure Technology, Beijing Institute of Technology, Beijing, China

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
1. Introduction

Recent years have witnessed the significant developments of stretchable strain sensors in a variety of fields, ranging from personal healthcare [1–4], sports performance monitoring [5–12], the human-machine interfaces, to virtual reality [13–18]. The stretchable sensors that can undergo a relatively sizable mechanical deformation without breaking have shown promising applications to accurately detect human activities or joint motions. With the increasing demands for the monitor or the real-time feedback of the external mechanical deformation, numerous efforts have been devoted to developing a stretchable strain sensor with exceptional sensitivity, stretchability, and durability [19–28]. Generally, the available working range, the gauge factor (or the sensitivity), the linearity, the hysteresis, the response time, and the durability represent the crucial factors that evaluate the sensing performances of a stretchable strain sensor. Among these indicators, the available working range, linearity, and durability are the most significant designing parameters for the promising application in detecting the joint motion and the deformed shape of the variant structure with significant mechanical deformation.

Ascribed to its inherent stretchability and high conductivity at room temperature, the liquid metal is introduced to serve as a candidate for the functional material in the stretchable strain sensors. Inspired by the vessel organ for sensing temperature variation, Chen, et. al. demonstrated a high-performance sensor including a microchannel injected with low toxicity liquid metal (LM) and demonstrated its advantages of no hysteresis (1.02%), a low detection limit (0.09% strain), and wide strain range of up to 320% [29]. However, the nonlinear dependences of the resistance change on the tensile strain observed in experiments impose certain limitations on its sensing applications for monitoring the deformed shape in real-time. Furthermore, the metal materials in nanoparticles and nanowires can also be utilized to fabricate the stretchable strain sensors after being deposited onto a soft elastomer substrate [25,30–33]. The underlying mechanism of the resistance change lies in the increasing contact resistance due to the emergence of the micro-crack as the tensile strain increases [25,32,34]. The supersensitive stretchable sensor fabricated by physically grinding the silver particles into the liquid PDMS according to a specific weight fraction can also be utilized to monitor the external deformation strain and force, whose gauge factor can reach as high as 939 when it was stretched to 36%. The minimum resolution for force detection is 0.02 N [35]. In 2018, Han, et. al. gave a nanowire-microfluidic hybrid (NMH) strain sensor that responded to multiscale strains from 4% to over 400%, with high sensitivity and durability under minor strain [36]. However, their attributes of these aforementioned stretchable sensors based on the NP or NW materials in offering a tunable gauge factor, both of the relatively narrow strain sensing range before the crack of the conductive network, the nonlinear increase as the increase of the tensile strain sets certain constraints on its sensing applications.

Recently, the carbon-based materials (i.e. the graphene, the carbon nanotube (CNT), and graphene foam) [26,28,37–43] and their composites (i.e. graphene-based composite fiber, the graphene-carbon black-silicone rubber) [39,40] have been demonstrated the capability to serve as the candidate of the functional material for their high conductivity and mechanical robustness. In 2015, Cheng et al. developed a graphene-based composite fiber with a compression spring architecture to detect the tension, bending, and torsion deformation with an ultra-high sensitivity (i.e. 0.2%), a wide sensing range (up to 100%
strain), and high reproducibility (up to 10,000 cycles) [39]. In 2018, Kuria, et al. provided graphene-carbon black-silicone rubber (G-CB-SR) composites, exhibiting stable and reversible performance with the mean GFs varying between 0.51 and 1.94 depending on the composition with a small hysteresis for a strain of 300%. However, the lower sensitivity of this composite sensor sets specific constraints on its applications in detecting tiny human activity [44]. The research of the mechanical properties of super-elastic rubber-like materials and homogenized composite paves the way toward the design of composite materials [45,46]. Instead of the commercial carbon materials to prepare the stretchable strain sensor, the natural fiber with sufficient carbon source can also be utilized to serve as the piezoresistive material after the pyrolyzation under a specific atmosphere and a high temperature. In 2018, Qu, et al. presented a simple and scalable fiber-processing technique to code different raw materials continuously. The thermal drawing of hundreds-of-meters long multi-material optical and electronic fibers and devices can sustain up to 500% elastic deformation [47]. However, the nonlinear dependences of the resistance change on the tensile strain arising from the demixing and stagger of the carbon-based materials in the stretchable sensor set particular constraints on its sensing applications. It is still very challenging to prepare the stretchable strain sensor to achieve a delicate balance of a wide sensing range (over 200%), the linearity and exceptional durability (over 2000 cycles) undergo a sizable tensile strain.

This paper presents a low-cost and straightforward fabrication technology for the stretchable strain fiber with a wide sensing range, exceptional linearity, and high durability. The hybrid composite consisting of carbon black (CB) and silicone is utilized as the functional material to respond to the external mechanical deformation due to the piezoresistive effect. To address the remarkable hysteresis of the CB-silicone composites, the latex tubes with excellent mechanical robustness and a considerable accessible tensile strain are introduced as the outer supporting components. The stretchable strain fibers are successfully prepared after injecting the soft and conductive CB-silicone hybrid composite into these tubes. Notably, the stretchable strain sensor exhibits linearity ($R^2 = 0.9854$) in a wide sensing range (0–400%) and remarkable durability even after the 2500 cycles under 100% tension. Additionally, the potential of this stretchable strain fiber as the wearable strain sensor and the real-time feedback is demonstrated by detecting the joint and gait motion, and the inflation expansion of a rubber balloon and hydraulic lever.

2. Experiments

2.1 Fabrication of CB-silicone hybrid composite

Figure 1(a) illustrates the carbon black (CB) and silicone hybrid composite fabrication process. The preparation began with the mixture of silicon (Sylgard 527, Dow Corning) with part A and part B in a 1:1 mass ratio. Then, the CB powder (Super P Li, Timcal) and silicone diluent (OS-20 Fluid, Dow Corning) were poured into the mixed silicone solution with a specific mass ratio (i.e. 3:97:97, 2:49:49 and 1:19:19). The CB-silicone hybrid composite was successfully prepared after 120 minutes of stirring by a magnetic stirrer (rotational rate of 1000 RPM) and 12 hours of laying in a fume hood to remove the diluent. In addition, the conductivity of the composite is very low (MΩ level) when the CB powder concentration is less than 3 wt.% (e.g. 2 wt.%). When the CB powder concentration is
greater than 5 wt.% (e.g. 6 wt.%), the CB/silicone composite cannot be mixed and cured completely. Therefore, the composite samples with the 3–5 wt.% CB powder concentration are systemically discussed in this paper.

2.2 Assembly of CB-silicone strain fiber sensors

After the preparation of CB-silicone hybrid composite, this composite was filled into the injector and then injected into the latex tube with an internal diameter of 2 mm and an external diameter of 4 mm, as shown in Figure 1(b). Figure 1(c) gives the assembly process of the CB-silicone stretchable strain fiber sensor. The stainless-steel capillaries with an internal diameter of 0.8 mm and an external diameter of 2 mm were inserted as electrodes at both ends of the latex tube. Then, two copper terminals were sheathed at both ends of the latex tube and secured with screws. After curing the CB-silicone composite at 55°C for 2 hours, the fabrication of the stretchable strain fiber was completed.

2.3 Characterization

Tensile experiments were conducted on a universal mechanical testing machine, and the dimensional size of the CB-silicone stretchable strain fiber is 55 mm (as shown in Figure 1(d)). The variation of the resistance because of the piezoresistive properties during the tension experiments, the monitoring of the joint motion, and the real-time feedback of
the expansion of a rubber balloon were recorded by the digit multimeters (i.e. 34465A, KEYSIGHT). The experiments involving human subject have been performed with the full, informed consent of the authors and volunteers.

3. Results and discussion

3.1 Piezo-resistivity of the stretchable strain fiber in the tension experiments

The exploitation of high-performance stretchable sensing materials with a wide accessible sensing range and a linear response in the resistance still remains a challenge. Here, the tension experiments under a considerable strain were conducted to reveal the piezo-resistivity of the stretchable strain fibers with different CB powder concentrations (i.e. 3 wt.%, 4 wt.% and 5 wt.%) and structures (i.e. with or without latex tube), as illustrated in Figure 2(a). The resistance of five samples of the same specification was recorded to verify

![Figure 2](image-url)

**Figure 2.** The stretchability and recyclability of the CB-based strain sensor. (a) The normalized resistance values the tensile strain for the CB-based sensors with different CB concentrations (i.e. 3 wt.%, 4 wt.% and 5 wt.%) and structure (i.e. with or without supporting tube). (b) The cyclic loading test of strain sensor under several loading cycles. Top: CB-silicone without supporting tube (i.e. CB concentration = 5 wt.%). Bottom: CB-silicone with the supporting tube (i.e. CB concentration = 5 wt. %). (c) Optical image of the mechanical testing platform and the initial state of the CB-silicone fiber sensor. (d) Optical image of the CB-silicone fiber sensor at the strain of 400%. (e) Relative change in resistance of the strain sensor versus a largely applied strain (i.e. 0–400%).
the repeatability of the preparation, avoiding accidental experimental results. The resistance value of the sample with a 5 wt.% CB powder concentration is 3% and 14% of that of samples with 3 wt.% and 4 wt.% CB powder concentrations, respectively. As the tensile strain increases from 0 to 150%, the normalized resistance increases nonlinearly from 0 to 2270% for specimens with a lower CB powder concentration (i.e. 3 wt.%), and increases proportionally from 0 to 650% for those with a higher CB powder concentration (i.e. 5 wt. %). The specimen with a 4 wt.% CB powder concentration shows a proportional increase of the resistance from 0 to 370% but with a relative narrow strain range (i.e. 100%). In order to obtain a stretchable sensor fiber with a wide range of monitoring capability in a high linearity response, the 5 wt.% CB powder concentration is optimal. The equation defined the electrical conductivity of the conductor is:

\[
R = \rho \frac{L}{A}
\]

Here, the R and \( \rho \) are the resistance and the resistivity of the conductive material, and L and A represent the length and the cross-sectional area of the strain fiber, respectively. With an external mechanical force along the axis of the stretchable strain sensor, the length of fiber increases while the cross-sectional area decreases, known as the Poisson’s effect. For a fixed conductivity of the functional material, the rising resistance of the fiber with a lower CB powder concentration (i.e. 3 wt.%) shows a quadratic curve as the strain increases, as shown in Figure 2(a). However, the normalized resistance increases almost linearly as the increase of the tensile strain for the specimen with a higher CB powder concentration (i.e. 5 wt.%), which is a crucial attribute for its application in the real-time feedback of more considerable deformation as the wearable electronics. Here, a decrease in the distance between the CB nanoparticles in the cross-section due to the reduction of the cross-sectional area leads to the variation of the conductivity of the functional material with a higher CB powder concentration and yields the linear piezoresistive performances of this stretchable strain fiber. The latex tubes improve the sensing range of the sensor and keep the sensor with a high linearity in resistance in a wider strain range from 0 to 140%. More specifically, the durability of the stretchable strain sensor also represents a fundamental parameter, especially for its application as a wearable device. Figure 2(b) depicts the piezoresistive performances of the stretchable strain fiber with and without the external supporting latex tube under the cyclic loading experiment with a 100% tensile strain. From the subfigure in the Figure 2(b), the CB-silicone composites without the external supporting latex tube show a remarkable hysteresis after experiencing the five cycles. As the cyclic tensile experiments proceed, the normalized resistance variation range of the CB-silicone composites without the supporting tube gradually decreases. Specifically, the maximum normalized resistance corresponding to the maximum strain is basically unchanged, while the minimum resistance after releasing the tensile strain increases significantly, revealing that the composite without the supporting tube cannot rebound back to its initial state with the gradually emerging hysteresis effect. To address the increasing demand of the durability, the latex tubes with an excellent mechanical robustness and a considerable accessible tensile strain are adopted as the external supporting components. From the bottom subfigure of Figure 2(b), the soft and elastic supporting tube can effectively compensate for the hysteresis of the CB-silicon composites and render the composite
with exceptional durability. Given the elasticity and the higher elastic modulus (6 times that of the CB-silicon composite) of the external supporting latex tube, the deformed composite will recover to its original shape in each loading process. Figure 2(c and d) illustrate the optical images of the CB-silicone fiber sensor at the initial state (i.e. the strain of 0%), and the deformed state undergoes a tensile strain of 400%, respectively. Figure 2(e) depicts the variation of the normalized resistance of the stretchable strain fiber versus the applied strain (i.e. 0–400%). The CB-based sensor supported with a latex tube exhibited an exceptional linearity in the variation of the resistance ($R^2 = 0.9854$) in a wide strain range (i.e. 0–400%). Notably, a more remarkable linearity in the variation of the resistance ($R^2 = 0.9911, 0.9976$) can also be observed for the strain range of (0 ~ 200%) and (200 ~ 400%), respectively.

3.2 Durability of the CB-silicone based stretchable strain sensor

In Figure 2(b), we depict the piezoresistive performance of the CB-silicone fiber under ten loading cycles under a 100% strain. Obviously, the number of cycles is insufficient to demonstrate the durability of our stretchable strain sensor. Thus, the experimental test with 2500 cycles under 100% tension is conducted, as illustrated in Figure 3(a). The stable piezoresistive performance of this sensor at the beginning and end of the cyclic test can be observed in Figure 3(b and c). Figure 3(d) depicts the variation of the maximum/minimum normalized resistance and the relative resistance change of each cycle versus the cycle number. The following equation defines the relative resistance change of each cycle:

$$\frac{\Delta R}{R} = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{max}} - R_{\text{min}}}$$

(2)

This sensor shows stable cyclic performance under different strain amplitudes and rates. As shown in Figure 3(e), the sensor is stretched to 100% at different loading rates to complete loading-unloading cycles in 120, 60, 30, and 15 seconds, respectively, with the maximum speed 8 times that of the minimum value. The approximate peak resistances and response curves guarantee an authentic expression of practical application. Figure 3(f) shows variations of normalized resistance of the stretchable fiber with different strain amplitudes of 50%, 100%, 200%, and 300%, respectively. The variation tendencies of resistance are stable and proportional to the tensile strain. As shown in Figure 3(g), high synchronization of the change of resistance and the corresponding stretching force are observed. The time difference between peak resistance and stress represents the sensor’s response time (i.e. 135 ms), and the accumulated time difference of a cycle represents the recovery time (i.e. 260 ms) of the sensor. Notably, the remarkable durability promises the capability of this CB-silicone stretchable fiber sensor in serving as a wearable electronical device. The comparison of strain range, sensitivity and linearity of the CB-silicone fiber sensor demonstrated in this paper to the recently reported strain–resistance sensors are shown in Table 1. The stretchable sensor presented in this paper has a relatively wide sensing range and remarkable linearity. In addition, the CB-silicone fiber sensor is fabricated in a simple mean without the use of nanomaterials or liquid metal, showing the advantage of low production cost.
Figure 3. Performances of CB-silicone fiber sensor under a cyclic loading condition. (a) Relative change in resistance under repeated loading and unloading of 100% strain for 2500 cycles. Results of durability test. 94 to 104 cycles (b) and 1924 to 1934 cycles (c). The red arrow shows the loading process, and green arrow the unloading process. (d) The variation of the maximum, minimum normalized resistance, and relative resistance variation range with the increased cycle number. The normalized resistance values of the stretchable fiber during tensile experiments with different strain rates (e), and different strain amplitudes (f). (g) The variation of the resistance and the stress of a stretchable fiber under two loading cycles.

Table 1. Comparison of the properties of the stretchable CB-silicone fiber sensor to the recently reported result.

| Functional materials     | Strain range | Sensitivity | High linearity | Ref. |
|--------------------------|--------------|-------------|----------------|------|
| Liquid metal             | 0–320%       | GF = 4.91   | No             | [29] |
| Ag NPs                   | 0–48%        | GF$\text{max} = 939$ | No             | [35] |
| Cu NWS/PEDOT             | 0–400%       | GF$\text{max} = 1678$ | No             | [36] |
| Graphene                 | 0–200%       | GF = 0.82   | No             | [39] |
| Graphene/CB              | 0–300%       | GF = 1.9    | Yes            | [44] |
| MWCNTs                   | 0–600%       | GF = 153    | No             | [48] |
| Mxene/CNTs               | 0–200%       | GF$\text{max} = 9002$ | No             | [43] |
| Ag NWs                   | 0–200%       | GF = 1.37   | Yes            | [33] |
| CB-based strain fiber    | 0–400%       | GF = 6.1    | Yes            | This work |
3.3 Applications of CB-silicone strain fiber sensors

Two demonstrations included monitoring the joint motion and detecting the inflation-induced expansion of a rubber balloon. The electrodes of the CB-silicone strain fiber sensors have a metal casing design, which allows the stretchable sensor to be conveniently fixed and connected to other devices. From Figure 4(a), a set of electrical signals is recorded to immediately reveal the bending angles of the arm after the stretchable strain fiber sensor is adhered onto the elbow of a volunteer. In the left subfigure of Figure 4(a),

![Figure 4(a)](image)

The bending angles of the arm recorded by CB-silicone fiber sensors fixed onto the elbow of the volunteer. I to IV represents the progression of the arm from maximum bending to extension.

![Figure 4(b)](image)

The real-time feedback for the expansion of a rubber balloon. I to IV represents the enlargement of the rubber balloon.

![Figure 4(c)](image)

The real-time monitoring for the extension of a hydraulic lever. The stage I and the stage II represent the shortest and longest states of the hydraulic lever.

![Figure 4(d)](image)

The real-time gait monitoring by an insole embedded with CB-silicone fiber sensor.

Figure 4. The application of the CB-silicone fiber sensors. (a) The bending angle of the arm recorded by CB-silicone fiber sensors fixed onto the elbow of the volunteer. I to IV represents the progression of the arm from maximum bending to extension. (b) The real-time feedback for the expansion of a rubber balloon. I to IV represents the enlargement of the rubber balloon. (c) The real-time monitoring for the extension of a hydraulic lever. The stage I and the stage II represent the shortest and longest states of the hydraulic lever. (d) The real-time gait monitoring by an insole embedded with CB-silicone fiber sensor.
the bending of the arm is indicated by the different angles between the upper and lower arms. The resistance of fiber sensor decreases with the arm uncurling (i.e. 65°–180°). The CB-silicone strain fiber can be designed to monitor the expansion of a rubber balloon. As shown in Figure 4(b), the fiber sensor exhibited a positive correlation between the resistance and the expansion of a rubber balloon. To prevent the sensor from falling off as the balloon expands, both ends of the CB-silicone fiber sensor are fixed on the air inlet and outlet of the rubber balloon. In the beginning, the rubber balloon expands from a flat, dry state (from I to II), and the resistance of the CB-based fiber sensor increases rapidly. Then the rubber balloon expands with uniform inflation (from II to IIIII), and the resistance of the sensor increases approximately in a linear process. The hydraulic lever is a common mechanical device. As shown in Figure 4(c), the CB-silicone fiber sensor presents a good linearity in monitoring the continuous staged elongation of the hydraulic lever. The sensor embedded in the insole can be easily used for wearable motion monitoring. Figure 4(d) depicts the real-time gait monitoring by the CB-silicone fiber sensing the foot pressure and frequency. The pressure produced in walking state is the lowest. Compared with walking state, stomping needs more force but hits the ground with less frequently, which is consistent with the response resistance curve of sensor. Running is the most intense gait, with the highest force and frequency of the three motion states. The applications indicate the potential of this sensor in motion capture and deformation detection of expansion structures.

4. Conclusions

In summary, we present a low-cost and straightforward fabrication technology for the CB-based strain fiber with the combined attributes of a wide sensing range, exceptional linearity, and high durability. The hybrid composite consisting of the CB and the silicone is utilized to act as the functional material to monitor the external mechanical deformation due to the piezoresistive effect. To address the hysteresis of the CB-silicone composites, we inject the soft and conductive CB-silicone hybrid composite into latex tubes, and the stretchable strain fibers are successfully prepared. Notably, the CB-silicone strain fiber exhibits linearity ($R^2 = 0.9854$) in a wide sensing range (0–400%) and remarkable durability even after the 2500 cycles under 100% tension. Ascribed to its unique piezoresistive performance, the stretchable strain sensor based on the CB-silicone hybrid composite is a promising candidate for the extensive deformation sensing system. Additionally, the potential of this stretchable strain fiber as the wearable strain sensor and the real-time feedback is demonstrated by detecting the joint and gait motion, and the inflation expansion of a rubber balloon and hydraulic lever.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant No. 12072030 and Young Elite Scientists Sponsorship Program by CAST.

Disclosure statement

No potential conflict of interest was reported by the author(s).
Funding

This work was supported by the National Natural Science Foundation of China [12072030].

Data availability statement

The data that support the findings of this study are available from the corresponding author [X. G.], upon reasonable request.

References

[1] Ma Y, Choi J, Hourlier-Fargette A, et al. Relation between blood pressure and pulse wave velocity for human arteries. Proc Natl Acad Sci USA. 2018;115(44):11144–11149.
[2] Sun B, McCay RN, Goswami S, et al. Gas-Permeable, multifunctional on-skin electronics based on laser-induced porous graphene and sugar-templated elastomer sponges. Adv Mater. 2018;30(50):e1804327.
[3] Xu K, Fujita Y, Lu Y, et al. A wearable body condition sensor system with wireless feedback alarm functions. Adv Mater. 2021;33(18):2008701.
[4] Lee SP, Ha G, Wright DE, et al. Highly flexible, wearable, and disposable cardiac biosensors for remote and ambulatory monitoring. Npj Digit Med. 2018;1(1). DOI:10.1038/s41746-017-0009-x.
[5] Rahimi R, Ochoa M, Yu W, et al. Highly stretchable and sensitive unidirectional strain sensor via laser carbonization. ACS Appl Mater Interfaces. 2015;7(8):4463.
[6] Atalay A, Sanchez V, Atalay O, et al. Batch fabrication of customizable silicone-textile composite capacitive strain sensors for human motion tracking. Adv Mater Technol. 2017;2(9):1700136.
[7] Gao Q, Li H, Zhang J, et al. Microchannel structural design for a room-temperature liquid metal based super-stretchable sensor. Sci Rep. 2019;9(1):5908.
[8] Yan C, Wang J, Kang W, et al. Highly stretchable piezoresistive graphene-nanocellulose nanopaper for strain sensors. Adv Mater. 2014;26(13):2022–2027.
[9] Araromi OA, Graule MA, Dorsey KL, et al. Ultra-sensitive and resilient compliant strain gauges for soft machines. Nature. 2020;587(7833):219–224.
[10] Gu G, Xu H, Peng S, et al. Integrated soft ionotronic skin with stretchable and transparent hydrogel-elastomer ionic sensors for hand-motion monitoring. Soft Robot. 2019;6(3):368–376.
[11] Wang H, Zhang B, Zhang J, et al. General one-pot method for preparing highly water-soluble and biocompatible photoinitiators for digital light processing-based 3D printing of hydrogels. ACS Appl Mater Interfaces. 2021;13:55507.
[12] Lu S, Samandari M, Li C, et al. Multimodal sensing and therapeutic systems for wound healing and management: a review. Sens Actuators B. 2022;4:100075.
[13] Ling Y, Pang W, Li X, et al. Laser-induced graphene for electrothermally controlled, mechanically guided, 3d assembly and human-soft actuators interaction. Adv Mater. 2020;32(17):e1908475.
[14] Lee J, Llerena Zambrano B, Woo J, et al. Recent advances in 1d stretchable electrodes and devices for textile and wearable electronics: materials, fabrications, and applications. Adv Mater. 2020;32(5):e1902532.
[15] Guo H, Shi L, Yang M, et al. Highly stretchable and transparent dielectric gels for high sensitivity tactile sensors. Smart Mater Struct. 2019;28:024003.
[16] Zhang Y, Li Z, Li H, et al. Fractal-based stretchable circuits via electric-field-driven microscale 3D printing for localized heating of shape memory polymers in 4D printing. ACS Appl Mater Interfaces. 2021;13:41414.
[17] Yang JC, Mun J, Kwon SY, et al. Electronic skin: recent progress and future prospects for skin-attachable devices for health monitoring, robotics, and prosthetics. Adv Mater. 2019;31(48):e1904765.
[18] Ma Y, Zhang Y, Cai S, et al. Flexible hybrid electronics for digital healthcare. Adv Mater. 2019;32:e1902062.
[19] Chen H, Zhu F, Jang KI, et al. The equivalent medium of cellular substrate under large stretching, with applications to stretchable electronics. J Mech Phys Solids. 2018;120:199–207.
[20] Liu J, Yan D, Zhang Y. Mechanics of unusual soft network materials with rotatable structural nodes. J Mech Phys Solids. 2021;146:104210.
[21] Yan D, Chang J, Zhang H, et al. Soft three-dimensional network materials with rational bio-mimetic designs. Nat Commun. 2020;11(1):1180.
[22] Ma Q, Cheng H, Jang KI, et al. A nonlinear mechanics model of bio-inspired hierarchical lattice materials consisting of horseshoe microstructures. J Mech Phys Solids. 2016;90:179–202.
[23] Ma Q, Zhang Y. Mechanics of fractal-inspired horseshoe microstructures for applications in stretchable electronics. J Appl Mech. 2016;83:111008.
[24] Pang W, Cheng X, Zhao H, et al. Electro-mechanically controlled assembly of reconfigurable 3D mesostructures and electronic devices based on dielectric elastomer platforms. Natl Sci Rev. 2020;7:342–354.
[25] Amjadi M, Pichitpajongkit A, Lee S, et al. Highly stretchable and sensitive strain sensor based on silver nanowire–elastomer nanocomposite. ACS Nano. 2014;8(5):5154–5163.
[26] Liu C, Han S, Xu H, et al. Multifunctional highly sensitive multiscale stretchable strain sensor based on a graphene/glycerol-KCl synergistic conductive network. ACS Appl Mater Interfaces. 2018;10(37):31716.
[27] Guo X, Wang X, Ou D, et al. Controlled mechanical assembly of complex 3D mesostructures and strain sensors by tensile buckling. Npj Flex Electron. 2018;14. DOI:10.1038/s41528-018-0028-y.
[28] Li Y, He T, Shi L, et al. Strain sensor with both a wide sensing range and high sensitivity based on braided graphene belts. ACS Appl Mater Interfaces. 2020;12(15):17691–17698.
[29] Chen J, Zhang J, Luo Z, et al. Superelastic, sensitive, and low hysteresis flexible strain sensor based on wave-patterned liquid metal for human activity monitoring. ACS Appl Mater Interfaces. 2020;12(19):22200–22211.
[30] Lee J, Kim S, Lee J, et al. A stretchable strain sensor based on a metal nanoparticle thin film for human motion detection. Nanoscale. 2014;6(20):11932–11939.
[31] Kim KH, Jang NS, Ha SH, et al. Highly sensitive and stretchable resistive strain sensors based on microstructured metal nanowire/elastomer composite films. Small. 2018;14(14):e1704232.
[32] Yin R, Yang S, Li Q, et al. Flexible conductive Ag nanowire/cellulose nanofibril hybrid nanopaper for strain and temperature sensing applications. Sci Bull. 2020;65(11):899–908.
[33] Qu X, Zhao Y, Chen Z, et al. Thermoresponsive lignin-reinforced poly(Ionic Liquids) hydrogel wireless strain sensor. Research. 2021;12:9845482.
[34] Bu Y, Shen T, Yang W, et al. Ultrasensitive strain sensor based on superhydrophobic micro-cracked conductive Ti3C2T MXene/paper for human-motion monitoring and E-skin. Sci Bull. 2021;66(18):1849–1857.
[35] Li H, Zhang J, Chen J, et al. Multidimensional flexible strain gauge sensor based on Ag/PDMS for human activities monitoring. Sci Rep. 2020;10(1):4639.
[36] Han S, Liu C, Xu H, et al. Multiscale nanowire-microfluidic hybrid strain sensors with high sensitivity and stretchability. Npj Flex Electron. 2018;2(1):1–10.
[37] Cai Y, Qin J, Li W, et al. A stretchable, conformable, and biocompatible graphene strain sensor based on a structured hydrogel for clinical application. J Mater Chem A. 2019;7(47):27099–27109.
[38] Gao J, Wang X, Zhai W, et al. Ultrastretchable multilayered fiber with a hollow-monolith structure for high-performance strain sensor. ACS Appl Mater Interfaces. 2018;10(40):34592.
[39] Cheng Y, Wang R, Sun J, et al. A stretchable and highly sensitive graphene-based fiber for sensing tensile strain, bending, and torsion. Adv Mater. 2015;27(45):7365–7371.
[40] Li Z, Qi X, Xu L, et al. Self-repairing, large linear working range shape memory carbon nanotubes/ethylene vinyl acetate fiber strain sensor for human movement monitoring. ACS Appl Mater Interfaces. 2020;12(37):42179–42192.

[41] Han S, Liu C, Lin X, et al. Dual Conductive Network hydrogel for a highly conductive, self-healing, anti-freezing, and non-drying strain sensor. ACS Appl Polym Mater. 2020;2(2):996–1005.

[42] Zhao Y, Shen T, Zhang M, et al. Advancing the pressure sensing performance of conductive CNT/PDMS composite film by constructing a hierarchical-structured surface. Nano Mater Sci. 2022;4. DOI:10.1016/j.nanoms.2021.10.002.

[43] Zhang D, Yin R, Zheng Y, et al. Multifunctional MXene/CNTs based flexible electronic textile with excellent strain sensing, electromagnetic interference shielding and Joule heating performances. Chem Eng J. 2022;438:135587.

[44] Kurian AS, Mohan VB, Bhattacharyya D. Embedded large strain sensors with graphene-carbon black-silicone rubber composite. Sens Actuator A Phys. 2018;282:206–214.

[45] Dal H, Açıkgöz K, Badenia Y. On the performance of isotropic hyperelastic constitutive models for rubber-like materials: a state of the art review. Appl Mech Rev. 2021;73:020802.

[46] Firooz S, Steinmann P, Javili A. Homogenization of composites with extended general interfaces: comprehensive review and unified modeling. Appl Mech Rev. 2021;73:040802.

[47] Qu Y, Nguyen-Dang T, Page AG, et al. Superelastic multimaterial electronic and photonic fibers and devices via thermal drawing. Adv Mater. 2018;30(27):e1707251.

[48] Tang Z, Jia S, Wang F, et al. Highly stretchable core-sheath fibers via wet-spinning for wearable strain sensors. ACS Appl Mater Interfaces. 2018;10(7):6624–6635.