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# Citric acid-based degradable polyester elastomers coated with silver nanowires for sustainable soft sensors

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## Abstract

Although soft electronic materials are of significant importance for flexible electronic devices, most of them are derived from commercial polymer elastomers, such as polydimethylsiloxane, polyurethane and Ecoflex. In this work, citric acid-based degradable polyester elastomers are prepared by a melt polycondensation process, utilizing citric acid, 1,8-octanediol and poly(ethylene glycol) (PEG) as monomers. Furthermore, poly(1,8-octanediol citrate acid) (POC)-PEG/silver nanowire (AgNW) conductive polyester elastomers (CPEs) are prepared by introducing a AgNW layer on the surface of the POC-PEG films. Scanning electron microscopy images reveal that the thickness of the AgNW layer is on the scale of several micrometers and the AgNWs form a continuous conductive network. Upon mechanical stimuli, POC-PEG exhibits recoverable deformation and induces variation in the AgNW conductive network, resulting in a conversion of strain to detectable resistance. When tensile strain is applied, the POC-PEG/AgNW CPEs achieve a gauge factor of 231.6, a response range of 0%-50%, a low response time of 35 ms and high stability. Moreover, the POC-10PEG/AgNW CPE also responds to bending deformation with a gauge factor of 3667.5, a response range of 0%-8.4%, a low response time of 62 ms and high stability. On the basis of strain sensitivity, wireless sensors are further assembled by integrating the POC-PEG/AgNW CPEs into a Bluetooth signal transmission system. Various human motions and physiological activities are successfully monitored using the wireless sensors. The results demonstrate that degradable citric acid-based polyester elastomers/AgNW CPEs are promising materials for next-generation sustainable and flexible electronic devices.



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**Keywords:** Polyester elastomers, citric acid, AgNWs, strain sensitivity, degradable

## INTRODUCTION

Soft electronic materials are of great significance for flexible electronic devices<sup>[1-6]</sup>; however, most of them are nanocomposites of commercial elastomers and conductive fillers. Commercial elastomers include polydimethylsiloxane (PDMS)<sup>[7-11]</sup>, polyurethane (PU)<sup>[12,13]</sup> and Ecoflex<sup>[14,15]</sup>, and conductive nanomaterials, such as metal and carbon nanomaterials, MXenes and liquid metals<sup>[16-21]</sup>, are mainly utilized as conductive fillers. In such nanocomposites, the properties of commercial elastomers are difficult to control due to their fixed structures. Moreover, most elastomers have poor degradability and biocompatibility, which limits their applications in sustainable and bio-related electronic devices<sup>[22,23]</sup>. The development of high-performance soft electronic materials for next-generation sustainable and wearable devices is therefore a crucial research area.

Polyester elastomers represent a class of polymers containing abundant ester groups in polymer chains and possess a glass transition temperature ( $T_g$ ) lower than room temperature. By tuning their structure, polyester elastomers can achieve comparable mechanical properties to that of most commercial elastomers, including strength, elongation at break and resilience. In particular, polyester elastomers have obvious advantages over other polymer elastomers (e.g., PDMS and PU) regarding degradability and biocompatibility, thereby making polyester elastomers soft and environmentally-friendly polymer materials<sup>[24-29]</sup>. Significant attention has been devoted to developing new polyester elastomers with high mechanical properties. For instance, polyester elastomers prepared from bis( $\beta$ -lactone) and star-shaped hydroxyl-terminated poly( $\gamma$ -methyl- $\epsilon$ -caprolactone) achieved a high breaking stress of 6 MPa, a Young's modulus of 2 MPa and an elongation at break of 850%. Moreover, such polyester elastomers have the ability to degrade within 60 h at pH 7 and 40 °C<sup>[30]</sup>. Interestingly, Zhang and co-workers systematically investigated a series of polyester elastomers utilizing bio-monomers or bio-derived monomers. The tensile strength and elongation at break can be controlled in the ranges of 1.2-16.0 MPa and 70%-800%, respectively, and such polyester elastomers also show excellent biocompatibility and promising applications in in-vivo soft tissue repair<sup>[31-34]</sup>. However, there has still been less work on the use of polyester elastomers in soft electronics.

Citric acid is a low-cost organic acid that widely exists in fruits (such as lemon, citrus, pineapple and others) and animals (bones, muscles and blood). In addition, citric acid can also be synthesized by a fermentation procedure utilizing sugar-containing raw materials. Citric acid is non-toxic and has been extensively used as a food additive. From the perspective of chemical structure, one citric acid molecule contains three carboxyl groups and one hydroxyl group, which can react with other monomers containing hydroxyl, carboxyl and amino groups by a condensation process. Citric acid is an important monomer in the preparation of degradable polyester elastomers. The development of citric acid-based degradable polyester elastomers may provide new insights for the fabrication of sustainable and flexible soft electronic devices.

Herein, degradable citric acid-based conductive polyester elastomer (CPEs) are developed and used in constructing soft and wearable sensors. The degradable polyester elastomers are prepared by a melt polycondensation utilizing citric acid (CA), 1,8-octanediol and poly (ethylene glycol) (PEG) as monomers. Condensation polymerization of CA and 1,8-octanediol leads to the formation of poly(1,8-octanediol citrate) (POC). PEG is used as a flexible monomer to tune the mechanical properties. Silver nanowires (AgNW) is introduced on the surface of the POC-PEG films to make CA-based polyester elastomer/AgNW CPEs. The strain sensitivity of the POC-PEG/AgNW CPEs is investigated, and soft and wearable sensors are fabricated on their basis.

## EXPERIMENTAL

### Materials

CA ( $\geq 99.5\%$ ) was purchased from the Tianjin Damao Chemical Reagent Factory. 1,8-octanediol (98%), PEG ( $M_n = 2000$ ) and phosphate-buffered saline (PBS) (pH 7.3) were supplied by Shanghai Aladdin Bio-Chem Technology Co., Ltd. AgNW was prepared according to a previously reported method<sup>[35]</sup>.

### Preparation of degradable POC-PEG polyester elastomers

The POC-PEG elastomers were synthesized by a melt polycondensation method and the detailed procedures were as follows. Under nitrogen protection and magnetic stirring, CA and 1,8-octanediol (molar ratio of 1.1:1) were added to a three-necked flask and heated to 140 °C to obtain a melt. PEG with different mass fractions was then added to the above melt and stirred to form a homogeneous solution. The polymerization was conducted at 140 °C for 0.5 h to obtain a viscous prepolymer mixture that was poured into a Teflon mold. The polymerization was further conducted at 80 °C for 72 h to obtain the target POC-PEG elastomers. By adjusting the mass fraction of PEG (0, 10 and 20 wt.%), different polyester elastomers (POC, POC-10PEG and POC-20PEG) were obtained.

### Preparation of POC-PEG/AgNW CPEs

POC-PEG/AgNW CPEs were prepared as follows. A AgNW dispersion in ethanol ( $1 \text{ mg mL}^{-1}$ ) was prepared with the assistance of ultrasound and then introduced onto the surface of the POC-PEG films by a droplet coating procedure. The thickness of the AgNW layer was controlled by the coating time.

### Fabrication of flexible strain sensors using POC-PEG/AgNW CPEs

Flexible strain sensors were fabricated as follows. The POC-10PEG CPE was tailored into dimensions of  $45 \text{ mm} \times 10 \text{ mm} \times 2 \text{ mm}$ . Two wires were then connected to the ends of the POC-PEG/AgNW CPE to obtain flexible strain sensors. Wireless sensors were fabricated by connecting the flexible strain sensors to a Bluetooth signal transmission system, as described in our previous work<sup>[36,37]</sup>.

### Characterization

Fourier transform infrared (FT-IR) spectra were collected on a Nicolet IS50 FT-IR spectrometer. The samples were coated on potassium bromide salt sheets and the scanning range was  $400\text{--}4000 \text{ cm}^{-1}$ .

The ultraviolet-visible (UV-Vis) spectra of the AgNW were collected on a Shimadzu UV-2550. AgNW was dispersed in ethanol and the concentration was  $0.01 \text{ mg mL}^{-1}$ . The scanning range was 200–800 nm. The surface and fracture morphology of the AgNW and POC-PEG/AgNW CPEs were observed using scanning electron microscopy (SEM, VEGA II XMU). The samples were sputtered with gold in a vacuum prior to observation.

Thermogravimetric analysis (TGA) was performed on a thermogravimetric analyzer (METTLER TOLEDO TGA/DSC) with a nitrogen flow of  $50 \text{ mL min}^{-1}$ . The weight loss of the sample was recorded by heating the sample from 25 to 600 °C at a heating rate of  $10 \text{ °C min}^{-1}$ .

The glass transition temperature ( $T_g$ ) was obtained from differential scanning calorimetry (DSC) curves of the polyester elastomers. The DSC curves were collected on a differential scanning calorimeter (METTLER TOLEDO DSC823e) under a  $\text{N}_2$  atmosphere. The heating rate was  $10 \text{ °C min}^{-1}$  and the scanning range was  $-50\text{--}150 \text{ °C}$ .

The stress-strain curves and tensile load-unload curves of the polyester elastomers were recorded on a universal testing machine (CMT2500). The sample size was 75 mm × 4 mm × 2 mm and the stretching speed was 20 mm min<sup>-1</sup>. The elastic modulus (E) of the POC-PEG elastomers was obtained from the slope of the stress-strain curve in the strain range of 0%-25% according to  $E = \Delta\sigma/\Delta\varepsilon$ , in which  $\sigma$  and  $\varepsilon$  are stress and strain, respectively.

For the degradability test, a piece of POC-PEG/AgNW CPE was immersed in a PBS solution or 0.1 mol L<sup>-1</sup> NaOH aqueous solution at room temperature. Morphological changes were recorded by taking photographs at different time intervals. The gel permeation chromatography curves of the polyester elastomer prepolymer and POC-PEG/AgNW CPEs after being degraded in a 0.1 mol L<sup>-1</sup> NaOH aqueous solution for 10 d were collected to evaluate the degradability.

The strain sensitivity, sensing stability, response time and resistive response to different strains were evaluated by recording the resistance change of the POC-PEG/AgNW CPEs under different applied strains. The sensors were fixed on a homemade electromotor reciprocating device and the strain was applied in different modes. During cyclic deformation, the resistance change was recorded by a digital bridge (LCR, UC2858A) [Supplementary Figure 1] equipped with a computer. The relative resistance change ( $\Delta R/R_0$ ) was calculated according to  $\Delta R/R_0 = (R_i - R_0)/R_0$ , where  $R_0$  and  $R_i$  represent the initial resistance of the POC-PEG/AgNW CPE and resistance under an applied strain, respectively.

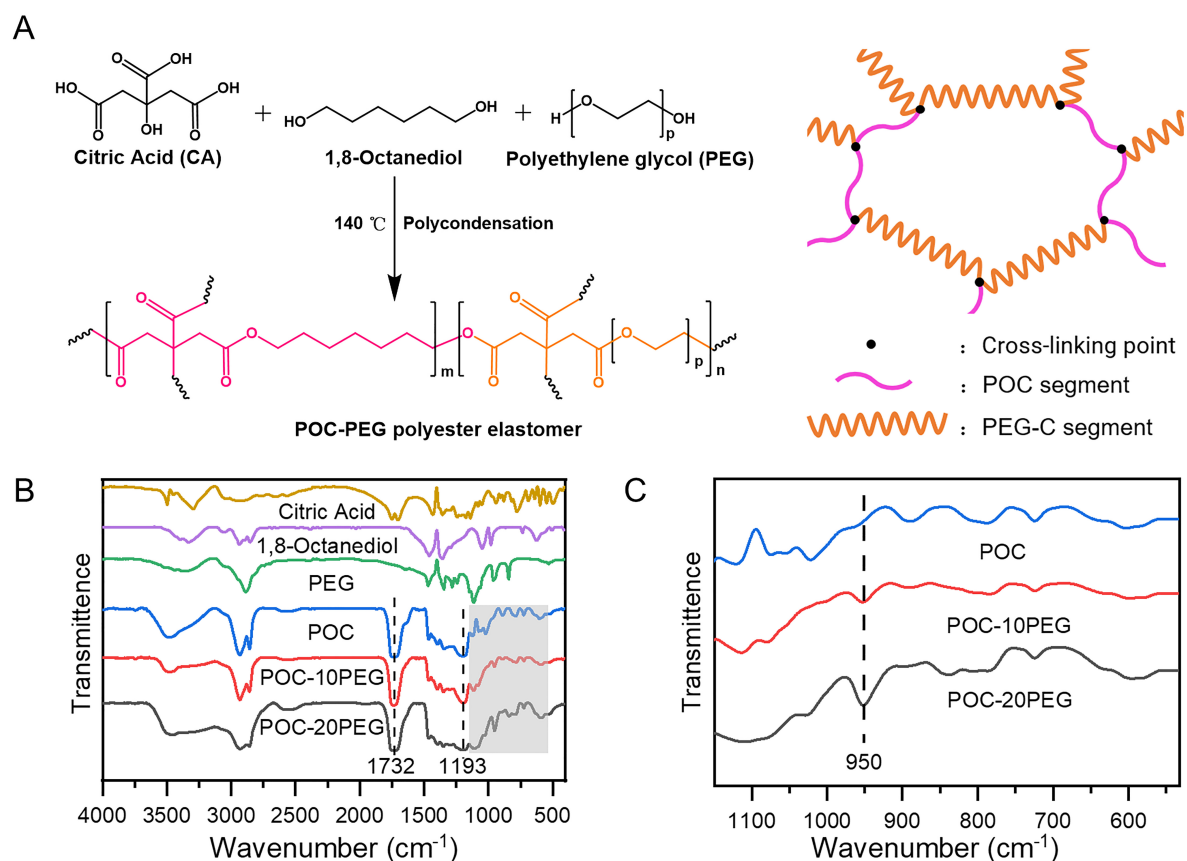
## RESULTS AND DISCUSSION

### Preparation and properties of POC-PEG/AgNW CPEs

The degradable POC-PEG polyester elastomers were prepared according to the synthetic route shown in Figure 1A. The POC-PEG elastomers were prepared based on a polycondensation process. CA was selected as the carboxyl group-containing monomer. Because the CA molecule has three carboxyl groups and one hydroxyl group, it also works as a crosslinker to bond polyester chains together. The preparation of the POC-PEG elastomers was conducted via a two-stage process of prepolymerization and post-polymerization and the feeding ratio of PEG was adjusted to prepare POC-PEG elastomers with different chemical structures. Figure 1B shows the FT-IR spectra of the monomers and POC-PEG elastomers. For POC, POC-10PEG and POC-20PEG, the characteristic peaks at 1732 and 1193 cm<sup>-1</sup> are related to the stretching vibration of the C=O and C-O bonds in the ester groups, respectively. Compared with the POC elastomer, the POC-PEG elastomer showed a new absorption peak at 950 cm<sup>-1</sup>, which was the symmetric stretching vibration peak of the ether bond (C-O-C), indicating the successful preparation of POC-PEG elastomers [Figure 1C].

The glass transition temperature ( $T_g$ ) of the POC-PEG elastomers was obtained from the DSC curves. As shown in Figure 2A, all the samples, including POC, POC-10PEG and POC-20PEG, exhibit an obvious glass transition. Because the  $T_g$  values are all below room temperature, POC, POC-10PEG and POC-20PEG are in their highly elastic state. With an increase in PEG content from 0 to 20 wt.%,  $T_g$  decreases from 1.3 to -17.4 °C, indicating that PEG works as a soft segment in POC-PEG elastomers. In addition, PEG has a relatively long molecular chain compared with other small monomers. The crosslinking density of elastomers is lowered when the PEG content is increased, which also helps to promote the chain segment motion of polymers and leads to decreased  $T_g$ .

Figure 2B shows the TG curves of POC, POC-10PEG and POC-20PEG. As seen, POC, POC-10PEG and POC-20PEG show good thermal stability below 210 °C. Between 210 and 500 °C the elastomers exhibit an obvious weight loss. There are two weight loss stages at 210-300 and 300-550 °C, respectively. At

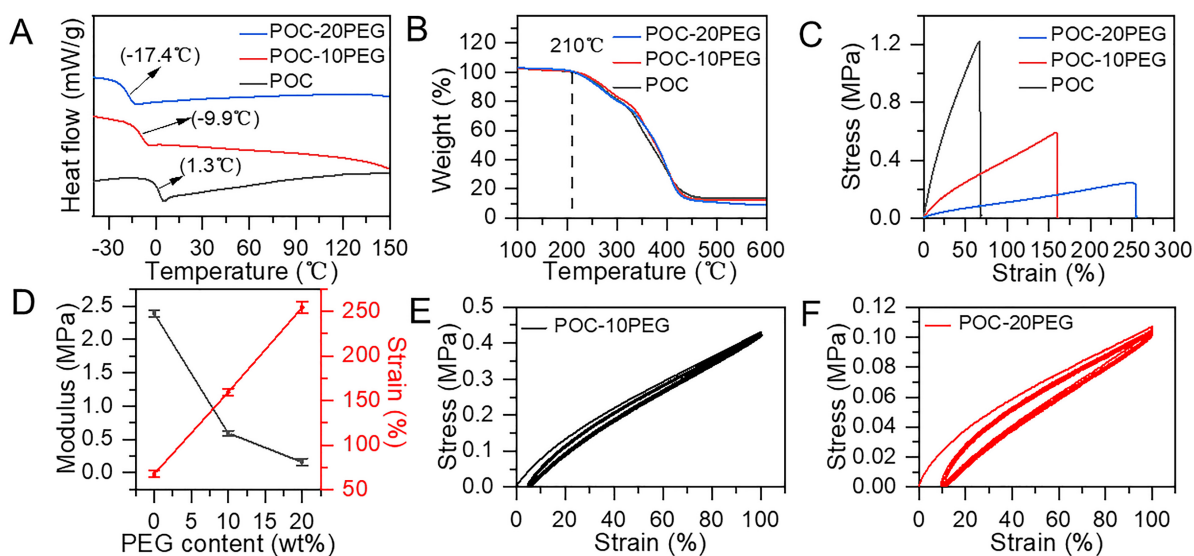


**Figure 1.** (A) Synthetic route for POC-PEG degradable polyester elastomers. (B) FT-IR spectra of monomers and POC-PEG elastomers with different PEG contents. (C) Enlarged infrared spectra of highlighted section in (B).

210–300  $^{\circ}\text{C}$ , the weight loss is  $\sim 20\%$  and the weight loss rate is relatively low, while at 300–550  $^{\circ}\text{C}$ , the weight loss is  $\sim 70\%$  and the weight loss rate is relatively high. The first weight loss stage may be related to the separation of small molecules from the polymer network. In the second stage, the ester bonds and carbon-carbon bonds existing in the polymer network are broken and the polymer network disintegrates into segments, thereby inducing a rapid weight loss.

Because of the low  $T_g$ , the POC-PEG elastomers exhibit excellent elasticity and stretchability. POC, POC-10PEG and POC-20PEG are all stretchable with an elongation at break of  $> 50\%$  [Figure 2C]. With increasing PEG content, the breaking strength and Young's modulus of the elastomers decreased, while the elongation at break obviously increased. For POC-10PEG, the breaking strength and the elongation at break are 0.6 MPa and 160%, respectively. Figure 2D shows that Young's modulus decreases from 2.39 to 0.16 MPa and the elongation at break increases from 67.2% to 254.7% when the PEG content increases from 0 to 20 wt.%. These results indicate that the mechanical performance of the POC-PEG elastomers could be well adjusted by the PEG content. Because of the longer molecular chain of PEG compared with other small monomers, an increase in PEG content leads to decreased crosslinking density. On this basis, the mechanical strength and modulus of the elastomers decrease and the elongation at break increases with increasing PEG content.





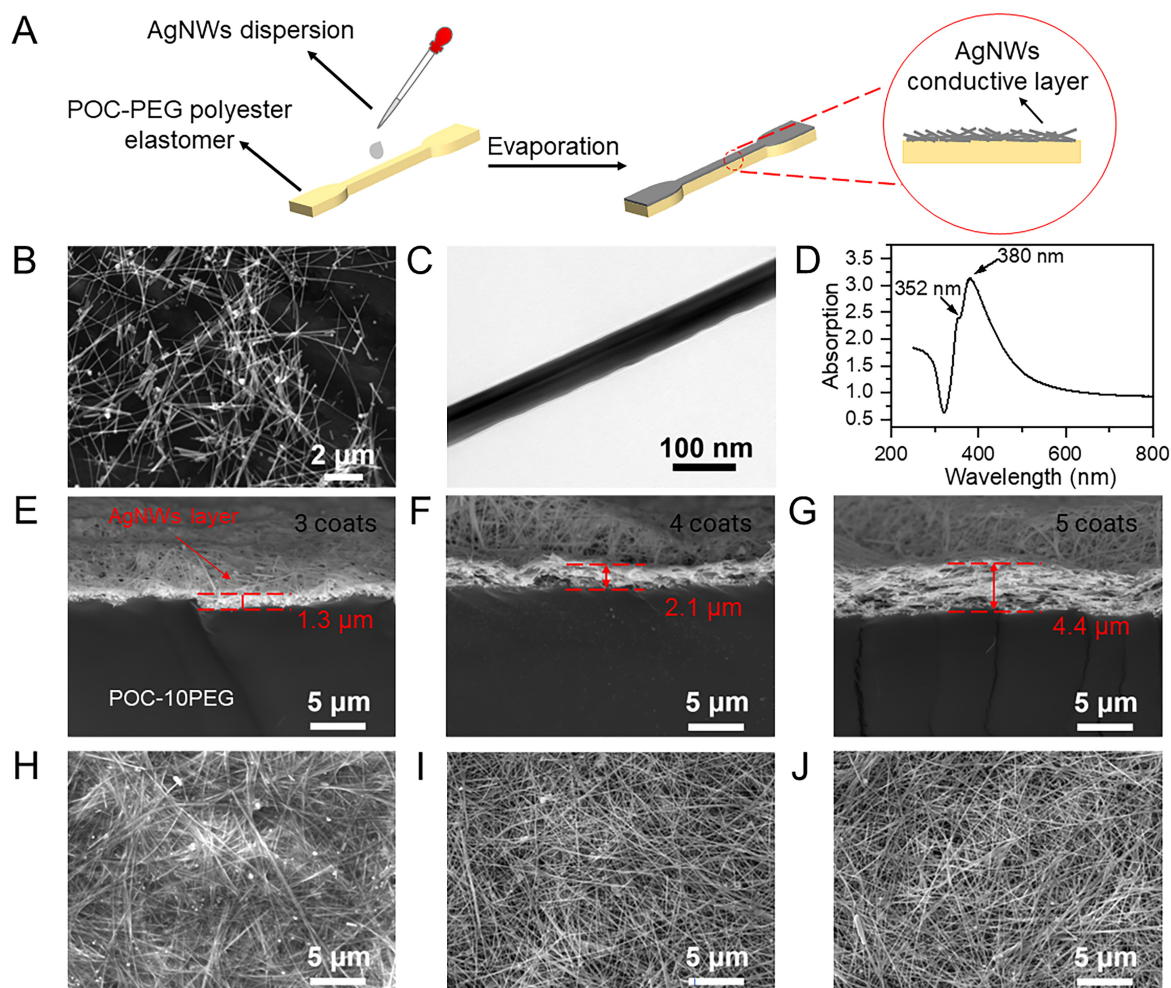
**Figure 2.** Thermodynamic and mechanical properties of POC-PEG elastomers. (A) DSC curves of POC, POC-10PEG and POC-20PEG elastomers. (B) TG curves. (C) stress-strain curves. (D) modulus and elongation at break of POC-PEG elastomers prepared for different contents of PEG. (E) tensile loading-unloading curves of POC-10PEG elastomer. (F) tensile loading-unloading curves of POC-20PEG elastomer.

Figure 2E and F show the cyclic load-unload curves of POC-10PEG and POC-20PEG, respectively. Hysteresis loops are observed for both POC-10PEG and POC-20PEG, and the residual strains in the first load-unload curve for POC-10PEG and POC-20PEG are 4.5% and 9.6%, respectively. In the subsequent cycles, the load-unload curves almost overlap and the residual strains remain unchanged with increasing load-unload cycles. The integrated mechanical properties endow POC-PEG polyester elastomers with potential soft materials for flexible devices.

The POC-PEG/AgNW CPEs were prepared by introducing a AgNW layer on the surface of POC-10PEG films, according to the procedures illustrated in Figure 3A. AgNW was first prepared according to a previously reported method<sup>[35]</sup>. From the SEM and TEM images displayed in Figure 3B and C, the prepared AgNW has a wire shape and their diameter is ~50 nm. Figure 3D shows the UV-Vis spectrum of the AgNW dispersion. As seen, the absorption peak at 380 nm was observed, further indicating the successful preparation of AgNWs<sup>[38]</sup>. The AgNW layer was introduced onto the surface of the POC-PEG elastomer film by a droplet coating procedure. The thickness of the coated AgNW layer was adjusted by the coating time. As displayed in Figure 3E-G, the thickness of the AgNW layer is in the range of 1.3–4.4  $\mu\text{m}$ . From the surface morphology of the POC-PEG/AgNW CPEs displayed in Figure 3H-J, the AgNW randomly stack and interlace to form a continuous network.

### Tensile strain sensitivity of POC-PEG/AgNW CPEs

The POC-PEG/AgNW CPEs inherit the mechanical flexibility of the POC-PEG elastomers and exhibit conductivity due to the AgNW layer. Upon deformation, the AgNW network changes accordingly and the POC-PEG/AgNW CPEs show excellent tensile strain sensitivity. The sensing mechanism of the POC-PEG/AgNW CPEs to applied strain is illustrated in Figure 4A. When gradually increasing strain is applied, the resistance of the PEG/AgNW CPEs increases accordingly [Figure 4B]. When the strain is kept at a certain value, the fluctuation of  $\Delta R/R_0$  is small and step-like curves were recorded. From the linear fitting of the  $\Delta R/R_0$ -strain curve, three gauge factors (GFs) were obtained, namely, 19.6, 82.5 and 231.6 in the

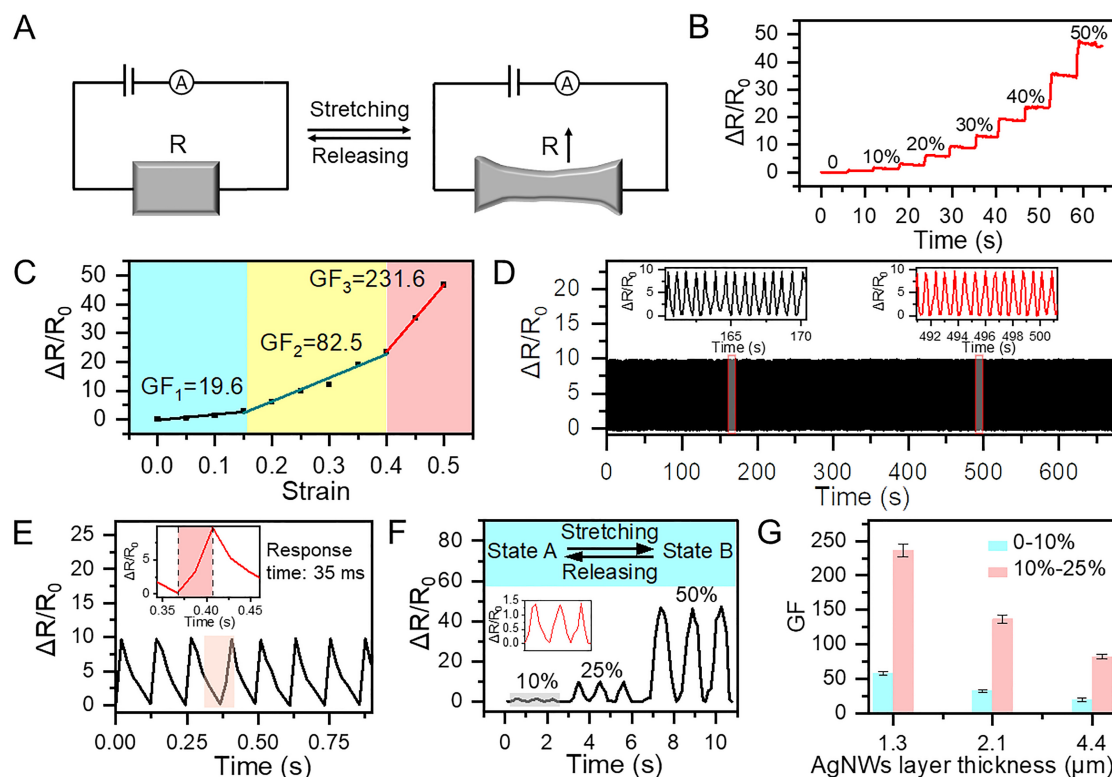


**Figure 3.** Preparation and characterization of POC-PEG/AgNW CPEs. (A) Illustration of preparation of POC-PEG/AgNW CPEs. (B) SEM image of AgNW. (C) TEM image of a single AgNW. (D) UV-Vis spectra of AgNW dispersed in ethanol ( $0.01 \text{ mg mL}^{-1}$ ). (E-G) SEM images of cross sections of POC-PEG/AgNW CPEs with different AgNW layer thicknesses. (H-J) SEM images of surface morphology of POC-PEG/AgNW CPEs with different AgNW layer thicknesses.

strain ranges of 0%-15%, 15%-40% and 40%-50%, respectively [Figure 4C]. Compared with other flexible sensors<sup>[9,39-42]</sup>, the POC-PEG/AgNW CPEs achieved a relatively high strain sensitivity.

There are three linear regions for the relative resistance change with increasing strain, which may be induced by the gradual destruction of the AgNW layer. When the AgNW layer is subjected to a tensile strain in the range of 0%-15% [Supplementary Figure 2], slippage between the AgNW occurs and the resistance slightly increases. With a further increase in strain, more and more cracks form because of the slippage between AgNW and the resistance changes obviously with increasing strain.

In addition, the POC-PEG/AgNW CPEs also respond reversibly to periodical strain for more than 800 cycles [Figure 4D]. From the insets of Figure 4E, the response is stable and the amplitude of  $\Delta R/R_0$  is almost the same. The response time can be as low as 35 ms [Figure 4E], which ensures the fast detection of strain. Figure 4F shows the resistance response of a POC-PEG/AgNW CPE under different strains. As seen, the



**Figure 4.** Tensile strain sensitivity of POC-PEG/AgNW CPEs. (A) Schematic illustration of strain sensing mechanism of POC-PEG/AgNW CPEs. (B) Resistance response of POC-PEG/AgNW CPEs to increasing strain from 0 to 50%. (C) Linear fitting of  $\Delta R/R_0$ -strain curve. (D) Resistance response of POC-PEG/AgNW CPEs to cyclic strain of 25% over 800 cycles. (E) Response time of POC-PEG/AgNW CPEs to transient strain. (F) Resistance response of POC-PEG/AgNW CPEs to different strains of 10%, 25% and 50%. (G) Strain sensitivity of POC-PEG/AgNW CPEs containing AgNW layers with different thicknesses.

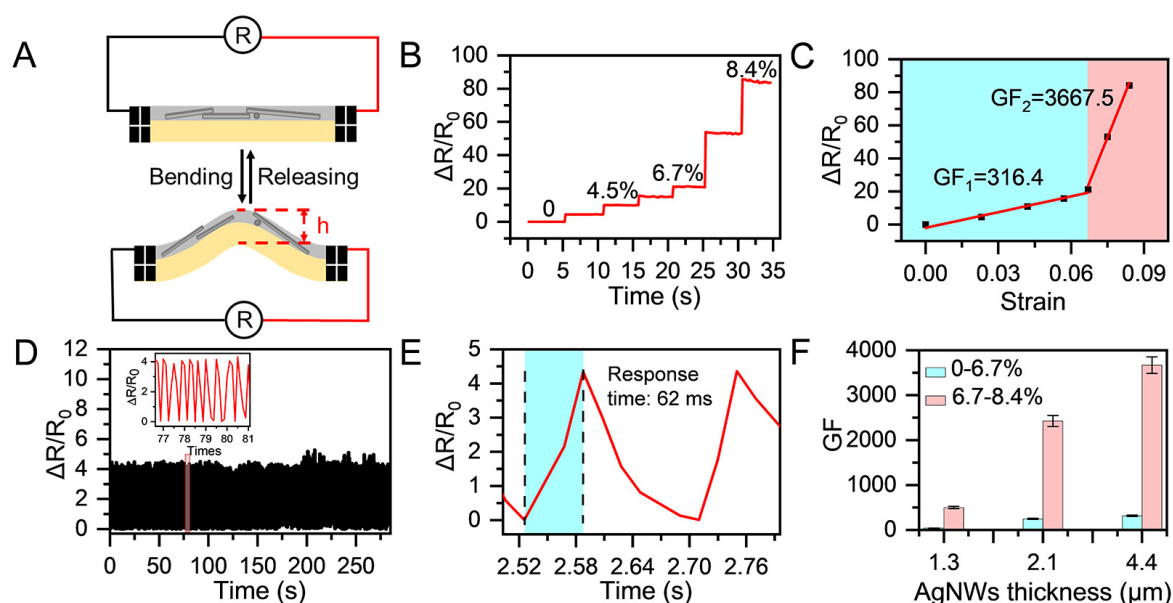
POC-PEG/AgNW CPE responds efficiently to cyclic strains of 10%, 25% and 50%.

Further investigations indicate that the tensile strain sensitivity of the POC-PEG/AgNW CPEs is dependent on the thickness of the AgNW layer [Figure 4G]. There is a general tendency that the GF decreases with increasing AgNW layer thickness. In the case of a AgNW layer thickness of 1.3  $\mu m$ , the GF reaches 58.1 and 236.6 in the strain ranges of 0%-10% and 10%-25%, respectively. Under low strain loading, the conductive network is less affected by deformation, while under high strain loading, the conductive network undergoes a drastic variation and the GF is relatively high. In the case of a thin AgNW layer, the conductive network can easily change along with the POC-PEG elastomers and is sensitive to deformation. In contrast, for an elevated thickness, the robustness of the conductive network is enhanced and the sensitivity is lowered. This provides an opportunity to tune the strain sensitivity of the POC-PEG/AgNW CPEs by regulating the thickness of the AgNW layer.

### Bending strain sensitivity of POC-PEG/AgNW CPEs

Similar to the resistance response of the POC-PEG/AgNW CPEs to tensile strain, bending strain also induces a variation in the AgNW conductive network that leads to resistance variation [Figure 5A]. With increasing bending strain, the resistance of the POC-PEG/AgNW CPEs increases gradually. When the bending strain is kept constant,  $\Delta R/R_0$  maintains constant and a step-like response curve is recorded, indicating the stability of the POC-PEG/AgNW CPEs during the bending strain response [Figure 5B]. The GF is calculated according to  $GF = (\Delta R/R_0)/\Delta \epsilon$ , where  $\epsilon$  is calculated according to  $\epsilon = h/2r$  ( $h$  is the thickness





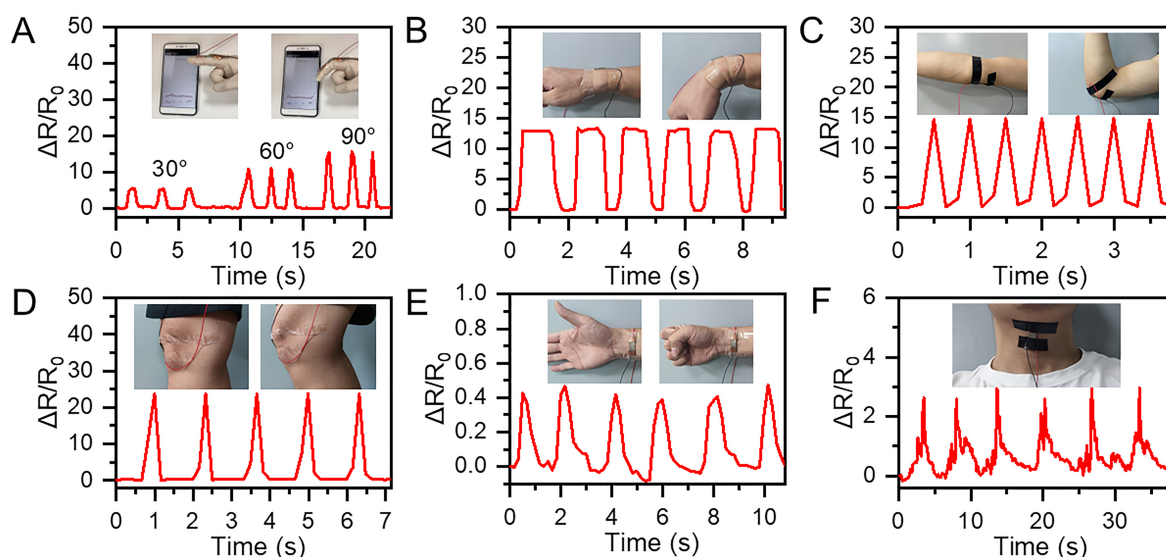
**Figure 5.** Bending strain sensitivity of POC-PEG/AgNW CPEs. (A) Schematic illustration of bending strain sensing mechanism of POC-PEG/AgNW CPEs. (B) Resistance response of POC-PEG/AgNW CPEs to increasing bending strain from 0-8.4%. (C) Linear fitting of  $\Delta R/R_0$ -strain curve. (D) Resistance response of POC-PEG/AgNW CPEs to cyclic bending strain. (E) Response time of POC-PEG/AgNW CPEs to transient bending strain. (F) Strain sensitivity of POC-PEG/AgNW CPEs containing AgNW layers with different thicknesses.

of the material and  $r$  is the radius of curvature)<sup>[43,44]</sup>. Figure 5C shows the linear fitting of the  $\Delta R/R_0$ -strain curve, with two GFs obtained:  $GF_1 = 316.4$  in the strain range of 0%-6.7%;  $GF_2 = 3667.5$  in the strain range of 6.7%-8.4%. The POC-PEG/AgNW CPEs also efficiently respond to cyclic bending strain over 300 cycles [Figure 5D] in 62 ms [Figure 5E].

The strain sensitivity of the POC-PEG/AgNW CPEs is closely related to the thickness of the AgNW layer and sensing range [Figure 5F]. With fixed a AgNW layer thickness, the GF in the low bending strain range (0%-6.7%) is lower than that in the high bending strain range (6.7%-8.4%). In the case of a AgNW layer thickness of 1.3  $\mu m$ , the GF reaches 42.6 and 499.4 in the strain ranges of 0%-6.7% and 6.7%-8.4%, respectively. Under a low bending strain loading, the AgNW conductive network is less affected and the GF is relatively low, while when a high bending strain is applied, the AgNW conductive network undergoes a drastic variation and the GF is high. When the AgNW layer thickness is increased, the GF decreases. The GF variation tendency with increasing AgNW layer thickness is opposite to that observed in the tensile strain response process. A possible reason for the decreasing GF with increasing AgNW layer thickness is as follows. When the thickness of the AgNW conductive layer is increased, a fluffy layer of AgNWs is obtained. Bending of the POC-PEG/AgNW CPEs induces full contact of the AgNWs and the high sensitivity of the CPEs to bending strain.

### Wearable sensors based on POC-PEG/AgNW CPEs

On the basis of the high sensitivity of the POC-PEG/AgNW CPEs to tensile and bending strain, wearable and wireless strain sensors are further assembled by connecting flexible sensors to our previously established Bluetooth signal transmission system<sup>[36,37]</sup>. Utilizing such sensors, various human motions and physiological activities were monitored. By mounting a sensor on a finger, joint bending was monitored by the resistance variation [Figure 6A and Supplementary Video 1]. Bending of the finger joint leads to an increase in resistance, while the resistance decreases when the finger joint is unbent. Different bending



**Figure 6.** Wearable and wireless strain sensors of POC-PEG/AgNW CPEs for human motion monitoring. (A) Resistance response of sensor to joint bending. (B) Wrist bending. (C) Elbow bending. (D) Knee bending during walking. (E) Tendon motion caused by fist clenching. (F) The movement of prominentia laryngea induced by swallowing.

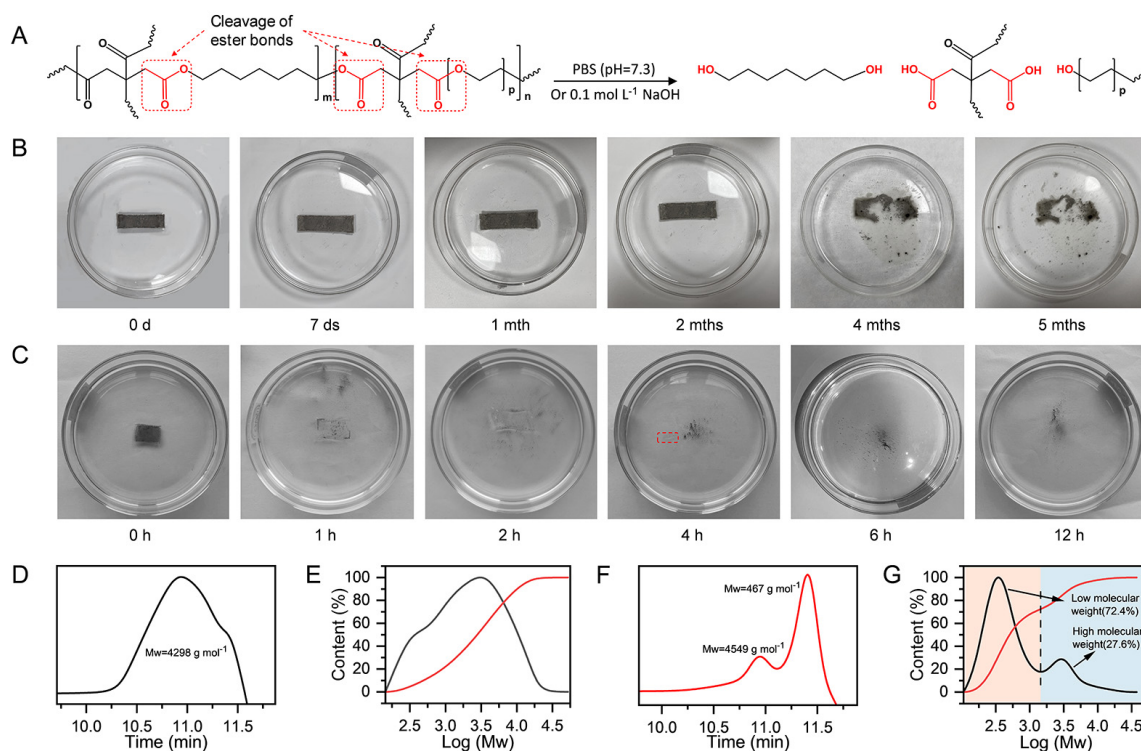
angles could be reflected by the amplitude of the resistance variation. In a similar manner, wrist, elbow and knee bending were also successfully detected [Figure 6B-D and Supplementary Video 2].

Due to the high strain sensitivity of the POC-PEG/AgNW CPEs, such sensors also have the ability to monitor small activities. Figure 6E shows the resistance response of the sensor to the tendon motion caused by fist clenching. As seen, periodical fist clenching induced an obvious resistance response and the tendon motion was monitored. Furthermore, by fixing a sensor near the prominentia laryngea, swallowing was also monitored by recording the resistance response induced by prominentia laryngeal motion [Figure 6F]. These results demonstrate that the POC-PEG/AgNW CPEs could be utilized in the construction of wearable and wireless sensors for both large strains induced by joint bending and small strains induced by physiological activities.

### Degradability of POC-PEG/AgNW CPEs

The degradability of the POC-PEG/AgNW CPEs under different conditions was further evaluated. As shown in Figure 7A, the citric acid-based CPEs were degradable because of the cleavage of the ester bond in the polymer chain. Figure 7B and C display photographs of a POC-PEG/AgNW CPE soaked in a PBS buffer (pH 7.3) and a 0.1 mol L<sup>-1</sup> NaOH aqueous solution, respectively. As seen, the POC-PEG/AgNW CPE continuously swells for 0-2 months and then begins to gradually degrade in 2-5 months, exhibiting a slow degradation rate. In contrast, when the POC-PEG/AgNW CPE was soaked in a 0.1 mol L<sup>-1</sup> NaOH aqueous solution, the CPE sheet almost disappeared within only 6 h, indicating its degradation ability.

To gain insights into the degradation behavior, gel permeation chromatography curves of the polyester elastomer prepolymer and POC-PEG/AgNW CPE after being degraded in a 0.1 mol L<sup>-1</sup> NaOH aqueous solution for 10 d were collected. Figure 7D and E show the flow curve and molecular weight distribution curve of the prepolymer of the citric acid-based polyester elastomer, respectively. The weight average molecular weight ( $M_w$ ) of the sample is  $M_w = 4298 \text{ g mol}^{-1}$ . For the sample after degradation,  $M_w$  for most of the polymers decreased to  $467 \text{ g mol}^{-1}$  [Figure 7F]. According to the molecular weight distribution curve in



**Figure 7.** Degradability test of POC-PEG/AgNW CPEs. (A) Schematic diagram of hydrolytic degradation of citric acid-based CPEs. (B) Photographs of POC-PEG/AgNW CPE soaked in PBS buffer for 0-5 months. (C) Photographs of POC-PEG/AgNW CPE soaked in 0.1 mol L<sup>-1</sup> NaOH aqueous solution for 0-12 h. (D) Elution curves of prepolymers of POC-PEG polyester elastomer. (E) Molecular weight distribution curve of prepolymer of POC-PEG polyester elastomer. (F) Elution curve of POC-PEG/AgNW CPE after degradation in 0.1 mol L<sup>-1</sup> NaOH for 10 d. (G) Molecular weight distribution curve of POC-PEG/AgNW CPE after being soaked in 0.1 mol L<sup>-1</sup> NaOH for 10 d.

Figure 7G, the contents of the low and high molecular weight polymers are 72.4% and 27.6%, respectively. This means that most of the citric acid-based CPEs have been degraded via breakage of the polymer chain. This demonstrates that such POC-PEG/AgNW CPEs have the ability to degrade and could be used as key materials for green electronic devices.

## CONCLUSIONS

In conclusion, degradable citric acid-based conductive polyester elastomers have been prepared by coating a silver nanowire layer on the surface of polyester elastomer films. The tensile strength, elongation at break and modulus of the polyester elastomers were found to be closely related to the feeding content of poly(ethylene glycol) during the melt polycondensation process. The excellent response ability of the conductive polyester elastomers to both tensile and bending strain and the strain sensitivity could be regulated by the thickness of the silver nanowire layer. On the basis of strain sensitivity, the conductive polyester elastomers were utilized as key sensitive materials for wearable and wireless sensors for the monitoring of various human motions and physiological activities. Degradability testing indicated that the conductive polyester elastomers have outstanding degradation ability in both neutral conditions and alkaline conditions. Overall, this work not only presents novel flexible electronic materials for further soft and wearable sensors but also provides an opportunity to develop sustainable electronics using degradable materials.

## DECLARATIONS

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### Authors' contributions

Methodology, investigation, writing - original draft: Wang Z

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### Availability of data and materials

Not applicable.

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### Conflicts of interest

All authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

All procedures performed in this study involved non-invasive placement of the device on the skin and posed no risk to participants. Therefore, the study qualified for exemption from ethical review. Informed consent was obtained from all participants prior to their involvement.

### Consent for publication

Not applicable.

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