Visible Light-driven Polyurethane Elastomer Bionic ‘Photo-Fingers’

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BACKGROUND

Light-driven soft robotic actuators based on photo-responsive materials can be utilised to mimic the biological functions, such as swimming, walking, crawling without involving rigid and chunky electromechanial actuations.[1] However, a robust photo-responsive material with desired mechanical and biological performance and facile synthetic process for constructing potential light-driven soft robotics, especially for assistive technology and biomedical applications, is yet to be developed.[2] Herein, we reported a new visible light-responsive elastomer synthesized by introducing photo-responsive moieties (i.e. azobenzene derivatives) into the main chain of poly(ε-carporlactone) based polyurethane urea (PCL-PUU). PAzo elastomer shows excellent hyperelasticity (stretchability of 575.2% and strength of 44.0 MPa) and good biocompatibility due to its unique nanostructure and nanophase transition. A visible light-driven bilayer actuator consisting of PAzo and polyimide film has been developed and the corresponding actuation mechanism in correlation to photothermal and photochemical coupling effects has been explored through experimental analyses and theoretical calculations. An exemplar application of visible-light-controlled soft robotic ‘fingers’ playing music through touching a piano on smartphone demonstrates a robust elastomer and scalable process for design and manufacture of light-driven wearable/implantable robots or assistive devices for medical rehabilitation and surgical reconstruction.

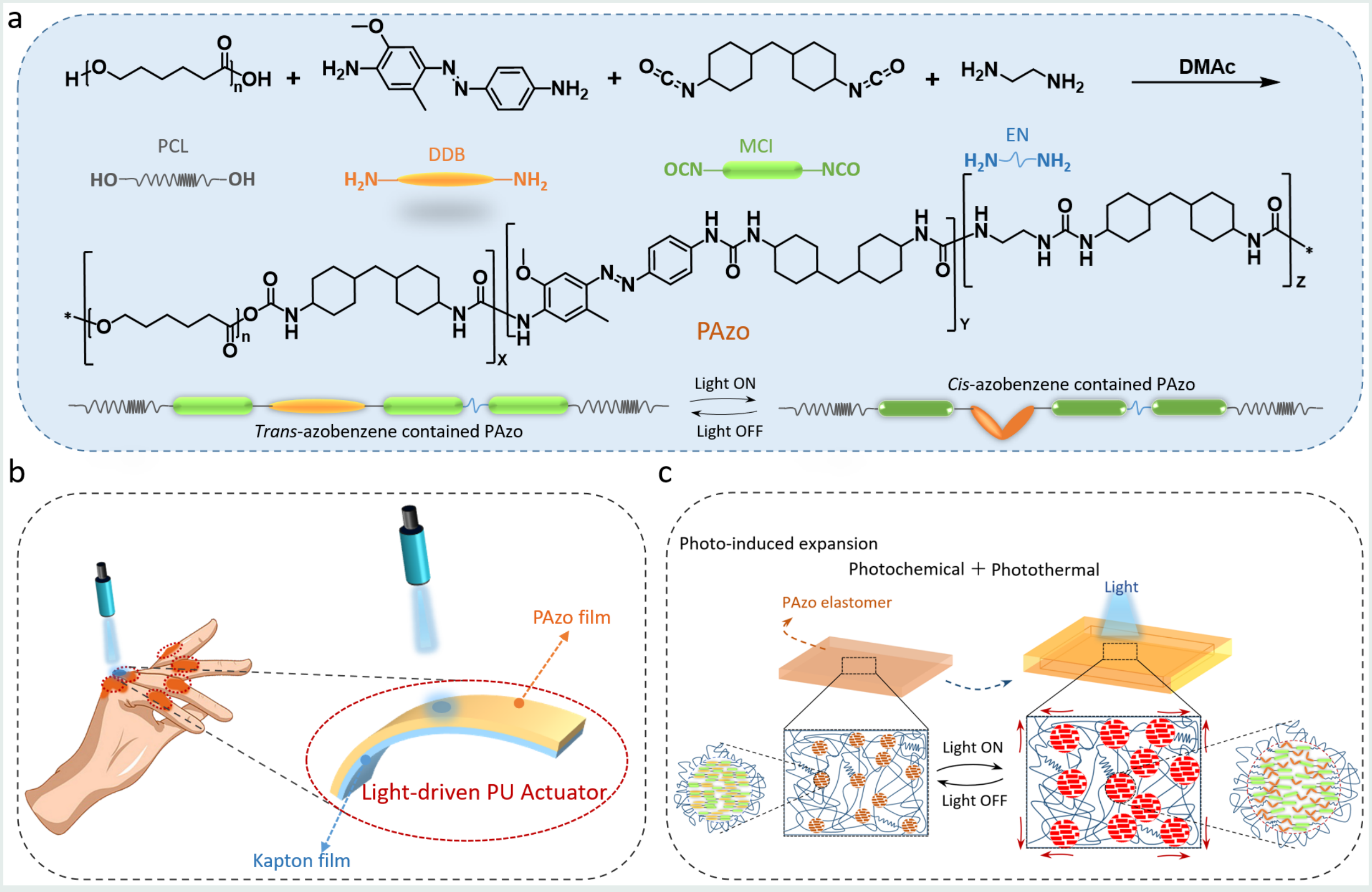


Figure 1. (a) Synthesis route to azobenzene-contained poly(urethane urea) elastomer (PAzo); (b) Schematic diagram of light-driven PU actuator for hand assistant application; (c) Schematic diagram of photochemical/photothermal effect of PAzo elastomer.

PHYSIO-CHEMICAL/ BIOLOGICAL CHARACTERIZATIONS OF PAZO

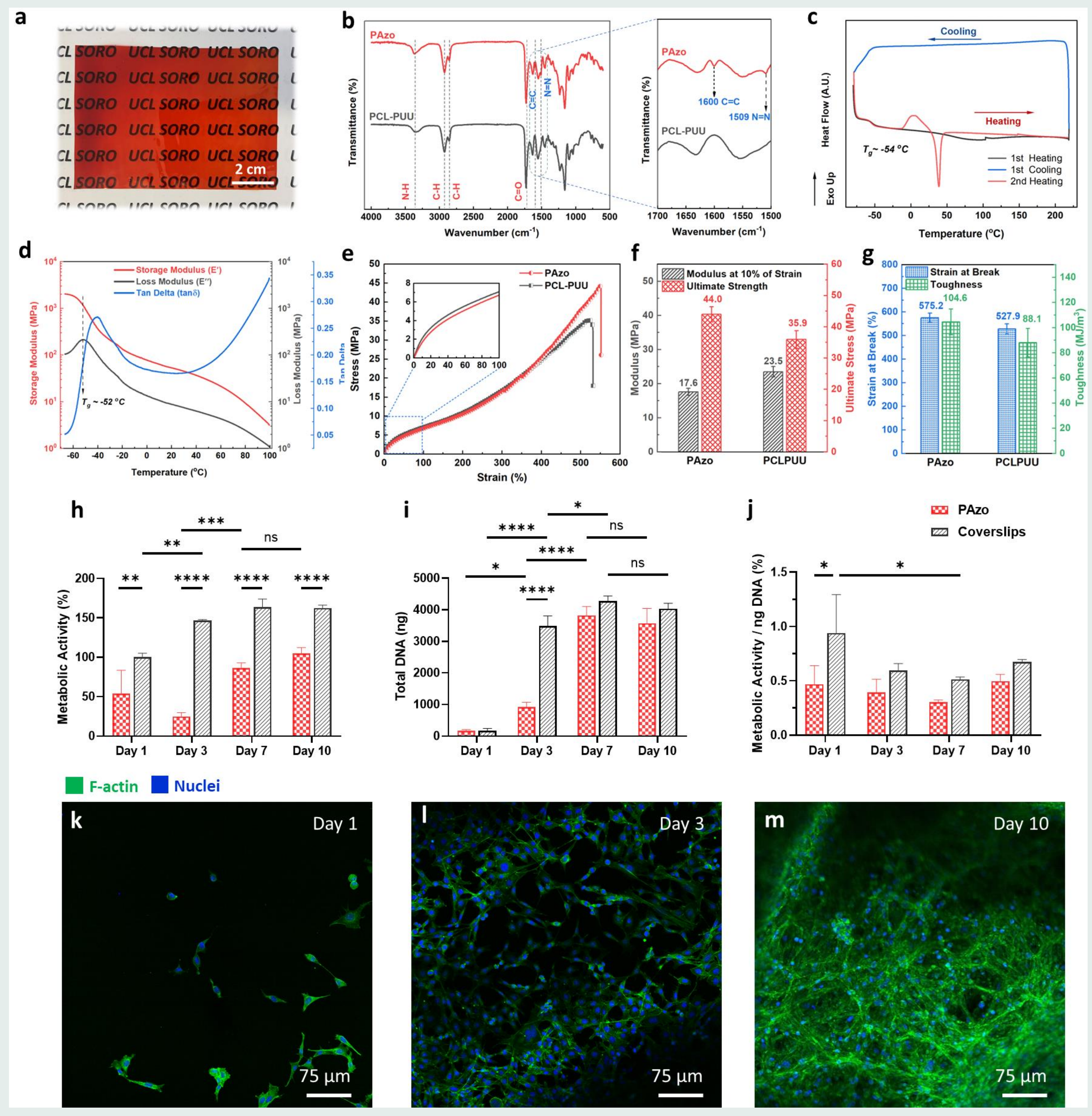


Figure 2. Physio-chemical characterizations of PAzo.
(a) Photo of a PAzo cast sheet;
(b) FTIR spectra of PAzo and PCL-PUU films;
(c) DSC scans of casted PAzo;
(d) DMA curves of PAzo;
(e) Stress-strain curves of PAzo and PCL-PUU;
(f) Tensile modulus, ultimate strength, (g) strain at break and toughness of PAzo and PCL-PUU;
(h) Metabolic activities of 3T3 cells characterized by PrestoBlue assay;
(i) Proliferation of 3T3 cells by total DNA assay;
(j) Normalized metabolic activities results;
(k-m) Immunocytochemical images of morphology of 3T3 cells on PAzo discs on Day 1, Day 3 and Day 10.

SELF-ASSEMBLY AND NANOPHASE STRUCTURE OF PAZO ELASTOMER & COMPARISIONS BETWEEN PAZO AND OTHER MATERIALS

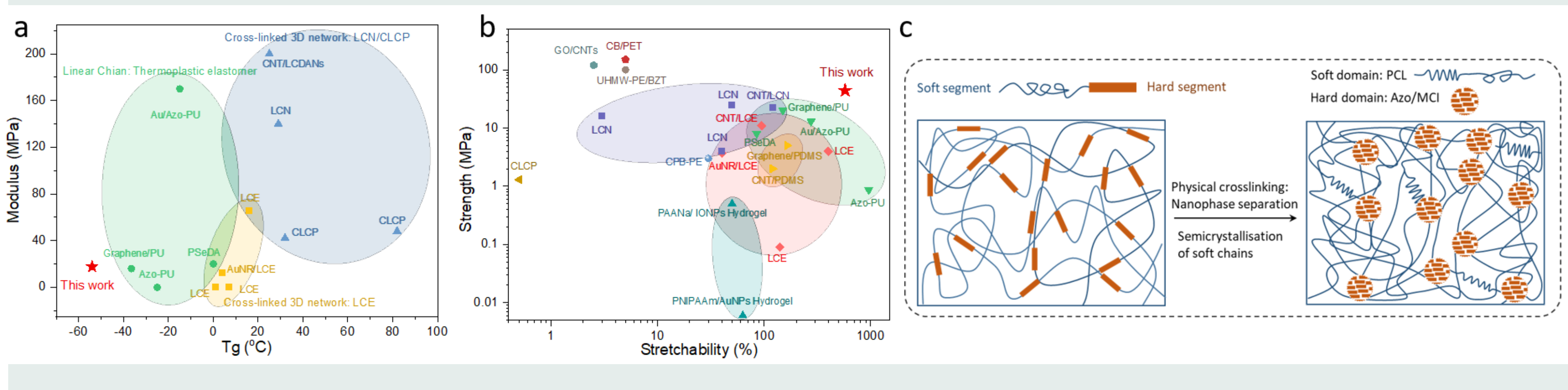


Figure 3. Ashby plots of (a) modulus versus glass transition temperature (T_g) and (b) strength versus stretchability of PAzo elastomer and other materials; (c) Self-assembly and nanophase structure of PAzo elastomer.

PHOTOCHEMICAL AND PHOTOTHERMAL MECHANICS OF PAZO

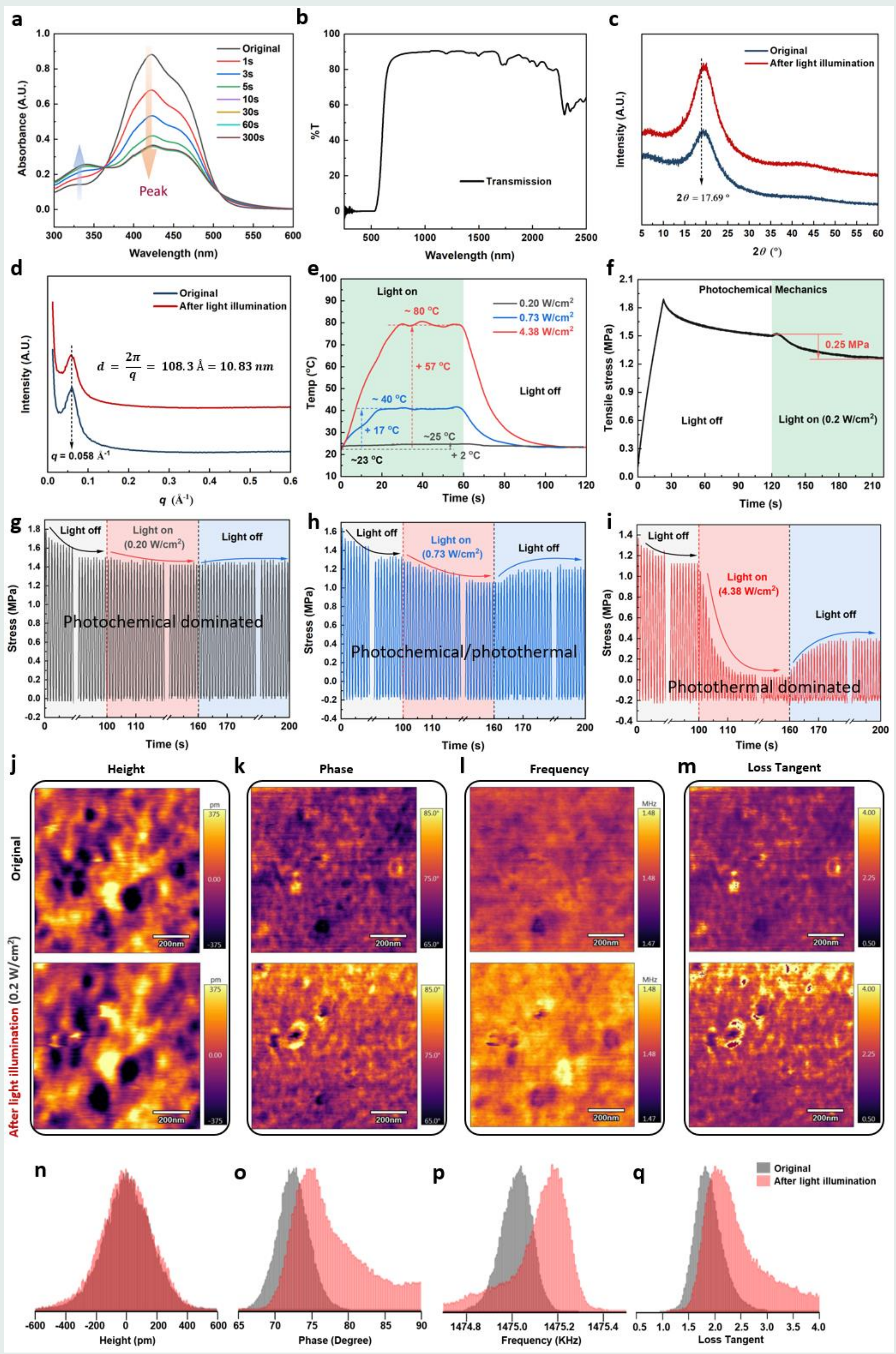
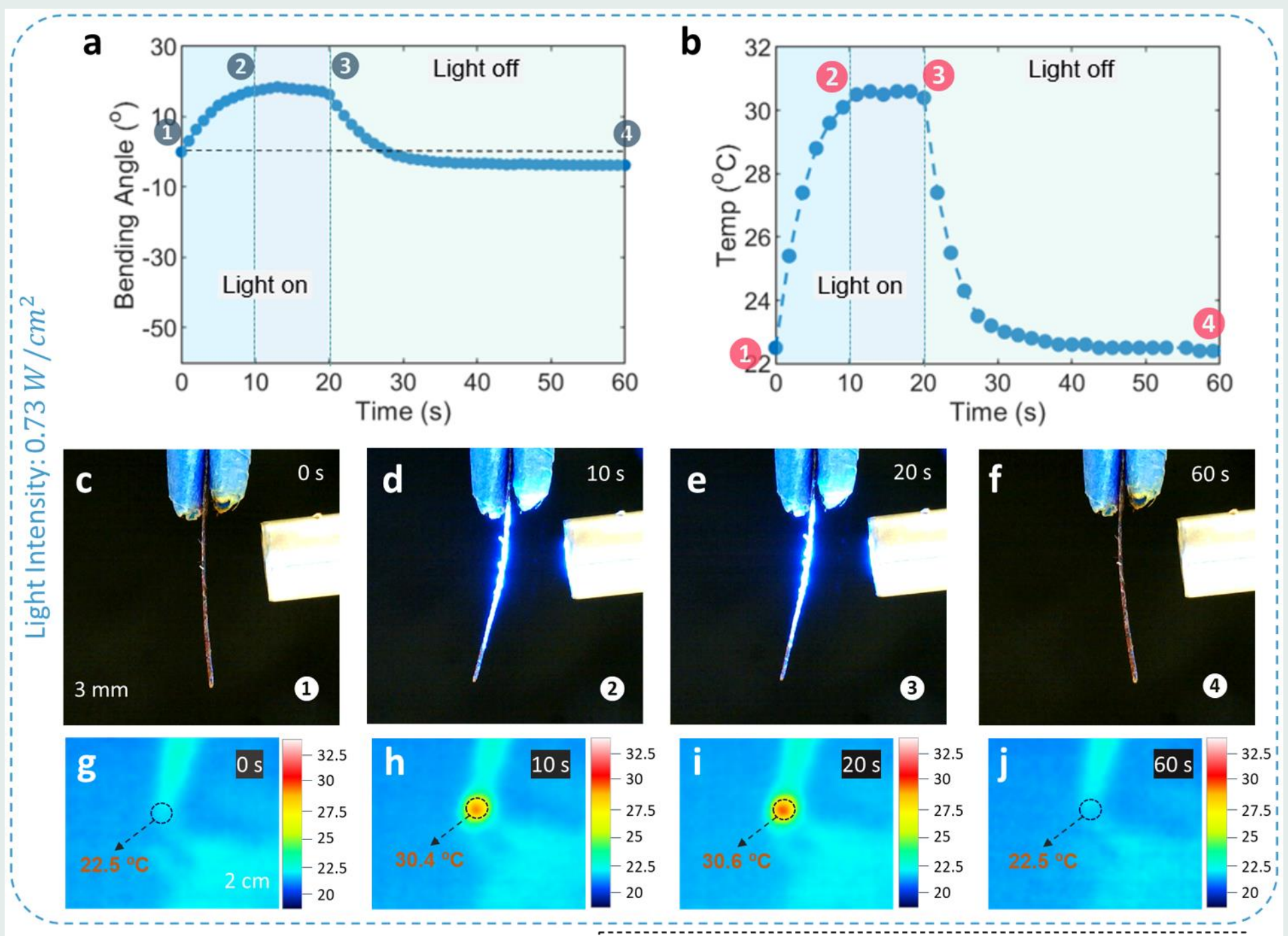


Figure 4.
(a) UV-Vis absorption spectra of PAzo solution upon the irradiation with 470 nm light (0.20 W/cm2) for different time;
(b) Transmission spectrum of PAzo film determined by Universal Measurement Spectrophotometer (UMS) across the spectral range from 250-2500 nm;
(c) WAXD and
(d) SAXS curves of PAzo film before and after light-illumination;
(e) Temperature changes of PAzo film when being irradiated with 470 nm light with different intensities;
(f) Tensile stress changes of PAzo film when irradiated with 470 nm light (0.2 W/cm2) (sample dimension of $20 \times 5 \times 0.15$ mm³);
Dynamic mechanical stress changes of PAzo when irradiated by light with different light intensities
(g) 0.20 W/cm2,
(h) 0.73 W/cm2,
(i) 4.38 W/cm2 (dynamic test condition: room temperature, 10% strain, 1 Hz, light off 100 s, on 60 s then off 40 s, sample dimension of $10 \times 2 \times 0.18$ mm³);
Atomic Force Microscope (AFM)
(j) height,
(k) phase,
(l) frequency and
(m) loss tangent images of original PAzo (top) and PAzo after in-situ light illumination (bottom) (470 nm light, 0.2 W/cm2), and corresponding histogram distribution changes of
(n) height,
(o) phase,
(p) frequency and
(q) loss tangent.

BENDING BEHAVIOUR ANALYSIS OF BILAYER ACTUATOR & DEMO OF LIGHT-DRIVEN PAZO BASED ROBOTIC FINGERS FOR PLAYING PIANO

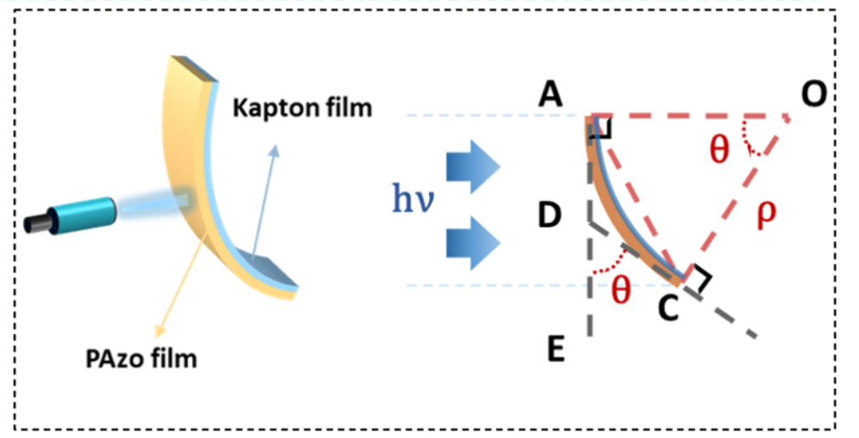


Timoshenko’s bending theory:

$$\frac{1}{\rho}=\frac{6(\alpha_2-\alpha_1)(t-t_0)(1+m)^2}{h(3(1+m)^2+(1+mn)(m^2+\frac{1}{mn}))} \quad ①$$

$$m=\frac{a_1}{a_2} \quad n=\frac{E_1}{E_2} \quad h=a_1+a_2 \quad ②$$

Geometry relationships: $$\theta=\frac{360}{2\pi}\cdot\frac{L}{\rho} \quad ③$$



Combining equations ①, ②, ③, we obtain $$\theta=\frac{1080L(\alpha_2-\alpha_1)m(1+m)}{\pi a_1(3(1+m)^2+(1+mn)(m^2+\frac{1}{mn}))}\Delta T \quad ④$$

Substitute all parameters into equation ④, when **W= 0.73 W/cm²** and $\Delta T = 9$ °C, $\boldsymbol{\theta \approx 6.14° \ll 20°}$ (Experiments)

Photochemical mechanism contributes to about 69.3% deflect angle (photothermal: 30.7%)

Figure 5. Bending behaviour of PAzo/Kap bilayer actuator under 470 nm light irradiation and related theoretical analysis.

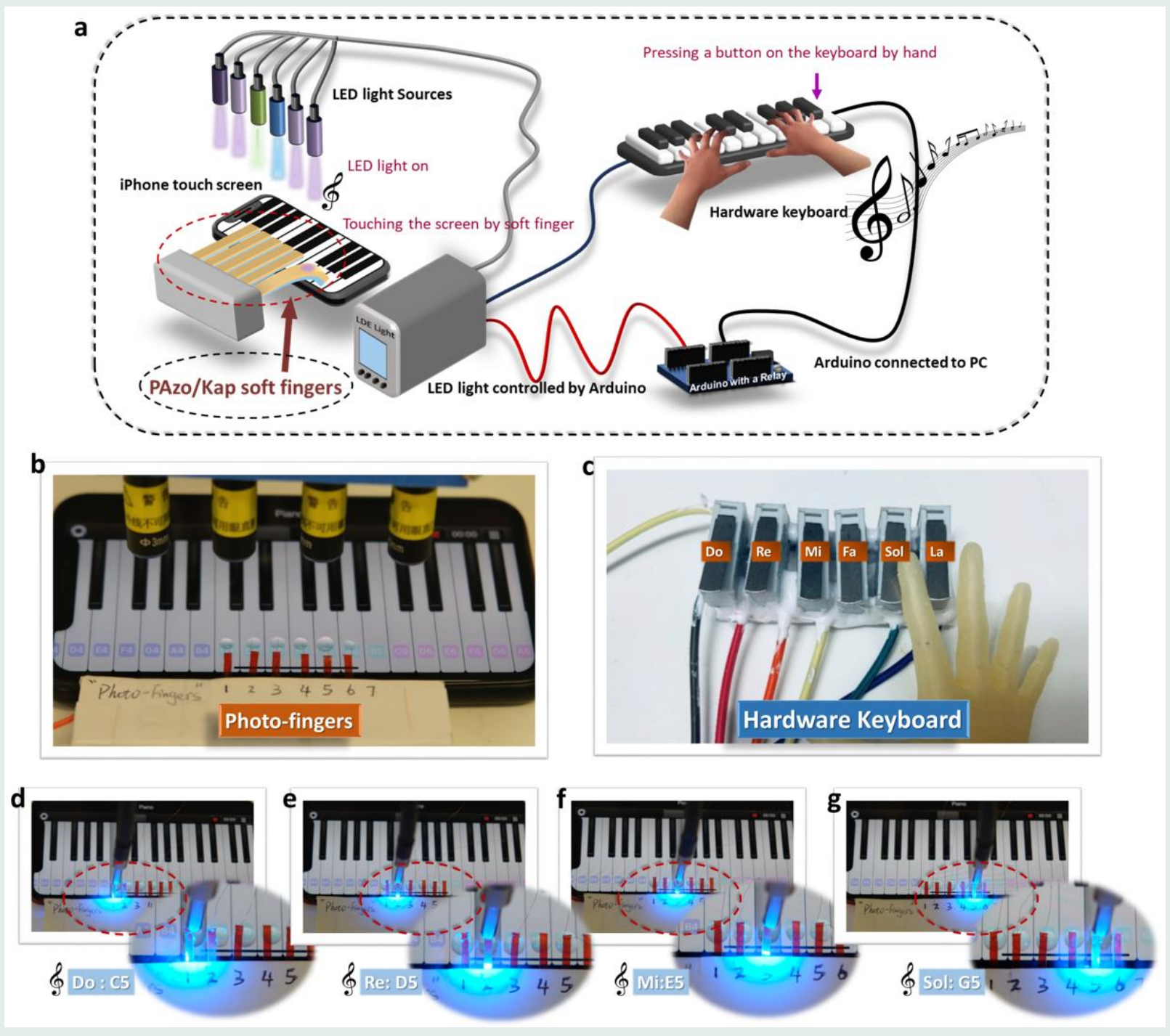


Figure 6. Fabrication and operation of light-driven soft robotic fingers to play piano.

CONCLUSION

In summary, a new visible light-responsive elastomer (PAzo) has been successfully synthesized in a facile route by introducing a photo-responsive molecule (i.e. azobenzene derivative) into the main chain of the biocompatible poly(urethane urea). PAzo elastomer shows pronounced and robust stiffness softening under blue light stimulation while remaining outstanding hyperelasticity and biocompatibility owning to azobenzene photochromic function as well as nanophase structure through self-assembling of soft and hard segments of block-copolymeric chains. The unique actuation mechanisms driven by the tuneable photochemical and photothermal coupling effects have been thoroughly studied by experimental analyses and theoretical calculations. Based on PAzo/Kap bilayer actuator, an application of light controlled soft robotic fingers for playing piano was demonstrated. This work may guide the design and manufacture of light-driven wearable/implantable robots or assistive devices for medical rehabilitation and assistance.

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