In-situ-grown silver–polymer framework with coordination complexes for functional artificial tissues

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***In-situ*-grown silver–polymer framework with coordination complexes for functional artificial tissues**

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Sensorized actuators are critical to imitate proprio-/exteroception properties of biological neuromuscular systems. Existing add-on approaches, which physically blend heterogeneous sensor/actuator components, fall short of yielding satisfactory solutions, considering their suboptimal interfaces, poor adhesion, and electronic/mechanical property mismatch. Here, we report a single homogeneous material comprising seamless sensing-actuation unification properties at nano-/molecule levels, in which *built-in* sensing functions originate from the actuator architecture itself. *In-situ*-grown silver nanoparticles and metal-ligand complexes cooperatively create a silver–polymer framework (SPF) that is stretchable (1200%), conductive (0.076 S/m), and strong (0.76 MPa in-strength). SPF displays concomitant multimodal sensing (mechanical and thermal cues) and sensorized actuation capabilities, which include proprio-deformation and external stimuli perceptions (simultaneous with load-lifting ability up to 3700× of own weight). In view of its human somatosensitive muscular systems imitative functionality, the reported SPFs bode well for use with next generation functional tissues including artificial skins, human-machine interfaces, self-sensing robots, and otherwise dynamic materials.

Muscles are admired for their remarkable ability to sense and interact with the external environment simultaneously *via* their inherent structure – an integrated system with receptors and motor structures evenly distributed throughout a biological network (**Fig. 1a**)¹. Such natural models inspire research avenues aimed at recreating coupled somatosensory and motor functions using synthetic substances²⁻⁵, where sensation and actuation are impeccably fused into a single stand-alone, dynamic material platform. This functions-unified system is expected to play a crucial role as an alternative platform to help exploit biological somatosensitive muscular system functionalities^{6, 7}. Efforts in devising artificial sensorimotor abilities *ex novo*, have focused on the use of soft and stretchable materials in light of their incomparable transmutability, conformability, and design freedom, especially when compared to rigid counterparts (*i.e.*, conventional sensors or actuators)⁸⁻¹⁰. Although notable advances on soft sensors and actuators have been reported individually¹¹⁻¹³, their distinct working mechanisms (*i.e.*, triboelectricity, piezoresistivity, piezoelectricity or colorimetry for sensing; and hydraulics, pneumatics, light, heat or electricity for actuation) have largely impeded a seamless sensing-actuation integration within a single material unit. For instance, the physical blending of various functional components to unify sensing-actuation as exemplified in conventional *add-on* approaches has shown interfacing problems, coupled with issues of multi-step integration, stress concentrations, poor adhesions, as well as the presence of dense wiring¹⁴⁻¹⁸. The resulting electronic/mechanical property mismatch among varying materials poses a dilemma to achieving the trinity of desirable properties, notably: sensing, actuation, and ideal integration of various functional parts. Thus, developing a stand-alone and dynamic-material-based platform for simultaneous sensory perception and stimulus-responsive motility (self-sensing actuator), which is established on a homogenous system where heterogeneous sensing and actuation functions are mutually assembled into a single material unit, remains an unmet goal.

One promising approach in devising muscle-like intelligent structures with ideal sensing-actuation unification is to use *built-in* techniques, by which sensing abilities originate from the actuator architecture itself¹⁹. However, current methods which rest on percolation theory or on the use of specific device structure design still suffer from the poor dispersion quality and interface compliance among external conductive fillers (for sensing) and substrate materials (for actuating) (**Fig. 1b**), as well as complexity on actuators' structural (geometry) optimization, which limits the

sensing modality^{20, 21}. Even though improvements for soft and stretchable self-sensing actuators, primarily using (ionic or electronic) conductive hydrogel composites with organic or inorganic fillers, have been made²², issues of ion leakage for unstable sensing and heterogeneity of filler dispersion for deteriorated mechanical deformation ability, still limit the fabrication of superlative sensing-actuation integration within a single material system. Furthermore, enabling multimodal sensory perceptions would, discouragingly, further complicate fabrication approaches¹². Consequently, a simple and effective processing technique is particularly necessary to help construct somatosensitive actuators in a single homogeneous artificial material platform, which must ultimately be soft, stretchable, and self-sensing (proprio-/exteroception) with muscle-like actuation performance.

We developed a single homogeneous material platform silver-polymer framework (SPF) with simultaneous sensing and actuation capabilities at nano- and molecule-level unification, using a one-step process to help mimic the somatosensitive muscular system. Specifically, the SPF was developed by leveraging on the basis of mechanical deformation functionality from dynamic $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes (for actuating) and electronic functionality from *in-situ*-grown silver nanoparticles (AgNPs, for sensing). The SPF was constructed by combining polyacrylonitrile (PAN) and silver ion (from AgNO_3) in a reducing solvent environment of dimethylformamide (DMF) (hereafter denoted as PANSion). The obtained PANSion was shown to be conductive ($0.076 \text{ S}\cdot\text{m}^{-1}$), soft/stretchable (1200% strain), yet strong ($>3700\times$ own-weight lifting capability, surpassing most of the state-of-the-arts and human muscles) (**Supplementary Table 1**). These properties, which originate from the one-step process formation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes with concomitant *in-situ*-grown AgNPs (**Fig. 1c**), enable multimodal sensing ability and seamless sensing-actuation unification, providing desired and previously unattained self-sensing actuation capabilities in a single homogenous material unit (**Extended Data Fig. 1**). In particular, we highlight the PANSion's application versatility by exploring its use in four representative applications: a multistimuli-responsive PANSion e-skin (responsive to mechanical and thermal cues), a sensing fabric *via* dip-coating PANSion solution, a PANSion fiber *via* in-air spinning, and a self-sensing PANSion-based pneumatic actuator. This work elucidates the broad applicability of PANSion in imitating natural tissues' versatile functions using a single homogeneous material platform, paving the way towards more integrated wearable devices and life-like soft robotics with

multimodal sensing and self-sensing actuation abilities, much like the biological somatosensitive muscular system.

Design and characterization of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ coordination complexes

Using PAN as a starting material, we first constructed metal-ligand complexes of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ among PAN chains by adding silver nitrate (see **Methods**), yielding an entangled PANSion chain network that is critical to forming a stretchable system. Compared with a PAN solution, which exhibits molecular interactions of $-\text{C}\equiv\text{N}$ *vs.* $-\text{N}-\text{C}=\text{O}$ (PAN *vs.* DMF), and $-\text{C}\equiv\text{N}$ *vs.* $-\text{C}\equiv\text{N}$ (PAN *vs.* PAN), a PANSion solution ought to have an additional interaction from $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes (**Fig. 1d** right). Given this, we verified the chemical environment change of $-\text{C}\equiv\text{N}$ using Fourier-transform infrared (FTIR) spectroscopy, which indicated constrained bond stretching with decreased intensity (**Fig. 1d** left; and **Supplementary Fig. 1**) due to the formation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes²³. Additionally, $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes also induce a structural change from an original semicrystalline PAN to an amorphous PANSion (**Supplementary Fig. 2**). Based on the density functional theory (DFT) calculations (**Supplementary Text 1**), we inferred that the binding energy between the metal ion and $-\text{C}\equiv\text{N}$ ligand was vital to obtaining a soft and stretchable network, considering only the PANSion (*i.e.*, Ag(I), $\sim 134.55 \text{ kJ}\cdot\text{mol}^{-1}$) sample showed excellent stretchability compared to the other films (**Extended Data Fig. 2**), which were prepared using several different metal ions with high binding energy (**Supplementary Table 2**, and **Supplementary Figs. 3–4**).

To originate and confirm the stretchability of PANSion networks, we characterized mechanical properties of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes at single-molecule level, using atomic force microscopy (AFM)-based single-molecule force spectroscopy (SMFS, see **Methods**)²⁴. Stretching PANSion by AFM-SMFS resulted in a force-extension curve with a clear detachment force peak, which could be assigned to the dissociation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes (either intra- or inter-chain mechanical failures as indicated by three individual curves in **Fig. 1e**, colored in purple/green/blue). By contrast, the control experiment on PAN chains recorded no distinguishable signals, possibly due to the molecular chains' free movement in DMF solvent (**Fig. 1e**, black line). Additionally, the contour length, L_c (length detected right before the force rupture peaks), was

observed to vary from ~106 to 389 nm (**Extended Data Fig. 3a–e**), which suggested random formation sites of coordination complexes formation along the molecule chains. These results validated that $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes, as cross-linkers, interconnected PAN molecules into a PANSion chain, exhibiting an extended effective-molecule-length (EML) (**Supplementary Text 2**). Notably, the cyclic stretching-releasing cycle test done *via* AFM-SMFS showed that the PANSion chains are highly elastic (**Fig. 1f**). Taken together, the cross-linked PANSion chain network displayed excellent molecular stretchability, where mechanical ruptures of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes could dissipate external energies during the stretching process. Note that $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes are also found to be dynamic, as based on binding energy calculations. However, we did not observe cyclic dissociation-reformation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes during AFM-SMFS tests, partially because PANSion's EML was still shorter than those of other reported polymer systems such as polydimethylsiloxane (**Extended Data Fig. 3f–g**)²⁴.

Rheological characterizations of PANSion solutions

Upon confirming the stretchability of PANSion chains originating from $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes at single-molecule level, we examined the rheological properties of PANSion solutions at a macroscale to help elucidate the entanglement and elasticity of the polymer networks. The concentration of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes, as cross-linkers, is key to fine tuning the polymer networks' entanglement and thus the PANSion's properties themselves. Consequently, we adjusted the weight ratio of AgNO_3 :PAN, ϕ , to investigate mechanical responses of five solutions ($\phi = 0, 0.5, 1.0, 1.5, 2.0$, **Supplementary Table 3**) using rheological measurements (**Supplementary Text 3**). It is worth mentioning that gel transition for $\phi = 2.0$ occurred after *circa* 10-days of storage at room temperature, although during this time, the other samples remained liquid (fig S8A), indicating that a physically/chemically entangled PANSion network (ϕ -dependent) gradually forms as time passes by. To confirm this speculation, we examined the rheological properties of PANSion solutions (1-day storage), which presented an increased viscosity and modulus in concomitance with ϕ value increase from 0 to 2.0 (**Fig. 1g**, and **Supplementary Fig. 5b–d**). This could be ascribed to the increasingly cross-linkage of the network brought about by the $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes. Once the cross-linking density reached a threshold, gel transition occurred, resulting in viscosity of several magnitudes higher when

149 compared to solution counterparts. Furthermore, the gelation evolution for $\phi = 2.0$ was associated
150 with the competing effect between storage modulus (G') and loss modulus (G''), where G' became
151 dominant once gelation occurred (**Supplementary Fig. 6**), implying the presence of a strongly
152 entangled and densely cross-linked PANSion network. These results are in accordance with other
153 reports²⁵ and our AFM-SMFS data, affirming that $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes, as cross-linkers,
154 cause structural changes to the PANSion network when compared to its antetype of PAN.

155 The dynamic mechanical properties of the samples were further studied after gelation (for $\phi = 2.0$).
156 **Fig. 1h** shows a broad linear gel region (orange lines) measured using strain-dependent oscillatory
157 rheology, with a gel-to-sol cross-over point at $\sim 300\%$. The high yield strain ($>100\%$) also
158 confirmed the dynamic nature of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes²⁶. **Fig. 1i** shows the fast mechanical
159 response with near full modulus recovery when alternating between 1 and 1000% strain, implying
160 excellent reversibility of PANSion gel due to the fast association kinetics of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$
161 complexes^{25, 27}. Interestingly, we observed an increase of G' at high oscillation strain for $\phi = 2.0$
162 when in a liquid-like gel state (*i.e.*, flowable with a cross-over point $>1200\%$) before reaching
163 solid-like state (green lines in **Fig. 1h**). Hypothetically, this could be reasoned to be the higher
164 reformation rate of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ than its dissociation rate at a higher oscillation strain, a highly
165 unusual observation. Thus, while experimental investigation on the dynamic nature of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$
166 complexes by SMFS is one of our future research focus, we note that much work is to be
167 done to consistently understand structural evolutions of the PANSion network from a solution to
168 a liquid-like gel, and up to a fully solid gel state. On a separate note, the gel time of PANSion
169 solutions was shown to be highly dependent on the ϕ value and the base concentration of the
170 starting PAN solutions (**Supplementary Fig. 7**). Such a factor could be accelerated using thermal
171 heating for various periods of time or at different temperatures (**Fig. 1j** and **k**). This information
172 helps establish the processing parameters for the preparation of freestanding PANSion films
173 (hereafter, $\phi = 2.0$ is used for further study unless otherwise specified).

174 **PANSion film with *in-situ*-grown AgNPs**

175 Having studied the properties of the PANSion molecule, solution, and gel, we were subsequently
176 confident to prepare the stretchable and freestanding film, introducing $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes

(**Fig. 2a**, and **Supplementary Text 3**) to do so. What substantially distinguished our PANSion from other coordination-complexes-based soft materials was indeed the concomitant implementation of conductive percolation network through *in-situ*-grown AgNPs that were reduced by DMF (supplementary test S4)^{28,29}. The presence of a reduction process in PANSion solutions was supported by a characteristic peak of ultraviolet-visible light (UV-Vis) spectra at 422 nm (**Fig. 2b**; and **Supplementary Fig. 8**) owing to the localized surface plasmon resonance effect of AgNPs³⁰, of which the intensity was notably correlated with the heating time (**Fig. 1j**). Thus, in light of these properties, we sought to obtain PANSion film that was conductive, stretchable, and sufficiently strong to withstand mechanical disturbances when deployed onto the human body or robotics for sensing and actuation applications.

We applied a solution casting approach with thermal drying to prepare the freestanding PANSion film (**Fig. 2a**) that was partially visible-light-transparent (thickness-dependent, **Supplementary Fig. 9**). It should be emphasized that the container during the drying process was open-ended to avoid the formation of a gel (**Supplementary Fig. 7c**). Under thermal heating (*e.g.*, 55 °C), the DMF evaporation rate was accelerated, and $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes were formed. Thus, the volume-normalized cross-linking density within the PANSion film was much higher than that within its gel counterpart, resulting in an extensively entangled network with high strength. **Fig. 2c** and **d** present the scanning electron microscopy (SEM) images of PAN and PANSion films which show morphologies of a grainy structure and smooth surface, respectively. Such structure contrast may stem from their crystalline differences where PAN is semicrystalline and PANSion is amorphous (**Supplementary Fig. 10**). Note that no AgNPs clusters at the microscale were found on the SEM images (namely, no aggregations). Additionally, the element distributions of linescan and mapping profiles based on energy-dispersive X-ray spectroscopy (EDS) further supported the notion of an evenly spread of silver (**Fig. 2e**; and **Supplementary Fig. 11**). For comparison, no trace silver was detected in the PAN film using either EDS or X-ray photoelectron spectroscopy (XPS), corroborating expected results (**Supplementary Fig. 12–13**).

Furthermore, the presence of *in-situ*-grown AgNPs was directly validated using transmission electron microscopy (TEM) images, where a notable scattering with an average lateral size of ~10 nm was observed (**Fig. 2f**; and **Supplementary Fig. 14**). Consequently, the as-prepared PANSion film, when used as a single homogeneous material unit, was expected to be electrically percolated

by AgNPs, bringing an improved electrical conductivity to PANSion, despite the inherent insulating nature of PAN. We further substantiated this claim of the *in-situ*-created electron conductive pathway by carrying out nanoscale-level conductive atomic force microscopy (C-AFM). As revealed in **Fig. 2g**, C-AFM results illustrated the transformation of the material from electrically insulating to percolatively functional current pathways when ϕ varies from 0 to 2.0. Especially, PANSion film of $\phi = 2.0$ exhibited the most noticeable change in helping to establish conductive networks. With respect to conventional *add-on* approaches used to construct conductive, soft, and stretchable composites, for instance, mixing AgNPs with elastomers or coating AgNPs on elastomers' surface, our PANSion *via a built-in* approach was shown to be far superior to creating a silver-polymer framework. By relying on PANSion, we were able to ultimately devise a methodology that is ideal on the fronts of dispersion quality, structure control and fabrication simplicity. Furthermore, we accomplished a seamless integration of both improved conductivity and stretchability in a single homogeneous material unit in just one step: introducing $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes with concomitant *in-situ*-grown AgNPs. Taken together of the coupled properties, we substantiate that the high stretchability of PANSion at the molecule level originated from $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes, whilst the improved conductivity at nanoscale rested on the *in-situ*-grown AgNPs, collectively empowering PANSion film with sufficient strength (for actuation) and multimodal sensing capabilities (for sensing) (discussed in following sections).

Mechanical properties of PANSion film

Having studied PANSion material properties at the molecular, nano, and microscale, we continued our studies to probe on macroscale mechanical performance. **Fig. 3a** shows the stretching-releasing of a PANSion film, suggesting a high stretchability and good strain recovery (**Supplementary Fig. 15**). Additionally, no cracks at the microscale were found on optical images taken during stretching (**Supplementary Fig. 16**). The highest stretchability (*i.e.*, failure strain) exceeded 1000% for PANSion of $\phi = 2.0$, which is a >500× improvement of elasticity compared to the control PAN (**Fig. 3b**; and **Supplementary Fig. 17a**). Moreover, Young's modulus (~820 kPa) was sufficiently low and enabled conformal fitting for curved surfaces (**Supplementary Fig. 17b**). On one front, the formation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes produced a structural change of crystallinity, leading to reduction of both strength and modulus (**Supplementary Fig. 17c**),

potentially due to the disorderliness of the viscoelastic PANSion network and its low glass transition temperature (T_g) (**Supplementary Fig. 18**). On another front, the residual solvent, DMF, also inexplicitly promoted PANSion chains' superelasticity as a lubricant (**Supplementary Fig. 19 and Supplementary Table 4**)^{31, 32}. As previously discussed, the energy dissipation owing to mechanical ruptures of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes was again confirmed by the stress-strain hysteresis measured during continuous stretching-releasing cycles from 20% to 300% (**Fig. 3c**; and **Supplementary Fig. 17d and e**). Considering these findings, we estimate that stretching- and releasing-associated network extension-contraction cycles were brought about by the dissociation and reformation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes together with molecular chain straightening (**Supplementary Fig. 20**). To validate this hypothesis, we performed computational calculations *via* first principles to help rationalize the reasoning behind the observed gained stretchability (**Supplementary Text 1**).

Having said that, perceptions on the samples' structural evolutions were carried out using coarse-grained molecule dynamic (CG-MD) simulations, which provided insights on the PANSion chain conformation and dynamics of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes during stretching. Unlike the semicrystalline PAN, the constructed model of PANSion, with an undeliberately regulated AgNPs distribution, showed an amorphous structure that agreed with our experimental observations (**Fig. 3d, Supplementary Fig. 21**). **Fig. 3e** presents the PANSion network's evolution when the applied stretch, ε , was escalated from 1 to 5 (*i.e.*, 100 to 500%). The network extension and sliding can justify the superelastic properties of the PANSion film (**Supplementary Video 1**). Concomitantly, chain alignment was also monitored (**Fig. 3f**), where a larger strain produced a higher alignment degree, corresponding to a large value of Herman's orientation factor ($f_{(\text{H})}$)²⁵. For instance, an $f_{(\text{H})}$ value of 0.3427 for $\varepsilon = 1$, while an $f_{(\text{H})}$ value 0.6331 for $\varepsilon = 5$, seems to substantiate our initial hypothesis²³. The non-overlapping of $f_{(\text{H})}$ between the first and second stretching-releasing cycles might also have arisen from the strain hysteresis or reformation of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes at different sites. Intriguingly, no mechanical mismatch of compliance between AgNPs and their surrounding matrix was noted during stretching (**Fig. 3g**), a welcomed finding considering the desired mechanical durability needed for PANSion-based electronics. It must be pointed out that post-added inorganic fillers usually deteriorate the softness or stretchability of the polymer matrix

due to strengthening effects. In contrast, PANSion with *in-situ*-grown AgNPs still exhibited low modulus and sufficient strength with high elasticity.

On a final note, we mapped the density distribution of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes at different strains, which seemingly does not seem to change (**Fig. 3h, Extended Data Fig. 4**). Such a phenomenon can be attributed to the dynamics of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes during stretching, where dissociation and reformation prevail simultaneously. Over 90% of complex bonds were newly regenerated as strain reached beyond 200% and was even higher for further stretching cycles (**Fig. 3i**). In brief, the obtained stretchability of PANSion can be ascribed to the introduction of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes that bring disorderliness and dynamic network entanglement alongside dissociation-reformation events. Together with percolation conductivity from *in-situ*-grown AgNPs, these two synchronous features encourage PANSion's use in soft and stretchable electronics, as well as in soft robotics as functional artificial tissues.

Multimodal sensing of PANSion for soft electronics

As a proof-of-concept, we first explored the piezoresistive sensing using PANSion film (**Supplementary Text 5**), taking advantage of its softness (~ 820 kPa in modulus), stretchability ($\sim 1200\%$ strain), and conductivity (0.076 S m^{-1}) (**Supplementary Figs. 22–25**). The PANSion sensor was implemented to monitor various body movements such as elbow bending, foot walking, and finger wagging with an acceptable sensitivity, good stability, and fast response (85 ms for responding and 0.5 s for recovering) (**Fig. 4a–b, Supplementary Figs. 26–28**). Taking a further step, PANSion solutions (*i.e.*, 10 wt% of PAN, $\phi = 2.0$) can be utilized for dip-coating on flexible substrates (*i.e.*, fabrics), yielding sensing textiles that can be used for motion detections (**Supplementary Fig. 29–32**, while still maintaining their original softness and stretchability (**Fig. 4c top, Extended Data Fig. 5**). Intriguingly, this versatile application was further endorsed by the direct spinning of PANSion fibers in the air, attainable when its viscosity was appropriately tuned (**Fig. 4c bottom**). As one subject of our future studies, PANSion fiber, inheriting stretchability, conductivity, and sensitivity from its film antetype (**Extended Data Fig. 6**), could provide a platform technology to be used as a basic building block for intelligent textiles^{33, 34}.

Furthermore, PANSion's multistimuli response properties were examined, showing two sensing modes of capacitive and piezoresistive mechanisms (**Supplementary Text 6**; and **Supplementary Fig. 33–34**). **Fig. 4d** illustrates the device structure with two electrodes and its corresponding sensing mechanisms when subjected to physical touch, thermal exposure, and mechanical disturbances that represent three primary natural stimuli that biological tissues encounter every day. After conformally wrapping a prosthetic finger with a PANSion film as e-skin (**Fig. 4e**), capacitance-modal sensing could be exploited to identify the presence of a pulse or static touch (**Fig. 4f**; and **Supplementary Video 2**), and even differentiate between different touch sources, depending on signal features (i.e., metal bar and human finger, **Fig. 4f** inset). Such a platform could bestow robotics components skin-like intelligent proprio- and exteroceptive capabilities, especially when coupled alongside specific machine learning algorithms used for signal analysis (**Supplementary Fig. 35**). Resistance-modal sensing is suitable for detecting thermal disturbances. Thus, PANSion e-skin can be used to allow a prosthetic finger to “feel” nearby cold or warm objects (**Supplementary Fig. 36–37**), including human respiration, as associated to body-temperature exhaled breath detection (**Fig. 4g–h**; and **Supplementary Fig. 38, Supplementary Video 2**). Note that one limitation for the current design is the detection of objects with a thermal profile similar or close to that of PANSion e-skin (i.e., the environment temperature) when approached or even contacted³⁵.

Additionally, we demonstrated PANSion e-skin's ability for finger touch behavior differentiation, including simple touch (gentle contact in the form of a thermal stimulus), as well as touch-and-stretch (full contact as thermal and strain stimuli) (**Fig. 4i**). A resistance drop occurred when the human finger (thermal source, ~36.5 °C) came into proximity with the PANSion e-skin. This is shown as the “touch” stage in **Fig. 4j**. A plateau of resistance change took place when performing the “touch and hold” stage because the thermal exchange reached equilibrium (**Supplementary Fig. 39**). If any strain stimuli (i.e., stretch or shear) are practiced during touch, PANSion e-skin can also perceive that mechanical disturbance as portrayed by distinct electrical signals, including small and large stretches (**Fig. 4j** inset). Such multifunctionality of PANSion e-skin based on multimodal sensing mechanisms enables versatile applications for soft and stretchable electronics onto the human body, as well as in robotic systems.

Self-sensing actuator using PANSion membrane

In addition to the aforementioned applications, we also explored PANSion's potential as a sensorized pneumatic actuator for soft robotics applications (**Supplementary Text 7**). It is worth highlighting that our PANSion actuator, benefiting from *in-situ*-grown AgNPs, is self-sensing, a feature usually absent for previously reported cases, or which requires additional post-treatments to be achieved (*e.g.*, surface conductive coating)^{5, 12, 19}. **Fig. 5a** illustrates the actuator design where a PANSion membrane was connected to a cone-shaped pneumatic circuit at the perimeter. Pressure within the chamber was increased ($\Delta P > 0$) to activate the actuator, resulting in PANSion membrane deformation with a displacement (Δd) and output force (F) (**Fig. 5b**). Here the applied strain (*i.e.*, areal strain) on the PANSion actuator due to pressure change was two-dimensional (2D) instead of 1D. The actuation performance was analyzed by plotting displacement, output force, and areal strain *versus* pressure (**Fig. 5c**, and **Extended Data Fig. 7**). In the current design, the displacement could reach ~20 mm (~184% areal strain) for outward direction ($\Delta P > 0$) with a maximum output force at ~3.6 N. Similar actuation performance was observed for inward direction ($\Delta P < 0$). When being actuated, the displacement characteristics, including amplitude (large/small) and frequency (high/low), were readily detected by monitoring the PANSion's piezoresistive behavior (**Fig. 5d and e**; **Supplementary Fig. 40** and **Supplementary Video 3**). These electrical signals could be further collected as inputs to enable a more dedicated control on PANSion actuators for specific tasks in future studies.

Concept validation of using a self-sensing PANSion actuator as an artificial muscle was also demonstrated for weight-lifting tasks, where a negative pressure ($\Delta P < 0$) was applied, resulting in an inward displacement (**Fig. 5g**). **Fig. 5h** presents snapshots of a sample used to lift a 50-g load to a height of ~15 mm (**Supplementary Video 4**). Remarkably, this setup could also lift a 100-g load cyclically (**Supplementary Video 5**), a load at least 3700× its own weight. With this pneumatic design, the PANSion actuator exhibited a maximum specific work of at least 350 J·kg⁻¹ (**Fig. 5j**) and power density of ~467 W·kg⁻¹ that were comparable with those of other state-of-art soft actuators based on synthetic materials, even surpassing natural tissues (**Extended Data Fig. 1**, and **Supplementary Table 1**). By controlling pressure, natural actuation patterns from muscles could be reproduced on our PANSion actuators, such as lifting-releasing, lifting-holding, and lifting-controlled releasing (**Supplementary Video 5**). What may attract more attention are

the distinct electrical signals obtained when performing different actuation behaviors (**Fig. 5i**, and **Supplementary Fig. 41**) or manipulating objects at different temperatures (**Fig. 5k–m**; and **Extended Data Fig. 8** and **Supplementary Video 6**). These could indeed be harnessed, as preliminary inputs of proprioception and exteroception signals, to monitor and control robotics' activity deliberately. For instance, **Fig. 5f** exhibited recognizable signals for actuation with and without loads that could be explored to endow robotics with sensing capabilities similar to that of biological tissues incurred when performing weight-lifting of large ("heavy"), small ("light"), and zero ("feather") loads. Such seamless unification of sensing and actuation in a single homogeneous material system is a necessary step toward achieving closed-loop feedback control of soft robots, machines, and haptic devices.

Outlook

In addition to *in-situ*-grown AgNPs and $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ coordination complexes, we report a silver-polymer-framework-based elastomer that is conductive, soft, stretchable, yet sufficiently strong. Dual functions in a single homogeneous material platform were realized on PANSion: multimodal sensing based on capacitive and piezoresistive mechanisms (for e-skin and other body-integrated electronics with conformal fitting) and sensorized soft actuator (for intelligent robotics with life-like sensing capabilities). PANSion technology represents one of the many steps for artificial materials with seamless integration of sensation and actuation capability on the path towards reproducing full sensorimotor-like functions natively found in biological tissues. The material we present can respond only to mechanical and thermal stimuli while actuating; what remains an opportunity is the inclusion of other sensing capabilities such as perspiration, gustation, etc.

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Methods

Materials. Polyacrylonitrile (PAN, average M_w 150,000), *N, N*-Dimethylformamide (DMF, 99.8%), silver nitrate (AgNO_3 , ACS reagent, $\geq 99.0\%$), calcium chloride (CaCl_2 , anhydrous, powder, $\geq 97\%$), magnesium sulfate heptahydrate ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, ACS reagent, $\geq 98.0\%$), zinc chloride (ACS reagent, $\geq 97.0\%$), iron (II) chloride tetrahydrate ($\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$, reagent grade, $\geq 98.0\%$), copper(II) sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, ACS reagent, $\geq 98.0\%$), were purchased from Sigma-Aldrich. All chemicals were used as received without any post-treatment.

Preparations of PANSion solutions and free-standing film. DMF was used as a solvent to obtain a well-dissolved PAN solution first (Hotplate/Stirrer, VWR, 500 rpm for 24 h), of which the base concentration was fixed at 2 wt%. All PANSion solutions were prepared by adding varying amounts of AgNO_3 into the PAN solutions mentioned above (stirring for 0.5 h). In this study, the weight ratio of AgNO_3 :PAN, ϕ , was adjusted from 0.5 to 2.0 (**Supplementary Text 1**, and **Supplementary Table 3**). The control sample included the 2 wt% PAN solution ($\phi = 0$). PANSion solutions were contained in sealed vials for observing the PANSion gelation transition. To obtain free-standing PANSion film, a specific volume of PANSion solutions (*e.g.*, 10 mL) was transferred into a PTFE mold for thermal drying (oven heating at 55 °C), where the temperature was intentionally controlled.

Conductive atomic force microscopy (C-AFM). Thin PANSion films prepared by drop-casting (200 μL) on silicon wafers with subsequent oven drying (at 55 °C) were used for C-AFM measurements. All tests were performed on a Bruker Dimension Icon Scanning Probe Microscopy (Bruker Nano Surfaces Division, Singapore), equipped with a cantilever of a resonance frequency of ~ 20 kHz, spring constant at 0.4 N m^{-1} , and probe tip radius at $\sim 20\text{--}50$ nm. During C-AFM scanning, both topography and current mapping results could be obtained. For PAN ($\phi = 0$) and PANSion of $\phi = 0.5, 1.0$, and 1.5 , a fixed bias of 150 mV was applied. Note that an external resistor was loaded as a current divider for $\phi = 2.0$ (since it was relatively more conductive than other samples) to avoid heat accumulation at the probe. All measurements were conducted at room temperature of ~ 23 °C.

AFM-based single-molecule force spectroscopy (AFM-SMFS). Atomic force microscopy-based single-molecule force spectroscopy (AFM-SMFS) experiments were performed on

Nanowizard 4 AFM (JPK Germany) at room temperature ($\sim 25^\circ\text{C}$). AFM cantilever (MLCT-Bio-DC, Bruker, United States) with a spring constant (k) of $\sim 40\text{ pN nm}^{-1}$ was used. The equipartition theorem was used to calibrate the k of each cantilever in solution with an accurate value before the experiment. Both PAN and PANSion solutions in sealed vials were subjected to heating at 55°C for 48 hours before the test. An evaporation blocker was used to prevent solvent evaporation, thus maintaining a stable test condition by minimizing the air disturbance. Typically, an $800\text{ }\mu\text{L}$ solution was added on a clean glass coverslip for AFM-SMFS measurement. First, the cantilever contacted the surface with an indentation force of $\sim 1\text{ nN}$ for 1 s and randomly picked up a molecule. Then, the cantilever moved up vertically in which the captured PNA or PANSion molecule was stretched. Finally, the molecule broke upon further stretching leading to a rupture force peak in the force-extension curve. The data analysis was carried out using the program Igor Pro 6.12 (WaveMetrics Inc.). The curves were fitted with the worm-like-chain (WLC) model of polymer elasticity.

Coarse-grained molecular dynamic (CG-MD) simulation. As illustrated in **Supplementary Fig. 24a**, in the CG model of PAN, each bead, named type A, represents a monomeric unit of PAN. An Ag^+ ion was modeled along with a NO_3^- as one bead, assigned as type B. The cluster of Ag was modeled as a spherical rigid body of 3 nm that was uniformly packed by 60 C beads at the surface. The residual solvents are implicated in our model system. The force field of the CG PAN model was developed based on that of the CG PVA (polyvinyl alcohol) model, which was built up previously³⁶⁻³⁸. Specifically, the potential functions and the parameters of intramolecular interactions in the PAN model are set the same as that of PVA since the two polymers share the same backbone. The parameters of inter-molecular non-bonded interactions are refitted according to the binding energies calculated by density functional theory between PAN and PAN and between PAN and Ag^+ ion. With the force field, the simulated crystallinity of pure PAN (48%) smaller than that of PVA (56%) was reasonable³⁹. The degree of crystallization was evaluated by the ratio of beads with the value of Q_6 exceeding 0.2 ⁴⁰. The CG simulations use a set of reduced units where the length unit was $\sigma_0 = 0.52\text{ nm}$, corresponding roughly to the diameter of PAN repeat unit, the energy unit was $\epsilon_0 = k_B T$ with $T = 550\text{ K}$, and the mass unit was the mass of PAN repeat unit, i.e., $m = 53\text{ amu}$. The time unit was thereby estimated as $\tau_0 = 1.63\text{ ps}$. The non-bonded interactions between CG beads are given by Lennard-Jones (9-6) potential

$$V_{LJ}(r) = 6.75\epsilon_{ij} \left[\left(\frac{\sigma_{ij}}{r_{ij}} \right)^9 - \left(\frac{\sigma_{ij}}{r_{ij}} \right)^6 \right], \quad (1)$$

where r_{ij} was the distance between bead i and bead j , the interaction parameters ϵ_{ij} and σ_{ij} are listed in **Supplementary Table 5**. This potential was cut off at $r_{\text{cut}} = 3.0 \sigma_0$ under NPT ensemble (at 1 atm). The harmonic potential was employed to describe bond stretching interactions,

$$V_{\text{bond}}(r) = \frac{1}{2} K_{\text{bond}} (r - r_0)^2, \quad (2)$$

where $r_0 = 0.5 \sigma_0$ and $K_{\text{bond}} = 2704 \epsilon_0/\sigma_0^2$. The angle bending interactions for PAN molecules are described by a numerical potential given by ref.³⁷, which was obtained by bottom-up coarse-graining from all-atom simulations.

Electrical conductivity and sensing performance characterization. Electrical conductivity was assessed using the two-wire method using Keithley Model 2450. The resistance change ($\Delta R/R(\%)$) vs. strain was obtained by continuously recording the resistance data while stretching the PANSion film using a linear motor. The stability of resistance change at 200% strain was assessed by holding the strain for ~30 min. The piezoresistive sensing performance of PANSion film was assessed using a linear motor to apply specific strains (from 1% to 400% strain) while recording resistance data. At each testing strain, at least 10 cycles were repeated. PANSion film was attached to the corresponding body region such as finger joint, elbow, and ankle joint for motion detections. PANSion coated fabric was sewed into a sleeve around the elbow area so that it could easily monitor the elbow bending motion. PANSion fiber was demonstrated to be strain sensitive by hand-stretching while fixing the fiber's two ends. A prosthetic finger wrapped with PANSion film as an artificial "skin" to detect different stimuli was demonstrated where capacitance mechanism ($\Delta C/C(\%)$) was applied for touch detection, including metal bar and a human finger. Cold (~2–5 °C) and hot water (~70 °C) in a vial were used as thermal stimuli to validate the temperature detection capability. Expiration was directed to the prosthetic finger for breathing out detection.

Self-sensing actuation characterization. A pneumatic-mechanism-based actuator was built for the application demo of PANSion since this type of actuator was well investigated and has broad applications such as object grasping, transferring, and weight-lifting. A PANSion membrane was connected to the periphery of the cone-shape chamber ($\varnothing = 50$ mm), constituting a single-chamber actuator. The pressure, indicated by a DP-101-E-P Panasonic pressure sensor, was adjusted controllably, leading to the PANSion membrane displacement (extracted manually from the video

footage) with an output force (detected by a load cell from Trancell Technology inc., model BAB-10M). Thus, the relationship between displacement, output force, and areal strain of the PANSion membrane with pressure was derived. A dead load of 50 or 100 g was glued to the PANSion membrane via sticky tape (the contact area between tape and membrane was small, at $\sim 20 \text{ mm}^2$). An electrical signal ($\Delta R/R$) was recorded simultaneously while performing the weight-lifting task where specific energy and areal strain were calculated based on the lifting height (*i.e.*, displacement, Δd). For object manipulation (*i.e.*, transferring) application, a soft and self-sensing gripper was designed using a two-chamber configuration (cylinder-shaped, **Supplementary Fig. 49a**).

Data availability

All data are contained within the manuscript. Raw data are available from the corresponding authors upon reasonable request.

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Author contributions

S.Z., S.C.T., and J.C., conceived the idea for PANSion. S.Z., Y.-L.Z., S.C.T., and J.C. designed the research. S.Z. developed the materials and methods for PANSion. Y.D. and P.Z. conducted the SMFS experiment and analysis. S.Z. characterized the morphology property of AgNPs. W.S. designed and conducted C-AFM characterization. J.Y. and L.Y. conducted XRD, DSC, and TGA analysis. Y.-L.Z. conducted DFT calculation and MD simulation. S.Z. designed the rheological measurements and conducted UV-vis spectrum absorbance analysis. All authors wrote the manuscript.

Competing interests

A patent invented by S.Z. and S.C.T. is under application.

Additional information

Supplementary information is available for this paper.

Fig. 1 | Schematic of the structure design and mechanical properties of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes. (a) A schematic of natural tissue with muscle spindle (receptor) well distributed within the fiber-reinforced muscle. (b and c) Schematics of conductive elastomers based on (b) a typical metal-ligand complex with post-added fillers and (c) the proposed silver-nitrile coordination complex with *in-situ*-grown AgNPs. (d) FTIR spectra (left) of PAN and PANSion showing different chemical environments of nitrile groups and schematics (right) for primary molecular interactions within the PANSion network. (e and f) Representative force-extension curves of PAN and PANSion chains at the single-molecule level (e) and the stretchability of the PANSion chain facilitated by $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes (f). (g) Apparent viscosity of PANSion solutions with various ϕ values. Gelation significantly increased the viscosity ($\phi = 2.0$). (h) Oscillation-strain-dependent (1–2000%) modulus changes of PANSion gel ($\phi = 2.0$, $\omega = 0.628 \text{ rad}\cdot\text{s}^{-1}$, 25°C),

594 showing a broad viscoelastic regime with a yielding strain beyond 100% (cross-over point at
595 ~300%, yellow scatter-line curves). Green scatter-line curves present the mechanical responses of
596 liquid-like gel (cross-over point at ~1200%). (i) Step-strain oscillatory rheology of PANSion gel
597 ($\phi = 2.0$, $\omega = 0.628 \text{ rad}\cdot\text{s}^{-1}$, 25 °C, 5 cycles). At 1% strain, storage modulus (G') is leading over
598 loss modulus (G''). After increasing to 1000% strain, both G' and G'' respond rapidly and can
599 nearly alternate to their initial values when strain is back to 1%, demonstrating good recyclability.
600 (j and k) Gel time of PANSion solutions ($\phi = 2.0$) as a function of heating time (j) and temperature
601 (k).

Fig. 2 | Conductive PANSion from *in-situ*-grown AgNPs. (a) Schematic of PANSion film preparation. (b) UV-vis spectra of PANSion solutions ($\phi = 2.0$) with an absorbance peak at 422 nm due to the localized surface plasmon resonance effect of AgNPs. (c and d) SEM images showing the morphologies of (c) PAN (scale bar, 2 μm) and (d) PANSion (scale bar, 5 μm) films. Dashed line in (d) indicates the edge between a surface (right) and fracture cross-section (left). (e) Through-thickness elemental distribution of PANSion based on EDS linescan profiles. (f) TEM image of a AgNP embedded PANSion matrix (scale bar, 5 nm). Inset shows a histogram of AgNP size (i.e., diameter) distribution (averaged at ~ 10 nm). (g) Current mapping results at various ϕ values, by conductive atomic force microscopy (C-AFM, scale bar, 200 nm), showing the evolution from an insulative status ($\phi = 0$) to a conductive percolation network ($\phi = 0.5$ to 2.0) because of *in-situ*-grown AgNPs.

Fig. 3 | Mechanical properties of PANSion film. (a) Images showing the high stretchability and recovery capability. Scale bars, 1 cm. (b) Stress-strain curves for $\phi = 0.5$ to 2.0. (c) Cyclic stretching-releasing from 20% to 300%. (d) Constructed model of PANSion film *via* CG-MD simulation with a dimension of 20×20×20 nm³. Green, dark orange, and light grey represent PAN chains, Ag⁺, and AgNPs, respectively. (e) Snapshots of network evolutions at various stretches (ϵ). Insets show the alignment effect of the PANSion chain at $\epsilon = 1, 3$, and 5. (f) Herman's orientation factor ($f_{(H)}$) as a function of strain (in %) during two stretching-releasing cycles. (g) Strong interactions between AgNP and its surrounding PANSion matrix showing no delamination during stretching. (h and i) Density distribution of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ complexes (h, scale bar, 1 nm) and the ratio of regenerated complex bonds (i) under stretching, indicating the dynamic process of dissociation-reformation.

Fig. 4 | Multimodal sensing of a single-layer PANSion electronic skin. (a) Finger flexion recognition of both small-to-large angles, slow-to-fast frequencies, and continuous bending variations. (b) Response and recovery time of PANSion film under a 10% cyclic strain. (c) Demonstrations on PANSion versatility, including solutions for dip-coating on textiles (top, scale bar, 500 μm) and direct-spun fiber as a functional unit for sensing fabrics (bottom, scale bar, 10 cm). (d) Schematic of PANSion-based multimodal sensor for various stimuli sensing, including gentle touch, strain, and temperature. (e–h) A prosthetic finger wrapped with PANSion film (e, scale bar, 4 cm) and its responding signals to touches from a metal bar or human finger (f), and its capability for breathing detection (g, scale bar, 3 cm), including long and short expirations (h). (i) Schematic (left) and images (right) showing the human finger touch and stretch on PANSion “skin”. Scale bar, 1 cm. (j) Real-time monitoring signals of the touch-stretch actions by a human

638 finger (temperature and strain stimuli). Enlarged area shows the stretch of both large and small
639 mechanical disturbances.

Fig. 5 | Self-sensing PANSion actuator. (a) Schematic of the pneumatic actuator using a PANSion film and a cone-shaped holder. (b) Pressure changes within the actuator's chamber

643 resulting in the PANSion film deformation with a displacement (Δd) and output force (F). (c) The
644 displacement and output force as a function of applied pressure, reaching the maximum (inward
645 and outward) of ~18–21 mm (~140% areal strain) and ~3.8 N. (d and e) Sensing signals from the
646 PANSion actuator when performing both (d) small/large deformations (*i.e.*, amplitude) and (e)
647 slow/fast actuation (*i.e.*, frequency). (f) Sensing signal comparison of actuation with and without
648 loads at both small and large displacements. (g) Schematic of using self-sensing PANSion actuator
649 as an artificial muscle. (h) Images showing a lifting-releasing cycle of a 50-g weight. Scale bar,
650 2cm. (i) Real-time sensing signals from the artificial muscle, implying the actuation procedure and
651 behaviors. (j) Output specific work, resistance change, and areal strain while performing a weight-
652 lifting task at different displacements. (k–m) PANSion-actuator-based soft gripper for object
653 manipulation (k) and the corresponding electrical signals when transferring objects of different
654 temperatures (l and m).

*Note: fast (<100 ms), medium (100-1000 ms), n/a (not mentioned)

Extended Data Fig. 1 | Comprehensiveness of PANSion in properties of sensing and actuation. Radar plot of the performance matrix of PANSion film comparing to other engineering soft actuators in terms of sensing and actuation properties.

Extended Data Fig. 2 | PAN/metal ion composite films. **a**, PAN solutions (in DMF) with six different metal ions including calcium (Ca^{2+}), magnesium (Mg^{2+}), zinc (Zn^{2+}), iron (Fe^{2+}), copper (Cu^{2+}) and silver (Ag^{+}). **b–g**, PAN/metal ion composite film in a petri dish (left) and the corresponding fracture morphology. All composite films are brittle and easily broken (b–f) except the one with silver ion (g). PAN/silver ion composite film (namely, PANSion film) is soft and stretchable.

Extended Data Fig. 3 | Mechanical properties of $[\text{Ag}(-\text{C}\equiv\text{N})_x]^+$ characterized by AFM-SMFS.
a, Phase separation of PAN and PANSion solutions after an air exposure. **b–e**, Representative force-extension curves of PAN and PANSion chains. **f** and **g**, Schematic of the stretching-releasing process via AFM-SMFS for (f) short-chain molecule and (g) long-chain molecule.

Extended Data Fig. 4 | Mappings of the number of coordination bonds of PANSion film under stretching. No obvious difference in the total coordination bonds was observed when the strain was increased from 0 to 5.

Extended Data Fig. 5 | PANSion solution coated PU fabric. **a**, A PU fabric before and after PANSion solution coating: (i) original PU fabric (left) and the one after coating (right); (ii and iii) enlarged area showing the knitting structure before (ii) and after (iii) coating; (iv) SEM image of the coated fabric, showing the yarn structure without any aggregation of PANSion polymer. **b**, The knitted PU fabric after PANSion solution coating is still as flexible as the uncoated one, demonstrating no changes to the mechanical properties of the original fabric. **c–e**, Good wearing properties are still retained, including twistability, foldability, and drapability. **f**, Sensing property of the coated PU fabric at strain from 5 to 50%.

Extended Data Fig. 6 | PANSion fiber spinning and fiber's sensing property. **a**, The spinnability of PANSion solution ($\phi = 2.0$) with a different base concentration of PAN. After storing PANSion solutions at room temperature for several days, the viscosity of solutions is different from each other. 10 wt% and 12 wt% PANSion solutions possess suitable viscoelastic properties for direction fiber spinning, as demonstrated by the continuous dope dripping from a plastic pipette. **b**, The dripping test of 10 wt% PANSion solution from a height of ~ 8 cm (left) shows good flowability and spinnability. A single fiber can be directly drawn from a PANSion dope in the air without any post-treatment. **c**, Optical image of a PANSion fiber with a diameter $\sim 90 \mu\text{m}$. **d** and **e**, Sensing property of PANSion fibers. The as-spun PANSion fiber is as stretchable as the PANSion film. Interestingly, the electromechanical sensing property is also retained. It displays distinguishable resistance change responses for various external strains (d) with decent response time (e).

Extended Data Fig. 7 | Displacement (mm) and area strain (%) as a function of applied pressure. a, Schematic of how the area strain was calculated (supplementary text S7). **b**, Results of displacement and area strain when pressure was changed accordingly.

Extended Data Fig. 8 | Soft gripper using self-sensing PANSion actuator and its application for object manipulation. **a**, The schematic of the pneumatic circuit design for a soft gripper based on a self-sensing PANSion actuator (left) and the digital image of the gripper (right). **b–d**, The thermal and digital images showing that the self-sensing actuator-based gripper is transferring various objects: room temperature object (b), cold object (c), and warm object (d). **e**, The corresponding real-time electrical signals from the gripper can be further used as input for smart robotics to distinguish the thermal profile of the transferred object.

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