

Teleoperation of Soft Robots with Real-Time Fingertip Haptic Feedback Using Small Batteries

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Soft robots are promising candidates for robust grasping and manipulation of different types of objects; however, their development has been a scientific challenge because of the lack of compact, yet precise, controllable soft actuators. In this work, innovative haptic interactive systems based on sensor-integrated actuators powered by small batteries are reported. A liquid-metal strain sensor with a versatile form factor and robust sensing performance is incorporated into a fast-switching high-force ionic polymer actuator. The structure of the sensor-integrated actuator is rationally designed through encapsulation technology to achieve the best sensitivity and actuation while maintaining compactness, allowing for accurate, real-time estimation and tracking of the actuation process. In a closed loop between the user and sensor-integrated actuator, the motion and manipulation dynamics of a soft gripper made of sensor-integrated actuators can be controlled by hand motions during a task. By combining with a thimble-type haptic feedback device, the states of the gripper can be transmitted back to the user in real-time via the proprioception of the integrated sensor. The approach opens a prospective avenue for the development of future robotic technologies without requiring camera-based sensors for versatile, wearable, and scalable haptic systems.

robotic manipulators and sophisticated, integrated perception and control.^[3] Soft robots are preferred over their rigid counterparts for grasping and manipulating different types of objects, owing to their flexibility and ease of scalability into various small shapes and sizes.^[4] There has been considerable research on soft robotics in the past few decades, with remarkable advancements in producing artificial muscles,^[5] biomimetic devices,^[6] and wearable electronics.^[7] Soft actuators are key components of soft robotics. They undergo mechanical deformation in response to external stimuli such as electricity,^[8–11] light,^[12] heat,^[13] pressure,^[14] and humidity.^[15] Among the various types of soft actuators, electroactive polymer (EAP)-based actuators have unique advantages such as compactness and low weight.^[16] In particular, ionic EAP (iEAP) actuators have recently gained attention for securing wearable characteristics in human-friendly soft robots running on small batteries.

Studies on advancing iEAP actuators have mainly focused on the exploration of innovative EAP materials^[8,11] and diversification of actuator structures,^[17] aimed at developing compact systems with low-power consumption. For example, Park et al. conducted a series of studies that addressed several challenges: 1) superfast switching response of tens of milliseconds at 1 V for iEAP actuators based on single-ion conducting polymers,^[8] 2) low-voltage-driven linear motion from iEAP actuators designed in multilayer structures with meticulous control of ion diffusion,^[17] and 3) development of high-force iEAP actuators through the synthesis of superionic polymer electrolytes with high mechanical strength.^[11]

Despite these remarkable achievements, low-voltage iEAP actuators have not yet been used in practical robotic applications. To envisage such soft robots, three important requirements must be met: 1) An iEAP actuator encapsulation technology must be established such that it does not significantly deteriorate the actuation properties,^[18] 2) A self-sensing iEAP actuator should be developed to track the real-time state of actuation,^[19] and 3) All the constituents should be soft, flexible, compact, and thermodynamically compatible for stable actuation during long-term operation. Elastomers have been typically used for encapsulation technology in most wearable elec-

1. Introduction

Grasping, transporting, and deforming objects are easy tasks for humans; making robots perform these tasks, however, requires considerable effort.^[1,2] In particular, manipulating delicate objects on a small scale using robots requires well-designed

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tronics; however, introducing an elastomer material into an iEAP actuator without significantly degrading the actuation properties is challenging because of the nonuniformity in its mechanical properties.

Research has been conducted on developing EAP actuators with self-sensing characteristics based on the interplay between the bending strain and electrical charge across the two electrodes;^[20] however, the driving voltage and measured charge are coupled, resulting in inaccurate real-time estimation.^[21] The integration of an additional sensor into the iEAP actuator can be an alternative, but thus far it is still in its infancy.^[19] Vision sensors (e.g., optical cameras) have been introduced into the iEAP system;^[22] however, the use of external devices limited their applicability to a wide range of systems, such as wearable devices and mobile systems on a small scale. Hence, the self-sensing capability, analogous to proprioception^[23] in biological muscles, of the actuator is highly desirable while maintaining a compact form factor and portability. It is also important for the sensor to accurately estimate the state of the actuator while in contact with an object.^[24]

In addition to real-time sensing capability, a high-level control of sensor-integrated iEAP actuators by users remains a key scientific challenge in the development of intelligent soft robots. This requires closing the sensing–signal processing–actuation loop. The concept of human-in-the-loop^[25] has been widely used in recent robotics technologies for this purpose, including cell manipulation, grasping in cluttered environments, and robotic surgeries, accompanied by an interactive system that provides tactile feedback to users' motion and contact state of robots.^[26] Although various haptic feedback devices composed of rigid and bulky units have been combined with pneumatic actuators, these are cumbersome and not truly wearable.^[27] Haptic devices using EAP actuators have also been investigated, but their scope has been limited to dielectric elastomer actuators (DEAs). Despite the inherent advantages of DEAs, including large strain, high generated force, and fast response, their driving voltage ranges from several hundred volts to kilovolts, requiring additional shielding and voltage converters when used in wearable devices, which impede the compactness of the systems and reduce overall energy efficiency.^[28] A haptic feedback system that can demonstrate real-time control of soft robots using low-voltage iEAP actuators is desired.

Herein, we report the first example of a haptic interactive system teleoperated by a human hand with real-time haptic feedback based on sensor-integrated iEAP actuators. An advanced iEAP actuator was developed through the synthesis of superionic polymer electrolytes^[11] and soft conducting electrodes, demonstrating a bending angle of $>20^\circ$ and force of >1 mN at 2 V and 10 Hz. The sensor-integrated iEAP actuator was rationally designed by introducing conductive liquid-metal-based strain sensors into the iEAP actuator based on the actuation–sensitivity relationship. By identifying the dynamic model of the system, a controller was designed for the actuators to accurately track the trajectories during a task, and a decision algorithm was implemented to determine the contact state of the actuator. Furthermore, we combined a wearable fingertip iEAP haptic device with a dynamic system model to transmit the sensor signal as cutaneous haptic feedback, thus enabling robust grasping by providing accurate information on the interaction.

2. Results and Discussion

2.1. Haptic Interaction System Teleoperated by a Human Hand with Real-Time Haptic Feedback

Figure 1a schematically illustrates haptic interaction systems based on sensor-integrated iEAP actuators and a wearable fingertip iEAP haptic feedback device. To develop soft robots that can be teleoperated by a human hand with real-time haptic feedback from physical contact, we devised a system comprising three main components: a human hand with a sensing glove, soft gripper made of sensor-integrated actuators, and thimble-type haptic device for providing feedback to the fingertip. Each part is connected to another through the interface and cohesively operated inside a closed loop.

The key component in fabricating both the sensor-integrated actuator and the fingertip haptic feedback device is the iEAP actuator. Figure 1b shows the structure of the tri-layered iEAP actuator used in this study, in which a polymer electrolyte layer is sandwiched between two soft electrodes. To enable real-time monitoring of actuator motion, a room-temperature liquid-metal (EGaIn) strain sensor^[29] was integrated into the iEAP actuators using silicone elastomers as protective layers, as depicted in the right panel of Figure 1b (details are provided in Experimental Section and Figure S1, Supporting Information). EGaIn sensors have been used in a variety of soft sensing systems for their stability, repeatability, and linearity in sensing small strains as well as large deformations, and also for notably simple fabrication processes compared to other strain sensing mechanisms.^[30] The same type of EGaIn sensor was used to devise the sensing glove (Figure S2, Supporting Information). When bending the finger while wearing the sensing glove, the sensor signal appears as a change in the electrical resistance, and a tracking control is generated to synchronize the finger motion with the actuator motion. This allows the user to give commands to the gripper, and the states of the gripper can be transmitted back to the user in real-time via the proprioception of the integrated sensor. The haptic iEAP module was attached to the user's thumb, and the cross-sectional images of the haptic modules generated by 3d CAD rendering are shown in Figure S3, Supporting Information.

2.2. Synthesis of a Tailor-Made PS-3H4S Electrolyte

Because the performance of the sensor-integrated actuator is inevitably reduced by the inserted elastomer layers, it is crucial to achieving a high force and large deformation from the iEAP actuator at high frequencies to successfully drive the haptic interactive system. To this end, a tailor-made bifunctional polymer electrolyte was prepared, in which ions can rapidly diffuse into the polymer matrix with high mechanical strength. Figure 2a shows the chemical structure of the polymer electrolyte composed of a bifunctional polymer and an ionic liquid. The 3-hydroxyl, 4-sulfonic acid polystyrene, PS-3H4S, with a molecular weight of 8 kg mol^{-1} was synthesized by aqueous reversible addition-fragmentation chain-transfer polymerization to obtain a narrow molecular weight distribution (Figure S4, Supporting Information). The $-\text{SO}_3\text{H}$ group offers ionic interactions with 1-ethyl-3-methylimidazolium (EMIm^+) cations, whereas the $-\text{OH}$ group enables additional hydrogen bonding interactions with

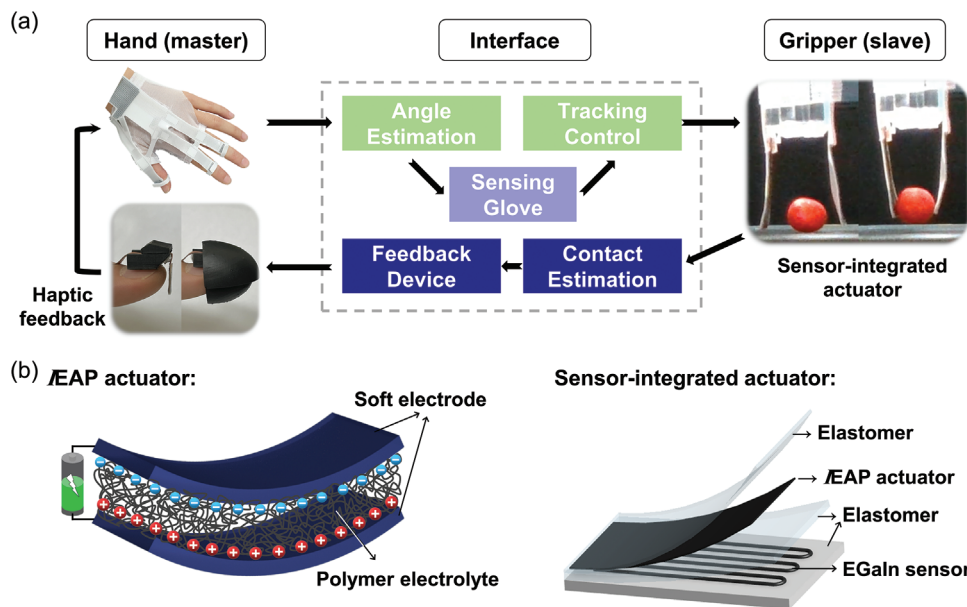


Figure 1. Haptic interaction system based on sensor-integrated actuators. a) Schematics of a haptic interaction system teleoperated by a human hand with real-time haptic feedback. The system comprises a sensing glove, haptic interface, a soft gripper based on sensor-integrated actuators, and a thimble-type haptic device with iEAP actuator. b) Tri-layer structure of the iEAP actuator (left) and the laminated structure of sensor-integrated actuator by elastomer, iEAP actuator, and EGaIn sensor (right).

bis(trifluoromethylsulfonyl)imide (TFSI[−]) anions to facilitate ion dissociation.

The ion transport and mechanical properties of the PS-3H4S electrolytes were controlled by the loading amount of [EMIm⁺][TFSI[−]], which has an inverse relationship, as shown in Figure 2b. Our discussion will focus on the device based on the PS-3H4S electrolyte containing 60 wt.% [EMIm⁺][TFSI[−]], corresponding to 1:1 molar ratio of ionic liquid to [−SO₃H] in PS-3H4S, showing an ionic conductivity of 0.4 mS cm^{−1} and a shear modulus of 3.3 MPa at 22 °C. A further increase in the ionic liquid content in PS-3H4S resulted in an abrupt reduction in the mechanical strength, yielding a non-self-standing electrolyte layer.

The morphology of the PS-3H4S electrolyte was investigated by X-ray scattering experiments. Figure 2c shows scattering profiles of neat PS-3H4S and PS-3H4S containing 60 wt.% [EMIm⁺][TFSI[−]], revealing the formation of 2.3 nm-wide ion channels (d_i) composed of ion clusters at 1.6 nm spacing (d_c). The correlation between TFSI[−] anions (d_a) at a distance of 0.7 nm was also clearly seen, indicative of well-arranged ionic moieties in nanoscale ion channels. The structure of the ion channel (blue) formed inside the polymer matrix (gray) with high mechanical strength is schematically illustrated on the right.

The charge migration kinetics in the PS-3H4S electrolyte is directly related to the switching speed of the corresponding actuator. Figure 2d shows the specific capacitance of PS-3H4S/[EMIm⁺][TFSI[−]] as measured by electrochemical impedance spectroscopy. The results for PVdF-HFP/[EMIm⁺][TFSI[−]], the most commonly used polymer electrolyte in iEAP actuators, are also shown for comparison. Evidently, the specific capacitance of the PS-3H4S electrolyte is considerably higher than that of the PVdF-HFP analog, that is, ≈ 4 times higher at 10 Hz, indicating efficient ion dissociation

and transport in the bifunctional PS-3H4S matrix via effective molecular interactions with the ions.

The improved charge accumulation at the electrode–electrolyte interface using the PS-3H4S electrolyte was further quantified using in situ ATR–FTIR experiments. As schematically depicted in the inset of Figure 2e, the polymer electrolyte is coated with ≈ 20 nm-thick gold electrodes, and a potential of 1.5 V is applied. Upon monitoring the IR absorbance at the positively charged electrode surface, the intensities of SO₂ stretching (1349 cm^{−1}), CF₃ stretching (1184 cm^{−1}), SO₂ scissoring vibration (1133 cm^{−1}), and SN stretching (1053 cm^{−1}) from [TFSI[−]] rapidly increased within 2 s, with the values gradually saturating after 6 s. This is in sharp contrast to the low and gradual increment in the IR signals observed for the PVdF-HFP counterpart (see inset plot, which showed the normalized intensity ratio at 1184 cm^{−1}).

2.3. Actuation and Sensing Characteristics of the Sensor-Integrated iEAP Actuator

We fabricated an iEAP actuator by sandwiching a bifunctional PS-3H4S electrolyte between soft conducting electrodes. PEDOT:PSS was chosen as a model soft conducting electrode, and its conductivity (546 S cm^{−1}), thickness (≈ 12 μ m), and mechanical strength (Young's modulus of 1.5 Pa) were optimized (Figure S5, Supporting Information). The specific capacitance of PEDOT:PSS electrode obtained using PS-3H4S electrolyte was considerably higher than that with PVdF-HFP electrolyte (Figure S6, Supporting Information). Subsequently, a sensor-integrated iEAP actuator was prepared by direct printing of the EGaIn liquid-metal patterns.^[31]

Figure 3a shows the cross-sectional structure of the sensor-integrated iEAP actuator, where the layers of the iEAP actuator

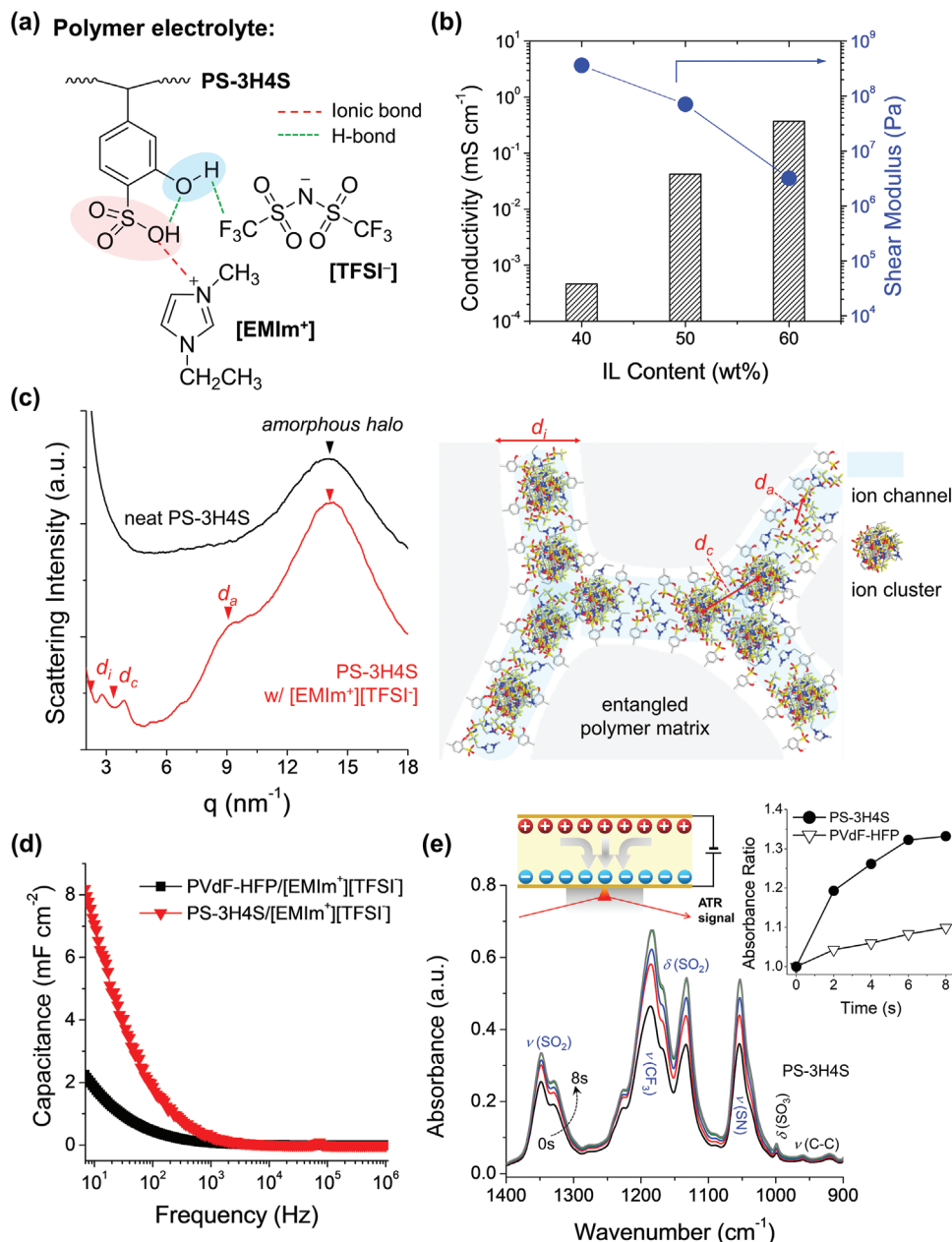


Figure 2. Structure and ion migration in PS-3H4S electrolytes. a) Chemical structure of bifunctional PS-3H4S containing [EMIm]⁺[TFSI]⁻. Possible intra- and intermolecular interactions within the electrolytes are depicted. b) Ionic conductivity and shear modulus of PS-3H4S electrolytes with different [EMIm]⁺[TFSI]⁻ contents. c) X-ray scattering profiles of neat PS-3H4S and PS-3H4S electrolyte at 60 wt.% [EMIm]⁺[TFSI]⁻ loading. Scheme on the right shows the ion channel structure of P3-3H4S electrolyte. d) Capacitance plots as a function of frequency for PS-3H4S and PVdF-HFP electrolytes at 60 wt.% [EMIm]⁺[TFSI]⁻ loading. e) In situ ATR-FTIR spectra of PS-3H4S and PVdF-HFP electrolytes under an applied voltage of 1.5 V. The inset figures show a schematic of the experimental setup and the normalized intensity ratio at 1184 cm⁻¹.

and the EGaIn sensor are embedded in the elastomer matrix. We defined the input voltage (V_{in}) as positive when the actuator bent in the stretching direction of the sensor layer. Therefore, the expansion of EGaIn when $V_{in} > 0$ causes an increase in the resistance ($\Delta R > 0$), whereas the contraction of EGaIn when the actuator bends in the opposite direction results in a decrease in the resistance ($\Delta R < 0$).

To amplify the sensor signal ($\Delta R/R_0$), the inner elastomer layer between the EGaIn sensor layer and iEAP actuator layer was de-

signed to be thick (d) to induce a greater strain (ϵ) at the same bending angle (θ). The bending angle from the vertical axis was measured by tracking the position of the actuator tip (marked by a red circle).

The modulus of the elastomer ($E_{ela} \approx 0.07$ MPa, Ecoflex 00–30, Smooth-On) is considerably lower than that of the iEAP actuator (≈ 650 MPa). Thus, assuming pure bending of the sensor-integrated actuator, its neutral axis ($\bar{y}$) can be approximated to be equal to that of the iEAP actuator layer by the following

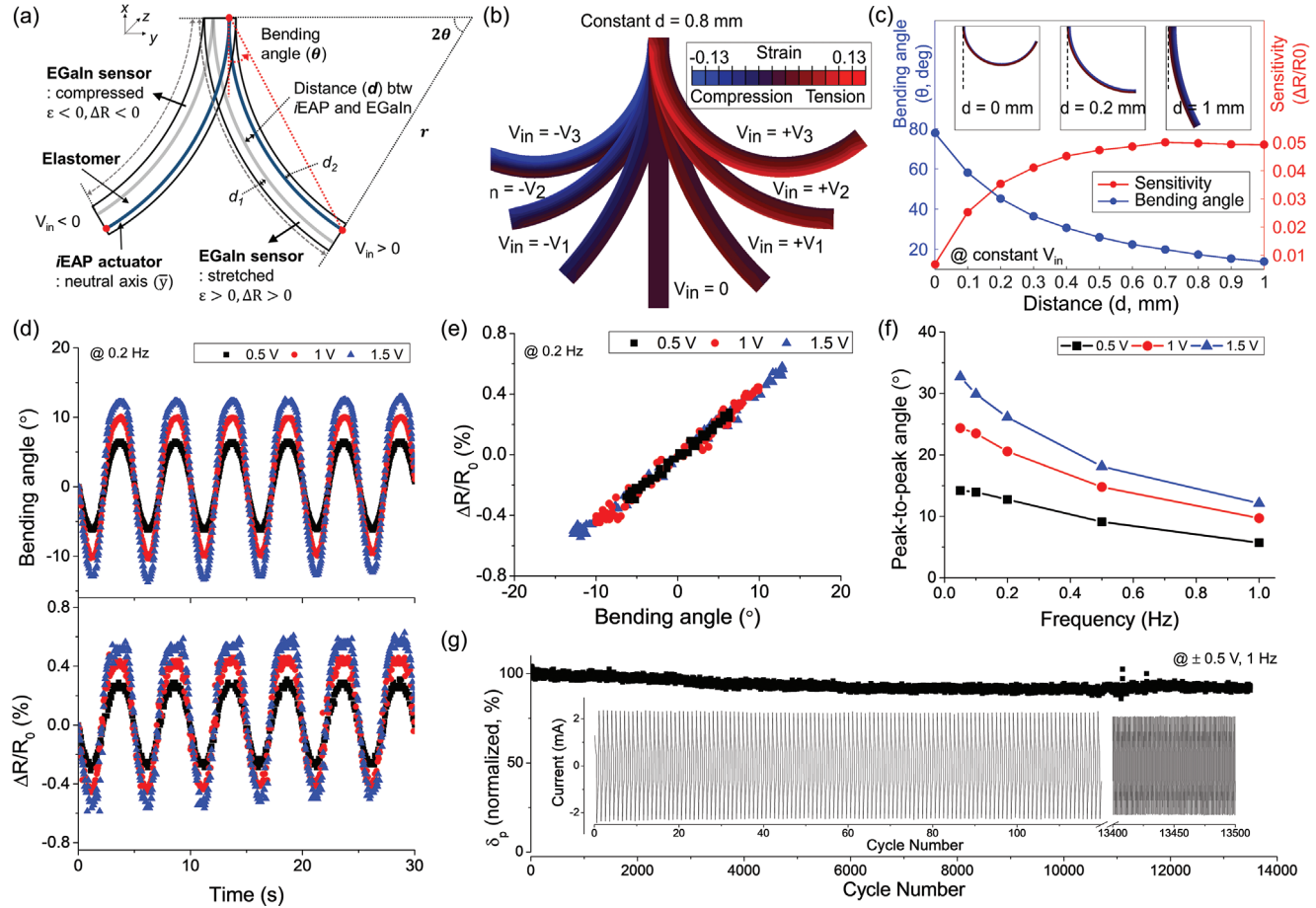


Figure 3. Actuation and sensitivity of the sensor-integrated iEAP actuator. a) Structure and electrical resistance changes of the sensor-integrated iEAP actuator under mechanical deformation. b) Deformation of the sensor-integrated actuator depending on the voltage inputs predicted by finite element analysis. c) Simulated bending angle and sensitivity of the sensor-integrated actuators depending on the d value. d) Time-dependent bending response and sensitivity of the sensor-integrated actuator under sine-wave voltages of 0.5, 1, and 1.5 V at 0.2 Hz. e) Linear relationship of the sensor signal to the bending angle measured under various voltage inputs at 0.2 Hz. f) Peak-to-peak bending angles of the sensor-integrated actuator as a function of the sine-wave voltage frequency. g) Cycling stability of the sensor-integrated actuator at ± 0.5 V and 1 Hz.

equation:

$$\bar{y} = \frac{E_{\text{EAP}} A_{\text{EAP}} \bar{y}_{\text{EAP}} + E_{\text{ela}} A_{\text{ela}} \bar{y}_{\text{ela}}}{E_{\text{EAP}} A_{\text{EAP}} + E_{\text{ela}} A_{\text{ela}}} = \frac{\bar{y}_{\text{EAP}} + (E_{\text{ela}} A_{\text{ela}} / E_{\text{EAP}} A_{\text{EAP}}) \bar{y}_{\text{ela}}}{1 + (E_{\text{ela}} A_{\text{ela}} / E_{\text{EAP}} A_{\text{EAP}})} \cong \bar{y}_{\text{EAP}} \quad (1)$$

Because the thickness of the iEAP actuator ($\approx 50 \mu\text{m}$) is negligible relative to the total thickness ($\approx 0.8 \text{ mm}$), ϵ of the sensor layer is determined by d :

$$\epsilon = \kappa d = \frac{2d\theta}{L_0} \quad (2)$$

where κ is the bending curvature, and L_0 is the actuator length.

The model shown in Figure 3a was verified using finite element analysis (FEA) software (Abaqus, Dassault Systems) (Methods). The detailed method and parameters used in the analysis are provided in Supporting Information. As shown in Figure 3b,

at a fixed d value of 0.8 mm, the iEAP actuator layer is subjected to the lowest strains (i.e., the neutral axis) at any pair of positive and negative V_{in} values. In contrast, the sensor layer underwent the largest deformation (stretching, colored in red; compression, colored in blue) under a given V_{in} . The effect of d on the sensitivity and bending angle of the sensor-integrated iEAP actuator was further investigated. The strain energy (U) of the sensor-integrated iEAP actuator under pure bending with bending moment M can be calculated as follows:

$$U = \frac{M^2 L_0}{2EI} = \frac{(EI\kappa)^2 L_0}{2EI} = \frac{1}{2} EI\kappa^2 L_0 \quad (3)$$

$$I = \int y^2 dA = \int_{-d_2}^{d+d_1} y^2 w dy = \frac{w}{3} \left\{ (d+d_1)^3 + d_2^3 \right\} \quad (4)$$

where E is Young's modulus, I is the area moment of inertia of the actuator, d_1 is the thickness of the elastomer covering the EGaIn pattern, d_2 is the thickness of the elastomer covering the

iEAP actuator, and w is the actuator width. Here, the thickness of the iEAP layer is ignored, and the strain energy can be expressed as:

$$U = \frac{2}{3} \frac{Ew}{L_0} \left\{ (d + d_1)^3 + d_2^3 \right\} \theta^2 \quad (5)$$

Given a constant energy input U_0 (i.e., constant electric energy), there is an inverse relationship between θ^2 and d^3 . Assuming a constant volume of the inner elastomer layer, the sensitivity of the EGaIn strain sensor can be calculated as follows:^[32]

$$\frac{\Delta R}{R_0} = (1 + \epsilon)^2 - 1 \quad (6)$$

Using Equations (2), (5), and (6), the bending angles and sensitivities of the sensor-integrated actuators with different d values in the range of 0–1.0 mm were simulated under a constant energy input. As shown in Figure 3c, with the increase in d , the bending angle decreases, whereas $\Delta R/R_0$ shows the opposite tendency. In other words, the greater distance of the EGaIn sensor layer from the iEAP actuator produced a higher sensitivity but a smaller bending angle. In this study, the d value was optimized to $\approx 350 \mu\text{m}$ to create a sufficient bending angle by the actuation of the thin iEAP actuator and the high sensitivity of the EGaIn sensor layer. The final thickness of each layer in the sensor-integrated actuator is shown in Figures S7 and S8, Supporting Information.

The bending angle and the sensitivity of the optimally designed iEAP actuator were experimentally characterized (Figure S9, Supporting Information). Figure 3d shows the experimental results of the bending angle and the sensitivity of the sensor-integrated iEAP actuators under sine-wave voltages of 0.5, 1, and 1.5 V at 0.2 Hz, demonstrating an excellent real-time change in the resistance to deformation (data measured at different frequencies are provided in Figure S10, Supporting Information). The blocking forces of the iEAP actuators measured at 2 V and 0.2 Hz without and with encapsulation are provided in Figure S11, Supporting Information. Figure 3e further confirms the consistency of the sensitivity under different driving voltages at 0.2 Hz by showing an excellent linear correlation between θ and $\Delta R/R_0$ without hysteresis. Although increasing the frequency of the sine-wave voltages resulted in a reduction in the peak-to-peak angle (Figure 3f), the relation in which the angle increases with V_{in} was maintained. A high peak-to-peak angle of 12° was achieved at 1 Hz and 1.5 V, which is unprecedented for sensor-integrated actuators driven by an iEAP actuator, which constitutes only 6% of the total thickness.

Owing to the excellent flexibility, high electrical conductivity, and high compatibility of EGaIn with silicone elastomers, durable sensor signals with high sensitivity were obtained. This enabled a durable actuation performance for the sensor-integrated iEAP actuator with a stable current flow over 12,000 cycles without significant decreases in the bending performance. Figure 3g shows the representative data obtained at ± 0.5 V and 1 Hz, demonstrating the potential applications of our sensor-integrated iEAP actuator to various programmable soft robots with long-term use. The slight drift of the actuation and the sensor signal is due to the Mullins effect,^[33] which could be easily handled by a simple recalibration since the sensor signal is highly linear to the bending angle (Figure 3e).

The accurate measurement of the actuator motion in real-time by the introduction of a liquid-metal sensor layer enabled active control of the sensor-integrated iEAP actuator by modeling the dynamic deformation and corresponding sensor signal.^[34] For this purpose, the θ and $\Delta R/R_0$ values were sampled under various sinusoidal voltage inputs with different amplitudes and frequencies, which were used to fit the discrete-time linear system model (Figure S12, Supporting Information):

$$\theta_{k+1} = A_d \theta_k + B_d V_{\text{in},k} \left(\frac{\Delta R}{R_0} \right)_k = C_d \theta_k \quad (7)$$

2.4. Tracking Control and Teleoperation

The sensor-integrated iEAP actuator was successfully controlled based on the identified system model to track a predetermined trajectory. Figure 4a shows representative results, where the actuators accurately track the predefined target trajectories (dotted red curves) with various shapes (sine, triangle, square, and random) and frequencies of 0.1, 0.2, and 0.5 Hz. During tracking control, the input voltage was calculated using the model predictive control (MPC) method, which determines the optimal control in a receding time horizon.^[35]

As shown in Figure 4b, the sensor-integrated iEAP actuator is controlled to follow the joint motion of a human finger (see images), measured independently using a wearable sensing glove. The measured signal was transformed to the target bending angle of the iEAP actuator (dotted red curves) using pre-determined mapping in real-time. The calculated bending angles were entered into the controller as a receding reference for each time step. As shown in Figure 4b, the sensing actuator follows the slow (0.03 Hz), step (0.1 Hz), and fast (0.2 Hz) motions of the finger. The delay between the target trajectory generated from the finger and the controlled motion trajectory of the actuator is attributed to the size of the time window of the reference bending angles;^[36] this can be resolved by reducing the window size. However, this will increase the tracking error because the identified dynamics in Equation (7) cannot be fully utilized.

The proposed interactive teleoperation of the sensor-integrated iEAP actuator (Figure 1) requires a closed loop between the user and the sensor-integrated actuator. After the actuator moves according to the user's command, its status must be transmitted to the user again to determine the next command. Taking advantage of the precisely controllable bending deformation of the sensor-integrated actuator, similar to the motion of human fingers, we discuss the results obtained when using it in gripper applications.^[14] In this case, the most important information is whether the gripper holds the object. Encouragingly, without the need to introduce additional sensors, our sensor-integrated actuator can statistically provide contact information, through the proprioceptive strain signal. We established two different system models based on the motion of the sensor-integrated actuator in two ways: free motion and contact phases. These can be distinguished by the strain sensor signal using the interactive multiple model (IMM) method (Details are provided in Supporting Information).^[37]

Figure 5 shows the representative results of the IMM estimation for the three different motions of the sensor-integrated actuator. Unlike the case of free movement without contact

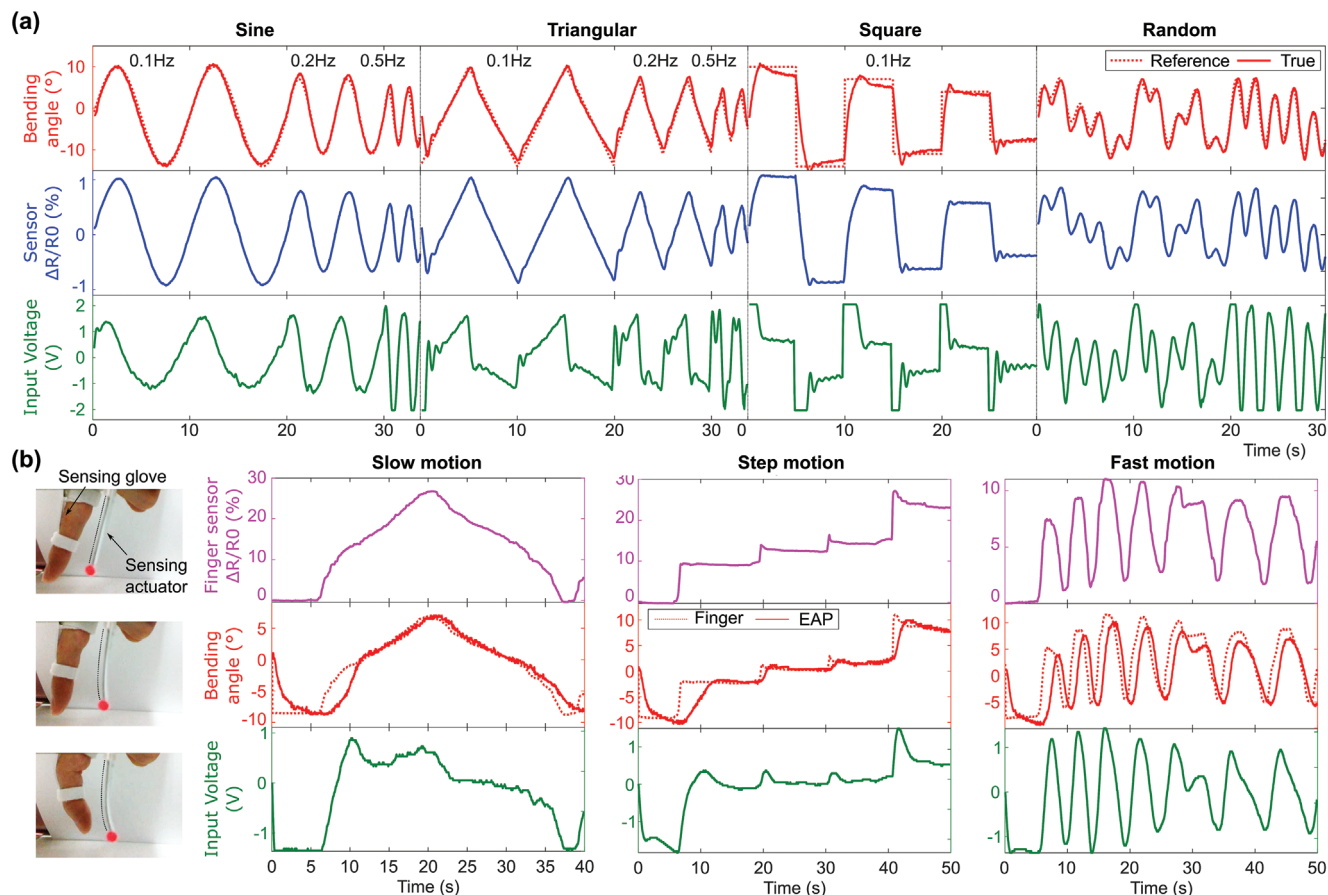


Figure 4. Tracking and teleoperation of the sensor-integrated iEAP actuator. a) Tracking the pre-defined trajectories of various shapes and frequencies. b) Teleoperation with the actuator to follow the motion of a human finger in real-time.

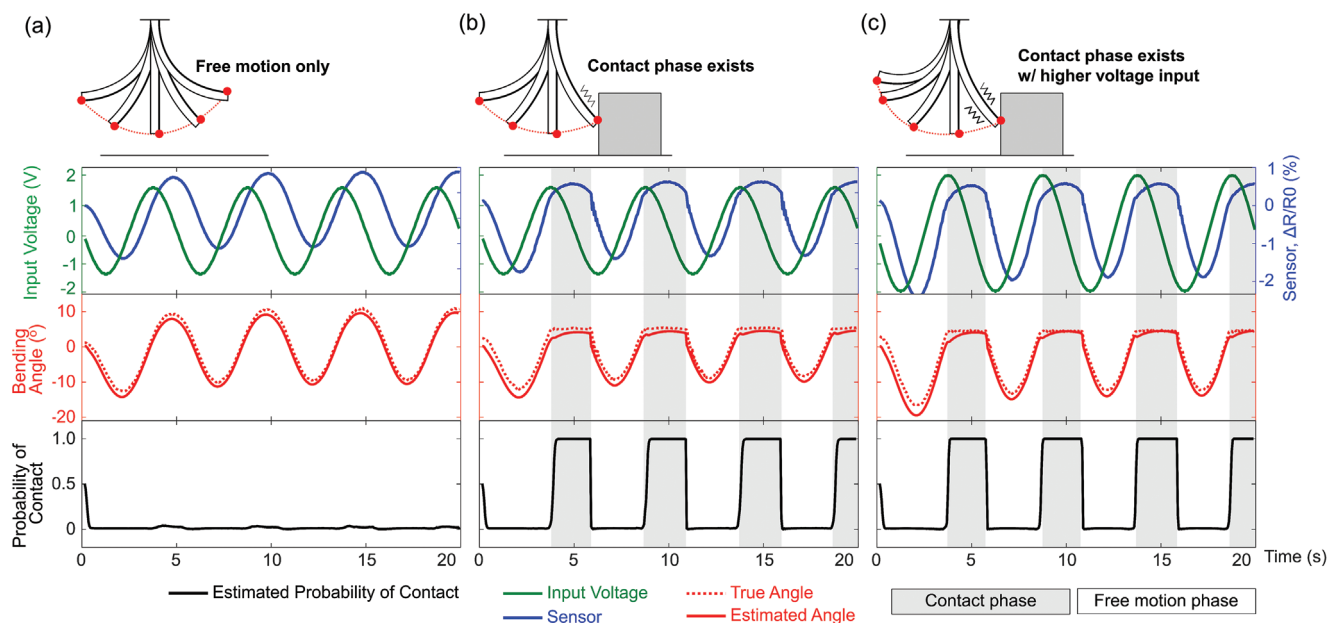


Figure 5. IMM estimation for the motions of the sensor-integrated actuator. Estimating the contact phase of the sensor-integrated iEAP actuator by interactive multiple model (IMM) analysis during a) free motion; b) contacting an obstacle under various input voltages; c) contacting an obstacle under increased input voltage.

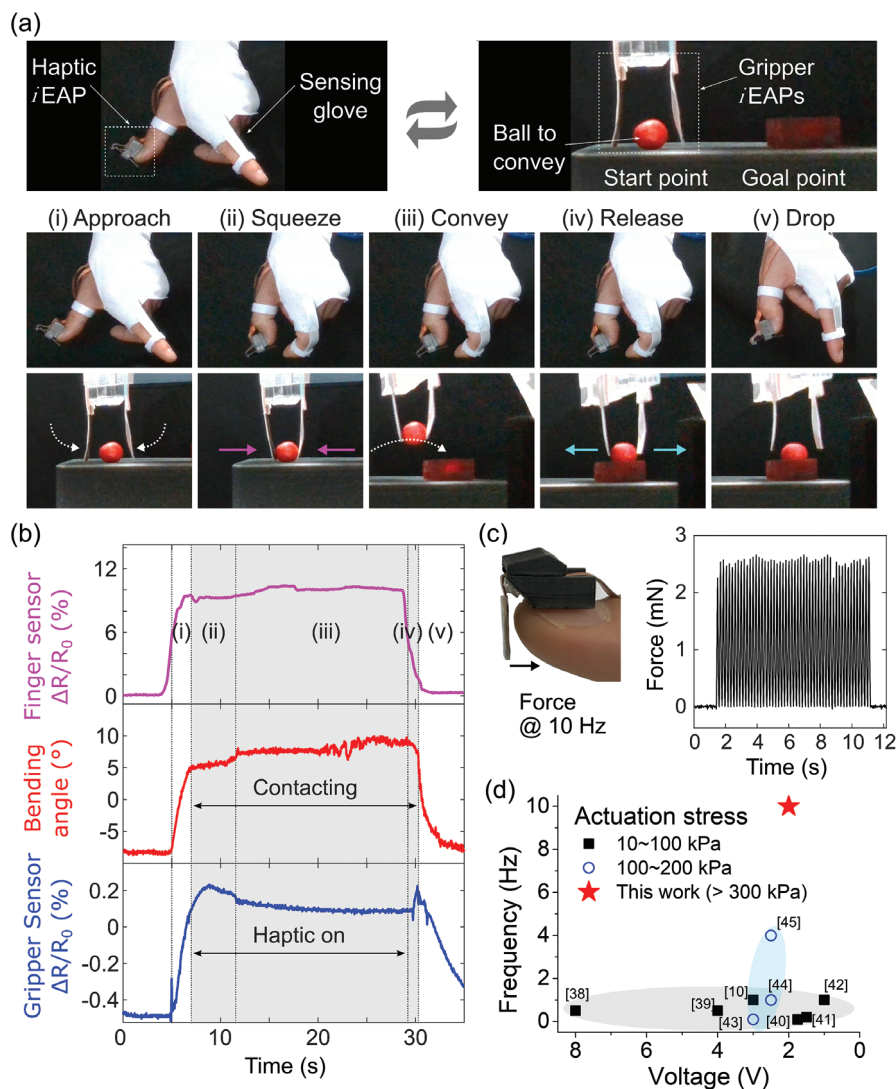


Figure 6. Teleoperation of a soft gripper with real-time haptic feedback. a) Interactive teleoperation of sensor-integrated iEAP actuators with real-time haptic feedback for conveying a ball. Five steps to perform the task are shown. b) Measured finger sensor signal, bending angle, and gripper sensor signal while completing the task. c) Haptic iEAP module on the user's thumb and the measured force at the fingertip at 2 V and 10 Hz. d) Comparison of voltage–frequency–actuation stress of our iEAP actuator with literature, focusing on low-voltage systems with encapsulation technology.

with the object (Figure 5a), a plateau of the bending angle was observed for the actuator during the contact phases even when the changed input voltage was continuously applied (Figure 5b,c). However, the EGaIn sensor signal continued to change owing to the compressive force acting on the contact area of the EGaIn pattern, as well as further deformation of the actuator while its tip was fixed. Using these signals, the IMM estimates the contact phase (as the probability of contact in the bottom plots) to match the true state (shaded in gray when it is in contact).

2.5. Interactive Teleoperation of Soft Gripper with Haptic Feedback

Based on this model, we developed a haptic interactive system that can teleoperate a soft gripper using a human hand and pro-

vide versatile self-sensing functions, as illustrated in Figure 6a. In particular, the introduction of a wearable fingertip haptic device based on the iEAP actuator that can provide cutaneous feedback with small batteries enables truly portable low-voltage-based haptic systems. Note that the bending angle of the user's hand is greater than that of gripper tip, and linear mapping was used to match the maximum finger angle and maximum gripper angle. The bottom panel of Figure 6a shows the interactive teleoperation of the gripper by the human hand in performing five tasks (Movie S1, Supporting Information). First, the gripper approached the ball by tracking the target angles, which were calculated from the finger motion tracked using the sensing glove. When the gripper started to contact the ball, the user bent the fingers to squeeze the ball for a stable grasping motion. The user then conveyed the ball to the goal point to release and drop it. The detailed information about the demonstration is described in Supporting Information.

Figure 6b shows the measured states of the system upon task completion. When the gripper was in contact with the ball, the sensor signal of the gripper changed significantly. Once this difference was detected by the IMM algorithm, the haptic iEAP module was activated to provide tactile feedback to the user. Based on this tactile feedback, the user could decide whether to squeeze further or move the ball to the goal point. When the ball was released from the gripper, the gripper signal showed a peak owing to frictional resistance and static attraction. Contact with the ball was communicated to the tip of the thumb as a tactile feedback signal by the haptic iEAP module, as shown in the image in Figure 6c. (Movie S2, Supporting Information). When the module is turned on, the iEAP actuator vibrates at 10 Hz to provide unprecedented stimuli to the fingertip. The normal force measured by the haptic iEAP module at 2 V and 10 Hz is shown on the right plot. (Movies demonstrating the rapid motions of iEAP actuators without and with encapsulation are provided in Movies S3 and S4, Supporting Information)

The iEAP haptic device operating at a high frequency is unprecedented. Figure 6d shows a direct comparison of the voltage–frequency–actuation stress of our iEAP actuator with literature values.^[10,38–45] Examples of iEAP actuators with encapsulation technology are very rare, and data were collected from the existing literature on all types of low-voltage actuators, such as ionic polymer-metal composite, bucky gel, conducting polymer, and hydrogel actuators. It is clear that our iEAP actuator moves rapidly and generates high actuation stress at a low driving voltage, which enabled the proposed haptic interactive systems. The creation of a Morse code-like signal with combinations of various haptic feedbacks operating at different frequencies can be further envisioned. The development of advanced haptic feedback devices that can generate controlled contact strengths by increasing the force level of the iEAP actuator remains a future work.

Notably, in the absence of haptic feedback, users have to rely on visual information, making it difficult to confirm the stable grasping motion. For example, when gripping through point contact or when trying to grasp a fragile object, it is important to apply an appropriate level of grip force.^[46] From this standpoint, our approach establishes a platform for practically viable haptic devices that do not require additional sensors for versatile and scalable haptic systems with small batteries.

3. Conclusion

We developed a haptic interactive system comprising only soft materials teleoperated by a human hand with real-time haptic feedback using small batteries. Inspired by proprioception in the human muscles, a soft actuator with a self-sensing capability was developed by integrating a liquid-metal-based strain sensor with a tailor-made iEAP actuator to simultaneously improve the sensitivity and actuation performance. A structural design based on system models established an unprecedented sensor-integrated iEAP actuator with tailored encapsulation technology that can accurately track the real-time trajectories of actuation during a task. A decision algorithm based on the change in the sensor signal was implemented to determine the contact state of the sensor-integrated iEAP actuator. A thimble-type self-sensing iEAP device was implemented in a closed loop; when a gripper made of sensor-integrated iEAP actuators came in contact with

an object, the corresponding change in the sensor-signal activated tactile haptic feedback for the user. This allows interactive teleoperation of a soft gripper by a human hand while securing a stable grasping motion and interactive manipulation of objects without requiring any vision sensors upon transmitting real-time cutaneous haptic feedback to the fingertip. The developed sensor-integrated iEAP actuator can help produce truly portable, wearable, untethered, and artificial-intelligence-embodied soft robots.

4. Experimental Section

Synthesis of and Characterization of PS-3H4S Electrolytes: The PS-3H4S was synthesized by reversible addition–fragmentation chain-transfer polymerization of 3-methoxy-sodium 4-styrenesulfonate monomer, followed by the cation exchange and deprotection of methoxy group. Structure, ion transport, and mechanical properties of the PS-3H4S electrolytes were investigated while varying the amount of loaded ionic liquid.

Fabrication of Trilayer iEAP Actuators: The PS-3H4S electrolyte layer with a thickness of $\approx 25 \mu\text{m}$ was prepared by hot pressing at 60°C . The PEDOT:PSS electrode with a thickness of $\approx 12 \mu\text{m}$ was prepared by casting of aqueous PEDOT:PSS dispersion containing 5 wt% dimethyl sulfoxide onto oxygen plasma-treated polydimethylsiloxane substrate. After sandwiching the PS-3H4S layer with PEDOT:PSS electrodes, the interfacial properties of the actuator were improved by applying heat at 60°C .

Fabrication and Characteristics of Sensor-Integrated iEAP Actuators: EGaln channel was directly printed onto the surface of the silicone substrate using an automatic pneumatic dispensing system with a 300 μm needle. After covering the EGaln channel with silicone elastomer, the copper electrode was fixed to the elastomer surface using a silicone adhesive and physically attached to the iEAP actuator using a silver paste. The opposite electrode was connected in the same way. After drying the silver paste, the sensor-integrated iEAP actuators with $20 \text{ mm} \times 5 \text{ mm} \times 0.8 \text{ mm}$ were fabricated by encapsulation with $\approx 50 \mu\text{m}$ thick elastomer. The sensor-integrated iEAP actuators were actuated under programmable voltages and at the same time, the sensor signal was collected by applying constant current (16 mA) through the EGaln channel and measuring the voltage between the two ends. The bending motions of the sensor-integrated iEAP actuators were recorded by a camera at ambient conditions. The generated force of the actuator was measured using a load cell.

Finite Element Analysis (FEA): FEA was conducted using a commercialized software (Abaqus, Dassault Systems). The lateral dimension of the sensor-integrated iEAP actuator was set to be $20 \text{ mm} \times 5 \text{ mm}$ while the thickness of the silicone substrate layer between the EGaln channel and the iEAP actuator was varied from 0 to 1 mm. One end of the actuator was fixed, and its bending angle was calculated by applying a moment to the other end. The displacement and strain along the length of the actuator were used to calculate the change in sensitivity of the embedded EGaln channel.

Tracking Control and Teleoperation: The estimation and control system was operated at 20 Hz. The bending angles and sensor signals of the sensor-integrated iEAP actuators were sampled under various input voltages. The linear fitted model was shown to describe the system. For model predictive control, the prediction horizon and control horizon were chosen as 5 and 3, respectively. At the same time that the controller observed the sensor signal from the EGaln resistance change, the bending angle of the iEAP actuator was also recorded by the camera as a control experiment for the purpose of evaluating the accuracy.

Interactive Teleoperation of Soft Gripper with Haptic Feedback: The wearable sensing glove was fabricated by placing the EGaln strain sensor at the joint of each finger to measure the motions of thumb and index finger. A soft gripper was prepared by facing two sensor-integrated iEAP actuators ($20 \text{ mm} \times 5 \text{ mm}$) with a 15 mm gap. Thumb interphalangeal joint and index proximal interphalangeal joint can generate the command for motion of each actuator. The finger sensor signals and the bending angles were linearly mapped, enabling the calculation of the target bending

angles for teleoperation from the user's joint motions. The haptic iEAP module was firmly anchored to the fingertip of the user by employing 3d-printed parts, which were activated to vibrate at 10 Hz when the IMM estimator detected the contact between the iEAP actuator and the object. The participant (H.H.) agreed to all tests in this study with written informed consent.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

haptic feedbacks, low voltage soft actuators, nanochannels, teleoperation, wearable sensing devices

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- [1] A. Billard, D. Kragic, *Science* **2019**, *364*, eaat8414.
- [2] C. Laschi, B. Mazzolai, M. Cianchetti, *Sci. Rob.* **2016**, *1*, eaah3690.
- [3] Y. Tu, F. Peng, D. A. Wilson, *Adv. Mater.* **2017**, *29*, 1701970.
- [4] W. Q. Dou, G. L. Zhong, J. L. Cao, Z. Shi, B. W. Peng, L. Z. Jiang, *Adv. Mater. Technol.* **2021**, *6*, 2100018.
- [5] Q. G. He, Z. J. Wang, Z. Q. Song, S. Q. Cai, *Adv. Mater. Technol.* **2019**, *4*, 1800244.
- [6] S. Z. Wei, T. K. Ghosh, *Adv. Mater. Technol.* **2022**, *7*, 2101521.
- [7] K. C. Xu, Y. Y. Lu, K. Takei, *Adv. Mater. Technol.* **2019**, *4*, 1800628.
- [8] O. Kim, H. Kim, U. H. Choi, M. J. Park, *Nat. Commun.* **2016**, *7*, 13576.
- [9] Y. Wu, Y. X. Shi, Y. Y. Wang, Y. F. Wang, L. H. Li, S. M. Feng, L. Liu, L. Li, T. Li, T. Zhang, *Adv. Mater. Technol.* **2022**, *7*, 2200258.
- [10] J. Ko, C. Kim, D. Kim, Y. Song, S. Lee, B. Yeom, J. Huh, S. Han, D. Kang, J. S. Koh, J. Cho, *Sci. Rob.* **2022**, *7*, eabo6463.
- [11] R. Y. Wang, S. Jeong, H. Ham, J. Kim, H. Lee, C. Y. Son, M. J. Park, *Adv. Mater.* **2023**, *35*, 2203413.
- [12] K. W. Kwan, A. H. W. Ngan, *Adv. Mater. Technol.* **2019**, *4*, 1900746.
- [13] M. Leveille, X. Shen, W. Fu, K. Jin, M. Acerce, C. Wang, J. Bustamante, A. M. Casas, Y. Feng, N. H. Ge, L. S. Hirst, S. Ghosh, J. Q. Lu, *Adv. Sci.* **2021**, *8*, e2102077.
- [14] N. R. Sinatra, C. B. Teeple, D. M. Vogt, K. K. Parker, D. F. Gruber, R. J. Wood, *Sci. Rob.* **2019**, *4*, eaax5425.
- [15] O. Cakmak, H. O. El Tinay, X. Chen, O. Sahin, *Adv. Mater. Technol.* **2019**, *4*, 1800596.
- [16] O. Kim, S. J. Kim, M. J. Park, *Chem. Commun.* **2018**, *54*, 4895.
- [17] D. Barpuzary, H. Ham, D. Park, K. Kim, M. J. Park, *ACS Appl. Mater. Interfaces* **2021**, *13*, 50381.
- [18] P. Rinne, I. Poldsalu, U. Johanson, T. Tamm, K. Pohako-Esko, A. Punning, D. van den Ende, A. Aabloo, *Smart Mater. Struct.* **2019**, *28*, 074002.
- [19] B. Rivkin, C. Becker, F. Akbar, R. Ravishankar, D. D. Karnaushenko, R. Naumann, A. Mirhajivarzaneh, M. Medina-Sanchez, D. Karnaushenko, O. G. Schmidt, *Adv. Intell. Syst.* **2021**, *3*, 2000238.
- [20] T. F. Otero, *Electrochim. Acta* **2021**, *368*, 137576.
- [21] K. Kruusamäe, A. Punning, A. Aabloo, K. Asaka, *Actuators* **2015**, *4*, 17.
- [22] R. Mutlu, G. Alici, W. Li, *IEEE Trans. Syst. Man, Cybern.: Syst.* **2016**, *47*, 2562.
- [23] B. C. Stillman, *Physiotherapy* **2002**, *88*, 667.
- [24] M. Suomalainen, Y. Karayiannidis, V. Kyrki, *Rob. Auton. Syst.* **2022**, *156*, 104224.
- [25] M. Raessa, J. C. Y. Chen, W. W. Wan, K. Harada, *IEEE Trans. Autom. Sci. Eng.* **2020**, *17*, 1800.
- [26] E. Gerena, F. Legendre, A. Molawade, Y. Vitry, S. Regnier, S. Haliyo, *Micromachines* **2019**, *10*, 677.
- [27] J. Yin, R. Hinchet, H. Shea, C. Majidi, *Adv. Funct. Mater.* **2021**, *31*, 2007428.
- [28] J.-H. Youn, S. M. Jeong, G. Hwang, H. Kim, K. Hyeon, J. Park, K.-U. Kyung, *Appl. Sci.* **2020**, *10*, 640.
- [29] J.-B. Chossat, Y.-L. Park, R. J. Wood, V. Duchaine, *IEEE Sens. J.* **2013**, *13*, 3405.
- [30] M. Amjadi, K. U. Kyung, I. Park, M. Sitti, *Adv. Funct. Mater.* **2016**, *26*, 1678.
- [31] D. Kim, Y. Yoon, S. K. Kauh, J. Lee, *Adv. Funct. Mater.* **2018**, *28*, 1800380.
- [32] J. C. Case, E. L. White, R. K. Kramer, *Soft Rob.* **2015**, *2*, 80.
- [33] L. Mullins, *Rubber Chem. Technol.* **1969**, *42*, 339.
- [34] Y. Zhang, H. Liu, T. Ma, L. Hao, Z. Li, *Mech. Syst. Sig. Process.* **2021**, *148*, 107133.
- [35] E. F. Camacho, C. B. Alba, *Model Predictive Control*, Springer Science & Business Media, Berlin **2013**.
- [36] P. Arcara, C. Melchiorri, *Rob. Auton. Syst.* **2002**, *38*, 49.
- [37] Y. Bar-Shalom, K. C. Chang, H. A. Blom, *IEEE Trans. Aerosp. Electron. Syst.* **1989**, *25*, 296.
- [38] G. H. Feng, S. Y. Hou, *Sens. Actuators, A* **2018**, *275*, 137.
- [39] S. J. Kim, C. Cho, Y. H. Kim, *Smart Mater. Struct.* **2009**, *18*, 115009.
- [40] G. Bubak, D. Gendron, L. Ceseracciu, A. Ansaldo, D. Ricci, *ACS Appl. Mater. Interfaces* **2015**, *7*, 15542.
- [41] S. T. McGovern, M. Abbot, R. Emery, G. Alici, V. T. Truong, G. M. Spinks, G. G. Wallace, *Polym. Int.* **2010**, *59*, 357.
- [42] S. Naficy, N. Stoboi, P. G. Whitten, G. M. Spinks, G. G. Wallace, *Smart Mater. Struct.* **2013**, *22*, 075005.
- [43] S. J. Kim, I. T. Lee, H. Y. Lee, Y. H. Kim, *Smart Mater. Struct.* **2006**, *15*, 1540.
- [44] G. Bubak, A. Ansaldo, D. Gendron, L. Brayda, L. Ceseracciu, D. Ricci, *Proc. SPIE* **2015**, *9430*, 94300V.
- [45] B. Kim, D. H. Kim, J. H. Jung, J. O. Park, *Smart Mater. Struct.* **2005**, *14*, 1579.
- [46] C. Choi, W. Schwarting, J. DelPreto, D. Rus, *IEEE Rob. Autom. Lett.* **2018**, *3*, 2370.