High-Output Force Electrohydraulic Actuator Powered by Induced Interfacial Charges

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Herein, a novel soft actuator design is presented that simultaneously enables a high-output force at a low operating voltage and an adjustable large normal displacement. The electrohydraulic actuator powered by induced interfacial charge (EPIC) uses the amplified electrostatic force when the surface charge-inducing phenomenon of the polyvinyl chloride (PVC) gel and the geometrical gradient of the actuator are combined to reinforce the zipping motion of the liquid layer. This actuator produces a more than 50-fold higher blocking force than conventional dielectric liquid-coupled electrostatic actuators at 2 kV. This implies the possibility of expanding the applicability of soft actuators to high-power transducers. This actuator is modeled as parallel capacitors by considering the interfacial-induced charge; the ratio of the dielectric constant of the polymer film to that of the dielectric liquid is analyzed as the principal design criterion for optimizing the performance characteristics. The actuator prototype exerts a force as high as 16 times its body weight (25.5 g) and exhibits a large normal displacement of more than 20% of its height (8.5 mm). Furthermore, four actuators can lift a weight of 1.25 kg and one actuator can be used as a large-aperture (diameter: 30 mm) varifocal lens (374% focal length variation).

1. Introduction

Over the past few years, soft robotics have received significant attention as a new technology for solving human–robot interaction problems.[1,2] Unlike conventional robots, a soft robot (with its inherent compliance) enables safe interaction with humans and robust functioning in versatile environments. One key component of soft robots is their soft actuators made of compliant material, which have their own function or functional configurations. The various proposed soft actuator technologies can be categorized as fluidic elastomer actuators (FEAs), dielectric or ionic electroactive polymer (EAP) actuators, and others.[3–5]

Although previously proposed soft actuators exhibit many advantages, they have deficiencies regarding, e.g., the external driver, speed, and power source. For example, FEAs are easy to fabricate into various geometries and have inherent compliance.[6,7] However, the external pump utilized for pressure input can greatly limit the advantages of the soft robot (e.g., its lightness and mobility).[8] Similarly, EAP actuators have high strains and high specific power densities; because they are similar to natural muscle, they are commonly called “artificial muscles.”[9,10] However, dielectric EAP actuators generally require high-voltage circuitry for drivers,[31] which makes them potentially unsafe in applications such as wearable robots,[12]; in addition, in ionic EAP actuators, despite their advantageous use at low voltages, the actuation speed is limited by the diffusion speed of the ions and the actuator performance is greatly affected by electrolyte variation.[13]

One method for realizing a practically powerful soft actuator is merging the principles of two different soft actuators for their synergy. For example, introducing the gel actuator’s principle into a dielectric elastomer actuator (DEA) can reduce the DEA’s operating voltage.[14] Soft pneumatic manipulators formed by combining tendon-driven mechanisms provide better stiffness control.[15] Moreover, soft pneumatic actuators without external pumps were created using phase-change material[16] and DEA grippers with enhanced gripping force were created by exploiting electroadhesion.[17,18]

Among these kinds of hybrid soft actuators, the hydraulically amplified self-healing electrostatic (HASEL) actuator shows remarkable characteristics.[19,20] This actuator combines the DEA and DEA principles, which amplify the output force of the actuator with the additional self-healing ability. In addition, from the DEA perspective, the HASEL actuator does not require an external pump. Due to these advantages, biomimetic scorpion robots, soft manipulators,[21] tubular pumps,[22] and tactile displays[23,24] have been realized with the HASEL actuator.

Polyvinyl chloride (PVC) gel is highly plasticized PVC that accumulates negative charge near the anode side surface in an electric field. This “heterospace charge distribution
phenomenon contributes to a creeping motion of the soft material to the anode.\textsuperscript{[25,26]} PVC gel itself is a nonionic polymer gel; the working principle of this actuator is based on the electrostatic force between the accumulated negative charge and the anode, which corresponds to the dielectric-EAP actuator principle.\textsuperscript{[14]} However, the HSCD is understood to be caused by charge transfer in the polymer network, which corresponds to the ionic-EAP actuator principle.\textsuperscript{[27,28]} Due to these principles, PVC-gel-based artificial muscles realize expansion–contraction operations at low operation voltages (below 400 V) and relatively fast general operations (maximal bandwidth of 9 Hz).\textsuperscript{[29]} Furthermore, a walking assistance device,\textsuperscript{[30]} soft tunable lens,\textsuperscript{[31]} and tactile display device\textsuperscript{[32,33]} with PVC-gel actuators have been investigated.

This article presents a novel soft actuator design based on the synergetic effect between the powerful response of an HASEL actuator and the charging characteristics of PVC. It is named based on the actuator’s working principle: “Electrohydraulic actuator Powered by Induced interfacial Charge (EPIC).” In the proposed approach, the HSCD of PVC gel is used to amplify the electrostatic force and reduce the pull-in voltage of the actuator. Due to the suggested principle, the proposed actuator exhibits a more than 50-fold higher blocking force (3.09 N) than an actuator using only the electrostatic force between its electrodes (53.7 mN) at 2 kV. Consequently, the proposed circular EPIC actuator (60 mm width, 8.5 mm height, and 25.5 g weight) shows a high output force (>4 N, which is 16 times that of its own weight) at a low operating voltage (3.5 kV) and an adjustable large normal displacement (23.5% of its own height). The great potential of this actuator is demonstrated by its ability to lift a weight of 1.25 kg using four actuators and the application of one actuator as a large aperture (30 mm diameter) lens with tunable focal length (374% variation possible).

2. EPIC Actuator
2.1. Design and Working Principle

Figure 1a shows the structure and dimensions of the EPIC actuator. The actuator is composed of a PVC-gel film, dielectric liquid, a bottom substrate, and two electrodes. The dielectric liquid is covered and sealed by the PVC-gel film and bottom substrate. One electrode is attached to the outer surface of the PVC gel and the other is attached to the upper surface of the bottom substrate. These electrodes induce the HSCD inside the PVC gel. As the PVC gel exhibits a zipping motion toward the anode, the anode shape should be carefully designed according to the PVC-gel deformation.

Figure 1a also shows the operating principle of the EPIC actuator. Due to the applied electric field, negative charge accumulates on the PVC-gel surface near the anode and forms an HSCD according to the PVC-gel characteristics. According to Coulomb’s law

\[ F = \frac{1}{4 \pi \varepsilon_0} \frac{q_1 q_2}{r^2} \]

where \( q_1 \) and \( q_2 \) are the charge amounts, \( \varepsilon_0 \) is the permittivity of vacuum, and \( r \) is the distance between the two charges \( q_1 \) and \( q_2 \); the electrostatic force is inversely proportional to the squared distance between the two charges. Therefore, after applying the voltage, a high electrostatic force is induced at the position where the PVC-gel contacts the anode because the distance between the negative charge at the surface of the PVC gel and the positive charge at the anode is very short. Thus, the HSCD and special geometry, which enables the short distance between the PVC gel and anode, result in the high output force of the EPIC actuator. This electrostatic force causes the PVC-gel film to be attracted to the bottom electrode; the resultant physical motion moves the

\[ \text{Figure 1. Working principle and structure of the circular-type EPIC actuator. a) Structure of the circular-type EPIC actuator and working principle; b,c) voltage on and off conditions of the EPIC actuator.} \]
liquid to the center, which induces hydraulic pressure. The prototype of the circular EPIC actuator is shown in Figure 1b,c (fabrication process in Figure S1 and video clip, Supporting Information). Before actuation, the PVC-gel surface has a slight curvature due to the inner liquid pressure; however, the center of the actuator bulges as the PVC gel attaches to the anode when a voltage is applied.

2.2. Experimental Evaluation

The proposed actuator concept was evaluated by comparing the EPIC actuator with an actuator that only depends on the electrostatic force between its electrodes. To determine the effects of the electrical characteristic of the PVC gel, the material of the polymer film was an operation variable, whereas the other parameters (e.g., the actuator geometry and viscoelasticity of the polymer) were control variables.

For the counterpart actuator, the polymer material Elastosil P7670 was selected because it does not form an HSCD at an applied electric field. The PVC gel for the EPIC actuator was prepared such that its viscoelasticity was similar to that of Elastosil P7670 by adjusting the mixing weight ratio of the PVC resin and plasticizer (dibutyl adipate; DBA) to 1:2.59 (Figures S2–S4, Supporting Information). The two different actuators have identical designs and geometries (Figure 1a); only the polymer materials are different.

The actuators were compared by measuring the peak-to-peak differences in their blocking forces. Figure 2a shows the experimental setup for measuring the blocking force. The detailed procedure is described in the Experimental Section. For the actuation, a 1 Hz square wave input voltage with different amplitudes was applied to the actuator. Figure 2b shows the blocking forces of the actuators fabricated with different polymer materials. The proposed EPIC actuator has a much higher maximal blocking force than the actuator, which only exploits the electrostatic force between its electrodes. The remarkable point of this result is that the blocking force of the EPIC actuator at 1 kV is even higher than that of its counterpart at 7 kV. Moreover, the blocking force of the EPIC actuator is more than 50 times that of the counterpart at 2 kV. This is why the proposed actuator can overcome the limitations of dielectric EAPs (high-voltage requirement). This result validates the hypothetical principle of EPIC actuators: the amplification of the electrostatic force based on the surface charge induced in the PVC gel.

2.3. Electrostatic Model

The proposed actuator was theoretically modeled by considering the interfacial-induced charge to investigate the crucial parameters of the optimal performance. The actuator was simplified to piecewise parallel capacitors with different dielectric materials (PVC gel and dielectric liquid) between the electrodes, as shown in Figure 2c. In this model, the HSCD of the PVC gel in the electric field can be represented quantitatively by borrowing the concept of the surface-bound charge density. Consequently, the sum of the two electrostatic pressures acting on both sides of the polymer film, \( P_{\text{net}} \), can be represented as follows (the theoretical derivation is in Equations (S1–S17), Supporting Information)

\[
P_{\text{net}} = \frac{\epsilon_0 V_0^2}{2 \epsilon_1 \mu t} \left( \frac{\epsilon_2 \epsilon_1}{\epsilon_0} + \frac{\nu}{t} \right) \tag{2}
\]

where \( \epsilon_0 \) is the permittivity of vacuum, \( V_0 \) is the applied voltage, \( t \) and \( z \) are the thicknesses of the polymer shell and liquid, respectively, and \( \epsilon_1 \) and \( \epsilon_2 \) are the dielectric constants of the polymer shell and liquid, respectively. This pressure value determines the output force of the actuator, which depends on the liquid pressure and, thus on the force transmitted by the polymer film.

According to Equation (2), the actuator performance is proportional to the squared operation voltage and inversely proportional to the squared thickness of the polymer film. This result corresponds to the common dielectric EAP model in terms of the effects of the operation voltage and polymer thickness.\(^{[34]} \) The essential part of this model is the effects of \( \mu \) and \( \nu \). As shown in Figure 2d, the net electrostatic pressure is inversely related to \( \mu \) and \( \nu \). According to Equation (2), \( \mu \) is the dielectric constant of the liquid normalized by the dielectric constant of the polymer shell; thus, if the dielectric constant of the polymer film is higher than that of the liquid, the actuation is more powerful. This explains the high output force of the EPIC actuator. In reports of studies dealing with the dielectric constant of PVC gel,\(^{[35,36]} \) the recorded values are very high (>1000 at 1 Hz) in the low-frequency range; the resultant low \( \mu \) values cause the EPIC actuator to have a high output force.

This result is outstanding because the conventional dielectric EAP model states that the actuation force is proportional to the dielectric constant of the internal material.\(^{[19,34]} \) This discrepancy is based on whether the model considers the bound charge. Without bound charge (Figure S8, Supporting Information), the net electrostatic pressure can be calculated as follows

\[
P_{\text{net}} = \frac{\epsilon_0 \epsilon_2 V_0^2}{2 \epsilon_1 \mu} \tag{3}
\]

Here, the only difference from Equation (2) is the added term \( \epsilon_1 \) in the numerator.\(^{[36]} \) The two conflicting models were compared by measuring the net electrostatic force with a customized parallel capacitor with two serial dielectric layers, a polymer film, and a dielectric liquid. To determine the effect of \( \mu \), five dielectric liquids with different dielectric constants (Figure S9, Supporting Information) were tested as second dielectric layers. Subsequently, the net electrostatic force acting on the polymer film was measured with a load cell under 1 Hz sine-wave operation conditions (Figure S10, Supporting Information). Figure 2e shows the measured net electrostatic forces exerted on the polymer films and the expected force according to the two models. The experimental data show lower electrostatic forces when the dielectric constant of the liquid is higher, which matches well with the trend of the model that considers the effect of a bound charge. Hence, the model in Equation (2) is suitable for incorporating the effect of the interfacial charge between two dielectric layers.

Similarly, \( \nu \) represents the thickness of the dielectric liquid layer normalized by the thickness of the polymer shell. Therefore, the effect of \( \nu \) can represent the nature of the electrostatic force, which is inversely related to the distance. The validation of the effect of \( \nu \) is conducted using the same customized parallel capacitor (Figure S11, Supporting Information) by changing the dielectric liquid thickness. The result shows that, for a smaller dielectric liquid thickness, a higher electrostatic
force is applied to the polymer film, which agrees with the model (Figure S12, Supporting Information). Thus, it can be concluded that the overall actuation force of the EPIC actuator is dominated by the electrostatic pressure at the position where the PVC-gel film almost contacts the anode.

3. Performance Measurement

To characterize the performance of the EPIC actuator, the output force and displacement were measured under various conditions (Figure 3a–c), and the application of the actuator as a soft tunable lens with large aperture was evaluated (Figure 3d). The measurement environments are described in detail in the Experimental Section.

Figure 3a shows the actuators’ blocking forces and displacements at various voltages at 1 Hz. A total of six independent actuators were fabricated with identical design parameters, three of which were tested in each measurement to investigate general trends. In the blocking force measurement, every EPIC actuator exerts a force greater than 5 N before its breakdown at 4–5 kV in the blocking force measurements and the averaged blocking...
force exceeds 4 N at 3.5 kV. This indicates that the actuator can lift $\approx 16$ times its own weight. Interestingly, in the stable operation voltage range (0–3.5 kV), the blocking force and operation voltage have a linear relationship, as shown by the dotted red simple linear regression line ($r^2 = 0.9888$) in Figure 3a. In the displacement measurement, the actuator induces $\approx 2$ mm maximal displacement (23.5% of the actuator height) at $\approx 1.5$ kV, which is much lower than the breakdown voltage (4–5 kV). One notable feature of this actuator is that the displacement of the actuator can be adjusted with the amount of injected liquid; this has a tradeoff relationship with the blocking force. The increased amount of liquid enlarges the average distance between the PVC-gel film and the bottom electrode, which weakens the electrostatic force based on Equation (2). In addition, the actuator induces more displacement when actuated due to the increased amount of liquid displaced by zipping. Thus, in the case of Figure 3a, the displacement performance can be further enhanced by adding more liquid.

Figure 3b shows the blocking forces of the three actuators with the same design parameters at various operation frequencies at 2 kV. Accordingly, the actuators exhibit high output forces at low operation frequencies. This corresponds to the trend of the dielectric constant of the PVC gel [25,35] because the EPIC actuator follows Equation (2) and is affected by the ratio of the dielectric constant of the polymer film to that of the dielectric liquid. At high operation frequencies, the output force of the actuator decreases because the surface charge induction of the PVC gel cannot follow the frequency of the field change. However, at $\approx 230$ Hz, the peak-to-peak difference in the blocking force recovers to 1.5 N. This phenomenon can be interpreted as the resonance response of the actuator. The actuator is composed of a viscoelastic polymer film (spring and damper), viscous liquid (damper), and a pair of overlapped electrodes (capacitor). This composition comprises the R–L–C system in an electromechanical way. Therefore, the resonance output of the system can be expected. According to this interpretation, the actuator can be used as a soft haptic device with a proper resonance design, which should be optimized by considering the vibrotactile threshold of the human body [37].

Figure 3c shows the displacement of a plate pushed up by four circular EPIC actuators at a 3.5 V sine-wave voltage. The picture and plot show that the four EPIC actuators can lift a total weight of 1.25 kg (a 1 kg weight plus a 0.25 kg plate). As the total weight of the four actuators is 102 g, the lifted weight with an
observable displacement is \(\approx 12\) times greater; this demonstrates the great potential of the artificial muscle.

Finally, the actuator was applied as a soft tunable lens due to the high transparency of the PVC gel and tunable surface curvature. Although various dielectric EAP tunable lenses have been presented\(^{[38–43]}\) their apertures are limited compared with their actuation part due to the actuator’s limited output performance. The EPIC tunable lens fabricated in this study exhibits a large aperture (diameter: 30 mm) with high optical resolution because a small part of the actuating area induces a strong squeezing force (Figure S13, Supporting Information). In addition, the focal length can vary by \(\approx 374\%\) (65–243 mm) by increasing the voltage from 0 to 3 kV, as shown in Figure 3d. When the saturation of the focal length is considered, the operating voltage can be reduced to \(<1.6\) kV, which corresponds to a 94.6% decrease in the total focal length. The video file in Supporting Information shows the focal length-variation ability of this actuator at different switching speeds (up to 4 Hz).

4. Conclusion

The proposed soft actuator design synergizes the HSCD of the PVC gel and dielectric liquid-coupled structure with a geometrical gradient. The proposed protrusive actuator can lift up to 12 times its weight and its transparency and strong squeezing force allow its application as a large-aperture vari-focal lens. Although the operation voltage of the actuator can be remarkably reduced due to the actuator’s working principle, the HSCD-fortified actuation results in a greater force than that of the conventional design. Therefore, the actuator is a promising candidate for e.g., artificial muscles and optical devices.

Nevertheless, there are several problems that must be solved to further improve the EPIC actuator such as the high-frequency operation. Due to the electrical properties of PVC gel, the EPIC actuator produces a high output force at low frequencies. To solve this problem, resonance-based operation can be chosen, as shown in Figure 3b. However, for resonance-optimized design, accurate dynamic modeling of the actuator should be preceded. This is still an unexplored research area in which various dynamic properties of the system should be considered, including the viscoelastic property of polymer film, the viscosity of the dielectric liquid, the dielectric relaxation of the polymer film, and the actuator geometry. In this perspective, recent research about the dynamic behavior of electrohydraulic actuators considering liquid viscosity is very inspiring.\(^{[42]}\) Furthermore, the electromechanical properties of PVC gel can be modulated with additives such as silicon dioxide, graphene oxide, and ionic liquid\(^{[32,43,44]}\) The effects of additives on the PVC-gel characteristics will be investigated in terms of the frequency response of the EPIC actuator in a later study. There is another problem regarding the durability of the actuator. The cathode material used in this study is carbon grease, which easily dries out in air. In addition, at certain strain values, the resistance of carbon grease exhibits a high peak. For the reliable operation of the EPIC actuator, stable and consistent compliant electrode materials such as water-retaining hydrogel and carbon nanotube electrodes\(^{[45–47]}\) may be required; their properties and suitable adhesion methods for PVC gel will be investigated in the future. Finally, the rigid frame material of this actuator such as poly(methyl methacrylate) (PMMA) can be a limitation when entire system softness is required. In this case, the materials that have a low Young’s modulus or low stiffness can be used as a substrate with an appropriate fabrication method. However, joining and completely sealing soft materials require a thorough understanding of the materials’ chemical properties. Furthermore, adding geometrical features in such a soft structure may require an innovative fabrication method. In this context, recent work in which 3D printing was used as a fabrication method for an electrohydraulic actuator presents a good example, where a soft material (silicone-urethane elastomer \(\approx 1\) MPa) was used as a substrate.\(^{[48]}\)

5. Experimental Section

**Measurement of Blocking Force**: Figure 2a shows the experimental setup. The actuator was installed under the load cell (UMI-C500, DACELL), and the position of the load cell was adjusted such that the initial blocking force was 0.03 N. Moreover, the load cell contacted the actuator with a 3 cm-diameter circular stud. An alternative voltage with specified high and low peak levels (10% of the high peak level with opposite sign) was applied to diminish the residual charge on the PVC-gel surface.

**Measurement of Displacement**: The displacements were measured using a laser displacement sensor (LK-G85, LK-G3001, KEYENCE). A 1 Hz AC voltage with specified high and low peak levels (10% of the high peak level with the opposite sign) was applied to diminish the residual charge on the PVC-gel surface. In the measurement in Figure 3a, polytetrafluoroethylene tape was attached to the top of the actuator as a reflector, and the displacement of the actuator was measured by applying an AC voltage to the actuator under the laser displacement sensor. In the measurement in Figure 3c, four circular EPIC actuators were installed under a PMMA plate (256.5 g); when the AC voltage was applied to the actuators, they pushed the plate and additional load up. Aluminum tape was attached around the center of the PMMA plate as a reflector.

**Measurement of the Focal Length**: Figure 3d shows the experimental setup. A 633 nm-wavelength laser beam was used as the light source, and an iris diaphragm was used to control the laser beam inside the visible area of the EPIC tunable lens. The focal point of the lens was detected using an image profiler at different DC operating voltages.

**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.

**Author Contributions**

H.K. devised the main idea of this study, designed the actuator, and conducted the theoretical modeling of the actuator. J.M., M.K., and...
Data Availability Statement

Research data are not shared.

Keywords

hydraulically amplified self-healing electrostatics, polyvinyl chloride gel, soft actuators, soft robotics