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Development and Characterization of PVC Gel Actuator for Haptic Applications

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I. Introduction

Electroactive polymers (EAPs) offer a promising solution as compact haptic actuators due to their inherent softness, lightweightness, and fast actuation speed, making them ideal for use in handheld devices. However, current EAP technologies, such as dielectric elastomer actuators (DEAs) [1] and dielectric liquid crystal elastomer actuators (DLCEAs) [2], present challenges related to high voltage requirements and actuator size [1]. To overcome these limitations, polyvinyl chloride (PVC) has emerged as a potential actuator material, owing to its ability to achieve high strain at low operating voltages [3-5]. Despite its promising strain performance, PVC gel alone has not yet been explored for haptic applications due to its relatively low force output. To date, no research has utilized PVC gel alone as a haptic actuator.

In this paper, we present a normal force haptic device that utilizes PVC gel as the actuation material. Our primary focus is on enhancing the force output of PVC gel actuators by improving the fabrication process. While increasing the degree of cross-linking improves actuator performance, this simultaneously raises the material's viscosity, complicating the fabrication of the thin films necessary for low-voltage operation. To overcome this challenge, we introduce a fabrication method that enables the production of thin, high-performance PVC gel layers. Through careful optimization of the actuator's design and configuration, we demonstrate that PVC gel-based systems offer a viable and efficient alternative to conventional haptic actuation technologies.

II. PVC Gel Actuator

A. Our Approach for PVC Gel Enhancement

PVC gel actuators are composed of PVC and a plasticizer, and are coated with compliant electrodes on the top and bottom. When an electric field is applied across the PVC gel, plasticizer molecules migrate toward the electrodes. This movement causes the PVC chains to shift toward the cathode, resulting in expansion on the cathode side and contraction on the anode side. To improve the performance of PVC gel, increasing the degree of cross-linking within the PVC chains has been identified as a critical strategy [4, 5], and studies have reported that applying heat during the fabrication process can promote cross-linking [5]. However, in these studies, the gel thickness remained relatively thick, hindering the use of low voltages required for practical applications.

In this work, we present a fabrication strategy that enables the formation of thin, highly cross-linked PVC gels with an accelerated cooling process to enhance actuator performance. Specifically, we propose the use of an applicator to control gel thickness even under high-viscosity conditions, combined with rapid cooling to preserve the cross-linked network formed during heating. We hypothesize that this combination not only improves mechanical force output but also reduces the actuation voltage by facilitating faster solidification and maintaining a highly cross-linked structure, thereby enhancing both the safety and efficiency of PVC gel actuators for haptic applications.

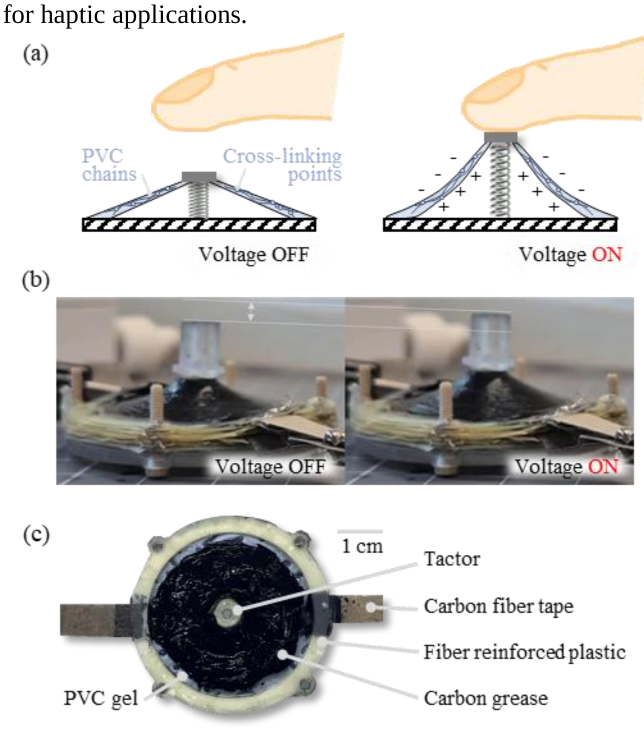

Figure 1. Actuation mechansim of PVC gel and fabricated haptic actuator. (a) Actuation mechanism (b) 1.5kV actuation (c) Design of a unit actuator

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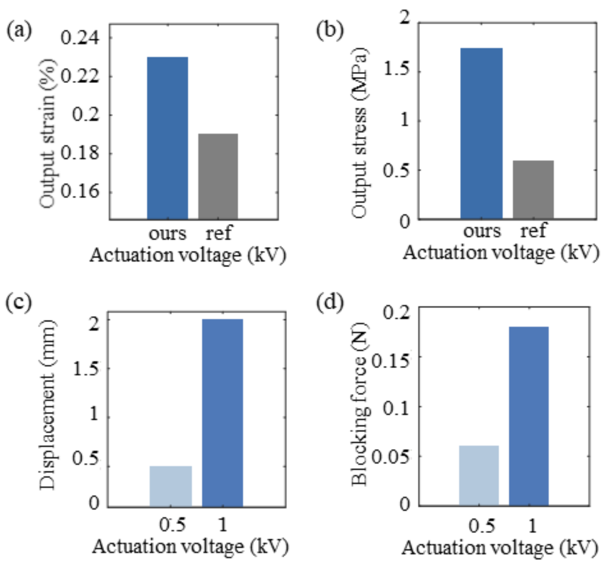

Figure 2. Force and displacement measurement. (a) Displacement and (b) blocking force of a unit actuator with respect to the PVC/DBA ratio. (c) Displacement and (d) blocking force relative to the driving voltage

B. PVC gel fabrication

The PVC-DBA mixture was prepared at a weight ratio of 1:5, with 1.5 g of PVC powder (Sigma Aldrich, USA) and 7.5 g of DBA (Sigma Aldrich, USA. The mixture was stirred with a magnetic stirrer at 150 °C and 400 rpm for four hours. It was then poured onto a Kapton film placed on an applicator pre-heated to 150 °C. The applicator, set to a thickness of 400 µm, ensures uniform spreading of the gel. To preserve the polymer cross-links, the generated film was immediately transferred to a refrigerator for rapid cooling and solidification.

C. Stress and strain characterization

Under the same experimental conditions as those employed in the previous study [5], the PVC gel fabricated using our method exhibited a 1.32-fold increase in output strain, increasing from 19% to 25%, as illustrated in Fig. 2(a). Furthermore, the output stress showed a substantial improvement from 0.6 MPa to 1.74 MPa—a 2.9-fold increase compared to the previous study [5]—as shown in Fig. 2(b). These enhancements demonstrate a significant improvement in the force-generating capability of the PVC gel actuator, thereby highlighting its potential for advanced applications in haptic actuation.

III. Haptic Device Prototype

A. Haptic device design

A haptic device was developed by combining a stacked diaphragm PVC gel actuator and a spring, as shown in Fig. 1(a). Through its coupling with a spring mechanism, the expansion of the PVC gel upon application of voltage is transmitted into a vertical displacement.

The PVC gel is pre-stretched to adjust its performance. A larger pre-stretch increases blocking force but reduces displacement, and vice versa. Considering this trade-off, we fabricated the gel using a biaxial pre-stretch of 130 %. To maintain the pre-stretch, an adhesive was applied to secure the pre-stretched gel to a supporting frame structure. As shown in Fig. 1(c), carbon grease was used as the stretchable electrode, and the electrical connection was made using carbon fiber tape. To further increase the output force, we stacked eight-unit actuators.

B. Force and displacement characterization

The actuator's blocking force was measured in a benchtop setup using a linear stage (Zaber, USA) and a force sensor (Mark-10, USA). Displacement was quantified via image analysis from a camera aligned perpendicular to the motion.

Fig. 2(c) and 2(d) show the measured blocking force and displacement, respectively. A clear voltage-dependent behavior of the actuator is observed, with both blocking force and displacement increasing in response to higher applied voltages. Notably, the blocking force and displacement produced by the proposed haptic device exceed the just noticeable difference (JND) thresholds of 0.1 N for force and 1 mm for displacement, as defined in [6,7], thereby demonstrating its capability to deliver perceptible haptic feedback. These findings indicate the device's strong potential for practical implementation as a haptic actuator.

IV. Conclusion

In this work, we developed a high-performance PVC gel actuator through the optimization of cross-linking and fabrication processes, aiming to produce thin, mechanically robust gels with enhanced blocking force. Following successful fabrication, the actuator demonstrated a 1.31-fold higher strain and 2.9-fold higher actuation stress. These actuators were formed into a haptic device that delivers normal haptic feedback to a fingertip up to 2 mm of displacement and 0.18 N of force. These initial results suggest the feasibility of PVC gel-based actuators in haptic systems.

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