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Dielectric elastomer fingers for versatile grasping and nimble pinching

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Boneless soft robotic fingers cannot apply concentrated forces to pinch a delicate object. This letter reports a three-dimensional design of dielectric elastomer fingers with higher flexural stiffness and close to 90° voltage-controllable bending for object gripping and pinching. It makes use of tension arch flexures to elevate a pre-stretched dielectric elastomer actuator (DEA) into a roof shape and thus magnifies the tension-induced moment, 40 times higher than a flat DEA does, to bend a stiff base frame. Such fingers make normally close-grippers to lift a payload 8–9 times their weight. They also make normally open grippers that pinch a highly deformable raw egg yolk.

With dexterous fingers, a human hand can versatility grasp and grip objects of varying shapes and hardness. For example, it can grasp a hard cylinder, a block, and a sphere, while it can also pinch a coin, a fruit, or a hard-boiled egg. While having a pinch strength of up to 4.2 kg, human fingers (i.e., thumb and pointer) are nimble enough to pinch a delicate object, given the tactile feedback and pulpy tissues between the finger skin and bones. They can apply a gentle grip, free from impact and oscillations.

Recently, under-actuated robotic grippers have been developed for adaptive and versatile gripping. They are equipped with (1) tendon-like flexural joints between rigid linkages to enable passive adaptation to object shapes and (2) soft tips to avoid impact upon unplanned contact. Yet, the grip force control of these adaptive robotic grippers is poor. For example, 3-finger adaptive robot grippers from Robotiq are subjected to the 15% variation of a 15 N maximum pinch force. The force variation is due to the friction of the tendon sheath and pad viscoelasticity. Over-pinch by the grippers risks crushing a delicate object. Sizing down the grippers does not necessarily reduce the variation of grip force as friction becomes more pronounced at a smaller scale.

Dielectric elastomer actuators (DEAs) can possibly make soft grippers with better force control due to elastic actuation directly by Maxwell stress. A DEA is bonded on a passive layer to make a bilayer unimorph, which can curl like a finger. The initial curvature of the unimorph varies with the DEA pre-stress. A unimorph with a pre-stressed DEA is initially curled, whereas a unimorph with a non-stressed DEA is initially flat. Voltage activation of the DEA can change the unimorph curvature by applying Maxwell stress to vanish the membrane pre-stress or induce an areal expansion. Yet, a single-layer DEA does not produce much force to bend a stiff passive layer of the unimorph given the limited moment arm. Thus, DEA-based unimorphs show little flexural strength, for example, inducing merely a 2.2 mN grip force. However, they have enough axial strength to lift/hang a heavy object (of 80 g) with electro-adhesion to the object. Some objects cannot be electro-adhered, for example, cellular membranes, which are prone to electro-porating and heating upon high-field electro-adhesion.

A dielectric elastomer minimum energy structure (DEMES) is also useful as a bendable or a rollable claw. Multiple DEMES claws make versatile grippers but show limited strength to lift a payload. This is because a DEMES has a flexible frame buckled by a highly pre-stretched DEA membrane, which is bonded on the frame borders. A large flex of the buckled frame is at the expense of the reduced frame stiffness due to the limited moment generation by DEA pre-tension. Hence, a rollable DEMES can generate little voltage-induced grip force, less than 1–2 g. Multilayer DEAs can produce more force, but their increased flexural rigidity is not good to the bilayer’s bending, not to mention the worsened dielectric strength. Over-stiffening makes the grippers behave like tweezers.

Pincing of an object presents a great challenge for boneless soft grippers because it requires strength and force concentration. This is particularly challenging if the object to be pinched is soft and flowable like a raw egg yolk. An egg yolk is enclosed by a vitelline membrane, which has a low rupture strength around 2 g force when compressed by a 1 mm diameter probe, corresponding to 6.2 kPa stress). Interestingly, after some trials, human fingers with skeletal bones can gently pinch and lift an egg yolk without puncturing the delicate vitelline membrane.

In this study, we devise a dielectric elastomer (DE) actuated finger (Figure 1) with mechanical strength for versatile grasping and even pinching of a raw egg yolk. This DE finger can operate like a DEMES claw, but it is equipped with the arch flexures that shape a DEA membrane into a roof shape to magnify the moment generation by the DEA pre-tension. Unlike the DEMES, the DE finger together with a stiff base frame bends rather than buckles. Voltage activation induces Maxwell stress across the DEA and reduces the biaxial pre-stresses to unbend the DE finger.

This DE finger has a roof-shape DEA membrane on the support of a flexible frame to bend a stiff base frame. The flexible frame has the cross bars transversely buckled to elevate the initially flat DEA membrane into a roof close to a

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half cylindrical shape. These buckled cross bars appear like tension arch structures that keep a canvass roof in tension, and they are thus named as tension arch flexures. The DEA roof helps elevate the tension center several-ten folds higher than a flat DEA does to a bilayer design, and thus, it can bend largely above the base frame, 45 mm long and 10 mm wide. In this work, an acrylic elastomer tape (VHB 4910, a 3M trademark for very high bond adhesive tape) is used to make a DEA. According to Ref. 23, this tape is 1 mm thick initially and has a relative dielectric constant \( \epsilon_r = 4.7 \). To make a DEA, it is pre-stretched 5 times axially and 6 times transversely an axial pre-stress \( \sigma_0 \) of 0.675 MPa induced. This pre-stretched VHB membrane is 33.3 \( \mu m \) thick and shows an axial tangent modulus \( E \) of 0.448 MPa as measured by Instron. Its half cylindrical roof of radius \( r = 12.7 \ mm \) can induce a moment 40 times higher than that produced by a flat DEA in a bilayer design (Figure 1(c)). Hence, the DEA roof can bend a stiff base frame (103 mm long and \( k_0 \theta \) of the base frame, which leads to a bilayer unimorph.

Application of a high voltage \( V \) induces a Maxwell stress \( \epsilon(V)^2 \) across the DEA membrane, where \( \epsilon \) is the dielectric permittivity. This reduces the biaxial membrane stresses, and thus, the active net moment becomes

\[
\begin{align*}
M(\theta, V) &= \int_0^\theta \sigma_0 - \epsilon(V)^2 \frac{E \cos(\theta/6)}{6} r d\phi \\
&= 2r^2 \epsilon(V)^2 \cos(\theta/6) \left\{ \sigma_0 - \epsilon(V)^2 \right\},
\end{align*}
\]

where the dielectric permittivity \( \epsilon \) is a product of dielectric constant \( \epsilon_r \) and air permittivity \( \epsilon_0 \), i.e., \( \epsilon = \epsilon_r \epsilon_0 \). This model predicts that the voltage activation at \( t \sqrt{\sigma_0/\epsilon} \) can fully undo the bending by vanishing the DEA’s membrane pre-stress.

In this work, a three-dimensional dielectric elastomer finger is used. It has a base frame of a 0.38 mm thick polyvinyl chloride (PVC) shim, a flexible frame of a 0.127 mm thick polyimide (PI) film, and multiple-segment DEAs. Designs and dimensions of the polyimide and PVC frames are shown in Figure S1 in the supplementary material. The stiff PVC frame is built from adhesive bonding of two 103 mm long and 10 mm wide spines and three PVC cross bars of less than 45 mm width \( d \) and 10 mm long. The polyimide frame is a monolithic piece polyimide film with multiple cross bars (\( w = 45 \ mm \) wide) to hold the multi-segment DEAs. Rectangular windows (i.e., cut-out of 40 mm wide and 10 mm long) in the polyimide frame allow the DEA free deformation within the frame borders. The flexural stiffness of this PVC frame is 17.8 times higher than that of the polyimide frame.
was held flat by a rigid frame and applied with carbon grease electrodes not shown. Second, two PVC spines were adhesively bonded to the four corners of each two-segment unit of the polyimide frame. Third, the reinforced DEA was cut out from the holding frame. The released DEA on the PI frame and PVC spines curls up slightly into a saddle shape. Fourth, a PVC base frame was built up by adhesively connecting the two spines with three cross bars. The narrower PVC cross bars help buckle up the polyimide cross bars (due to width mismatch) and form the arch bridges to heighten the DEA membrane into a roof shape. The assembly finally makes a dielectric elastomer finger with a large residual bending and adequate mechanical strength.

Figure 2(b) shows that 45 mm wide PI cross bars buckle transversely with a 12 mm height \( h \) upon being bonded to a short base frame of 35 mm wide (at a mismatch ratio of \( d/w = 0.78 \)). This DEA finger with tension arch flexures undergoes a large residual bending close to 90°. In comparison, the design with the matched-width flexures (\( d/w = 1 \)) bends 60° due to the interlayer freedom and the saddle formation of the relaxed DEA membrane. In contrary, a DEMES, which has the same pre-stretched DEA directly bonded to the PVC frame without interlayer freedom, can hardly bend (see row 4 of Figure 2(b)).

Figure 3 (Multimedia view) shows one of the best performing fingers (\( d/w = 0.78 \)) that can fully uncurl close to 90° upon 6 kV (i.e., 109 MV/m) activation. A 1-Hz 6 kV pulse activation excites this finger into a pulsed response, with minor oscillation upon unbending and large oscillation upon bending. This pulsed response is cyclically repeatable without fatigue. Yet, samples of the same designs are subjected to variations due to the tolerances of manual assembly and the pre-stress variation. The average electrical uncurling is close 80° for the \( d/w = 0.78 \) design and 82.4° for the \( d/w = 0.89 \) design. In comparison, the design with the matched width (\( d/w = 1 \)) can merely unbind 46.3° upon 6 kV activation (with an electric field of 127.7 MV/m) across the DEA membrane.

These dielectric elastomer fingers are good to make normally close grippers with natural curling (Figure 4). The grippers have enough mechanical strength to passively grasp and lift a payload 8–9 times the grippers’ weight. For example, the 3-finger grippers (Figure 4(a)) of a 7.5 g total weight can grasp and lift a styrofoam sphere hanged with a bunch of paper clips (for a total weight of 65.6 g). Voltage activation can uncurl the grippers and thus releases the object. The ability of the normally close grippers to carry a payload depends on the finger’s stiffness. Figure 4(b) shows that each DE finger has a relatively high tip compliance of 3.47 mm/g in the unbounding direction (y-axis). But it is less compliant in the orthogonal directions: 1.07 mm/g in the side-way direction (z-axis) and 0.41 mm/g in the longitudinal direction (x-axis).

When being oriented back to back, two DE fingers make normally open grippers for object pinching (Figure 5 (Multimedia view)). Each finger tip is mounted with a silicone rubber pad (Sylgard 186) of an area of 10 mm × 20 mm for conformal grip. Such gripper design can achieve controllable and nimble pinching, which is not possible by the
passive grasp of the normally close grippers. Figures 5(a)–5(c) show that such 2-finger grippers pinch and pick a raw egg yolk (10–12 g) like human fingers do. A 6 kV activation uncurls the DEA fingers and brings the finger tips into contact with a part of the vitelline membrane. The stopped finger tips exert a block force \( F_b \) for pinching the vitelline membrane, while the tip pads induce a friction force \( 2F_l \) to counter the gravity \( W \) of the egg yolk.

The blocked force is a released elastic force of PVC spines upon the DEA’s activation that reduces the membrane stress. Figure 5(d) shows that the DE fingers can produce an averaged maximum blocked force of up to 143 mN upon 6 kV activation. This maximum blocked force generated is close to 6 times the finger’s weight (2.5 g each). In comparison, the previous designs of DEMES produce a lesser maximum blocked force. For example, a 1.2 g DEMES with a triangular Polyethylene terephthalate (PET) frame and a VHB DEA can produce a 12 mN maximum grip force (close to the DEMES weight); a 0.65 g DEMES with a multi-segment rectangular PET frame and silicone DEAs can produce only 2.2 mN.

Figure 5(e) shows that a sample finger \( (d/w = 0.78) \) does hold with a steady blocked force of 139.5 mN ± 1.8 mN upon the 6 kV activation. This accurate force control by voltage activation enables a gentle handling of the cellular material. The finger’s rise time is close to 100 ms during a step activation. Figure 5(f) shows that two such DE fingers can pinch and lift a payload, for example, 12 g at 6 kV.

Lifetime of such DE fingers ranges between 1 and 2 weeks. The ultimate failure is due to creeping and tearing of the highly pre-stretched VHB membrane. The VHB membrane is prone to snap from the edges when it loses adhesiveness and detaches from the polyimide frame. It is anticipated that a less-viscous and high tear-strength dielectric elastomer could replace this acrylic elastomer (VHB) to make the variable-tension grippers last longer.

This letter presented a three-dimensional design of a DE finger with higher mechanical strength for gripping as compared to a DEA-based bilayer unimorph. Tension arch flexures of the DE finger elevate a pre-stretched DEA into a roof shape and thus magnify the moment generation by the DEA pretension to bend a stiffer base frame. These DE fingers make soft robotic grippers capable of versatile grasping and firm pinching of a payload, which is a few times the grippers’ own weight. In future, tactile sensory with capacitive read out will be integrated to these DE fingers to enable closed-loop force control.

See supplementary material for (1) the component material, frame design, and fabrication methods for making a dielectric elastomer finger and (2) measurement techniques for tip deflection and blocked force.

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