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Dielectric elastomer fingers for versatile grasping and nimble pinching

Gih-Keong Lau,^{a)} Kim-Rui Heng, Anansa S. Ahmed, and Milan Shrestha

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798

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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. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4983036>]

With dexterous fingers, a human hand can versatilely 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,¹ 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.² They can apply a gentle grip, free from impact and oscillations.

Recently, under-actuated robotic grippers³ 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 Robotiq⁴ 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.³ 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.^{5–7} 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,^{8–12} whereas, a unimorph with a non-strained DEA is initially flat.^{13–16} 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.¹² However, they have enough axial strength to lift/hang a heavy object (of 80 g) with electro-

adhesion¹² 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.¹⁷

A dielectric elastomer minimum energy structure (DEMES) is also useful as a bendable or a rollable claw.^{8,9,18} Multiple DEMES claws make versatile graspers but show limited strength to lift a payload.^{8,9} 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.^{8,9,18} Multilayer DEAs^{13,14,16,19} can produce more force, but their increased flexural rigidity is not good to the bilayer's bending, not to mention the worsened dielectric strength.¹⁹ Over-stiffening makes the grippers behave like tweezers.^{20,21}

Pinching 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 strength²² (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

^{a)} Author to whom correspondence should be addressed. Electronic mail: mgklau@ntu.edu.sg

FIG. 1. Working principles of a DEA finger with tension-arch flexures for magnifying the moment generation: (a) the passive and active states of a segment of the DEA finger; (b) the negative-tension induced moment acting on an in-active finger, bending the base frame that was initially flat; and (c) the equilibrium angle of a DEA roof as calculated from Eq. (1) and Hooke's law using the parameters as given in the text.

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 the stiff base frame, which a flat DEA hardly buckles.

This design of DEA finger has 6 DEA segments, each located in a window bordered by the flexible frame. Every two segments of the flexible frame have the four corners bonded adhesively to the spines of a stiff base frame (Figure 1(a)). The discrete bonding spots between the flexible and base frames reduce the interfacial resistance and thus allow inter-layer freedom for a large bending. As such, the DEA roof and flexible frame do not add much stiffness to the base frame.

The analysis of a two-segment unit (Figure 1(b)) can predict the response of a whole DE finger with six segments. Consider a DEA roof with a half-cylindrical cross sectional profile: $y = r \sin \phi$, where y is the membrane-height position above the base frame, r is the radius, and ϕ is the angular position that ranges from 0 to π . The arch length of this DEA roof is $w = 2\pi r$, longer than the base width $d = 2r$. A pre-stress σ_0 in the roof-like DEA membrane of thickness t can induce an initial tension $T_0 = 2\pi r t \sigma_0$ and thus a bending moment $\int \sigma_0 y r t d\phi = 2r^2 t \sigma_0$ acting on the base frame of thickness t_b . The equivalent tension center for the moment generation is $h_c = M_0/T_0 = 2h/\pi$, and it is $2h_c/t_b$ times that of a flat DEA does to a bilayer unimorph.

Figure 1(c) shows that the residual bending of a DE finger is an equilibrium between the moment induced by the

DEA's membrane tension and the elastic resistance moment $k_\theta \theta$ of the base frame. The moment induced in the DEA roof decreases slightly with the bending angle θ . As the two-segment roof unit of length $L/3$ bends for $\theta/3$, the membrane becomes shorter, for example, $L_c/3 = 2(L/\theta - h_c) \sin(\theta/6)$ at the tension center $h_c = 2h/\pi$, and it becomes less tangent ($\theta/6 < \pi/2$) to the base frame. Hence, the tension-induced moment at 0 kV becomes $M(\theta, 0V) = \int (\{\sigma_0 - Ee(\theta)\} y \cos(\theta/6) r t d\phi$, where $e(\theta) = (1 - L_c/L)$ is the axial strain and E is the tangent modulus at the axial pre-stretch.

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

$$M(\theta, V) = \int_0^\pi \{\sigma_0 - \epsilon(V/t)^2 - Ee(\theta)\} y(\phi) \cos\left(\frac{\theta}{6}\right) r t d\phi \\ = 2r^2 t \cos(\theta/6) \{\sigma_0 - \epsilon(V/t)^2 - Ee(\theta)\}, \quad (1)$$

where the dielectric permittivity ϵ is a product of dielectric constant ϵ_r and air permittivity ϵ_0 , i.e. $\epsilon = \epsilon_0 \epsilon_r$. 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, 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 1mm 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 (σ_0) of 0.675 MPa induced. This pre-stretched VHB membrane is $33.3 \mu\text{m}$ thick and shows an axial tangent modulus (E) of 0.448 MPa as measured by Instron. Its half cylindrical roof of radius $r = 12.7 \text{ mm}$ 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 $k_\theta = 4.29 \text{ N mm/rad}$ stiff) close to 90° (θ). At the maximum residual angle, the axial strain (relative to its initial pre-stretched length) of the relaxed DEA is less than 13% (e), which justifies the small-displacement assumption of this model.

Figure 2 shows the initially flat components to build a three-dimensional dielectric elastomer finger. They are 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 ($w = 45 \text{ mm}$ 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.

Figure 2(a) shows the assembly steps in a pictorial series. First, the polyimide frame was applied flatly onto a biaxially pre-stretched DEA membrane (VHB 4910), which

FIG. 2. (a) assembly steps for a DE finger from flat components, namely, VHB membrane, polyimide (PI) flexible frame, and PVC base frame; and (b) the height (h) effect of the PI arch flexure on the VHB roof shape and PVC's residual bending.

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 unbend 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 unbending 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 $\times$ 20 mm for conformal grip. Such gripper design can achieve controllable and nimble pinching, which is not possible by the

FIG. 3. Voltage-induced unbending of a DE finger: (a) quasi-static activation by a gradual voltage ramp (1 kV step/min) and (b) dynamic activation by a 1 Hz, 6 kV voltage pulse. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4983036.1>]

FIG. 4. Operation of 3-finger normally close grippers ($d/w = 0.78$): (a) passive lifting of a styrofoam ball with a bunch of paper clips, which weigh 65.6 g in total and (b) the finger's tip compliance in three orthogonal directions.

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 ($2F_\mu$) 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

FIG. 5. Operation of 2-finger ($d/w = 0.78$) normally open grippers: (a) opening of finger tips at 0 kV; (b) closing of finger tips at 3 kV and contact with an egg yolk; (c) pinching and lifting of the egg yolk ($W = 10$ –12 g) with 6 kV activated fingers; (d) the voltage-induced pinch force (as measured from the tip blocked force F_b); (e) time response of the tip blocked force to a pulsed activation for 6 kV at 1 Hz; and (f) maximum payload (frictions $2F_\mu$ between the closed tips) upon voltage activation. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4983036.2>]

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 DEMES¹⁸ 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 DEMES⁹ 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 $139.5 \text{ mN} \pm 1.8 \text{ mN}$ 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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