

3D PRINTED DIELECTRIC ELASTOMER ACTUATOR

Field of Invention

- 5 The present disclosure generally relates to actuators, and more particularly relates to dielectric elastomer actuators.

Background

- 10 The listing or discussion of a prior-published document in this specification should not necessarily be taken as an acknowledgement that the document is part of the state of the art or is common general knowledge.

- Dielectric elastomer actuators (DEAs) have widespread use in soft actuators due to their
15 considerable deformation and feature of rapid response. Typically, DEAs are constructed with a middle dielectric elastomer (DE) film (or membrane), sandwiched by two compliant electrodes, serving as transducers that convert electrical energy into mechanical energy. Actuation in DEAs is facilitated by the Maxwell stress, a result of electrostatic pressure generated by charge accumulation at the electrodes. Upon applying a voltage across the
20 electrodes, the elastomer film undergoes thickness reduction and lateral expansion, leading to substantial electrically controlled deformation. When constrained with a rigid frame, buckling actuation can result. DEAs offer several advantages over conventional actuators, including high energy density, efficiency, lightweight, and cost-effectiveness. However, single-layer dielectric DEAs are known to generate low-force outputs, largely limiting their applications.
25 Therefore, multilayer DEAs, have garnered significant attention due to their ability to generate larger force output.

- DEA has found applications in numerous haptic systems, including tactile feedback systems designed to deliver lifelike sensations to users. Nevertheless, a common limitation of DEA-
30 based vibrotactile devices is their relatively low force output, which confines their usage primarily to highly sensitive regions like fingertips. Additionally, many of these devices necessitate preloading onto the skin, or incorporate rigid assistive components, thereby potentially restricting their overall applicability. Developing multilayer DEA for vibrotactile devices remains unexplored due to the challenges in assembling the layers at various length
35 scales or form factors.

A typical method for fabricating multilayer DEAs entails assembling individual DE membranes and electrode layers manually in a layer-by-layer fashion, making it time-consuming, limiting form factor and leading to issues such as short lifespan due to dielectric breakdown, which can adversely affect the overall performance of the actuator. Different approaches to fabricating multilayer DEA have been developed, including 3D printing. However, most of these previous works use direct ink writing (DIW) 3D printing, which extrudes ink materials through a nozzle to create structures. This method has a low printing resolution (usually more than 100 μm), which leads to rough surface quality. Moreover, all these DIW-printed DEAs require the whole structure to be printed before curing into a solid structure, which restricts the choice of printing materials and makes it difficult to print intricate 3D structures, such as structures with microchannels.

Therefore, to overcome at least one of the aforementioned problems, there exists a need for new methods of manufacturing dielectric elastomer actuators and new dielectric elastomer actuators.

Summary of Invention

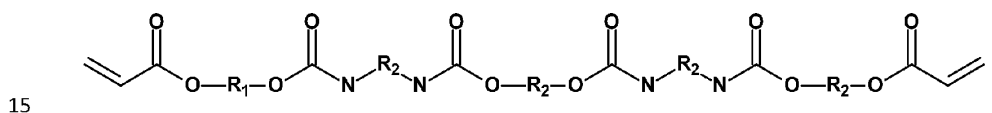
Aspects and embodiments of the invention are provided in the following numbered clauses.

1. A method of manufacturing a dielectric elastomer actuator, the method comprising:
 - (a) providing an additive-manufactured dielectric structure formed from a dielectric elastomer that comprises:
 - a first surface and a second surface opposite to the first surface, the first and second surfaces separated by a body of the dielectric structure;
 - a first plurality of channels that extend from the first surface into the body of the dielectric structure, where each of the first plurality of channels does not penetrate the second surface; and
 - a second plurality of channels that extend from the second surface into the body of the dielectric structure, where each of the second plurality of channels does not penetrate the first surface; and
 - (b) inserting into the first and second plurality of channels an electrically conductive material to provide the dielectric elastomer actuator, wherein:
 - the dielectric elastomer is formed from a resin that comprises an aliphatic urethane diacrylate and an epoxy aliphatic acrylate.

2. The method according to Clause 1, wherein the method further comprises manufacturing the dielectric structure using an additive manufacturing process, optionally wherein the additive manufacturing process is digital light processing.

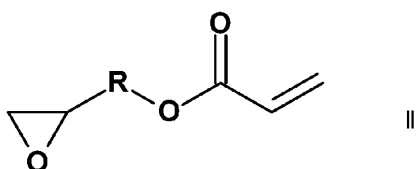
5 3. The method according to Clause 2, wherein the additive manufacturing process comprises light curing the resin comprising an aliphatic urethane diacrylate and an epoxy aliphatic acrylate and a photoinitiator at a suitable wavelength for a suitable period of time, optionally wherein the wavelength is about 405 nm and the period of time is about 0.7 seconds, further optionally wherein a light used in the curing process is provided at a distance to provide
10 a power density of about 30 mW/cm².

4. The method according to any one of the preceding clauses, wherein the aliphatic urethane diacrylate has the general structure of formula I:



where each R₁ and R₂ is independently an aliphatic group, optionally wherein the aliphatic urethane diacrylate is Ebecryl™ 8413.

20 5. The method according to any one of the preceding clauses, wherein the epoxy aliphatic acrylate has the general structure of formula II:



where R is an aliphatic group, optionally wherein the epoxy aliphatic acrylate is Ebecryl™ 113.

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6. The method according to any one of the preceding clauses, wherein a weight to weight ratio of the aliphatic urethane diacrylate to the epoxy aliphatic acrylate is from 1:9 to 9:1, such as from 3:7 to 7:3, such as about 1:1.

7. The method according to any one of the preceding clauses, wherein the electrically conductive material is selected from one or more of a metal rod, and a carbon grease (e.g. a carbon grease), for each of the channels in the first and second plurality of channels.

5 8. The method according to any one of the preceding clauses, wherein the first plurality of channels and the second plurality of channels that extend from the first and second surfaces, respectively, into the body of the dielectric structure are arranged in an alternating pattern of channels, such that each of the first plurality of channels is only adjacent to one or more channels of the second plurality of channels and *vice versa*.

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9. A dielectric elastomer actuator comprising:

an additive-manufactured dielectric structure formed from a dielectric elastomer that comprises:

15 a first surface and a second surface opposite to the first surface, the first and second surfaces separated by a body of the dielectric structure;

a first plurality of channels that extend from the first surface into the body of the dielectric structure, where each of the first plurality of channels does not penetrate the second surface; and

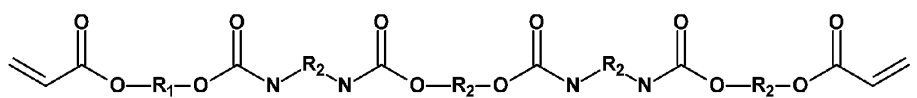
20 a second plurality of channels that extend from the second surface into the body of the dielectric structure, where each of the second plurality of channels does not penetrate the first surface; and

an electrically conductive material within the first and second plurality of channels, wherein:

the dielectric elastomer is formed from a resin that comprises an aliphatic urethane diacrylate and an epoxy aliphatic acrylate.

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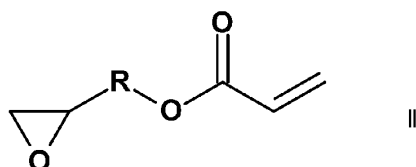
10. The dielectric elastomer actuator according to Clause 9, wherein the aliphatic urethane diacrylate has the general structure of formula I:



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where each R₁ and R₂ is independently an aliphatic group, optionally wherein the aliphatic urethane diacrylate is Ebecryl™ 8413.

11. The dielectric elastomer actuator according to Clause 9 or Clause 10, wherein the epoxy aliphatic acrylate has the general structure of formula II:



5 where R is an aliphatic group, optionally wherein the epoxy aliphatic acrylate is Ebecryl™ 113.

12. The dielectric elastomer actuator according to any one of Clauses 9 to 11, wherein a weight to weight ratio of the aliphatic urethane diacrylate to the epoxy aliphatic acrylate is from 1:9 to 9:1, such as from 3:7 to 7:3, such as about 1:1.

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13. The dielectric elastomer actuator according to any one of Clauses 9 to 12, wherein the electrically conductive material is selected from one or more of a metal rod, and a carbon grease (e.g. a carbon grease), for each of the channels in the first and second plurality of channels.

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14. The dielectric elastomer actuator according to any one of Clauses 9 to 13, wherein the dielectric elastomer actuator further comprises a first end cap and a second end cap each comprising a wire and an electrically conductive surface, wherein the first and second end caps are electrically attached to the first and second surfaces, respectively.

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15. The dielectric elastomer actuator according to any one of Clauses 9 to 14, wherein the dielectric elastomer actuator has one or more of the following properties:

- (i) a modulus of from 0.26 to 1.45 MPa (e.g. from 0.29 to 1.45 MPa);
- (ii) a hysteresis loss of from 12.8% to 28.5%;
- 25 (iii) a dielectric constant of from 5.5 to 10.4;
- (iv) a dielectric strength of from 15 to 45 V/μm, such as about 37.8 V/μm; and
- (v) a blocked force of from 0 to 270 mN, such as about 270 mN when a voltage of 6.5 kV is applied to it.

30 16. The dielectric elastomer actuator according to any one of Clauses 9 to 15, wherein the first plurality of channels and the second plurality of channels that extend from the first and second surfaces, respectively, into the body of the dielectric structure are arranged in an

alternating pattern of channels, such that each of the first plurality of channels is only adjacent to one or more channels of the second plurality of channels and *vice versa*.

Drawings

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Fig. 1 depicts the characterization of dielectric (DE) printing resin. a) Composition of the printing resin. b) Fourier-transform infrared (FTIR) spectra of pristine uncured epoxy aliphatic acrylate (EAA) and aliphatic urethane diacrylate (AUD) resins alongside cured polymers of different AUD:EAA ratios. c) Ultraviolet–visible (UV–Vis) spectra of resins with varying AUD:EAA ratios.

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Fig. 2 depicts the characterization of the dielectric properties of polymer films with varying formulations. a) Dielectric constant of polymer films with different AUD:EAA ratios measured over a frequency range of 1 kHz–100 MHz. b) Dielectric constants of polymer films with varying AUD:EAA ratios measured at 1 kHz. c) Dielectric loss of polymer films with different AUD:EAA ratios measured over a frequency range of 1 kHz–100 MHz. d) Dielectric strength measured on polymer films with varying AUD:EAA ratios.

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Fig. 3 depicts the characterization of the mechanical properties of polymer films with varying formulations. a) Stress–strain behaviors of polymer films with different AUD:EAA ratios. b) Comparison of modulus and maximum elongation of different polymer films. c–g) Cyclic curves of polymer films with different AUD:EAA ratios for five cycles. h) Comparison of hysteresis loss during the first cycle between polymer films with different AUD:EAA ratios.

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Fig. 4 depicts the breakdown field of 19 samples of DLP-printed DE material.

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Fig. 5 depicts the cyclic stress-strain curves for (a) Very High Bond (VHB) and (b) CN9021.

Fig. 6 depicts the fabrication of a DLP-printed DEA. a) Flow chart illustrating the fabrication process of the DLP-printed DEA. b) Schematic diagram depicting the structure of the DLP-printed DEA. c) Photograph showing the DLP-printed DEA.

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Fig. 7 depicts the finite element method (FEM) simulation of the breakdown strength of the DEA. a) The simulated electric field distribution of the annular DE layer with an inner radius of 5 mm and a thickness of 5 mm, and applied voltage of 6.5 kV. b) The calculated breakdown voltage of the DE layer using the simulated result, with a variation of inner radius.

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Fig. 8 depicts a) a photo of 6 DE structures printed simultaneously on a printing platform. b) A photo of an array of DLP-printed DEA mounted on textile.

Fig. 9 depicts a model for the actuation performance simulation. a) The simplified 3D model for simulation with cross-section. b) The radial cross-sectional diagram of the annular DE layer.

Fig. 10 depicts a simplified model utilized for finite element method simulation.

Fig. 11 depicts a comparison between the experimental and simulated static actuation performance of the DLP-printed DEA. a) Comparison between the experimental and simulated static axial displacement with varying applied voltage. b) FEM simulation result showing the axial displacement of the DLP-printed DEA under a voltage of 6.5 kV. c) Comparison between the experimental and simulated static blocked force with varying applied voltage. d) FEM simulation result showing the axial stress of the DLP-printed DEA under a voltage of 6.5 kV.

Fig. 12 depicts the dynamic performance of the DLP-Printed DEA. a) A potential application of a DLP-printed DEA as a vibrotactile device integrated into a prosthetic limb. b–d) Cyclic displacement testing of the DLP-printed DEA over 300 cycles at different frequencies with an applied voltage of 5.5 kV. e) Dynamic displacement performance of the DLP-printed DEA as a function of voltage frequency. f) Schematic illustration of blocked force testing on a soft block using a DLP-printed DEA. g) Comparison of dynamic blocked force performance on rigid and soft surfaces as a function of frequency.

Fig. 13 depicts the displacement curves for 3000 cycles of actuation under 10 Hz.

Fig. 14 depicts the tensile stress-strain curves of the different elastomer substrates.

Description

It has been surprisingly found that the present disclosure provides methods for rapid and efficient fabrication of multilayer DEAs, with the capacity to print multiple structures simultaneously. In addition, the fabricated DEAs can produce adequate force and displacement at high frequency of an applied voltage to serve as vibrotactile devices for prosthetic applications.

Thus, in a first aspect of the invention, there is provided a method of manufacturing a dielectric elastomer actuator, the method comprising:

(a) providing an additive-manufactured dielectric structure formed from a dielectric elastomer that comprises:

a first surface and a second surface opposite to the first surface, the first and second surfaces separated by a body of the dielectric structure;

5 a first plurality of channels that extend from the first surface into the body of the dielectric structure, where each of the first plurality of channels does not penetrate the second surface; and

10 a second plurality of channels that extend from the second surface into the body of the dielectric structure, where each of the second plurality of channels does not penetrate the first surface; and

(b) inserting into the first and second plurality of channels an electrically conductive material to provide the dielectric elastomer actuator, wherein:

the dielectric elastomer is formed from a resin that comprises an aliphatic urethane diacrylate and an epoxy aliphatic acrylate.

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In embodiments herein, the word “comprising” may be interpreted as requiring the features mentioned, but not limiting the presence of other features. Alternatively, the word “comprising” may also relate to the situation where only the components/features listed are intended to be present (e.g. the word “comprising” may be replaced by the phrases “consists of” or “consists essentially of”). It is explicitly contemplated that both the broader and narrower interpretations can be applied to all aspects and embodiments of the present invention. In other words, the word “comprising” and synonyms thereof may be replaced by the phrase “consisting of” or the phrase “consists essentially of” or synonyms thereof and *vice versa*.

25 The phrase, “consists essentially of” and its pseudonyms may be interpreted herein to refer to a material where minor impurities may be present. For example, the material may be greater than or equal to 90% pure, such as greater than 95% pure, such as greater than 97% pure, such as greater than 99% pure, such as greater than 99.9% pure, such as greater than 99.99% pure, such as greater than 99.999% pure, such as 100% pure.

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As used herein, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a compound” includes mixtures of two or more such compounds, reference to “a composition” includes mixtures of two or more such compositions, and the like.

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When used herein, the term “dielectric elastomer actuator” is intended to refer to a dielectric elastomer actuator that requires the components listed above, but which may also contain additional components.

5 It will be appreciated that in some embodiments that may be mentioned herein, the first plurality of channels and the second plurality of channels that extend from the first and second surfaces, respectively, into the body of the dielectric structure may be arranged in an alternating pattern of channels, such that each of the first plurality of channels is only adjacent to one or more channels of the second plurality of channels and *vice versa*.

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In representative or exemplary embodiments of the present disclosure, there is an additive-manufactured dielectric structure 810 formed from a dielectric elastomer, as shown in Fig. 6a. As shown in Fig. 6a, the dielectric structure 810 includes a first surface 840 and a second surface 850 opposite to the first surface 840, a first plurality of channels 841 that extend from the first surface 840 into the body of the dielectric structure 810, where each of the first plurality of channels 841 does not penetrate the second surface 850, and a second plurality of channels 851 that extend from the second surface 850 into the body of the dielectric structure 810, where each of the second plurality of channels 851 does not penetrate the first surface 840. As will be appreciated, the first plurality of channels 841 alternate with the second plurality of channels 851, so that each of the first plurality of channels is adjacent to at least one of the second plurality of channels and *vice versa*.

In some embodiments that may be mentioned herein, the method of manufacturing a dielectric elastomer actuator may further comprise manufacturing the dielectric structure using an additive manufacturing process. As will be appreciated, any suitable additive manufacturing process may be used to manufacture the dielectric structure.

In particular embodiments that may be mentioned herein, the additive manufacturing process may be digital light processing (DLP). In such embodiments, the additive manufacturing process may comprise light curing the resin comprising an aliphatic urethane diacrylate and an epoxy aliphatic acrylate and a photoinitiator at a suitable wavelength for a suitable period of time. For example, the wavelength may be about 405 nm and the period of time may be about 0.7 seconds. In further examples, a light used in the curing process may be provided at a distance to provide a power density of about 30 mW/cm².

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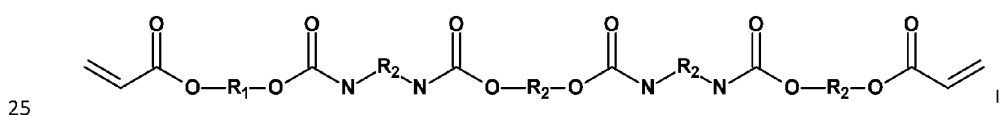
It will be appreciated that any suitable light source may be used to effect the curing of the resin. Examples of suitable light sources may include a visible light source or an ultraviolet (UV) light source.

- 5 It will be appreciated that the manufacturing speed and the number of dielectric structures that may be manufactured may be dependent on the printer. For example, if the printer has a larger printing stage, then more devices can be printed at the same time, and if the printer has a larger light intensity or motor speed, it may print faster.
- 10 Any suitable photoinitiator may be used in the additive manufacturing process. Suitable photoinitiators include, but are not limited to, benzoin methyl ether, irgacure 819, and diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide.

15 In some embodiments that may be mentioned herein, manufacturing the dielectric structure using an additive manufacturing process may further comprise ultrasonically cleaning the printed dielectric structure in isopropyl alcohol (IPA) to remove any uncured resin on the surface of the printed dielectric structure. Additionally, the cleaned dielectric structure may be dried in an oven at 80 °C for 5 minutes to provide a printed dielectric structure with a clean surface.

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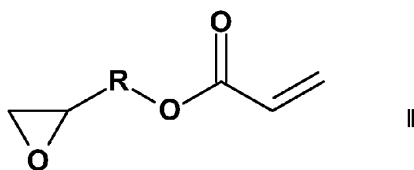
Any suitable aliphatic urethane diacrylate may be used in the method of manufacturing a dielectric elastomer actuator. In some embodiments that may be mentioned herein, the aliphatic urethane diacrylate may have the general structure of formula I:



where each R₁ and R₂ is independently an aliphatic group. For example, the aliphatic urethane diacrylate may be Ebecryl™ 8413.

- 30 Any suitable epoxy aliphatic acrylate may be used in the method of manufacturing a dielectric elastomer actuator. In some embodiments that may be mentioned herein, the epoxy aliphatic acrylate may have the general structure of formula II:

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where R is an aliphatic group. For example, the epoxy aliphatic acrylate may be Ebecryl™ 113.

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The resin may have any suitable weight to weight ratio of the aliphatic urethane diacrylate to the epoxy aliphatic acrylate. In some embodiments that may be mentioned herein, the weight to weight ratio of the aliphatic urethane diacrylate to the epoxy aliphatic acrylate may be from 1:9 to 9:1, such as from 3:7 to 7:3, such as about 1:1.

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The electrically conductive material may be any suitable material that is an electrical conductor. Suitable electrically conductive materials include, but are not limited to, a stretchable or compliant electrode, a metal rod, or a carbon grease. In some embodiments that may be mentioned herein, the electrically conductive material may be selected from one or more of a metal rod, and a carbon grease (e.g. a carbon grease), for each of the channels in the first and second plurality of channels.

Any suitable method may be used for inserting into the first and second plurality of channels the electrically conductive material to provide the dielectric elastomer actuator. For example, the electrically conductive material may be inserted into the first and second plurality of channels using a needle.

In representative or exemplary embodiments of the present disclosure, the method of manufacturing a dielectric elastomer actuator is depicted in Fig. 6a. As shown in Fig. 6a, there is provided a DLP-printed dielectric structure 810. Then, in step 820, the electrically conductive material (e.g. a carbon grease) is applied into the channels of the DLP-printed dielectric structure 810.

In some embodiments that may be mentioned herein, the method of manufacturing a dielectric elastomer actuator may further comprise electrically attaching a first end cap and a second end cap to the first and second surfaces, respectively.

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In a second aspect of the invention, there is provided a dielectric elastomer actuator comprising:

an additive-manufactured dielectric structure formed from a dielectric elastomer that comprises:

- 5 a first surface and a second surface opposite to the first surface, the first and second surfaces separated by a body of the dielectric structure;
- a first plurality of channels that extend from the first surface into the body of the dielectric structure, where each of the first plurality of channels does not penetrate the second surface; and
- 10 a second plurality of channels that extend from the second surface into the body of the dielectric structure, where each of the second plurality of channels does not penetrate the first surface; and
- an electrically conductive material within the first and second plurality of channels, wherein:
 - the dielectric elastomer is formed from a resin that comprises an aliphatic urethane
 - 15 diacrylate and an epoxy aliphatic acrylate.

For the avoidance of doubt, the dielectric elastomer actuator may be as described hereinbefore. As such, a full description of the dielectric elastomer actuator is not included here again for the sake of brevity.

- 20 In some embodiments that may be mentioned herein, the dielectric elastomer actuator may further comprise a first end cap and a second end cap each comprising a wire and an electrically conductive surface, wherein the first and second end caps are electrically attached to the first and second surfaces, respectively (for example, see Fig. 8b). It will be appreciated
- 25 that the first and second end caps may be electrically attached to the first and second surfaces via any suitable method known to a person skilled in the art. For example, the first and second end caps may be electrically attached to the first and second surfaces with a conductive silver paste, where the conductive silver paste acts as an adhesive for sealing the dielectric elastomer actuator with the first and second end caps.

- 30 In representative or exemplary embodiments of the present disclosure, there is a dielectric elastomer actuator 800, as shown in Fig. 6b. The dielectric elastomer actuator 800 comprises a printed dielectric elastomer 810, carbon grease electrode 821, a first cap 831, a second cap 832, and silver paste 833.

- 35 In some embodiments that may be mentioned herein, the dielectric elastomer actuator may have one or more of the following properties:

- (i) a modulus of from 0.26 to 1.45 MPa (e.g. from 0.29 to 1.45 MPa);
- (ii) a hysteresis loss of from 12.8% to 28.5%;
- (iii) a dielectric constant of from 5.5 to 10.4;
- (iv) a dielectric strength of from 15 to 45 V/ μm , such as about 37.8 V/ μm ; and
- 5 (v) a blocked force of from 0 to 270 mN, such as about 270 mN when a voltage of 6.5 kV is applied to it.

The methods for determining modulus, hysteresis loss, dielectric constant, dielectric strength, and blocked force are provided in more detail in the following non-limiting examples.

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As will be appreciated, the present disclosure provides the following advantages:

- a. fast fabrication;
- b. large force output;
- c. high yield;
- 15 d. high dielectric constant; and
- e. low Young's modulus.

Additionally, the present disclosure showcases the potential of integrating the dielectric elastomer actuator disclosed herein into a prosthetic as a vibrotactile device, thereby highlighting its capacity for assisting in rehabilitation and improving the quality of life for individuals with disabilities. Accordingly, the present disclosure demonstrates that the combination of DLP printing technology and tailored resin formulations holds promise for the advancement of dielectric elastomer actuators and their applications in soft robotics and prosthetics.

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Further aspects and embodiments of the invention will now be discussed by reference to the following non-limiting examples.

Examples

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Materials

Ebecryl 8413 and Ebecryl 113 were purchased from Allnex. Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO), and isopropyl alcohol (IPA) were purchased from Sigma Aldrich. Carbon grease was purchased from Yamate Lubricants. A commercial printing resin (transparent green) was purchased from Creality. Conductive silver paste was purchased from TED PELLA. PDMS (including Sylgard 184 part A and part B) were purchased Dow. Ecoflex 00-50 and Ecoflex 00-30 were purchased from Smooth-on.

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Example 1. Design of DE Layer*DE printing resin preparation*

- 5 The SUV elastomer polymer resin was prepared by mixing aliphatic urethane diacrylate (AUD, Ebecryl 8413) and epoxy aliphatic acrylate (EAA, Ebecryl 113) of different ratios with 2 wt.% of TPO using a planetary mixer (1500 rpm, 10 minutes) until a homogeneous mixture was obtained.

10 *Polymer films with different AUD:EAA ratios*

- After weighing AUD and EAA in appropriate proportions, they were combined and mixed with a photoinitiator. Once thoroughly mixed, the resin was blade coated onto glass slides with a thickness of around 500 μm . These slides were then exposed to UV light for a sufficient duration to ensure complete curing. Following curing, the polymer films were carefully peeled
15 off the glass slides to obtain the desired freestanding polymer films.

Ultraviolet–visible (UV–vis) spectroscopy

- Uncured resin samples were placed into a UV-vis spectrophotometer (Brand: Shimadzu, Model: UV2700), where the instrument collects their UV-vis signals. This process involves
20 recording the absorbance spectrum of the resin across a range of wavelengths, allowing for analysis of its optical properties.

Fourier-transform infrared (FTIR) spectroscopy

- FTIR spectroscopy involves placing uncured resin samples and cured polymer films onto an
25 FTIR-compatible holder and recording their infrared absorbance spectrum using a calibrated FTIR spectrometer (Brand: PerkinElmer, Model: Frontier). This process allows for the identification of functional groups present in the resin, aiding in its chemical analysis and characterization.

30 Results and discussion

- The DLP printing resin system was composed of two commercial printing resins, namely Ebecryl 8413, an AUD-based material, and Ebecryl 113, an EAA-based material, with a photoinitiator, TPO. Their chemical structures are depicted in Fig. 1a.

- 35 To identify the optimal resin formulation for a DLP printable DE material, resins of different AUD:EAA ratios were prepared. UV–vis spectroscopic characterization was conducted on the resins with different formulations, and the results are presented in Fig. 1c. All the resins

displayed significant absorption at a wavelength of 405 nm, which can be attributed to the absorption of the TPO photoinitiator, and indicates the resins' suitability for printing complex and hollow structures. This absorption feature is a good match with the wavelength of the LED in the printer, resulting in reduced light penetration depth and minimized overexposure. This characteristic is particularly desirable when printing closed microchannels within a DE structure.

FTIR analyses were carried out to monitor the evolution of chemical structures during the curing process, as shown in Fig. 1b. The FTIR spectra of the cured polymers exhibited a notable decrease in the intensity of the C–C stretching peak between 1610 and 1630 cm⁻¹ associated with the acrylate group, compared to the FTIR spectra of the uncured AUD and EAA resins. This reduction in C–C functional groups is in line with the decrease in the concentration of the acrylate group, which is suggestive of a successful copolymerization of the resins with different formulations.

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Example 2. Dielectric constant and mechanical properties of polymer films

Dielectric constant is a crucial property of DE materials, as it determines the electric static force generated under the same electric field. The dielectric constant at different frequencies was derived for all polymer films with different AUD:EAA ratios (prepared in Example 1). The mechanical properties of the elastomers fabricated using varying ratios of AUD to EAA (as described in Example 1) were also evaluated.

Dielectric constant

When a DEA is subjected to an electric field, charges of opposite polarity accumulate at its two electrodes, resulting in compression of the DE-film due to Maxwell pressure. This compressive force causes the thickness of the DE-film to decrease while the area increases. In cases where the strain is small, typically less than 20%, the DE material is often assumed to have linear deformation with a constant modulus. Thus, the thickness strain can be calculated by dividing the Maxwell pressure P by the modulus of the DE material Y , as shown in Equation (1).

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$$S_z = \frac{P}{Y} = \frac{\epsilon_r \epsilon_0 E^2}{Y} \quad (1)$$

where ϵ_r and ϵ_0 are the vacuum permittivity and dielectric constant of the DE material, respectively. Based on this equation, it can be expected that a DE material with a high dielectric constant and low modulus is desirable, as it will exhibit a larger strain for a given electric field.

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For determining the Weibull distribution, each sample was subjected to increasing electric fields until breakdown occurred, and the breakdown voltage data were analyzed statistically to fit a Weibull distribution curve, providing insights into the material's reliability and failure characteristics under high electric fields.

DE material characterization

Mechanical properties were assessed using an electromechanical universal test system (MTS Criterion Model 42), with test samples measuring $\approx 30 \text{ mm} \times 10 \text{ mm} \times 0.5 \text{ mm}$. Dielectric constant and dielectric loss were determined using an impedance analyser (Agilent 4294A) on samples of identical dimensions to those used in the mechanical tests. To measure the breakdown electric field, a custom-built experimental setup was employed. The DE material, sandwiched between electrodes, was immersed in silicon oil, and a gradually increasing voltage was manually applied using a high-voltage power source (Model PD05034, Trek) until breakdown occurred.

Cyclic loading and unloading

The cyclic loading and unloading experiments involved subjecting the specimen to 10 cycles of loading up to 100% strain at a constant speed of 10 mm/min using an electromechanical universal test system (MTS Criterion Model 42). Load and displacement data were recorded throughout the experiments for analysis of the material's mechanical response.

Results and discussion

The dielectric constant at different frequencies was derived for all polymer films with different AUD:EAA ratios and shown in Fig. 2a. For all the polymer films, the dielectric constant decreases as the frequency increases. At higher frequencies, the dipoles in the material have less time to respond to the applied electric field, leading to incomplete alignment with the field and a resulting decrease in the dielectric constant. It was found that the dielectric constant of the material is higher when the EAA fraction increases. This effect can be attributed to the polar nature of the epoxy groups, which effectively induces the alignment of dipoles in the material and contributes to an overall increase in the dielectric constant. Furthermore, a decrease in the AUD fractions also leads to a lower crosslinking density, promoting the alignment of dipoles for a higher dielectric constant. By manipulating the fractions of each resin, elastomers with high dielectric constants ranging from 5.5 to 10.4 can be achieved, as shown in Fig. 2b. This value is significantly higher than those of other DE materials typically used in DEAs, such as polydimethylsiloxane (PDMS) of ≈ 2.5 (X. Zhang *et al.*, *Mater. Des.* **2020**, 192, 108783), an acrylic adhesive (very high bond, VHB, 3M) of ≈ 4.4 (L. Liu *et al.*,

Polymer **2018**, 144, 150), and another urethane acrylate material (CN9021, Sartomer) of ≈ 5.5 (M. W. M. Tan *et al.*, *NPG Asia Mater.* **2019**, 11, 62). In addition, the dielectric losses of the polymer films were compared and presented in Fig. 2c. It was observed that the polymer film with a lower AUD ratio exhibited a higher dielectric loss, which can be attributed to the lower crosslinking density. The decreased crosslinking density results in higher mobility of the polymer chains, which in turn leads to an increase in the dielectric loss. The breakdown strength of each polymer film was also characterized by the standard measurement based on ASTM D3755-97 and shown in Fig. 2d. The breakdown strength of an elastomer can be increased from 29.7 to 48.8 V μm^{-1} by increasing the AUD ratio. This is likely due to the increase in crosslinking density which affects the mechanical properties of the elastomer and its ability to withstand high electric fields.

Fig. 3a presents and compares the measured elastic properties of the polymer films. At high strain, the polymer film exhibits a strain-hardening behavior due to the limited extensibility of polymer chains. The maximum strain and apparent modulus were also extracted from the stress-strain curve (Fig. 3b). As expected, an increase in the AUD crosslinker concentration led to a higher modulus. This can be attributed to the increased crosslinking density, which in turn reduces the mobility of the polymer chains and leads to a stiffer material. Moreover, the maximum strain also increased with an increase in the AUD ratio, which may be attributed to the increased number of hydrogen bonds present in the polymer. This increase in hydrogen bonding is thought to be responsible for the dissipation of energy and alleviates local stress during mechanical loading, which enhances the stretchability of the polymer. The AUD:EAA ratio can be adjusted to achieve a modulus ranging from 0.29 MPa to 1.45 MPa (at 10% strain).

The dielectric constant of different polymer films was characterized using an impedance analyzer over a frequency range of 1-1000 kHz, and the results are presented in Fig. 2a. Fig. 2b compares the dielectric constants of the DE materials under 1 kHz. By adjusting the formulation, the polymer film's dielectric constant can be increased from 5.5 to 10.4, which is higher than other commonly used DE materials like PDMS (~ 2.3), VHB (~ 4.4), and CN9021 (~ 5.5). Based on the material properties, the printing resin with a AUD:EAA ratio of 5:5 was selected. We characterized the breakdown electric field of 19 samples of the cured DE material (Fig. 4), and the dielectric strength of 37.8 V/ μm was obtained using the Weibull distribution. The breakdown field in air was 20 V/ μm .

As our DEA is designed to respond rapidly and work repeatedly, cyclic curves of each polymer film were obtained to evaluate the energy dissipation characteristics (Figs. 3c-g). An example of the first cycle curve of the 5:5 ratio is presented in Fig. 3e. During the cyclic loading and

unloading process, the stress on reloading was observed to be lower than the stress on the initial loading for the same strain, resulting in a stress-softening phenomenon known as the Mullins effect. This effect contributes to a large hysteresis loss in the first cycle, which is the ratio of dissipated energy to loaded energy, represented by the area of the curve and the integration of the loading curve, respectively. Thus, we calculated the hysteresis loss of each polymer from the cyclic curve and compared the hysteresis loss of the first cycle in Fig. 3h, and interestingly, the polymer film with an AUD:EAA ratio of 5:5 exhibited the lowest hysteresis loss, at 12.8%, indicating better actuation performance when the DEA is operating under high frequency. A small fraction of EAA with respect to AUD results in a large hysteresis loss due to the significant presence of hydrogen bonding between the hard segment of AUD in the polymer, leading to energy dissipation and the hysteresis effect. The higher the EAA ratio, the smaller the modulus because there would be lesser hard segment in AUD and lesser crosslink density. In addition, increasing the EAA ratio leads to a significant decrease in the amount of hydrogen bonds as the distribution of the hard domains becomes diluted. However, this effect only dominates up to a certain extent as the AUD chemical crosslinking effect can limit motion and decrease the dissipative energy. Therefore, further decreasing the proportion of AUD can lead to an increase in the hysteresis effect. The DE material with an AUD:EAA ratio of 5:5 has the minimum hysteresis loss of 12.8%, which is also much smaller than other commonly used DE materials with high dielectric constant, like VHB of 42.7% and CN9021 of 25.4% (Fig. 5). Table 1 presents a comparison of the dielectric and mechanical properties of the polymer films. Based on this comparison, the polymer film with a AUD:EAA ratio of 5:5 was selected as the DE material for preparing DEA.

Table 1. Comparison of the dielectric and mechanical properties between polymers with different AUD:EAA ratios.

AUD:EAA ratio	Dielectric constant	Dielectric loss	Dielectric strength [V μm^{-1}]	Modulus [MPa]	Hysteresis loss [%]
9:1	5.6	0.037	48.8	1.450	28.5
7:3	6.6	0.051	40.6	1.111	13.3
5:5	7.3	0.059	40.9	0.508	12.8
3:7	8.1	0.086	38.6	0.261	16.3
0:10	10.3	0.090	29.7	0.122	40.8

Example 3. DLP-printed DEA fabrication

DLP can print structures with high resolution, speed, and accuracy, as it can cure an entire layer at once and control the light-controlled patterning precisely. This enables rapid, high-throughput, and accurate printing of elastomer structures with smooth surfaces and complex structures.

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A device fabrication process is depicted in Fig. 6a. As shown in Fig. 6a, there is provided a DLP-printed DE structure 810. Then, in step 820, carbon grease is applied into the channels of the DLP-printed DE structure 810. In step 830, the DLP-printed DEA 800 is formed by sealing the carbon grease applied-DLP-printed DE structure with printed caps 831 and 832 (made of printed commercial resin).

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A multi-layer cylindrical DE structure 3D model was designed and printed using DLP printing, with alternating vacant channels at both top and bottom for electrode infilling. As shown in Fig. 6b, there is a DLP-printed DEA 800 which includes a printed dielectric elastomer 810, carbon grease electrode 821, a top cap 831, a bottom cap 832, and silver paste 833. The DE structure has 4 effective layers and the layer thickness, channel width, and inner diameter are 500 μm , 300 μm , and 3 mm, respectively. It is worth noting that a thickness of 500 μm was deliberately chosen for the DE layer for two significant reasons. First, the DE layer is vertically printed, and maintaining its vertical position during the printing process is crucial to its success. A thinner layer might wrinkle during printing and fail to complete the process. Second, due to the limitations of pixel size on the printer and the light scattering properties of the resin, printing a thinner DE layer would increase the risk of printing failures. Thinner DE layers might stick together or end up thicker than the intended design. Hence, the chosen thickness of 500 μm addresses these practical printing constraints and ensures a high yield of printing.

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More specifically, the design for the DE structure in the DEA was created using SOLIDWORKS. A multilayer cylindrical structure was constructed with channels that alternate between opening at the top and bottom, providing space for applying the electrodes. The 3D model was uploaded and the DE structure was printed using a DLP 3D printer (Max, Asiga) equipped with a 405 nm UV LED light source. Each layer of the structure had a thickness of 100 nm and was cured for 0.7 s with a light intensity of 30 mW cm^{-2} . After printing, the DE structure was immersed in IPA and sonicated in a sonicator (Elmasonic P) under 37 kHz for 3 minutes to remove any remaining uncured resin. The DE structure was then dried in an oven at 80 °C for 5 minutes to obtain a DE structure with a clean surface. A thin layer of carbon grease was then applied into the channels of the DE structure using a needle. Additionally, caps for the DEA were 3D printed using a commercial printing resin (transparent green), and conductive silver paste was used as an adhesive to seal the DEA with the caps. The DEA may be

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connected to an external power source using copper wires. After a high voltage is applied on the DEA, it will be activated and it will generate an extension on the axial direction.

As discussed above, after the DE structure was printed and rinsed, carbon grease was applied to the vacant channels to serve as the electrode. Each annular DE layer is sandwiched between a positive electrode and a grounding electrode and can be activated when electrical power is supplied. Subsequently, the top and bottom of the device were sealed with silver paste and furnished with printed caps. These caps, boasting a breakdown voltage exceeding 15 kV, ensure user safety by far exceeding the device's working voltage. Moreover, a thoughtful design feature ensures that electrodes near the top cap and the outermost protective dielectric layer are always connected to the grounding electrode, effectively mitigating any risks associated with human contact, even in situations where the top cap or surrounding protective layer may become compromised. Finally, even if the DEA comes into contact with the human body, it's important to highlight that the current limit of the power source remains at 2 mA. This value is significantly below the established safety threshold for human exposure, which stands at 20 mA.

Example 4. Simulated electric field distribution of annular DE layer

Different from the common plane DEA, the annular DE structure in the present disclosure may cause inhomogeneous electric field distribution. Thus, the effect of the inner radius on the breakdown voltage of the device (prepared in Example 3) was studied (Fig. 7).

In order to study the influence of inner radius on the breakdown voltage of the DEA, the electric field distribution of each annular DE layer was analyzed using the finite element method (FEM) simulation. In contrast to planar DE layers that exhibit a homogeneous electric field distribution, annular DE layers demonstrate an inhomogeneous electric field distribution, as depicted in Fig. 7a. When the same amount of electric charge is distributed on the smaller inner surface, the electric field on the inner side becomes larger. This electric field inhomogeneity becomes more pronounced as the inner radius decreases, primarily due to the increased ratio of the outer surface to the inner surface. Considering that 3D printable DE materials typically possess a breakdown electric field of 20 V/ μm in the air, the breakdown voltage of annular DE layers with varying inner radii was estimated and presented in Fig. 7b. The estimated breakdown voltage exhibits an increasing trend as the inner radius increases, with a particularly substantial increase observed when the inner radius is small. However, it is important to note that increasing the radius results in a larger ineffective area in the center and

also affects the overall diameter of the final device. Hence, for the final device, an inner radius of 1.5 mm was selected.

Example 5. Multiple printing of the DE structure and DEA array

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The entire DEA fabrication process requires only 40 minutes which is a few times faster than the manual stacking process, and Fig. 8a illustrates the capability to print multiple DE structures simultaneously.

- 10 The DE structure was fabricated layer by layer in the axial direction (as described in Example 3), and the printing time depends on the height of the device once the printing parameters were optimized. Consequently, multiple DE structures can be printed simultaneously without increasing the overall printing time. The number of devices that can be printed concurrently is limited by the size of the printing platform in the DLP 3D printer. As shown in Fig. 8a, the
- 15 effective printing area of our DLP printer (Asiga Max) enables a maximum of six devices to be printed at once. Nevertheless, utilizing a larger printer would facilitate large-scale fabrication.

- Fig. 8b depicts a 2×3 DEA array affixed to a textile substrate using an adhesive. In this configuration, all the DEAs share a common grounding electrode, while each DEA is equipped
- 20 with a separate positive electrode, thereby enabling individual activation for each DEA.

- This reduces the fabrication time and allows a more scalable manufacturing process. The final device, shown schematically in Fig. 6b and photographically in Fig. 6c, has a diameter and height of ≈ 1.2 cm. Up to 6 DE structure can be printed at the same time with high yield, which
- 25 reduces the fabrication time of the device. Unlike many other DEA structures that require prestrain and rigid frames, the DEA in the present disclosure is prestrain-free and soft in the axial direction, avoiding problems such as fatigue and enabling a broader scope of applications for the device. In addition, an array of the DLP-printed DEA can be conveniently assembled using the printed caps and easily mounted with adhesive onto substrates such as
- 30 textiles, as demonstrated in Fig. 8b, thereby further expanding the application possibilities of the device.

Example 6. The FEM simulation of the displacement and blocked force performance of the DLP-printed DEA

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To better evaluate the actuation performance of the DEA (prepared in Example 3), FEM simulations were employed to predict its ideal performance (Fig. 9). A 3D model was

constructed, including all active parts of the device, while omitting some passive components to simplify the simulation process. The electrode used in the DEA is a conductive viscous material, carbon grease, which exerts minimal constraint on the DE material and was therefore ignored in the simulation. Furthermore, since the DEA's deformation is minimal, the DE material's deformation was assumed to be linearly elastic, with a constant Young's modulus.

Fig. 9a illustrates the simplified 3D model used for the simulation. The model focuses on capturing the effective area of the DEA, which comprises the annular layers sandwiched between two electrodes. Most of the passive parts, which have minimal impact on the actuation performance, were neglected to simplify the simulation and improve computational efficiency and accuracy. Additionally, the constraining effect of the electrode was disregarded due to the low constraint imposed by the viscous carbon grease electrode. Considering that the deformation of the DEA is minimal, the DE material was assumed to exhibit linear deformation with a constant modulus. In the simulation, the four annular layers are defined as the DE material, while the top round cap is defined as a rigid material with fixed contact to the DE material.

As depicted in Fig. 9b, each annular DE layer pressure generated on the inner and outer surface, p_i and p_o , respectively, can be calculated by Equation 2 and Equation 3 (F. Carpi & D. De Rossi, *Mater. Sci. Eng. C.* **2004**, 24, 555; and W.-P. Yang & L.-W. Chen, *Smart Mater. Struct.* **2007**, 17, 015011):

$$p_i = \frac{\epsilon_r \epsilon_0 V^2}{2 \ln^2 \left(\frac{r_o}{r_i} \right) r_i^2 r_o (r_o^2 - r_i^2)} \times \left[r_i^6 + r_o^6 - r_i^2 r_o^4 - r_i^4 r_o^2 + 8 \ln \left(\frac{r_o}{r_i} \right) (r_o^2 - r_i^2) r_i^2 r_o^2 + 4 \ln^2 \left(\frac{r_o}{r_i} \right) (r_o^2 + r_i^2) r_i^2 r_o^2 \right]^{1/2} \quad (2)$$

$$p_o = \frac{\epsilon_r \epsilon_0 V^2}{2 \ln^2 \left(\frac{r_o}{r_i} \right) r_i r_o^2 (r_o^2 - r_i^2)} \times \left[r_i^6 + r_o^6 - r_i^2 r_o^4 - r_i^4 r_o^2 + 8 \ln \left(\frac{r_o}{r_i} \right) (r_o^2 - r_i^2) r_i^2 r_o^2 + 4 \ln^2 \left(\frac{r_o}{r_i} \right) (r_o^2 + r_i^2) r_i^2 r_o^2 \right]^{1/2} \quad (3)$$

Where ϵ_r and ϵ_0 are the relative permittivity of the material and the vacuum permittivity, respectively, V is the voltage applied on the DE layer, and r_i and r_o are the inner radius and the outer radius, respectively.

Example 7. Static axial displacement of the DEA

As described above, applying a voltage to the DEA device generates Maxwell pressure between the positive and negative carbon grease electrodes. Since each annular layer is sandwiched by electrodes with opposite charges, it compresses in the radial direction, resulting in axial expansion. To measure the static axial displacement of the DEA (prepared

in Example 3), we used a laser displacement sensor and applied different voltages for 20 s to ensure a stable state.

Axial displacement and blocked force measurements

- 5 The axial displacement and blocked force were measured by an optoNCDT laser displacement sensor (IDL2300, Micro-Epsilon) and a force gauge (M5-025, Mark-10) respectively. The voltage was applied by a high-voltage power source (Model PD05034, Trek). The static actuation performance was measured by applying each voltage for 20 s, while the dynamic performance was measured using the amplifier mode of the same power source to
10 amplify a square pulse signal from a pulse generator (TGP110, Thurlby Thandar instruments).

ANSYS simulations

- For ANSYS simulations, a simplified model is imported into the ANSYS software. Different values of Maxwell stress are inputted into the software for each side of the polymer films within
15 each layer of the device. ANSYS then calculates the corresponding displacement and magnitude of the blocked force generated due to these applied voltages.

Results and discussion

- Axial displacement was simulated. Fig. 11a shows that displacement increases with applied
20 voltage, following a quadratic growth based on Equation (1). To prevent breakdown, we limit a maximum voltage of 6.5 kV, with a corresponding electric field of $\approx 13 \text{ V } \mu\text{m}^{-1}$, which produced a displacement of 55 μm , enabling the DEAs to perform many functions in soft robotics, such as haptic devices.

- 25 To better evaluate the actuation performance of the DEA, ANSYS simulations were employed to predict its ideal performance. A simulated result of the axial displacement under 6.5 kV is shown in Fig. 11b. The close match between the experimental and simulated results suggests the effectiveness of the design and fabrication method. However, the deviation between the simulated and experimental results may be attributed to factors that were not considered in
30 the simulation parameters, such as the weight of the device and other passive structures omitted in the simulation model that could influence the deformation.

- The blocked force refers to the force that is generated by a DEA when it is prevented from expanding or contracting due to mechanical constraints. To measure the static blocked force
35 of the actuator, a force gauge was used to fully block the axial displacement of the DEA. Upon actuation, the DEA generated a force that could be readily captured by the force gauge. Similar to the displacement, the blocked force also increased with the applied voltage, as shown in

Fig. 11c. Furthermore, a simulated axial stress result was obtained by conducting ANSYS simulations, as shown in Fig. 11d. By integrating the stress over the top surface, the simulated blocked force can be calculated and compared with the experimental results. The maximum blocked force achieved by the DEA, with four effectively activated DE layers, was 270 mN when 6.5 kV was applied, which is larger than the single-layer DEA of ≈ 10 mN, and comparable to other multilayer DEAs with similar structures having a blocked force of between 100 mN and around 1 N (Y. Shi *et al.*, *Science* **2022**, 377, 228; Y. Chen *et al.*, *Nature* **2019**, 575, 324; and H. Zhao *et al.*, *Soft Rob.* **2020**, 7, 451). These simulation outcomes are consistent with our experimental results, further validating the effectiveness of the simulation model and the fabrication method.

Table 2 compares the performance of our DLP-printed DEA with other 3D-printed DEAs from prior studies. Besides showcasing the novelty of our fabrication method, our DEA exhibits superior blocked force performance compared to the majority of 3D-printed DEAs, thanks to the relatively compact structure achieved by DLP printing.

Table 2. Comparison between the 3D-printed DEA devices.

Reference	Printing method	Printing part	Actuation performance
G. Haghighashtiani <i>et al.</i> , <i>Extreme Mech. Lett.</i> 2018 , 21, 1	Direct ink writing (DIW)	Planar DE and electrode films	21 mN blocked force
D. Gonzalez <i>et al.</i> , <i>Sens. Actuators A: Phys.</i> 2019 , 297, 111565	Fused Deposition Modeling (FDM)	Planar DE films	5.7% area strain
A. Chortos <i>et al.</i> , <i>Adv. Funct. Mater.</i> 2020 , 30, 1907375	Direct ink writing (DIW)	Interdigital electrode	9% thickness strain
Y. Zhu <i>et al.</i> , <i>ACS Materials Lett.</i> 2023 , 5, 704	Direct ink writing (DIW)	DEA fiber	105 mN blocked force
S. Su <i>et al.</i> , <i>Smart Mater. Struct.</i> 2023 , 32, 035021	Direct ink writing (DIW)	Planar DE film	5 mN blocked force

The present disclosure	Digital light processing (DLP)	Multi-layer cylinder DE structure with micro channels	270 mN blocked force
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Example 8. DLP-printed DEA in prosthetic applications

The DLP-printed DEA has a high force output and does not require to be preloaded on the skin, which may be suitable for the haptic device inserted in the wearable carrier substrates or suited for relatively insensitive skin areas. Fig. 12a demonstrates the conceptual integration of DLP-printed DEA as a vibrotactile device within a prosthetic leg. Individuals with disabilities, particularly those who have lost tactile sensation in their feet, often face mobility limitations despite using prostheses. In this proposed design, multiple DEAs are incorporated into the prosthesis socket and generate tactile feedback in response to the sensor data, aiming to replicate the sensation of a natural foot. This innovative approach has the potential to significantly enhance the quality of life for individuals with disabilities who depend on prosthetics, enabling them to better adapt to their artificial limbs.

To demonstrate the feasibility of our DLP-printed DEA (prepared in Example 3) in prosthetic applications, we investigated the dynamic actuation performance of these devices. As high-frequency AC voltage may potentially lead to premature breakdown, a voltage amplitude of 5.5 kV was selected for the dynamic tests.

Tensile test of different elastomer substrate

Four elastomers with different modulus were prepared, namely PDMS elastomer samples with two different prepolymer (Sylgard 184 part A):cross-linking curing agent (Sylgard 184 part B) ratios 20:1 and 30:1, and Ecoflex 00-50 and Ecoflex 00-30. To determine the moduli of these elastomers, tensile tests were conducted on these elastomers by following the protocol in Example 2.

Results and discussion

The displacement measurements obtained under this voltage amplitude and varying frequencies are depicted in Figs. 12b-e. As frequency increases, the displacement drops significantly due to insufficient time for the DEA to deform under Maxwell stress. Nevertheless, the DEA can still maintain 45% displacement under 100 Hz at $\approx 20.9\text{ }\mu\text{m}$ thanks to due to the low hysteresis loss of the DE materials. This is sufficient for prosthetic applications as it has surpassed the perception threshold of human beings even for the insensitive parts of the body, such as the calf ($5\text{ }\mu\text{m}$ at 100 Hz) (A. Wilska, *Acta. Physiol. Scand.* **1954**, 31, 285). An

extended cyclic test was also conducted by following the protocol in Example 2, as depicted in Fig. 13, demonstrating the DEA's remarkable ability to maintain a relatively stable performance even after enduring 3000 cycles.

5 We also evaluated the dynamic blocked force of the DLP-printed DEA. To assess the force generated by the DEA on the user, an elastomer mimicking the contact area of the residual limb was placed beneath the DEA (Fig. 12f). In the context of prosthetic application, because the DEA is pressed against the user's residual limb when the prosthetic is attached, the modulus of the contact area should reflect the muscle properties of the limb and typically
10 ranges from 100 to 400 kPa (J. van Kuilenburg, M. A. Masen, *Proc. Inst. Mech. Eng., Part J* **2013**, 227, 349). Therefore, a selection of elastomers (Ecoflex 00-30, Ecoflex 00-50, PDMS 30:1, and PDMS 20:1) covering this specific modulus range was prepared for testing purposes (Fig. 14). The elastomers were ≈ 1 cm thick, ensuring that their thickness significantly exceeds the displacement of the DEA, in order to avoid any influence from the rigid surface beneath
15 the elastomer on the test results. The blocked force generated on elastomers with different modules is depicted in Fig. 12g. Consistent with the dynamic displacement results, the blocked force exhibited a decrease as the frequency increased. The blocked force depends on how much the DEA can deform. When blocked by a rigid surface, the DEA cannot be displaced at all, and the blocked force is maximum. Conversely, when the DEA is working on a soft surface,
20 the DEA can deform to some extent, leading to a reduction in the blocked force. Thus, a softer elastomer will lead to a smaller blocked force. The results indicate that under 5.5 kV 100 Hz AC voltage, the DEA can generate a force of 54 mN on the elastomer with the lowest modulus of 95 kPa, surpassing the minimum force detectable by the human shin (≈ 10 mN) (R. Ackerley *et al.*, *Front. Behav. Neurosci.* **2014**, 8, 54), indicating its potential to generate sufficient force
25 for prosthetic applications. While the threshold value is dependent on the contact area, the configuration of our DEA can be tailored to adjust the contact area on the skin, enhancing its suitability for real-world prosthetic applications. Table 3 presents a comparison of several DEA-based haptic devices, indicating that our device can achieve a substantial force output without necessitating prestrain, rigid structures, or the need for preloading or attachment to
30 the human skin. These findings indicate that our DLP-printed DEA exhibits excellent dynamic actuation capabilities, making it a promising technology for various prosthetic applications.

Table 3. Comparison between the DEA-based haptic devices.

Reference	DE material	Electrode material	Requirement	Electric field	Force output
Ankit <i>et al.</i> , <i>Small</i>	3M VHB Acrylic 4910	Silver nanowires (AgNWs) and	Pre-strain and rigid substrate	21.4 V μm^{-1}	47 mN

2018, 14, 1702312		hydrogel			
H. Phung <i>et al.</i> , <i>Meccanica</i> 2015, 50, 2825	Silicone	Graphite particles	Pre-loading	60 V μm^{-1}	150 mN
J. Kang <i>et al.</i> , <i>Adv. Funct. Mater.</i> 2019, 29, 1902703	Polydimethylsiloxane (PDMS) and poly(ethylene terephthalate) (PET)	Silver microwires (AgMWs) and indium tin oxide (ITO)	Rigid structure	-	60 mN
H. S. Lee <i>et al.</i> , <i>Sens. Actuators A: Phys.</i> 2014, 205, 191	Silicone	Carbon and graphite	Pre-loading	78 V μm^{-1}	120 mN
X. Ji <i>et al.</i> , <i>Adv. Funct. Mater.</i> 2021, 31, 2006639	Silicone	single walled carbon nanotubes (SWCNT)	Pre-strain and preloading	75 V μm^{-1}	9 mN (estimated)
The present disclosure	DLP-printed PUA-based elastomer	Carbon grease	No pre-strain or rigid structure required	13 V μm^{-1} (average)	270 mN

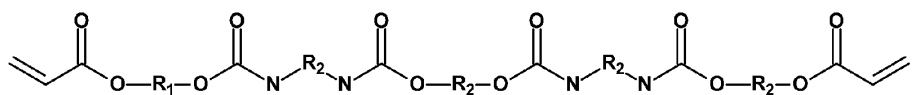
In the present disclosure, we utilized a combination of AUD, EAA, and TPO to create a printable DE structure for the development of a DEA using DLP 3D printing. By adjusting the AUD:EAA ratio, we obtained DLP-printable DE materials with varying mechanical and dielectric properties. Through comprehensive characterization, we identified a formulation with an optimal balance of dielectric constant, modulus, and minimal hysteresis loss, which was selected as the final printing resin. The designed and printed multilayer cylinder DEA demonstrated excellent actuation performance, as confirmed by static axial displacement and blocked force measurements. Furthermore, we successfully showcased the potential of integrating the DLP-printed DEA into a prosthetic as a vibrotactile device, thereby highlighting its capacity for assisting in rehabilitation and improving the quality of life for individuals with

disabilities. The combination of DLP printing technology and tailored resin formulations holds promise for the advancement of DEAs and their applications in soft robotics and prosthetics.

In the present disclosure, we present a novel method for fabricating multilayer dielectric elastomer actuators utilizing DLP 3D printing. By employing DLP, 3D intricate multilayer structures can be realized, at which DEAs of a cylindrical structure with integrated electrodes were designed. Unlike the conventional roll structure DEA that relies on friction and adhesion between the layers to prevent unwinding, the 3D printed structure disclosed herein eliminates the need for such constraints, thus reducing the internal stress and the circumference deformation of the device. This process enables rapid and efficient fabrication of multilayer DEAs, with the capacity to print multiple structures simultaneously. The formulation of the printing resin was tailored to obtain a printable DE material with a suitable dielectric constant, modulus, and low hysteresis loss. The resulting device exhibits a substantial force output of 270 mN and can operate at high frequencies. Moreover, the present disclosure also demonstrates that the DLP-printed DEAs can produce adequate force and displacement at high frequency to serve as vibrotactile devices for prosthetic applications. By providing feedback to users, DEAs are able to offer a realistic sense of touch and texture when integrated under a prosthetic leg, compensating for the loss of sensation. This enhancement improves the functionality of prosthetic devices, significantly impacting the lives of individuals with limb loss. Therefore, the present disclosure sheds new light on the development of efficient fabrication techniques for multilayer DEAs.

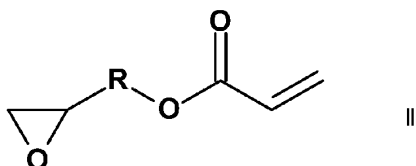
Claims

1. A method of manufacturing a dielectric elastomer actuator, the method comprising:
 - (a) providing an additive-manufactured dielectric structure formed from a dielectric elastomer that comprises:
 - a first surface and a second surface opposite to the first surface, the first and second surfaces separated by a body of the dielectric structure;
 - a first plurality of channels that extend from the first surface into the body of the dielectric structure, where each of the first plurality of channels does not penetrate the second surface; and
 - a second plurality of channels that extend from the second surface into the body of the dielectric structure, where each of the second plurality of channels does not penetrate the first surface; and
 - (b) inserting into the first and second plurality of channels an electrically conductive material to provide the dielectric elastomer actuator, wherein:
 - the dielectric elastomer is formed from a resin that comprises an aliphatic urethane diacrylate and an epoxy aliphatic acrylate.
2. The method according to Claim 1, wherein the method further comprises manufacturing the dielectric structure using an additive manufacturing process, optionally wherein the additive manufacturing process is digital light processing.
3. The method according to Claim 2, wherein the additive manufacturing process comprises light curing the resin comprising an aliphatic urethane diacrylate and an epoxy aliphatic acrylate and a photoinitiator at a suitable wavelength for a suitable period of time, optionally wherein the wavelength is about 405 nm and the period of time is about 0.7 seconds, further optionally wherein a light used in the curing process is provided at a distance to provide a power density of about 30 mW/cm².
4. The method according to any one of the preceding claims, wherein the aliphatic urethane diacrylate has the general structure of formula I:



where each R_1 and R_2 is independently an aliphatic group, optionally wherein the aliphatic urethane diacrylate is Ebecryl™ 8413.

5. The method according to any one of the preceding claims, wherein the epoxy aliphatic acrylate has the general structure of formula II:



where R is an aliphatic group, optionally wherein the epoxy aliphatic acrylate is Ebecryl™ 113.

6. The method according to any one of the preceding claims, wherein a weight to weight ratio of the aliphatic urethane diacrylate to the epoxy aliphatic acrylate is from 1:9 to 9:1, such as from 3:7 to 7:3, such as about 1:1.

7. The method according to any one of the preceding claims, wherein the electrically conductive material is selected from one or more of a metal rod, and a carbon grease (e.g. a carbon grease), for each of the channels in the first and second plurality of channels.

8. The method according to any one of the preceding claims, wherein the first plurality of channels and the second plurality of channels that extend from the first and second surfaces, respectively, into the body of the dielectric structure are arranged in an alternating pattern of channels, such that each of the first plurality of channels is only adjacent to one or more channels of the second plurality of channels and *vice versa*.

9. A dielectric elastomer actuator comprising:
an additive-manufactured dielectric structure formed from a dielectric elastomer that comprises:

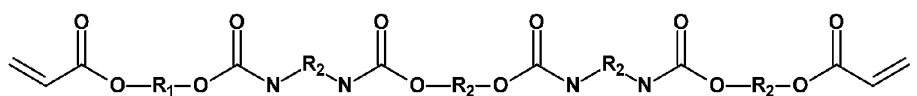
- a first surface and a second surface opposite to the first surface, the first and second surfaces separated by a body of the dielectric structure;
- a first plurality of channels that extend from the first surface into the body of the dielectric structure, where each of the first plurality of channels does not penetrate the second surface; and

a second plurality of channels that extend from the second surface into the body of the dielectric structure, where each of the second plurality of channels does not penetrate the first surface; and

an electrically conductive material within the first and second plurality of channels, wherein:

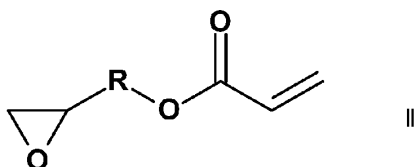
the dielectric elastomer is formed from a resin that comprises an aliphatic urethane diacrylate and an epoxy aliphatic acrylate.

10. The dielectric elastomer actuator according to Claim 9, wherein the aliphatic urethane diacrylate has the general structure of formula I:



where each R_1 and R_2 is independently an aliphatic group, optionally wherein the aliphatic urethane diacrylate is Ebecryl™ 8413.

11. The dielectric elastomer actuator according to Claim 9 or Claim 10, wherein the epoxy aliphatic acrylate has the general structure of formula II:



where R is an aliphatic group, optionally wherein the epoxy aliphatic acrylate is Ebecryl™ 113.

12. The dielectric elastomer actuator according to any one of Claims 9 to 11, wherein a weight to weight ratio of the aliphatic urethane diacrylate to the epoxy aliphatic acrylate is from 1:9 to 9:1, such as from 3:7 to 7:3, such as about 1:1.

13. The dielectric elastomer actuator according to any one of Claims 9 to 12, wherein the electrically conductive material is selected from one or more of a metal rod, and a carbon grease (e.g. a carbon grease), for each of the channels in the first and second plurality of channels.

14. The dielectric elastomer actuator according to any one of Claims 9 to 13, wherein the dielectric elastomer actuator further comprises a first end cap and a second end cap each comprising a wire and an electrically conductive surface, wherein the first and second end caps are electrically attached to the first and second surfaces, respectively.

15. The dielectric elastomer actuator according to any one of Claims 9 to 14, wherein the dielectric elastomer actuator has one or more of the following properties:

- (i) a modulus of from 0.26 to 1.45 MPa (e.g. from 0.29 to 1.45 MPa);
- (ii) a hysteresis loss of from 12.8% to 28.5%;
- (iii) a dielectric constant of from 5.5 to 10.4;
- (iv) a dielectric strength of from 15 to 45 V/ μm , such as about 37.8 V/ μm ; and
- (v) a blocked force of from 0 to 270 mN, such as about 270 mN when a voltage of 6.5 kV is applied to it.

16. The dielectric elastomer actuator according to any one of Claims 9 to 15, wherein the first plurality of channels and the second plurality of channels that extend from the first and second surfaces, respectively, into the body of the dielectric structure are arranged in an alternating pattern of channels, such that each of the first plurality of channels is only adjacent to one or more channels of the second plurality of channels and *vice versa*.