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Large Axial Actuation of Pre-stretched Tubular Dielectric Elastomer and Use of Oil Encapsulation to Enhance Dielectric Breakdown Strength

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Abstract. Rolled dielectric elastomer actuators (DEA) are subjected to necking and non-uniform deformation upon pre-stress relaxation. Though being rolled up from flat DEAs, they performed much poorer than the flat ones. Their electrically induced axial strains were previously reported of not more than 37.3%, while the flat ones produced greater than 100% strain. Often, the rolled DEAs succumb to premature breakdown before they can realize the full actuation potential like the flat ones do. This study shows that oil encapsulation, together with large hoop pre-stretch, helps single-wound rolled DEAs, which are also known as tubular DEAs, suppress pre-mature breakdown. Consequently, the oil-encapsulated tubular DEAs can sustain higher electric fields, and thus produce larger isotonic strain and higher isometric stress change. Under isotonic test, they sustained very high electric fields of up to 712.7 MV/m, which is approximately 50% higher than that of the dry tubular DEAs. They produced up to 55.4% axial isotonic strain despite being axially stiffening by the passive oil capsules. In addition, due to the use of large hoop pre-stretch, even the dry tubular DEAs without oil encapsulation achieved a very large axial strain of up to 84.2% compared to previous works. Under the isometric test, the oil encapsulated tubular DEA with enhanced breakdown strength produced an axial stress change of up to nearly 0.6 MPa, which is 114% higher than that produced by the dry ones. In conclusion, the oil encapsulation and large pre-stretch help realize fuller actuation potential of tubular dielectric elastomer, which is subjected to initially non-uniform deformation.

1. Introduction

Rolled dielectric elastomer actuators (DEA) have been recently used as artificial muscles to drive bio-inspired robots [1-8]. They are prepared by rolling up a flat pre-stretched membrane of DEAs into a single wound or multiple wounds in tubular shape [1-11] as shown in Fig. 1. Due to the relaxation from hoop pre-stress, the tubular membranes are subjected to necking and consequently non-uniform deformation [11-12]. Hence, the rolled DEAs produce much lesser axial actuation and sustain a lower electric field as compared to the flat ones [11-12]. Previously, multiple-wound rolled DEAs were reported of not more than 32% axial actuation strain [1-6]; whereas, the flat ones that undergo pure-shear deformation reported greater actuation, well beyond 100% axial strain [13]. Even, single-wound rolled DEAs reported at best 37.3% axial strain [11-12].

A single-wound roll, which is also known as a tubular DEA [9-11] as shown in Figure 2, can representatively reveal problems encountered by a multiple-wound roll, albeit being free from interfacial radial stress [5-6, 9, 11]. A short tube is found to produce more axial strain than a longer tube because it is subjected to stronger hoop constraint and less necking [11]. On the other hand, a long tube can be designed to perform as well as a short tube by means of hoop clamping using nylon fibers (0.2mm diameter) [11] or helical spring [1-6]. However, so far, these tubular DEAs are reported with only limited axial strain of up to 37.3% %, which is far less than the actuation strain achievable by the flat ones. In theory, the tubular DEA with large hoop pre-stretch could achieve a much larger axial actuation strain [12, 14]. However, in practice, they succumb to pre-mature electrical breakdown

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[11-12] and did not experimentally achieve as much axial actuation strain as theoretical prediction [12]. If the pre-mature breakdown could be suppressed, they could possibly realize its fuller potential of actuation.

Previously, oil encapsulation was shown to help a flat DEA with immobilized graphite compliant electrodes sustain an ultra high field of up to 835MV/m [15-16]. While replacing air surrounding the DEA, oil immersion helps prevent partial discharge [17], extinguishes electric arcing [15-17], and stops thermal runaway [15-16] from pre-maturely damaging the flat DEAs. However, it is not clear if the oil encapsulation remains effective to improve performance of tubular DEAs, which are subjected non-homogenous deformation and electric fields. In this study, we apply oil capsules over tubular DEAs (see Fig. 2(b)) and shall experimentally show that oil encapsulated tubular DEAs can sustain very high electrical field as compared to the dry ones. In addition, this study proposes using hyperboloid surface to describe this tubular shape change due to necking, and thus to estimate the average thickness of the tubular membrane. Subsequent sections will present design, fabrication and characterisation of the oil-encapsulated tubular DEAs, in comparison with the dry ones.

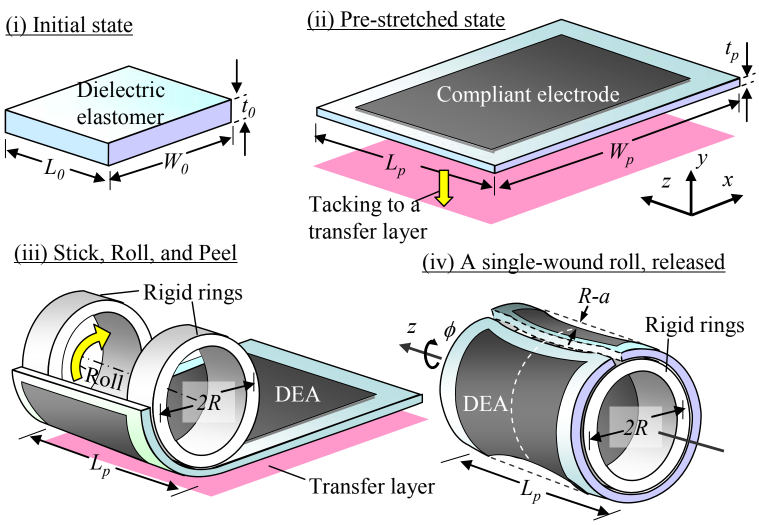

Figure 1. The processes in schematic drawing to make a single-wound rolled DEA with bi-axial pre-stretches.

2. Principles and Design

A tubular DEA is a roll-up of a flat DEA of pre-stretched membrane as shown in Figures 1 and 2. Initially, the flat DEA has uniform thickness when it is bi-axially pre-stretched at a longitudinal ratio of λ_z=L_p/L_0 and a transverse ratio of λ_x=L_p/L_0. When it is rolled up in the transverse direction and its longitudinal ends are clamped by rigid rings, the DEA is shaped like a hollow tube, albeit with non-uniform membrane thickness. The relaxed tubular membrane has a constant end-hoop pre-stretch $\lambda_\phi = \lambda_x$ due to clamping by rigid rings, but its free membrane is subjected to hoop stress relaxation and thus non-uniformly reduced pre-stretch. As such, the tubular DEA forms a waistline or the so-called necking (see Figure 2). Hence, the relaxed tubular membrane has its middle hoop reduced in diameter and thickened, while the membrane at the end hoop is much thinner. Activation of such tubular DEA yields longitudinally non-uniform field and axial strain. As the thickened part of the tubular membrane is subjected to a lower field, it contributes to lesser axial strain. However, the thinner parts of the tubular membrane, which contribute to a larger strain, are more prone to electrical breakdown due to field and stress concentration.

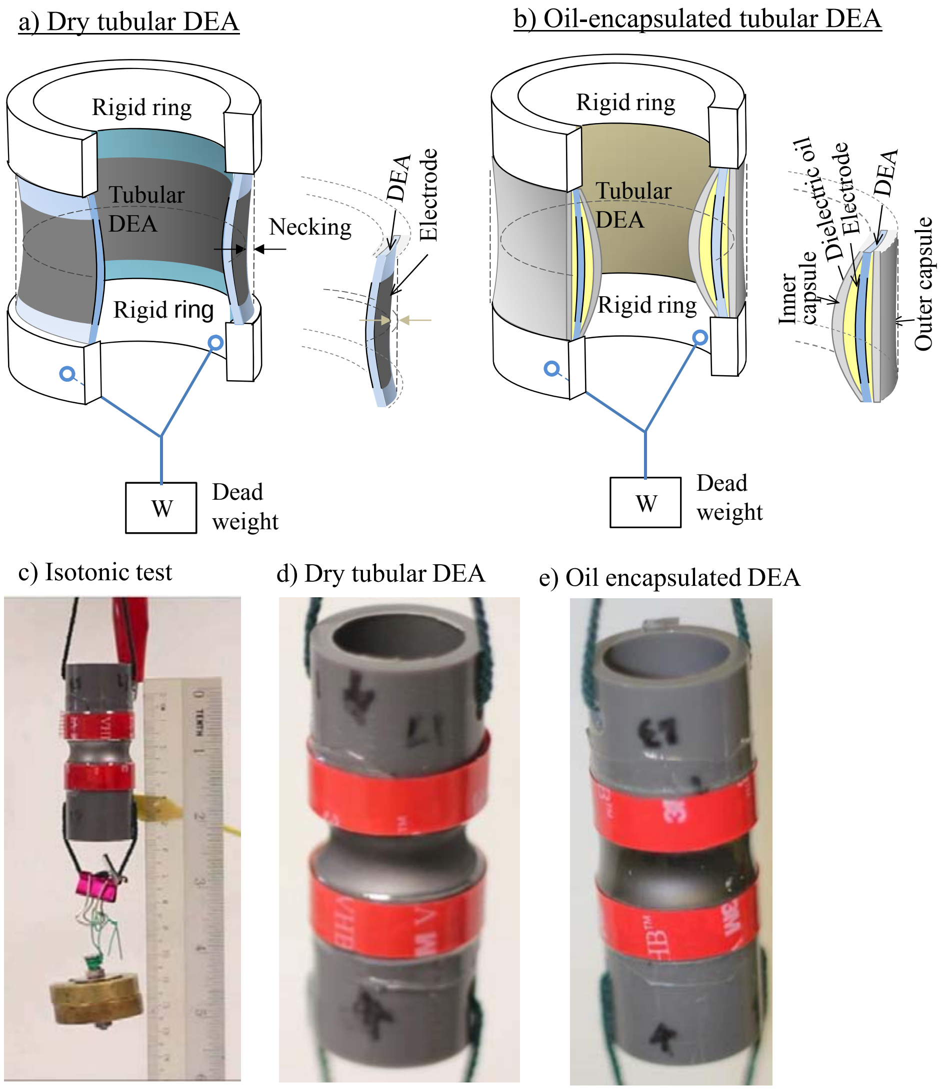

Figure 2. Design of tubular DEAs: (a) and (b) schematic drawing with sectional view of a dry tubular DEA and an oil-encapsulated tubular DEA, respectively; (c), (d) and (e) photographs of isotonic test configuration, the dry and the oil-encapsulated samples, respectively.

This study proposes the use of oil encapsulation over the compliant electrodes to suppress possible electrical breakdown and consequently improve actuation of tubular DEAs, which are subjected to large pre-stretch and necking. As shown in Figure 2, there are two passive oil capsules, on the inner and on the outer sides of the DEA tube. These oil capsules add passive weight, occupy more volume, and stiffen the tubular DEA. In addition, they alter the pre-stress required to maintain the same pre-stretch of active tube. By adjusting the volume of oil in the capsule, it is possible to slightly straighten the waistline of the active tube and make its deformation more homogeneous.

Under isotonic test as shown in Figure 3a-b, the oil-encapsulated tubular DEA is activated to produce elongation while it is axially pre-loaded by deadweight. While the core of tubular DEA elongates under Maxwell stress, the passive capsule membranes conforms to the electrically induced elongation.

The elongation is a sum of electrically induced axial strains in the core DEA, which varies longitudinally. The induced actuation strain is defined as

$$s_z = \frac{L_{act}}{L_p} - 1 \tag{1}$$

where L_{act} is the activated length and L_p is the idle pre-stretched length.

Under isometric test as shown in Figure 3c, a tubular DEA has two ends fixed and pre-stretched at a constant length L', resulting a blocked pre-stress σ_p. Electrically activation induces Maxwell stress across the DEA membrane, reducing the active membrane stress while the passive capsule membranes remain the same pre-stress σ_p. Consequently, the activation leads to a reduction of the blocked force as the actuator length is fixed. As the active membrane is not aligned with the tube axe, only vertical components of the active membrane stresses contribute to the axial blocked force measured ΔF_z:

$$\Delta F_z = 2\pi R t_p \Delta\sigma_{//} \cos\beta \tag{2}$$

where $\Delta\sigma_{//}$ is the in-plane membrane stress of constant pre-stretched thickness t_p and β is the inclination between the tubular membrane and vertical peripheral plane of the rigid ring. The axial stress is calculated as $\Delta F_z/(2\pi R t_p)$.

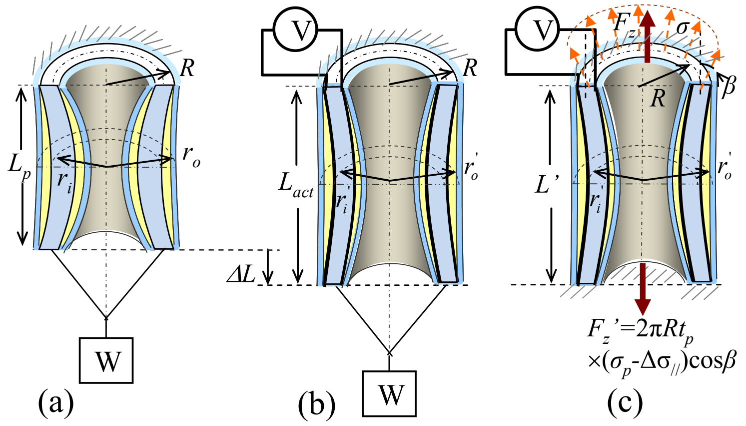

Figure 3. Different states of the oil-encapsulated tubular DEA: (a) the idle pre-stretched state under a pre-load W; (b) the activated state during the isotonic test where the DEA elongates by ΔL; (c) the activated state during isometric test where the DEA of fixed length L' electrically induces a change in the blocked force F_z.

During experiment, longitudinal profile of the tube radius is readily measurable as shown in Figure 3 and 4, but its membrane thickness is not. This makes estimation of electric field difficult even though the driving voltage is known. Here, we propose a method to estimate the membrane thickness, given the measured longitudinal profile of the tube radius, in either the relaxed or activated states. In this way, the measured actuation can be correlated to the electric field calculated.

We make use of a one-sheet circular hyperpoloid surface [18] to first approximate the tube radius r as a function of height z off the middle plane (see Figure 4e),

$$r = a\sqrt{1 + \left(\frac{z}{c}\right)^2} \tag{3}$$

where a is the radius of middle hoop or so called skirt radius, and c is the asymptotic constant, which can be determined using the end hoop radius r=R at the height of a half tube length, $z = L'/2$.

Derivative of this profile yields the offset angle β=dr/dz at z=$L'/2$ (as shown in Figure 3c) between the tubular membrane and the tube axis.

The surface area of this one-sheet circular hyperboloid (as shown in Figure 4e) is a sum of ring surface of small height increment dz a:

$$A' = 2\int_{z=0}^{z=L'/2} 2\pi r\sqrt{1+\left(\frac{\partial r}{\partial z}\right)^2}\,dz \tag{4}$$

Substitute Eq. (3) of radius r as a function of z into the integral, i.e. Eq. (4):

$$\begin{aligned} A' &= 2\int_{z=0}^{z=L'/2} 2\pi a\sqrt{1+\left(\frac{1}{c^2}+\frac{a^2}{c^4}\right)z^2}\,dz \\ &= 2\pi a\left[\frac{L'}{2}\sqrt{\left(1+\left(\frac{a}{c}\right)^2\right)\left(\frac{L'}{2c}\right)^2} + \frac{c}{\sqrt{1+(a/c)^2}}\sinh^{-1}\left(\frac{L'}{2c}\sqrt{1+\left(\frac{a}{c}\right)^2}\right)\right] \end{aligned}$$

whose analytical expression follows the form of integral for $\int\sqrt{x^2+b^2}\,dx$ [19] where x and b are a variable and a constant respectively.

Due to incompressibility of elastomeric membrane, the average membrane thickness $\bar{t}\,'$ of the waistline tube (see Figure 4b-c) can be determined from the volume conservation [20-21], following

$$\bar{t}\,' = \left(\frac{A_p}{A'}\right)t_p \tag{5}$$

in which t_p and A_p =2πRL_p are membrane thickness and surface area, respectively, for the initially cylindrical tube, which has constant radius R and a pre-stretched length L_p.

Likewise, the membrane thickness t_a at the middle hoop where z=0 is determined to be

$$t_a = \left(\frac{R}{a}\right)t_p\,. \tag{6}$$

When activated towards the full potential, the waistline of an activated tube could be straightened again. As the activated tube become cylindrical (see Figure 4a, c, d), the skirt radius at the middle approaches towards the end ring radius R and the membrane thickness become more uniform longitudinally. Hence, the membrane thickness change can be estimated from the length change, just like it was for the spring roll [1-6], following:

$$\bar{t}_{act}^{\,c} = \left(\frac{L_p}{L_{act}}\right)t_p \tag{7}$$

Indeed, the estimate from the cylindrical shape change is very close to that from the hyperboloid shape change within the range of skirt radius: 0.8<a/R<1.

In turn, the average electric field can be calculated as the driving voltage over the average membrane thickness. On the other hand, the localized field varies with the spatially varying membrane thickness. The thickened membrane at the middle hoop is subjected to lower field than the rest parts of the tube.

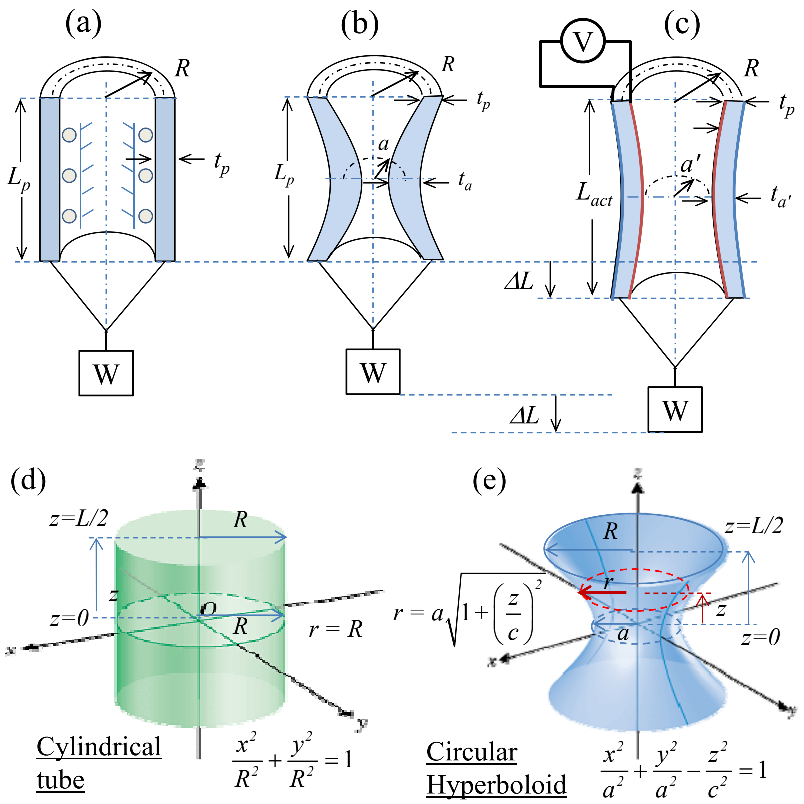

Figure 4. Shape change and thickness of the tubular DEA as a result of the hoop-stress relaxation at different states: (a) the initial pre-stretched state without the hoop-stress relaxation; (b) the idle state with the hoop-stress relaxation; (c) the activated state during isotonic test; (d) cylindrical model for surface area estimate; (e) hyperboloid model for surface area estimate.

3. Fabrication

Fabrication of an oil-encapsulated tubular DEA involves three major steps: 1) preparation of a flat DEA of pre-stretched membrane; 2) oil encapsulation over the flat DEA; 3) rolling up of the oil-encapsulated DEA and clamping the ends of a roll to two rigid rings. The fabrication steps are basically the same for preparing a dry DEA as shown in Figure 1, except the additional steps to prepare the oil encapsulation (see Figure 5). Outcome of the major steps of the sample preparation are shown in the photographs of Figure 6.

Firstly, as shown in Figure 1, a flat VHB 4910 tape is bi-axially pre-stretched for large ratios, for example λ_x=6 times in the transverse direction by λ_z=4 times in the axial direction. Subsequently, the pre-stretched membrane is kept tight on the support of a square acrylic-plate frame (10 cm by 10 cm) and it is left for 24 hours to complete stress relaxation. Compliant electrodes are coated onto both sides of the dielectric membrane by brushing fine graphite powder (Timcal KS6). The graphite powders are coated so thin that they are completely adhered or immobilized on the adhesive substrate of dielectric elastomer. Hence, the graphite-powder coating does not dislodge off the dielectric elastomer under oil immersion despite large deformation. Lead-out for the compliant electrodes consists of an aluminium strip, with has silver grease dotted to improve electrical contact between interfaces.

Figure 5 shows the process steps to prepare oil encapsulation over a flat DEA. The build of this oil capsule is similar to that for a tunable liquid lens [22, 23], but it serves to enhance breakdown strength of DEAs. Firstly, to make a capsule membrane, a passive adhesive layer is to be covered over the DEA substrate. This cover layer can be a thinner VHB tape, non-stretched or stretched. Here, we considered a 250µm thick VHB F9473 tape, which was not stretched at all, or a 90µm thick VHB93015LE, which was pre-stretched by 1.25 times by 1.33 times from an initial thickness of 150µm. Before bonding onto the DEA substrate, a patch of the adhesive cover layer is made non-adhesive by coating with talcum powder. Afterwards, the talcum-coated cover layer is laid on top of the flat DEA substrate. While its border is bonded to the substrate, the non-adhesive interface between the cover layer and the DEA substrate forms a cavity for catching liquid.

Subsequently, oil is injected from a needle of a syringe into the cavity. While doing injection, the air bubbles in the capsule are removed by drawing another syringe. Afterwards, the needle puncture is sealed by another adhesive patch. A Teflon layer is laid to protect the first oil capsule before the second oil capsule is made on the other side. Completion of these processes yields a flat DEA with oil encapsulation on both sides.

With the temporary backing by the Teflon transfer layer, the oil-encapsulated DEA membrane, even at high pre-stretch, can be rolled neatly over two rigid rings as shown in Figure 1 and 6. The end rings are first fixed temporarily to a shaft by set screws before they are placed and rolled over the flat DEA. As rolling goes on, the two rigid rings adhere to the DEA membrane. In this way, the membrane is rolled up and is subsequently slit cut to be apart from the flat pre-stretched membrane. Completion of the rolled process yields a tubular membrane on the transfer layer of nearly cylindrical shape (see Figure 6). When the transfer layer is removed, the tube relaxes from hoop pre-stress and forms a waistline as shown in Figure 7.

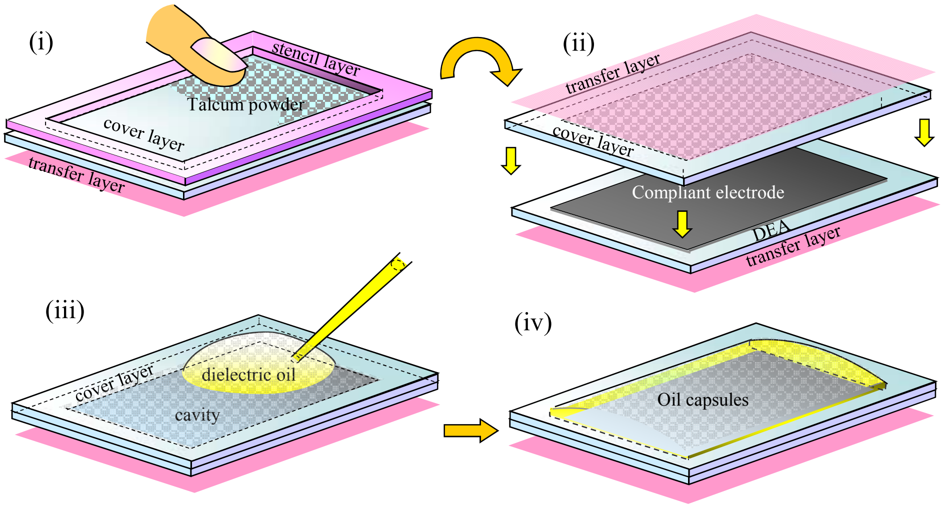

Figure 5. The process steps for oil encapsulation over a flat DEA in schematic drawings: (i) smear talcum powder on an adhesive over layer through a stencil; (ii) flip and bond the talcum-coated over layer onto the borders of a DEA layer to form a non-adhesive interface; (iii) injection of dielectric oil into the interface which were sealed by the cover and the DEA layers; (iv) Complete oil immersion of the DEA electrode in the capsule.

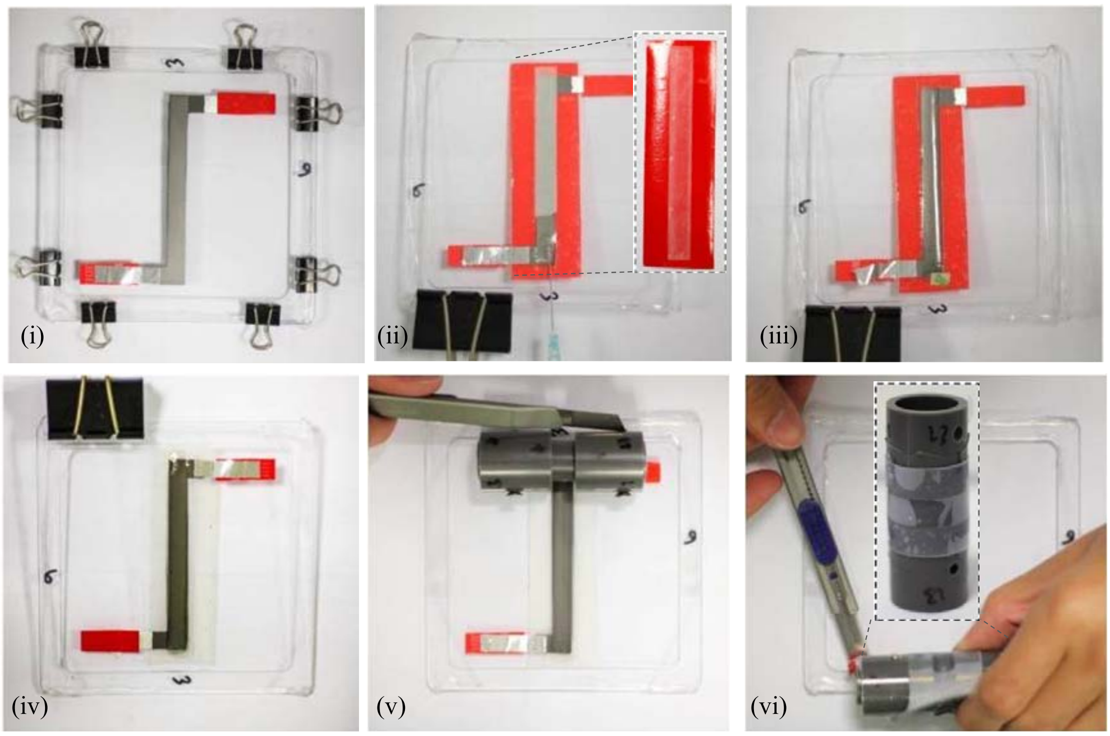

Figure 6. Major preparation steps for an oil-encapsulated DEA sample: (i) a flat DEA with graphite-powder electrodes; (ii) Lay up of a talcum-coated cover layer over the DEA layer to form a non-adhesive cavity for oil injection; (iii) completion of an oil capsule after oil injection by a syringe; (iv) lay-up with a Teflon layer to protect the oil capsule; (v) rolling up of the two-sided oil-encapsulated flat DEA; (vi) Completion of a single-wound rolled DEA, as known as a tubular DEA, with the Teflon protective layer on.

4. Effects of oil encapsulation

To show the effect of oil immersion, the oil encapsulated tubular DEAs are compared with those dry one without oil encapsulation. These tubular DEAs are made from 42 µm thick dielectric elastomer membrane, which was obtained by biaxially pre-stretching a 1mm thick VHB 4910 tape for 6 times along the hoop direction and 4 times along the axial direction and brushed with graphite-powder compliant electrodes. Both sides of the DEA are sealed by oil capsules, which has dielectric oil (Dow Corning Fluid 200 50cSt) enclosed by a 90µm thick cover membrane of lightly pre-stretched VHB93015LE and the DEA membrane. Large hoop pre-stretch of the membrane is clamped by the rigid rings of PVC, while the axial pre-stretch is kept by deadweight in the isotonic test. With extra capsule, the oil-encapsulated DEA is axially stiffer than the one without encapsulation and thus requires a higher axial pre-load to maintain the same axial pre-stretch. The oil-encapsulated DEA weighs 2.81 gram with 0.7 ml silicone oil in each capsule; whereas, the dry DEA weighs less at 1.3 gram.

4.1. Isotonic test

During the isotonic test, the tubular DEAs are subjected to a voltage ramp up at a step of 1kV until the electrical breakdown. During the activation, the high voltage supply (Spellman HV supply) is set with a current limit of 120µA. Each voltage step is held for one minute during which a snapshot of the activated tubular DEAs is taken. Meanwhile, time-varying axial displacements of the activated DEAs are measured continuously by a laser displacement sensor (Keyence LC-2440).

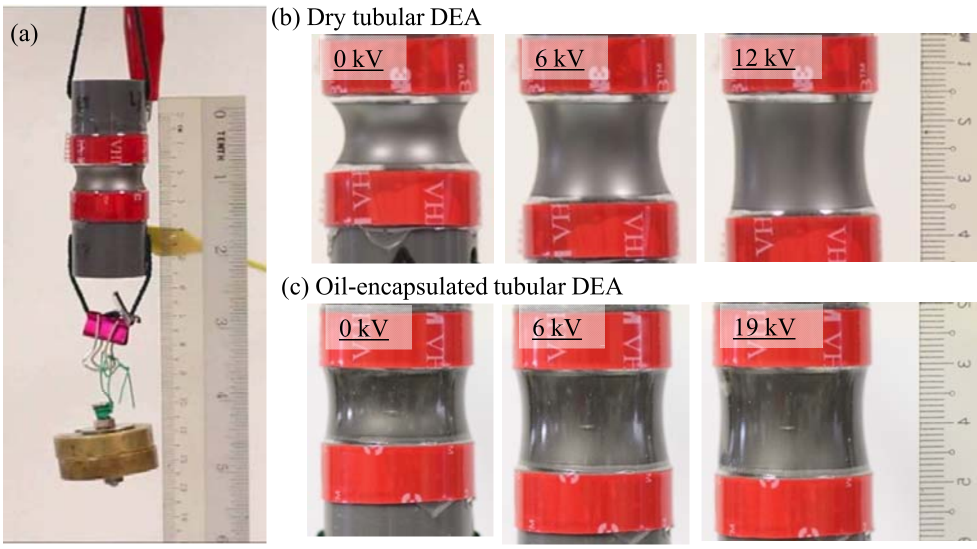

Figure 7. Photographs of tubular DEAs under isotonic test: (a) An actuator sample hanged with a deadweight under the isotonic test; (b) shape change and elongation of a sample of the dry tubular DEAs; (c) shape change and elongation of a sample of the oil-encapsulated tubular DEAs. These tubular DEAs are subjected to pre-stretch at the hoop ratio of 6 times and axial ratio of 4 times.

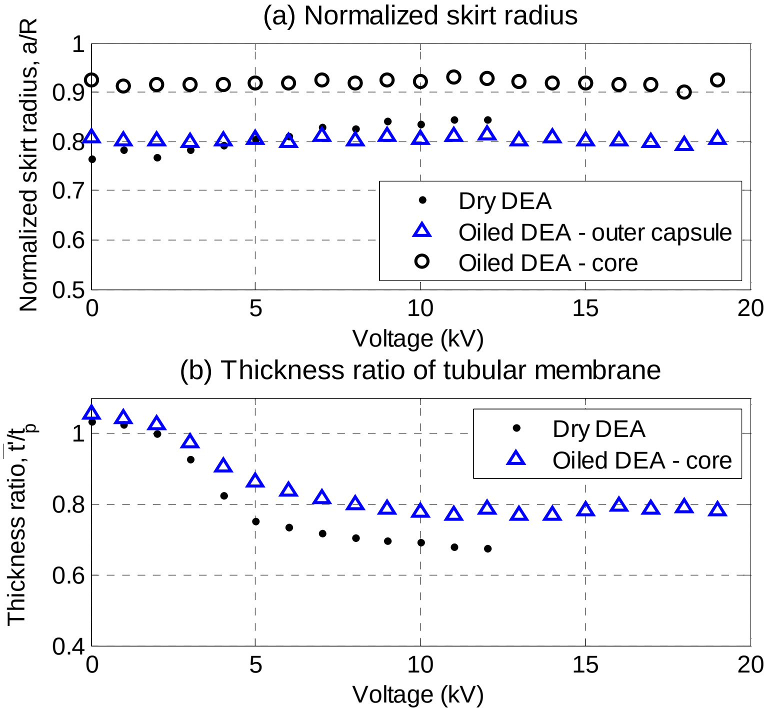

Figure 8. Effect of oil encapsulation on necking and thickness of tubular membrane: (a) the normalized skirt radius; and (b) the normalized membrane thickness, as functions of driving voltage.

Both the dry and oil-encapsulated tubular DEAs are subjected to necking (see Figure 7) due to hoop stress relaxation. Despite subjected to the same hoop-stretch, the dry tubular DEAs, however, exhibit more necking than the oil-encapsulated ones. The dry tubular DEAs' middle tube radius, i.e. the skirt radius, is reduced to be 75% of the end ring radius (see Figure 8a). In comparison, the oil encapsulated tubular DEAs have the initial skirt radii of 90% and 80% for its outer oil capsule and DEA core respectively. The oil-encapsulated DEAs maintain a rather constant waistline during activation. However, activation substantially reduces necking of the dry ones under the isotonic test. For example, the dry tubular DEA has its skirt radius increased to be 85% of the end radius towards maximum activation at the breakdown voltage.

Due to the necking, the inactive tube has membrane thickened (see Figure 8b), more than the pre-stretched membrane thickness. Hyperboloid model confirms the membrane thickening at 0kV. Activation of the tubular DEAs under Maxwell stress reduces the membrane thickness. As the tubular DEAs shape more cylindrical, their membrane thickness gets thinner but more uniform longitudinally. The thickness estimate from the hyperboloid model is 3-8% higher than that obtained by the cylindrical model. As the cylindrical model is simpler and close enough to the hyperboloid model, it is used for subsequent calculations of the average membrane thickness and the average electric field. The breakdown field for the dry tube, which is activated up to 12kV, is calculated to be 476.0 MV/m. On the other hand, the breakdown electric field for the oil-encapsulated one, which is activated up to 19kV, is calculated to be 712.0 MV/m. Comparison between the two confirms that oil encapsulation helps increase breakdown strength of tubular DEAs, just like it does to the flat DEAs [14].

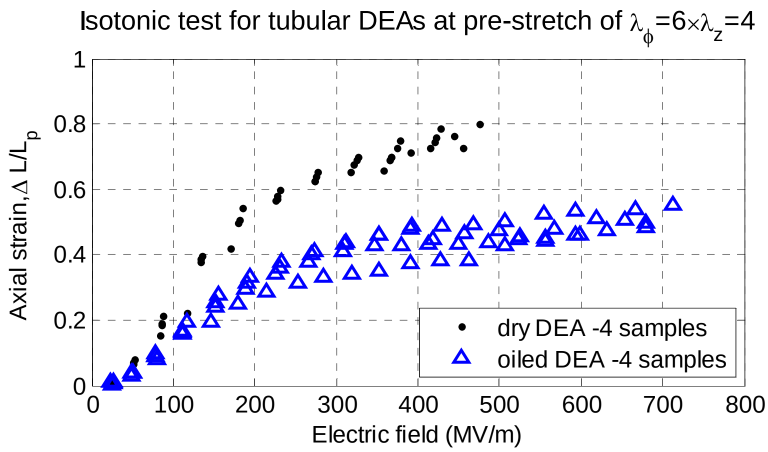

Figure 9. The induced axial strain as a function of the average electric field, which is estimated from the cylindrical model, for the tubular DEAs, which were pre-stretched at λ_ϕ=6 and λ_z=4 in the hoop and axial directions respectively during the isotonic tests.

When activated by high voltage during isotonic test, the tubular DEAs elongate axially as shown in Figures 7 and 9. This axial actuation increases with increasing electric field. Below 150MV/m electric field, the actuation shows a quadratic rise with respect to the applied electric field. At higher electric fields, however, the rate of actuation increment decreases with increasing electric field due to strain stiffening effect and geometrical nonlinearity [24]. The present tubular DEAs sustain very high field and produce much larger actuation strain due to high hoop pre-stretch and the use of fine graphite powder as compliant electrodes. Even the dry tubular DEAs achieve very high axial actuation of up to 80.2% strain at the breakdown field of 475.9 MV/m, which is far greater than the best reported axial strain of 37.3% at 40.9 MV/m. Meanwhile, the oil-encapsulated tubular DEA produces an axial strain of up to 55.4% at 712.0MV/m. The lower axial strain achievable by the oil-encapsulated one is attributed to stiffening effect by the inner and outer oil capsules, which have two additional 90 μm thick membranes as compared to the 42 μm thick DEA membrane.

It is found that oil encapsulation raises the electrical breakdown voltage of the same prepared tubular DEAs. Out of the 4 samples tested, 3 samples of oil encapsulated tubular DEA can sustain a high driving voltage up to 19kV while 1 sample fails at 15kV. On the other hand, the 4 samples of dry DEAs failed at about 10-12 kV. The electrically shorted tubular DEA is burnt with either observable punctures or less observable pin holes. The puncture size depends on the leakage current and joule heating at the defective spot in the DEAs. As shown in Figure 10, three samples of dry tubular DEAs, which failed terminally at 10-12kV, are observed with huge puncture; whereas, the other one does not have any observable punctures. On the other hand, three samples of the oil-encapsulated DEAs, which terminally failed at 19kV, are not observed with sizeable punctures; while the other imperfect sample, which failed at 15kV, is burnt with a huge puncture.

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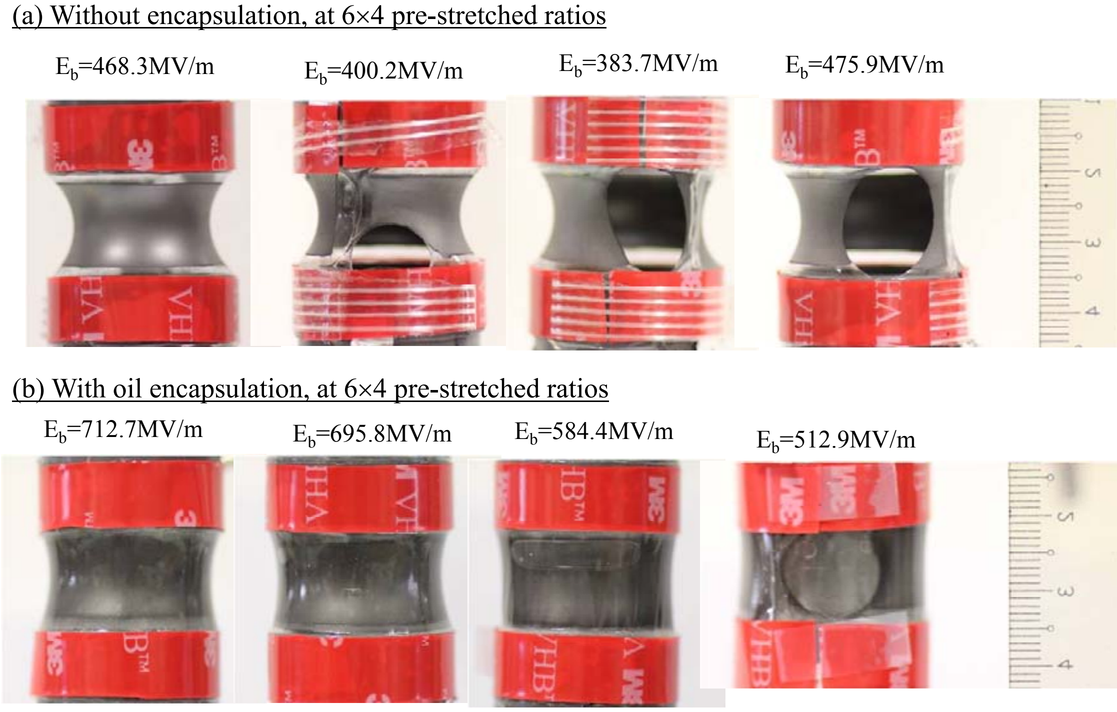

Figure 10. Appearance of the broken-down samples of the tubular DEAs: (a) 4 samples of the dry tubular DEAs without oil encapsulation; (b) 4 samples of the oil-encapsulated DEAs. These tubular DEAs were initially subjected to pre-stretch in the hoop and axial directions at the ratios of 6×4.

In addition, it is found that oil encapsulation helps tubular DEAs self-clear and stop pre-mature breakdowns. Figure 11 shows the DEA samples, with and without oil encapsulation, are subjected to voltage ramp while leakage current across them and the electrically induced axial displacements were monitored continuously over times. In the event of electrical breakdown, voltage falls and current surges were observed across the DEAs. Without oil encapsulation, a sample of dry DEA is completely damaged by current spikes at 13-14kV and eventually burnt with a big puncture. On the other hand, a sample of the oil-encapsulated DEA has current spikes at 16kV subdued and stopped so that the terminal breakdown is delayed to happen at a higher voltage at 19kV. Hence, the oil encapsulation is expected to improve life time of tubular DEAs by means of self-clearing, like it did to flat DEAs [15-17].

Figure 11c shows the time responses for the oil-encapsulated and dry DEA samples. At each voltage step during the ramp, the axial displacements of DEA samples increases at a decreasing rate with respect to time, just like a viscoelastic solid that creeps [8, 25]. Among the two types of DEAs, the dry tubular DEA produced larger stroke at each voltage step and it produced a maximum stroke of 7.6 mm, which exceeds the measurement range (i.e. 6.5 mm) of the laser displacement sensor (Keyence LC-2440) and thus needs to be determined alternatively by image analysis of the deformed shape. On the other hand, the maximum stroke achievable by the oil-encapsulated DEA sample is lower at around 5 mm though the sample sustains a higher driving voltage of up to 19kV. After all, the time responses for the oil-encapsulated and dry DEA samples differ slightly even though oil encapsulation was expected to increase the viscous effect.

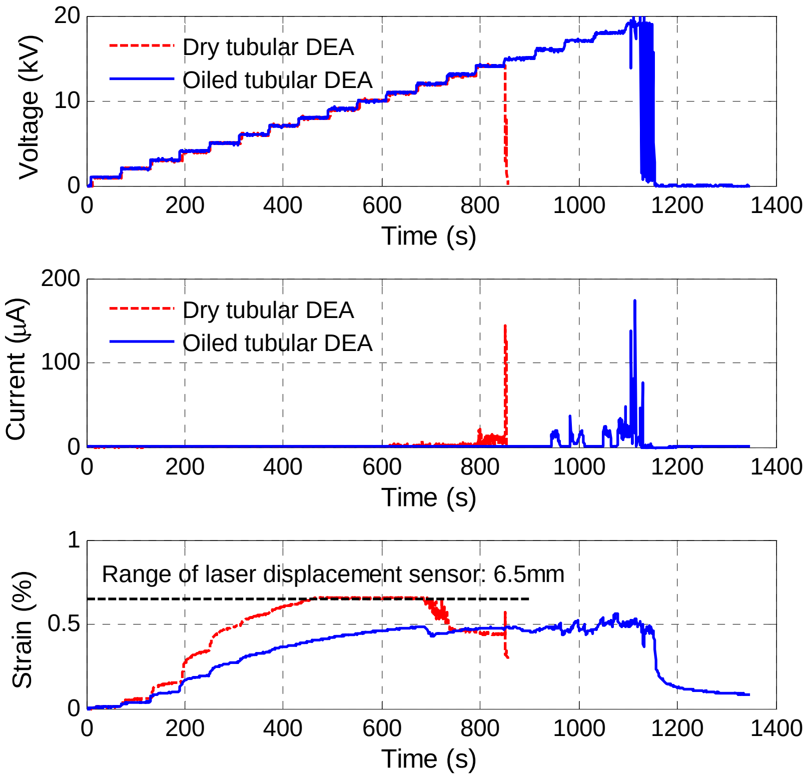

Figure 11. Monitor of (a) step-wise voltage ramp, (b) leakage current, and (c) axial displacement for tubular DEAs, which were pre-stretched at λ_ϕ=6 and λz=4 in the hoop and axial directions respectively, with or without oil encapsulation.

4.2. Isometric test

In the isometric test, the axial blocked force of the tubular DEAs is measured by a 10N-capacity load cell of a tensile tester (INSTRON 5569). To simulate the condition at the maximum isotonic free stroke, the actuator samples under test are pre-stretched 65% axially relative to the initial pre-stretched length. As a result, the total axial pre-stretch ratio becomes 6.6 times for this isometrically tested sample, instead of the 4 times for the isotonically tested samples. Before electromechanical testing, the pre-stretched tubular DEAs are let fully relaxed in axial pre-stress. Subsequently, the actuator samples were subjected to a stepwise voltage ramp towards the maximum achievable voltages and its field-activated change in the blocked force was measured.

Two types of tubular DEAs, with or without oil encapsulation, were tested. The passive capsule membrane of the oil encapsulated DEA is not expected to influence the electrically induced stress change, though it affects the initial pre-stress level. At the same axial pre-stretch when idle, the initial blocked forces are 0.70N and 1.27N for the dry and oil-encapsulated tubular DEAs respectively. The oil encapsulated tubular DEA is subjected to higher initial blocked force due to added stiffness of capsule membranes. These axial blocked forces are expected to be a vertical component of the membrane force as the waist-lined tubular membrane is offset from the tube axis at approximately 30° during the isometric tests. The electrically induced stress change is calculated as the electrically induced force change over the sectional areas of the tubular DEA membrane.

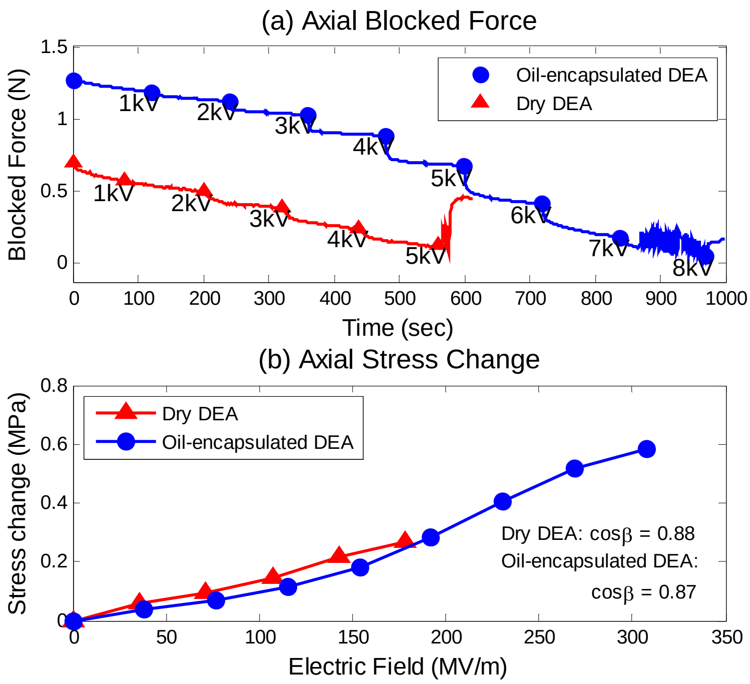

Figure 12. Isometric tests for the tubular DEAs, with or without oil encapsulation, while being pre-stretched at λ_ϕ=6 and λ_z=6.6 in the hoop and axial directions respectively: (a) time history of the measured axial blocked force as the driving voltage is ramped up stepwise; (b) the induced axial stress change as a function of the average electric field, which is estimated from the cylindrical model.

Figure 12 shows that electrical activation reduces the blocked forces for both types of DEAs. In response to stepwise voltage ramp, the axial blocked force decreases in steps. Each activation step is held for one minute and its response is an exponential decay due to the visco-elastic effect of the VHB material. The oil-encapsulated DEA sustains up to 8kV and produces a maximum blocked force change of 1.19 N. On the other hand, the dry DEA fails terminally at 5kV and produces a maximum blocked force change of 0.57N, which is lesser than the maximum change induced by the oil-encapsulated DEA. The breakdown voltages for the isometric test are found to be lower than those for the isotonic test because dielectric elastomer of fixed length are more prone to wrinkling and electrical breakdown, like flat DEAs do [16].

Figure 12b shows that the isometric stress change appears to increase with the electric fields in a quadratic trend. Oil encapsulation helps suppress electrical breakdown even during the isometric test. The oil-encapsulated isometric DEA sustains up to 307.5MV/m, which is 72.3% higher than 178.4 MV/m sustained by the dry DEA. As a result of improved breakdown strength, the oil-encapsulated DEA can induce an isometric stress change up to 0.58 MPa, which is 114.8% higher than the 0.27 MPA induced by the dry DEA.

Though it produced more blocked force change, the oil-encapsulated tubular DEA carrying passive oil capsules weighs more at 2.81 gram, as compared to 1.3 gram of the dry one without oil encapsulation. In terms of maximum blocked force change per unit mass, the oil-encapsulated tubular DEA produces 0.42N/g, slightly lesser than 0.44N/g of the dry DEA. In the current design of oil encapsulation, dielectric oil adds substantial passive weight more than the weight of active dielectric elastomer.

Further optimization and use of micro-fluidic channels can possibly reduce the passive weight of oil encapsulation.

5. Effect of capsule membrane stiffness

Even though it helps to suppress electrical breakdown, oil encapsulation contributes to additional stiffness and reduces actuation of the tubular DEAs. The additional stiffness depends on the capsule membrane thickness. To illustrate the stiffness effect, we prepared oil-encapsulated DEAs at two distinct membrane thicknesses. A thick capsule has its cover membrane made of 250µm thick non-stretched VHB 9473PC tape; whereas, a thin capsule has the membrane made of 90µm thick pre-stretched VHB93015LE tape, which has an initial thickness of 150 µm. They are laid over a DEA layer, which has a pre-stretched membrane thickness of 50µm and is prepared by pre-stretching an VHB4910 tape of 1000µm initial thickness for 5 times by 4 times in the hoop and axial directions respectively. Designs of these oil-encapsulated tubular DEA are listed in Table 1.

To measure the axial stiffness, different designs of oil-encapsulated DEAs are loaded with increasing deadweight and the resulting elongation is measured using a laser displacement sensor or imaging method. Figure 13 shows that the mechanically-induced elongation increases linearly with increasing load. The oil-encapsulated tube in thick capsules is found 2.23 times stiffer than a dry one without encapsulation; whereas the one in thin capsules is found 21.4% stiffer than the dry one. When subjected to activation during isotonic test, the tubular DEAs elongate. Figure 14 shows that the dry tubular DEAs produce a maximum axial strain of up to 84.2%. Meanwhile, the oil-encapsulated DEAs produce lesser maximum axial strain, of up to 32.0% for the one in thick capsules and of up to 50.1% for the one in thin capsules.

The oil encapsulation does help suppress electrical breakdown even at 5-times hoop pre-stretch. While the dry tubular DEA with the 5-times hoop stretch fails at 331.6 MV/m, the oil-encapsulated ones break at higher electric fields. The oiled ones in thin capsules sustain up to 527.0MV/m, whereas the oiled ones in thick capsules sustain up to 666.9MV/m. This suggests that the stiffer thick capsule could have helped delay the electrical breakdown of the oiled DEA.

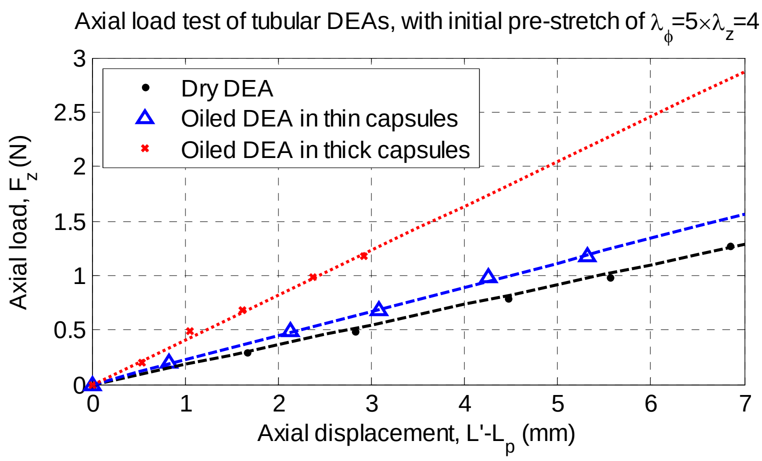

Figure 13. The effect of membrane thickness on the axial stiffness of the tubular DEAs, which were initially pre-stretched at λ_ϕ=5 and λ_z=4 while subjected to increasing axial stretch

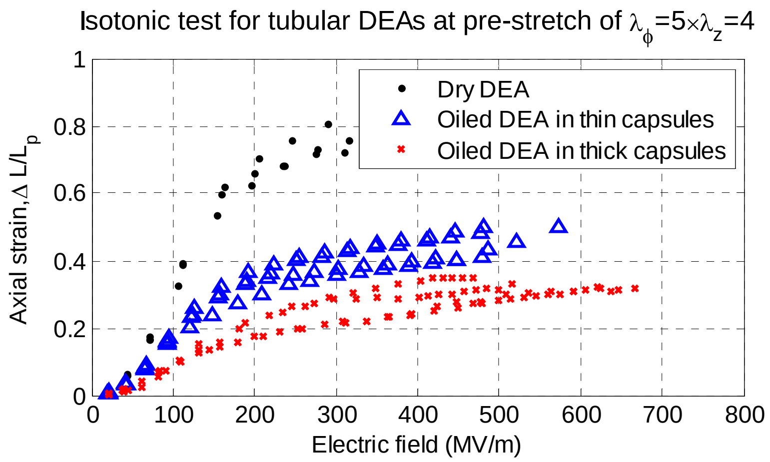

Figure 14. The induced axial strain as a function of the average electric field, which is estimated from the cylindrical model, for the tubular DEAs, which were pre-stretched at λ_ϕ=5 and λ_z=4 in the hoop and axial directions respectively during the isotonic tests

Table 1. Designs of oil-encapsulated tubular DEAs.

Specifications	Thin capsule #1	Thin capsule #2	Thick capsule
Capsule material	VHB93015LE	VHB93015LE	VHB9473PC
Capsule pre-stretch ratios	1.33 × 1.25	1.33 × 1.25	1 × 1
Capsule thickness	90µm	90 µm	250 µm
Dielectric oil volume	0.7 ml	0.4 ml	1 ml
DEA materal	VHB 4910	VHB 4910	VHB 4910
DEA pre-stretch ratios, $\lambda_\phi \times \lambda_z$	6 × 4	5×4	5×4
DEA membrane thickness	42 µm	50 µm	50 µm
Actuator length	10 mm	10 mm	12.5 mm
Actuator diameter	26 mm	26 mm	26 mm
Electrode area	83mm×7.5mm	83 mm×7.15mm	83 mm×10mm
Elastomer/oil mass	2.81 g	1.81 g	2.4 g
Rigid ring mass	16 g	16 g	16 g
Total actuator mass	18.81 g	17.81 g	18.4 g
Deadweight	182.6 g	202.6 g	220 g

6. Effect of hoop pre-stretch

In summary, three designs of oil-encapsulated tubular DEAs were prepared as listed in Table 1. Preceding discussions showed that the oil encapsulation helps suppress electrical breakdown, but its passive capsule stiffness reduces the isotonic strain achievable by the tubular DEA. In addition, performance comparison as listed in Table 2 shows that a larger hoop pre-stretch improves the electrical breakdown strength. It is noted that those 5-times pre-stretched DEAs demonstrated a lower breakdown electric fields as compared to those 6-times hoop pre-stretched ones. For example, the dry DEAs with the 5-times hoop pre-stretch see a 30% decrease in the breakdown electric field as compared to those with the 6-times hoop-pre-stretch. Likewise, the oil-encapsulated DEAs in thin capsules see a 20% decrease in the breakdown fields as a result of reduced hoop pre-stretch from 6 times to 5 times. This could be attributed to membrane pre-stress reduction, which results in more susceptibility to the electro-mechanical instability at a lower electric field.

Table 2. Effect of pre-stretch on best performance of tubular DEAs under isotonic tests.

Pre-stretch ratios $\lambda_\phi \times \lambda_z$	DEA thickness	Oil Capsule	Capsule Thickness	Breakdown Voltage	Breakdown Electric Field	Axial Strain
(5, 4)	50 μm	No	-	9 kV	331.6 MV/m	84.2%
	50 μm	Yes	250 μm	24 kV	666.9 MV/m	32.0%
	50 μm	Yes	90 μm	19 kV	572.0 MV/m	50.1%
(6, 4)	42 μm	No	-	12 kV	475.9 MV/m	80.2%
	42 μm	Yes	90 μm	19 kV	712.7 MV/m	55.4%

7. Comparison with Previous Works

Various rolled DEAs were previously developed as listed in Table 3 and 4. They differ from each other in terms of the number of wound, pre-stretch ratios, pre-load method, and electrode materials. Their dielectric elastomeric membranes are often subjected to large pre-stretch in order to help achieve high electric field. The reported rolled DEAs were axially pre-loaded by using either a helical coil spring or deadweight. Unlike the deadweight, the coil spring helps reduces necking and keeps a constant hoop pre-stretch along the actuator length. Hence, the spring rolls could sustain a higher electric field than the one with no hoop pre-stretch at all; though not necessarily produce more axial actuation strain than the latter. Despite these improvements, the breakdown electrical fields for these rolled DEAs are moderate. Here, we showed that oil encapsulation can greatly increase the breakdown electric fields for the one-wound roll, i.e. the tubular DEA. The oil-encapsulated tubular DEA can sustain up to 712.7MV/m. As a result of increased breakdown strength also in the isometric test, the oil-encapsulated tubular DEAs can produce higher axial stress change of up to 0.58 MPa. In other words, they can produce larger blocked force change. Having the capacity to produce high stress like muscles [16], these oil-encapsulated DEAs are anticipated to be useful for driving the development of future human-like robots.

In addition, our dry tubular DEAs sustain a lot higher field of up to 475.9MV/m as compared to the previous ones due to the use of fine immobilized graphite-powder electrodes, which does not short easily as the fluid carbon greases do [16]. The enhanced breakdown strength can improve reliability and extend life time of DEAs.

Table 3. Performance of rolled DEAs under Isotonic Tests

Works	Layers	DEA material	Pre-stretch ratios $\lambda_\phi \times \lambda_z$	Pre-load method	Electrode material	Oil Capsule	Breakdown field	Axial strain
Pei et al (2002) [1-3]	20	VHB 4905	5×1	Coil Spring	Carbon black	No	109MV/m	26.0%
Zhang et al (2006) [4]	30-40	VHB 4910	6.5×3	Coil Spring	Graphite powder	No	89.6MV/m	31.3%
Rajamani et al (2008) [6]	15	VHB 4905	3.5×2.3	Coil Spring	Carbon grease	No	66.1 MV/m	12.8%
Huang et al (2012) [11]	1	VHB 4910	1×2.13	Dead weight	Carbon grease	No	24.5 MV/m	37.3%
	1	VHB 4905	1×1.4	Dead weight	Carbon grease	No	40.9 MV/m	35.8%
This work	1	VHB 4910	6×4	Dead weight	Graphite powder	No	475.9 MV/m	80.2%
	1	VHB 4910	6×4	Dead weight	Graphite powder	Yes	712.7 MV/m	55.4%

Table 4. Performance of rolled DEAs under Isometric Tests

Works	Layers	DEA material	Pre-stretch ratios $\lambda_\phi \times \lambda_z$	Pre-load method	Electrode material	Oil Capsule	Breakdown field	Stress change
Kovac et al (2007) [5]	30-40	VHB4910	6.5×3	Coil Spring	Graphite powder	No	89.6MV/m	0.17MPa
This work	1	VHB4910	6×6.6	Dead weight	Graphite powder	No	178.4 MV/m	0.27MPa
	1	VHB4910	6×6.6	Dead weight	Graphite powder	Yes	307.5 MV/m	0.58MPa

8. Conclusions

In this paper, we have shown that the use of oil encapsulation and large pre-stretch help suppress pre-mature electrical breakdown. This study shows that oil encapsulation helps the same prepared tubular DEAs realize its fullest actuation potential, despite initially severe necking and non-uniform deformation of the tubular membrane due to large hoop pre-stretch. Under isotonic test, oil-encapsulated tubular DEAs sustained a very high electric field of up to 712.7 MV/m, which is 50.0% higher than that of the dry ones. They produced up to 55.4% axial strain despite being axially stiffening by the passive oil capsules. During the isometric test, the oil-encapsulated tubular DEA sustained up to 307.5MV/m, which is 72% higher than that of the dry one, and thus it produced a 114% higher stress change of up to nearly 0.6 MPa. In addition, it is noted that large pre-stretch helped even dry tubular DEAs sustain higher field of up to 476.0MV/m and thus produce also a very large axial strain of up to 80.2% as compared to the previous works. Future work will further investigate whether the oil encapsulation is also effective to multiple-wound rolled DEA, which are subjected to interfacial radial stresses.

9. References

[1] Pei, Q., Pelrine, R., Stanford, S., Kornbluh, R. D., Rosenthal, M. S., Meijer, K., & Full, R. J. (2002, July). Multifunctional electroelastomer rolls and their application for biomimetic walking robots. In *Proc. SPIE 4698, Smart Structures and Materials 2002: Industrial and Commercial Applications of Smart Structures Technologies*, 246 (July 9, 2002); doi:10.1117/12.475071

[2] Pei, Q., Pelrine, R., Stanford, S., Kornbluh, R., Rosenthal, M., Meijer, K., & Full, R. (2002). Multifunctional electroelastomer rolls. In *Materials Research Society Symposium Proceedings* (Vol. 698, pp. 165-172). Warrendale, Pa.; Materials Research Society.

[3] Pei, Q., Pelrine, R., Stanford, S., Kornbluh, R., Rosenthal, M. (2003). Electroelastomer rolls and their application for biomimetic walking robots. *Synthetic Metal*, 135/136, 129-131.

[4] Zhang, R., Lochmatter, P., Kunz, A., & Kovacs, G. (2006, March). Spring roll dielectric elastomer actuators for a portable force feedback glove. In *Proc. SPIE 6168, Smart Structures and Materials 2006: Electroactive Polymer Actuators and Devices (EAPAD)*, 61681T (March 22, 2006); doi:10.1117/12.658524.

[5] Kovacs, G., Lochmatter, P., & Wissler, M. (2007). An arm wrestling robot driven by dielectric elastomer actuators. *Smart Materials and Structures*, *16*(2), S306.

[6] Rajamani, A., Grissom, M. D., Rahn, C. D., & Zhang, Q. (2008). Wound roll dielectric elastomer actuators: Fabrication, analysis, and experiments. IEEE/ASME Transactions on Mechatronics, 13(1), 117-124.

[7] Benslimane, M. Y., Kiil, H-E, Tryson, M. J. (2010). Dielectric electro-active polymer push actuators: performance and challenges. *Polymer International*, *59(3)*, 415-421.

[8] Lau, G. K., Lim, H. T., Teo, J. Y., & Chin, Y. W. (2014). Lightweight mechanical amplifiers for rolled dielectric elastomer actuators and their integration with bio-inspired wing flappers. *Smart Materials and Structures*, *23(2)*, 025021.

[9] Carpi, F., and De Rossi, D. (2004). Dielectric elastomer cylindrical actuators: electromechanical modelling and experimental evaluation. M*aterials Science and Engineering: C*, 24(4), 555-562.

[10] Chuc, H. N., Koo, J. C., Lee, Y. K., Nam, J. D., Choi, H. R. (2008) Artificial Muscle Actuator Based on the Synthetic Elastomer, International Journal of Control, Automation, and Systems, 6(6), 894-903.

[11] Huang, J., Lu, T., Zhu, J., Clarke, D. R., & Suo, Z. (2012). Large, uni-directional actuation in dielectric elastomers achieved by fiber stiffening. *Applied Physics Letters*, *100*(21), 211901.

[12] Lu, T., Foo, C. C., Huang, J., Zhu, J., & Suo, Z. (2014). Highly deformable actuators made of dielectric elastomers clamped by rigid rings. *Journal of Applied Physics*, *115*(18), 184105.

[13] Kollosche, M., Zhu, J., Suo, Z., & Kofod, G. (2012). Complex interplay of nonlinear processes in dielectric elastomers. *Physical Review E*, 85(5), 051801.

[14] Zhou, J., Jiang, L., & Khayat, R. E. (2014). Electromechanical response and failure modes of a dielectric elastomer tube actuator with boundary constraints. *Smart Materials and Structures*, *23*(4), 045028.

[15] La, T. G., Lau, G. K. (2013). Very high dielectric strength for dielectric elastomer actuators in liquid dielectric immersion. *Applied Physics Letters*, 102(19), 192905.

[16] La, T. G., Lau, G. K., Tan, A. W.-Y., and Shiau, L. L. (2014). Muscle-like high-stress dielectric elastomer actuators with oil capsules, *Smart Mater. Struct.* 23 105006

[17] Yuan, W., Brochu, P., Ha, S. M., & Pei, Q. (2009). Dielectric oil coated single-walled carbon nanotube electrodes for stable, large-strain actuation with dielectric elastomers. *Sensors and Actuators A: Physical*, *155*(2), 278-284.

[18] Wolfram MathWorld. One-Sheeted Hyperboloid. http://mathworld.wolfram.com/One-SheetedHyperboloid.html [Online Access: August 2014]

[19] S.O.S. Mathematics. INTEGRALS CONTAINING THE SQUARE ROOT OF x2+a2. URL: http://www.sosmath.com/tables/integral/integ11/integ11.html, [Online Access: August 2014]

[20] Pelrine, R. E., Kornbluh, R. D., & Joseph, J. P. (1998). Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation. *Sensors and Actuators A: Physical*, 64(1), 77-85.
[21] Wissler, M., & Mazza, E. (2007). Electromechanical coupling in dielectric elastomer actuators. *Sensors and Actuators A: Physical*, *138*(2), 384-393.
[22] Carpi, F., Frediani, G., Turco, S., & De Rossi, D. (2011). Bioinspired Tunable Lens with Muscle-Like Electroactive Elastomers. Advanced Functional Materials, 21(21), 4152-4158.
[23] Shian, S., Diebold, R. M., & Clarke, D. R. (2013). Tunable lenses using transparent dielectric elastomer actuators. Optics express, 21(7), 8669-8676.
[24] Stark, K. H., & Garton, C. G. (1955). Electric strength of irradiated polythene. *Nature* 176, 1225 - 1226.
[25] Keplinger, C., Kaltenbrunner, M., Arnold, N., & Bauer, S. (2008). Capacitive extensometry for transient strain analysis of dielectric elastomer actuators. Applied Physics Letters, 92(19), 192903.