Review of Soft Linear Actuator and the Design of a Dielectric Elastomer Linear Actuator

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ABSTRACT Natural muscle provides excellent motilities for animals. As the basic unit of the muscle system, the skeletal muscle fibers function as a soft linear actuator. Inspired by the muscle fibers, researchers have developed various soft active devices with linear actuation. This paper reviews several soft linear actuators, such as the dielectric elastomer, thermal responsive hydrogels, pneumatic artificial muscle, and conducting polymers. The actuation mechanisms and performances of these soft linear actuators are summarized. Based on the dielectric elastomer, we propose a design of a hybrid system with linear actuation, driven by both the electric motor and dielectric elastomer cone. The electromechanical behaviors of the dielectric elastomer cone have been investigated in both experiment and finite element analysis. This work may guide the further design of soft actuators and robots.

KEY WORDS Soft linear actuator, Dielectric elastomer, Finite element analysis

1. Introduction

With the continuous development of control science, material science, and biomedicine, human's demands for robotics and rehabilitation medical technology have been continuously growing. Robots have been widely used in the application of complex terrain environment and engineering facilities. Traditional actuating devices for robots are usually made up of hard components such as motors and hinges, which cannot adapt to complex terrain well. Some domains like rehabilitation medicine require more friendly interaction with actuators, but hard actuators are incapable of well cooperating with human muscles and skins. Some discoveries in the material provide a new way.

The development of soft artificial muscle has attracted more and more attention. Artificial muscle has the characteristics of linear actuation, large deformation, and high efficiency. It can be widely used in many fields such as robot actuators, rehabilitation training, and aerospace. In recent years, the

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Fig. 1. Soft linear actuators driven by electro-active material (DE): **a** arm wrestling robot [6]; **b** bio-inspired wing flappers [8]; **c** DE tensile actuators with stacked laminates [14]; **d** DE ring actuator [9]; **e** self-healing actuator [15]; **f** loudspeaker actuator [12]

development of smart materials has played an important role in the manufacture of artificial muscle. Smart materials refer to a kind of materials that produce functional response under external stimuli such as electricity, heat, and catalyst. As the most important function of muscle, they produce deformation and force directly or indirectly. Compared with the traditional hard actuators, soft actuators with smart materials achieve continuous deformation, high degrees of freedom, high driving efficiency, and environmental adaptability. In this paper, Sect. 2 introduces the development of smart materials for linear actuators under different excitations in recent years. Section 3 describes the system design and mechanical investigation of the hybrid linear actuator. Experimental measurement and finite element analysis have been carried out on the inhomogeneously deformed DE membranes in the hybrid actuator.

2. Artificial Muscles with Various Mechanisms

2.1. Dielectric Elastomer Linear Actuators

The dielectric elastomer (DE) actuator has become one of the most common electro-active soft actuators because of its large voltage-induced deformation, high energy density, fast response, and low cost. Its typical structure includes a hyper-elastic membrane with high dielectric constant and flexible electrodes covered on both sides of the dielectric elastomer membrane. When the driving voltage is applied through the thickness direction, the dielectric elastomer membrane will deform under the action of Maxwell force, resulting in the reduction of thickness and the expansion of the area.

Linear DE actuators have been developed for over 20 years [1, 2]. Due to the material properties of the DE membrane, the output force of extension is not practical. To better fit the nature muscle and make it more practical, researchers generally combined the DE membrane with an elastic framework to form an antagonistic system. This system could achieve the function of electrified contraction like the nature muscle. The early linear DE actuator consisted of a spring and the DE membrane. Typically, a pre-stretched DE membrane was attached to the outside of the compressed spring to maintain the pre-stretch. In this design, the linear DE actuator would elongate when voltage was applied and contract when not [3–5]. Particularly, Kovacs et al. [6] fabricated an arm wrestling robot with over 240 DE actuators with springs inside and figured the experimental relationship between the number of layers and the output force. Another typical linear DE actuator is the core-free DE actuator. Without any springs inside, Tryson et al. [7] extended the orientated and corrugated metal electrode covered with DE membrane in a particular direction. Lau et al. [8] replaced the inner spring with a lightweight outer structure and increased the actuating frequency up to 10 Hz. However, due to the sliding between the two rolled DE membranes, the deformation is not inhomogeneous. The inhomogeneous deformation is

Fig. 2. Soft linear actuators driven by thermal responsive materials and structures: **a** nylon coiling fiber; **b** thermoresponsive hydrogel [59]; **c** bundle of SMA wires [32]; **d** SMA spring robot [31]; **e** robotic hand driven by SMA wires [34]; **f** high-speed microscale SMA actuators [35]; **g** Nitinol hydraulic bellow actuator [36]; **h** biocompatible shape memory polymer actuators [53]; **i** arm-like electrothermal actuator [55]

one of the main causes of actuating instability. Teh et al. [9] developed a cylindrical actuator, which significantly enlarged the electrically induced linear strains to 200%. Lu et al. [10] conducted the theoretical analysis of cylindrical actuator and found out how the height-to-radius ratio of the tube and loading conditions affected the actuation. There also existed some cone-like (loudspeaker-type) linear DE actuators [11–13] which could generate a large deformation out of the membrane plane when actuating and stay in the plane without actuating. All the above studies utilized the extension of the area of DE to fabricate actuators, the working principle of which, however, is opposite to that of nature muscles. During its actuation, the DE structure relaxes rather than contracts. To overcome this defect, some linear actuators with the feature of electrically induced contraction came up. Kovacs et al. [14] reduced the thickness of DE and stacked multiple DE layers to make an electrically contracted DE actuator. Acome et al. [15] made a self-healing electrostatic actuator by added filling liquid into the stacked structure to avoid the failure of actuator due to electric breakdown. As for microscale actuation, inspired by the McKibben's muscle, Lee et al. [16] made a DE membrane with braided fiber on both sides of a braided fiber sleeve with a specific bias angle. Some of the linear DE actuators are shown in Fig. 1.

Some studies focused on modeling the electromechanical behavior [17–22] and electromechanical stability [23–25]. Despite the advantages of dielectric elastomer, there are still some challenges. A flexible and stretchable electrode which can strongly adhere to the DE membrane is necessary for avoiding inhomogeneous deformation. And better material with higher dielectric constant, breakdown voltage and tension stiffening effect is critical for improving the mechanical properties of DE [26, 27].

2.2. Thermoresponsive Linear Actuators

Thermoresponsive linear actuators are mainly divided into two types: thermal deformation and thermal response. For the former, heating always results in phase transition or thermal stress, leading

Fig. 3. Soft linear actuators driven by ionic diffusion: **a** IPMC group actuator [61]; **b** single IPMC actuator [64]; **c** polyaniline-conductive polymer actuator [66]; **d** polypyrrole-conductive polymer actuator [68]; **e** area change in PPY (DBS) [73]; **f** PEDOT/PSS fiber bundle [72]

to a deformation. For the latter, heating means a chemical change whose effect would depend on the environment.

A famous study conducted by Haines et al. [28] showed that when an extremely twisted nylon fiber coiling around a mandrel with the same chirality was heated, it would tend to untwist and contract along the mandrel direction by up to 49%. It could also support an incredible tension force. Further study included painting it with twisted silver for efficient heating [29] and building a control system [30]. The similar linear actuator was made up of shape memory alloys (SMAs). After shaping the SMA at high temperature, to whatever it deformed at the cooling state, the material could completely restore to its pre-deformed shape when being heated to the martensite transformation temperature. Koh et al. [31] made an SMA spring actuator and designed a crawling robot. Mosley et al. [32] designed an SMA actuator with a bundle of wires, which could generate a force of 450 N. Laurentis et al. [33] analyzed the influences of the number and diameter of SMA wires. Andrianesis et al. [34] made a robot hand system with the SMA wires. Some recent studies focused on increasing the actuation frequency by using a diamond structure [35] and the application in minimally invasive surgeries (MIS) [36].

The shape memory polymer (SMP) is another important type of smart material. The SMP can respond to various stimuli, such as electric field, pH, light, magnetic field, sonic field, solvent, ions, and so on. To recover from its temporary shape, the conventional SMP usually depends on a reversible phase and a stable polymer network. The most typical SMP is the one triggered by temperature. The thermally reversible phase fixes the temporary shape when cooled to a temperature below T_{trans} and recovers to the original shape when heated [37–43].

The major advantages of SMPs are that they have much larger driven strain than SMAs and are easier to achieve different shapes by adding different thermal phases. The recoverable strain of SMP can be over 800% [44] while that of SMA is generally less than 8%; SMP can be changed into more than two shapes under the strain of over 600% [45]. However, there are also some challenges: The shape change is not reversible and the recovering stress is low. Some studies focused on the liquid crystalline elastomer (LCE), a typical reversible SMP or the so-called shape changing polymer (SCP) relying on the orientation of crystalline when heated [46, 47]. Recently, Jin et al. [48] made further progress in

Fig. 4. Soft linear actuators driven by pressurized fluidics: **a** programmable pneumatic actuator [76]; **b** bundle of four parallelized pneumatic actuators [77]; **c** a pneumatic artificial muscle-driven robot with reinforcement learning [78]; **d** fluid-driven artificial muscles [81]; **e** buckling pneumatic linear actuator [82]; **f** modular continuum robot [83]; **g** growth of pneumatic robot [79]; **h** a humanoid robot with McKibben [80]

programming the reversible LCE and made it a prototype robot. On the other hand, it is much more difficult to improve the recovering stress because the fixity would decrease under high pre-stretch or T_{trans} would be too high to achieve for practical conditions [49–51]. Sun et al. [52] utilized poly(methyl methacrylate) to achieve the maximum stress of 3.5 MPa at small strain; Song et al. [53] achieved 0.045 MPa at large strain ($> 90\%$) with 80/20 TPU/PLA blends. However, these are still insufficient for actuation applications. Some studies have shown a new way to achieve higher recovering stress by adding nanoparticles or SMA reinforcement. Miaudet et al. [54] significantly improved the stress to 130 MPa by fabricating an SMP with polyvinyl alcohol (PVA) and 20% CNT reinforced fibers. Zhou et al. [55] made a practical helix polymer membrane embedded with super-aligned carbon nanotubes, which could supply over 49% contraction.

The thermoresponsive hydrogel is another type of smart material to make linear actuators. Hydrogel is a hydrophilic functional polymer, which forms a three-dimensional network structure through physical or chemical crosslinking. The responsive hydrogels refer to those that can respond to changes due to the external environment. There are two main types of thermoresponsive hydrogel: one with a lower critical solution temperature (LCST) and the other with an upper critical solution temperature (UCST) [56]. The thermoresponsive hydrogel with a lower critical solution temperature exhibits hydrophilicity when the temperature is lower than its LCST and hydrophobicity when the temperature is higher than its LCST. The phase transition of the hydrogel polymer network causes a large

Table 1. Mechanical properties of some typical linear actuators

Mechanisms and materials	Stress or force	Strain (%)	Geometry and size	References
<i>Dielectric elastomer</i>				
Rolled (spring)	15 N	16	Rod, 20 layers	[6]
Stacked	20 N	10	Rod, 14 mm	[14]
Metal electrode	7 N	2	Rod, 5.26 cm ²	[7]
Ring	–	200	Ring, 100 mm	[9]
<i>Thermal responsive</i>				
Nylon fiber	19 MPa	49	Coil	[28]
SMA (spring)	250 mN	6	Coil, 0.5 mm	[31]
SMA (wire)	3.24 N	4	Wire, 0.15 mm	[32]
SMP	3.5 MPa	5	Clip	[52]
	0.045 MPa	160	Clip, 10 mm ²	[53]
SMP (CNT)	130 MPa	55	–	[54]
Hydrogel	–	70	Rod, 0.6mm	[59]
<i>Ionic diffusion</i>				
CP (polyaniline)	0.9 MPa	0.9	Rod, 0.21 mm	[66]
CP (polypyrrole)	20.4 MPa	26	Rectangle, 30 * 0.032 mm	[68]
<i>Pressurized fluidics</i>				
McKibben's muscle	2500 N	35	Rod, 55 mm	[75]

amount of water enter the hydrogel (temperature increases, shrinkage decreases, and water absorption decreases), which changes the volume and shape of the hydrogel. The two main indicators of responsive hydrogel actuator are increasing water absorption rate [57] and actuating deformation [58]. The recent work [59] significantly improved the deformation in a particular direction by adding cofacially oriented TiNS planes in the magnetic flux, which bear the electrostatic force that could be enhanced by heating. And the strain of hydrogel in the direction orthogonal to the TiNS plane could reach 70%. The actuating time reduced to 0.5 s due to the absence of substantial water uptake and release by using a similar structure to the above, which could be heated by light [60], as shown in Fig. 2. Because of its high bioactivity and suitable actuating requirements for living creature, the application of hydrogel is mainly focused on biomedical science.

2.3. Soft Linear Actuators Driven by Ionic Diffusion

The ionic polymer–metal composite (IPMC) is an intelligent material (ionic type) for electro-deformation, which possesses the characteristics of flexible deformation, repeatability, large displacement, and low voltage. The IPMC material generally consists of the Nafion ion exchange film and the electrode. In the water-containing state, cations in polymer films can move freely, while anions cannot move in the carbon chain. When a voltage is applied at both ends of the IPMC electrode, an electric field will be generated between the electrodes. Within the electric field, the hydrated cation moves to the negative electrode, while the position of the anion remains unchanged. As a result, the negative electrode swells and positive electrode shrinks, which leads to the bending deformation of IPMC.

Due to the mechanism of actuation, the main driving mode of IPMC is bending rather than linear driving. Some special structures were thus designed to produce linear displacement. Kamamichi et al. [61] made a structure composed of two groups of IPMCs, with each group of IPMCs fixed at both ends and articulated at the junction. They did further research in the controlling system and the effect of chemical change during actuating [62, 63]. Rossiter et al. [64] attached several segments of IPMC actuator with opposite polarities to a flexible conductive polymer to produce a linear displacement and proposed a manufacturing method [65].

There were also some studies on conducting polymers which expand and shrink by electrochemical doping and dedoping. Lu et al. [66] fabricated a linear electrochemical actuator with a particular structure in hollow polyaniline fibers using solid polyaniline fibers and realized isotonic strains of 0.9% and isometric stresses of 0.9 MPa. They got the stress of 0.42–0.85 MPa generated with ionic liquid electrolytes [67]. As for polypyrrole, Hara et al. [68] reached the stress of 20.4 MPa with TBACF₃SO₃ and the strain of 26% with bis(trifluoromethanesulfonyl)imide (TFSI) anion. New conducting polymers have

Fig. 5. **a** A hybrid actuating system driven by serially connected electric motor, spring, soft linear actuators (stacked DE cones) and stiff wire; **b** top view of the cone-like DE actuator; **c** side view of the cone-like DE actuator. a is the diameter of the inner ring ($a = 9 \text{ mm}$, 6.75 mm , 5.4 mm), and b is the diameter of the outer ring ($b = 54 \text{ mm}$). To apply load, a nylon wire is fixed at the center of the inner ring. F is the force applied on the wire, and u is the displacement of ring A while ring B is fixed. **d** Finite element simulation results of stress distribution of the DE cone with fixed displacement of $u = 16 \text{ mm}$ and the applied voltage of $\Phi = 0 \text{ kV}$; **e** finite element simulation results of stress distribution of the DE cone with fixed displacement of $u = 16 \text{ mm}$ and the applied voltage of $\Phi = 7 \text{ kV}$.

been recently fabricated with different dopants, such as PPy doped with dodecylbenzenesulphonate (DBS) (PPy/DBS) [69], and further with phosphotungstate anions (PT) to give PPy/DBS-PT [70] and with carbide-derived carbon (CDC) to give PPy/DBS-CDC-PT [71] linear actuators. These conducting polymers have been applied in wearable devices [72] and even in tissue engineering [73], which are shown in Fig. 3.

2.4. Soft Linear Actuators Driven by Pressurized Fluidics

Pneumatic artificial muscles (PAMs) are among the most successful actuators in robotics due to their high force-to-weight ratio, controllable compliance, and simple structure. The PAM, composed of an elastomer and a braided sleeve, was invented by J.L. McKibben, so the compliant linear soft actuator has been usually called the McKibben's artificial muscle [74, 75]. Recently, Martinez et al. [76] made a programmable pneumatic actuator with an embedded sheet and fiber. Robertson et al. [77] found that a bundle of small individual pneumatic actuators performed better than one single equivalent-volume actuator. Cui et al. [78] fabricated a PAM-driven humanoid robot hand, and applied the reinforcement learning algorithm to the PAM-driven robots. Hawkes et al. [79] reported a novel class of soft pneumatic robot that is capable of growing substantially in length. The peak rate of elongation is comparable to the rates of animal locomotion. The researchers at Tokyo Institute of Technology

Fig. 6. **a** Tension–displacement relationships of the DE cone actuators with various aspect ratios (b/a) and two applied voltages of $\Phi = 0$ (solid lines) and $\Phi = 7$ kV (dashed lines). F is the tensile force, and u is the displacement in the axial direction of the DE cone. **b** Actuating force–displacement relationships of the DE cone actuators with various aspect ratios (b/a) and the applied voltage of $\Phi = 7$ kV. ΔF is the force difference, and u is the displacement in the axial direction of the DE cone. **c** Relationships between the actuating strain $\Delta u/u$, and the force of the DE cone with various aspect ratios (b/a).

successfully mass-produced the McKibben. They bunched the muscles of tiny diameters together to develop characteristics of biological motion and produced a humanoid robot with muscles and skeleton as well as the clothes that serve as an auxiliary power suit. They also invented self-propelled colonoscopy and crawling robots based on McKibben [80].

PAMs could also be actuated by vacuum. Li et al. [81] came up with origami-inspired artificial muscles, which could contract over 90% of their initial lengths, generate stresses of 600 kPa, and produce peak power densities of over 2 kW/kg—all equal to, or in excess of, natural muscle. Yang et al. [82] made a linear buckling actuator with multi-chambers, which could respond within a second. Robertson et al. [83] invented vacuum-powered robots. These actuators are capable of achieving a variety of tasks, including multi-modal locomotion, object manipulation, and stiffness tuning. Some of them are shown in Fig. 4.

We summarize the strain and force data of various linear actuators introduced above and give their approximate sizes (diameters or areas) in the plane perpendicular to the direction of force (as shown in Table 1).

The inhomogeneous deformation of DE membrane possesses many advantages, such as large deformation, stackability, etc. We explored the relationship between the displacement and the output force with different ratios between the internal and external radius of fixed rings of the actuator and designed a spring–motor system to achieve the function of contraction.

2.5. Design of the Structure and Experiments

As shown in Fig. 5, we fabricated a two-layer DE actuator with a typical “sandwich” structure [84, 85], in which the outer ring A fixed the pre-tension, the inner ring B prevented crack propagation after piercing, and the VHB4910 with 3×3 biaxial pre-stretch, shear modulus $\mu = 45$ kPa, permittivity $\varepsilon = 4.7 \times 8.854 \times 10^{-12}$ F/m were applied [86].

3. Linear Cone-Like DE Actuators

We carried out the finite element analysis with user-defined materials (Abaqus UMAT) [87]. Hybrid, reduced integration elements (CAX4RH) were used in the simulation, as shown in Fig. 6d, e. The failure displacement u was determined to be greater than 20 mm. The breakdown voltage at $u = 20$ mm was higher than 9 kV by experiment. The system was set with the maximum displacement of $u = 16$ mm and the testing voltage of $\Phi = 7$ kV. We tested three types of actuators with different radius ratios ($b/a = 6, 8, 10$). In the tests, ring B is fixed on the lower splint of the stretcher, and ring A is fixed on the upper splint and connected with the force sensor. The measured displacement is the relative displacement between the upper splint and the lower splint, and the force is the tension obtained by the force sensor.

The experimental results are shown in Fig. 6. The solid lines are the force–displacement relationships of three actuators of different radius ratios with the voltage off, while the dashed lines are the force–displacement relationships at the voltage of 7 kV. The results show that under the same displacement load, decreasing the ratio of b/a will increase the pulling force produced by the membrane whether it is charged or not. For any given ratio of b/a , the actuating force linearly increases with the displacement u . The force reaches the highest value of 0.84 N at 7 kV and $b/a = 6$. This linear force–displacement relationship is control-friendly. We carried out the dead load actuation test to measure the force–displacement curve. With the data cutoff from 0.5 N to 2.5 N, the actuating strain decreases in inverse proportion to the load. The force–displacement relationships of three actuators with different aspect ratios were investigated. The actuator with the aspect ratio of $b/a = 8$ provides higher strain than the other two (as shown in Fig. 6c).

Besides, the displacement at failure increases with the decrease in aspect ratio. We could thus combine the cone-like linear actuators with different aspect ratios to satisfy different requirements, such as high actuating strain, high actuating force, or stable actuating condition.

3.1. System Design

Because of the extension of DE membrane when actuated, it is difficult to convert the output force into tension as the natural muscle does. Therefore, a spring–motor auxiliary actuation system is designed, as shown in Fig. 7a. When the system is under the non-working condition (State 2), ring A

Fig. 7. **a** u_1 is the pre-displacement, u_2 is the actuating displacement and u_3 is the displacement of the motor. State 1 shows the reference state of the system. The motor pulls the string in State 2, causing elongations of the spring and the DE cone ($\Phi_0 = 0$). When a voltage ($\Phi_1 \neq 0$) is applied, the DE membrane relaxes with elongation of the DE cone and contraction of the spring in their axial directions (State 3). The operation states 2–3 result in the linear displacement u_2 of the payload. **b** The relation of time and tensile force measured at the motor end. The actuating behavior of DE (the black curve) was measured when the actuator was fixed without any springs. The “spring-actuator” curve (the red curve) presents the actuating behavior of the whole system. The force was set as 3.3 N, and the motor velocity was set as 0.5 mm/s. ΔF_1 and ΔF_2 are the output forces which indicate the force difference with and without voltage. (Color figure online)

and ring B are in the same plane, and the membrane only keeps basic pre-stretching. While in State 2, the motor pulls the transmission line, and the tension in spring equals the tension in membrane plus the load. When under the working condition with applied voltage, the tension in membrane decreases, and the tension in spring becomes greater than the load. This voltage-induced force difference results in a linear motion until the system reaches equilibrium. To illustrate the process clearly, we tested the tension in the motor, as shown in Fig. 7b. The electromechanical output still relies on the deformation of the frame, which occurs in most bending actuators. The membrane is pre-stretched and fixed on an

elastic frame that deforms, and elastic energy of distortion accumulates. When voltage is applied, the membrane expands in area and the frame recovers to its original shape. In this system, the motor stops once it gives the initially biased displacement. As a result, the DE cone-like actuator reaches State 3.

4. Conclusion

Based on the cone-shaped dielectric elastomer membrane, the hybrid driving system achieves electromechanical actuation with linear stroke. The force difference of the dielectric elastomer with alternating voltages can tune the stroke and the driving force of the whole system. Challenges still exist for the control, fabrication and power supply of the “motor–muscle” hybrid system. Control and modeling of the soft linear actuator require further investigation due to the complex behaviors of soft polymers such as viscoelasticity and electromechanical coupling. Future design of the system may include a strain sensor of flexible electronics and closed-loop feedback control to enhance the accuracy of actuators. Enhanced learning based on massive experimental data can also be induced in the modeling of the complex system [78, 88]. The fabrication methods for both soft active materials and flexible electronics should also be investigated to enhance the flexibility and endurance of the composite structure and hybrid system. The system design and operating methods for this hybrid linear actuator may guide the design of soft robots and smart flexible devices.

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