ARTICLE IN PRESS
Extreme Mechanics Letters ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect
Extreme Mechanics Letters
journal homepage: www.elsevier.com/locate/eml

Fiber micro-architected Electro–Elasto-Kinematic muscles

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ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 3 March 2016
Accepted 4 March 2016
Available online xxxx

Keywords:
Electroactive polymers
Dielectric elastomer
Anisotropic actuation
Artificial muscles

ABSTRACT

Electro-active polymers (EAP) such as dielectric elastomers can reproduce biomimetic functions requiring micro-scale actuation such as color and texture change, or tunable wetting and adhesion. For these applications, large actuation strains and energy density are required. Recent studies with fiber reinforced elastomers demonstrated the ability to obtain anisotropic in- and out-of-plane actuation in macro-scale elastomer membranes. We design a new class of fiber micro-architected elastomers capable of anisotropic actuation in the two orthogonal in-plane directions under uniform electrostatic field. We reinforce the two sides of a pre-stretched VHB film with parallel arrays of stiff ultra-high molecular weight polyethylene fibers. By controlling the spacing and bias angle between the fibers, we create diamond shaped unit cells of 100–300 um size, and demonstrate a wide range of kinematics showing maximum extension of 26% at 45° and maximum contraction of −6.3% at 65° at maximum efficiency of 15%. We call these devices Micro-architected Electro–Elasto-Kinematic muscles (MEEKs). We use analytical modeling and finite element analysis to explain the observed actuation kinematics and the associated non-homogeneous strain distribution. We expect this principle to be suitable for micro-actuation and smart skins where anisotropy can be advantageous.

1. Introduction

Various tunable micro-scale functionalities can be achieved by inducing mechanical stimulation in the form of local strain. This could potentially enable local structural coloring [1], wetting control [2] and adhesion [3]. For example, various animals and sea creatures use visual and neural cues to examine and match their environment's background by camouflage [4]. Cephalopods (e.g. the cuttlefish) use chromatophores to control pigments patterns in layers of tissue thus locally changing their skin's colors [5]. Moreover, the cuttlefish and octopus can also change the surface texture of their outer tissue to create intricate disguise textures, an intriguing function enabled by up to 500% strain capacity of their skins.

To mimic these phenomena and micro-engineer local strains in material systems, there is need to design a new class of micro-muscles, which should ideally be energy dense, reliable, and cheap (and hence simple), without the need of high force generation or fast response rate [6,7].

For macro-scale systems however, existing actuators suffer from a trade-off between the maximum force they can apply and the maximum actuation stoke or strain. For tunable micro-actuation requiring large strains and energy density, dielectric (acrylic) elastomers (DE) are possibly the most suitable choice [8]. Owing to their large strain [9], higher efficiencies [10], energy density and faster response rate, they favorably compare to heat based muscles such as wax-filled CNTs or shape memory materials which have efficiencies <5% and have response rate limited by cooling [11].

The most common form of DE muscle is a thin membrane of flexible elastomer with high voltage breakdown strength, such as 3M VHB, which deforms under the pressure of electrostatic potential of two sandwiching flexible

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http://dx.doi.org/10.1016/j.eml.2016.03.003
2352-4316/

electrodes. The membrane is usually pre-stretched which enhances its breakdown strength, reduces the electromechanical instability and leads to larger actuation strains. The actuation is typically isotropic in the plane (equibiaxial). The expansion actuation scheme of DE is known to somewhat limit their applications. Generally speaking, an ideal bio-mimetic muscle would contract uniaxially (when Voltage is turned ON).

Several approaches have been explored to design and fabricate macroscale muscles with anisotropic actuation strain. An early approach was rolling a stack of dielectric elastomer and electrode to significantly constrain the radial expansion [12]. Plante has used diamond-shaped compliant frame to fix a DE membrane which restricted the DE expansion in certain direction and created anisotropy on the macroscale [13]. Fiber reinforcement emerged as a third approach to achieve unidirectional actuation in DE [14]. In the study by Suo and co-workers, the DE is fixed vertically between 2 flat rigid plates, with an applied weight at the bottom to keep it under tension. Several fiber configurations are tested including fibers sandwiched between two thin layers of VHB and fibers printed on only one side. It is observed that the fibers enhance the actuation in the vertical direction (perpendicular to the fibers) to 28%, while the precise actuation parallel to the fiber direction is not reported. A recent fiber-reinforced DE used glass fibers thus overcoming lateral buckling and achieving 142% strain [15]. Finally, a similar configuration has been tested in rolled configuration such that the fibers are aligned in the circumferential direction, and the cylindrical actuator was fixed vertically between two rigid PVC tubes and a weight attached to the bottom [16]. The authors observed similar enhancement in the vertical actuation, where the cylinder expands by up to 35.8% when the voltage of ∼20 kV is applied. Recently, Subramani and co-workers demonstrated anisotropic composite dielectric elastomers with actuation strain approaching 70% parallel to highly elastic and polyurethane fibers with high dielectric constant; they reported maximum actuation anisotropy of close to 2 (defined as the ratio between strain in the unconstrained direction to the strain in the constrained direction) [10]. More recently, using a few number of stiff fibers on a non-pre-stretched DE membrane out-of-plane deformation has been achieved and a DE gripper was demonstrated [17].

In this letter, we study the kinetics of a new micro-architectured DE muscle expansion and contraction in the two orthogonal in-plane directions, resulting in large anisotropy. We designed an actuator with two sets of well-aligned, equally spaced high strength ultra-high molecular weight polyethylene (UHMWPE from Berkley NanoFil, 25 μm diameter) fibers, sandwiching the DE membrane (3M VHB 4910), with a bias angle between each set (Fig. 1(a)). Details of device fabrication are described below. The geometry of fiber micro-architecture is similar to what is seen in pneumatic McKibben muscles [18]. McKibben air muscles use a soft deformable and sealed core with braided fiber sleeve, such that the stiff fibers helix angles determine the kinematics of actuation. While primarily used to axially contract, they can exhibit a plethora of motion kinematics including rotation and expansion

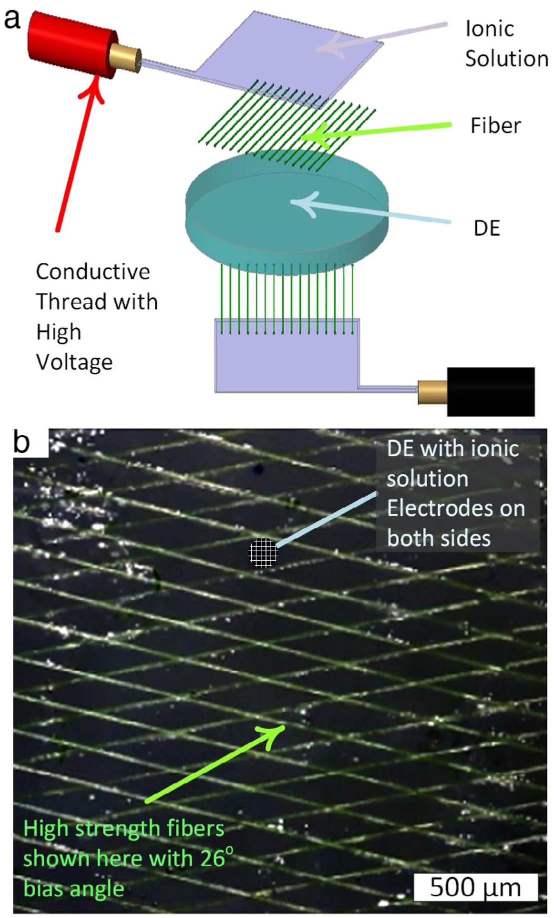

Fig. 1. Fiber micro-architected Electro–Elasto-Kinematic (MEEK) muscles. (a) Schematic showing the construction of the fibers on both sides of the dielectric elastomer (DE); (b) microscope image showing the muscle with fibers having 26° bias angle. The muscle appears black because it is transparent and the experiments are carried over a phenolic resin lab bench.

[19,20]. Fig. 1(b) shows a MEEK muscle with 26° bias angle. We designate this new class of actuators as Micro-architected Electro–Elasto-Kinematic (MEEK) muscles.

2. Theoretical modeling

The behavior of DE muscles is in general governed by the balance among the external and Maxwell electrostatic stresses, and the effective strain energy of the fiber-reinforced muscle. This can be written in the form [14]:

$$\sigma_i + \varepsilon\psi^2 = \lambda_i \frac{\partial W_{stretch}(\lambda_i, \lambda_j)}{\partial \lambda_i} \tag{1}$$

where σ_i is the external stresses in a principal stretch direction i, $\varepsilon\psi^2$ is the Maxwell stress with ε being the dielectric permittivity having a value of 3.98×10^{-11} F m^{-1} and ψ the actuation electric field, λ_i is an in-plane principal stretch direction (final length/initial length), and $W_{stretch}$ is the Helmholtz free energy of stretching. For example, for simple VHB tape sandwiched between compliant electrodes, the external stress is the pre-stretch, which