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Helical dielectric elastomer actuators

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Abstract
This paper presents a new type of contractile polymer-based electromechanical linear actuator. The device belongs to the class of dielectric elastomer actuators, which are typically capable of undergoing large deformations induced by an applied electric field. It is based on a novel helical configuration, suitable for the generation of electrically driven axial contractions and radial expansions. The architecture, the principle of operation, a fabrication method and results of a preliminary prototype testing of the new device are described. An axial strain of -5% at about 14 V μm^{-1} was obtained from first prototypes.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Electroactive polymers (EAPs) offer attractive properties of energy transduction from the electrical to the mechanical form for actuation. They are classified into two major groups: ionic EAPs (activated by an electrically driven diffusion of ions and molecules) and electronic EAPs (activated by an electric field) [1]. The two classes include several types of materials, which operate in accordance with different principles and with different properties, explored for many applications. One of the most fascinating of them is devoted to the development of 'artificial muscles' [1–3]. Q.1

A subclass of EAPs, represented by dielectric elastomers, includes polymers which are able to be manufactured as deformable actuators with high active strains (of the order of 10–100%), high active stresses (up to the order of 1 MPa), low response times, high reliability, high stability and low costs [4, 5]. The basic operational principle of a dielectric elastomer actuator is represented by an electrostatic squeezing of a sample of rubber-like insulating material coated with compliant electrodes and electrically charged by a high-voltage power supply.

So far, several shape configurations for dielectric elastomer actuators have been proposed, demonstrated and studied, including planar, tube, roll, extender, diaphragm and bender [4–13]. As a common property, these devices elongate along their main dimensions when an electric field is applied between the electrodes.

Nevertheless, certain applications may benefit from the availability of linearly contracting compliant actuators. The development of 'artificial muscles' is certainly one of the most representative examples. Such a property of contractility is not owned by devices having the configurations mentioned above, unless adopting auxiliary mechanical components used, for instance, to transfer motion in privileged directions.

The only configuration available for dielectric elastomer actuators intrinsically capable of offering linear contractions with amplitudes of practical use is currently represented by the stack-like configuration. Derived from piezoelectric technology, this configuration has been adopted even for dielectric elastomers [4]. It consists of a multilayer structure of elementary planar actuators connected mechanically in series and electrically in parallel. The electrically activated thickness compression of each layer generates a resulting contraction of the entire device along its main axis.

Despite their usefulness, elastomeric stack actuators require fabrication processes typically made onerous by the discontinuous nature of their structure. In fact, they entail the realization of several layers of dielectric elastomer, alternated by layers of electrode material, and the electrical shorting of the two resulting series of electrodes [14]. Accordingly, in contrast to the configurations mentioned before, this kind of devices has not been widely used so far.

In order to obtain a viable electrically contractile monolithic actuator, a new actuating configuration is presented here. It has been designed more generally for EAP actuators [15–17] and in its implementation for dielectric elastomers it comprises two helical compliant electrodes and an elastomeric insulator interposed between them (figure 1(a)).

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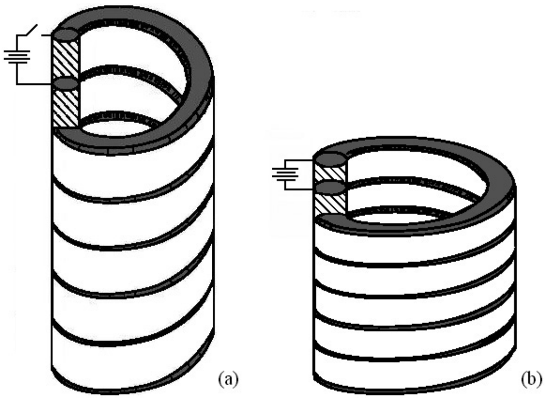

Figure 1. Schematic drawing of the structure and actuation principle of the new configuration. The actuator is represented in its rest condition (a) and under electrically activated axial contraction and radial expansion (b).

Each electrode is helicoidally alternated to the other and continuously extends along the overall length of the structure.

By applying a voltage difference between the electrodes, electrostatic interactions among their free charges generate axial contractions of the actuator, as well as related radial expansions (figure 1(b)). Such deformations are supported by the compliance of both the electrodes and the dielectric material. Devices working with this actuation principle may be regarded as electrically activated polymer springs.

A fabrication technique and results of a preliminary testing of contractile dielectric elastomer actuators based on this new configuration are presented and described in the following sections.

2. Materials and methods

2.1. Fabrication

Prototypes of the new type of actuator were fabricated according to a multi-step procedure summarized in figure 2 and described below.

Step I. Fabrication of dielectric elastomer tubes. Cylindrical hollow tubes (figures 2(a) and 3) made of a silicone rubber were fabricated by mould-casting in Delrin® moulds (figure 3). Silicone was chosen as a dielectric elastomer, owing to its suitable mechanical properties and ease of processing. In particular, a very soft and commercially available silicone rubber (TC-5005 A/B-C, BJB Enterprises Inc., USA) was selected and used as an elastic dielectric enabling high active strains. This silicone consists of a three-component (A, B, C) product, whose elastic modulus can be modulated by varying the amount of softener (component C) added during the material processing. To obtain samples with different compliances, 10 wt% (according to the manufacturer's specifications) of component B (curing agent) was mixed with component A and the softener C was added to the mixture A/B with a proportion of 10 or 20 wt% in this study.

Furthermore, in order to investigate the potential enhancement of the material's electromechanical response, some early samples were prepared by mixing a ferroelectric ceramic powder with the elastomer. In fact, according to studies we have performed [18, 19], following the work of Zhang *et al* [20], the permittivity of a dielectric elastomer (on which the material's electromechanical response proportionally depends) can be increased at great advantage, by loading the material with highly dielectric ceramics. In particular, in the present work a powder of lead magnesium niobate–lead titanate (PMN–PT) was dispersed with a proportion of 10 vol% in silicone matrices processed with 10 wt% of softener. For this purpose, a commercial

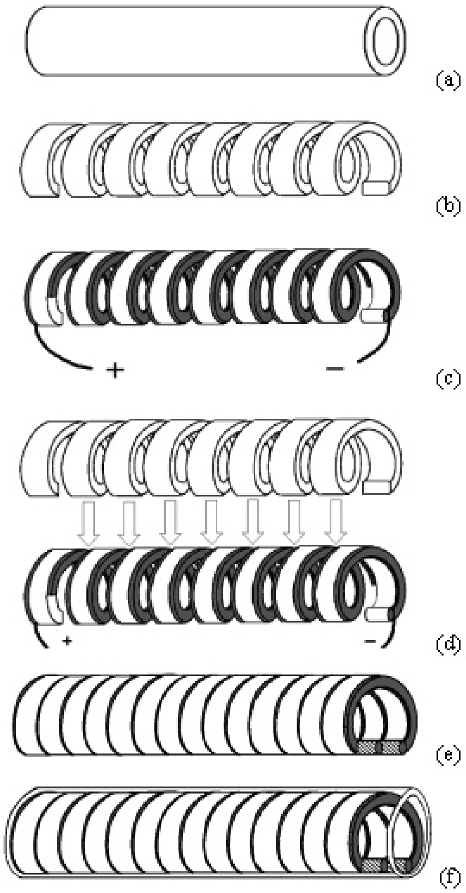

Figure 2. Sketch of the steps of the procedure followed for the realization of the new actuator: fabrication of dielectric elastomer tubes (a); cutting of dielectric elastomer helices (b); deposition of the electrodes and application of the electric contacts (c); assembling of the device (d)–(e), including a final coating (f).

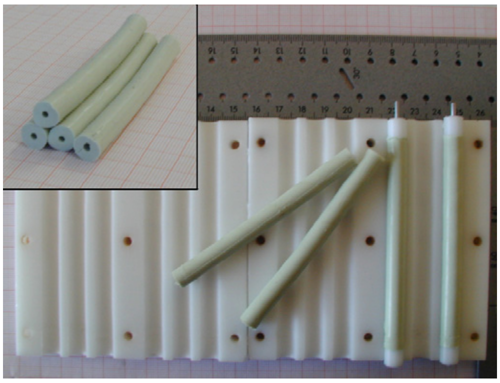

Figure 3. Dielectric elastomer tubes and moulds used for their fabrication.

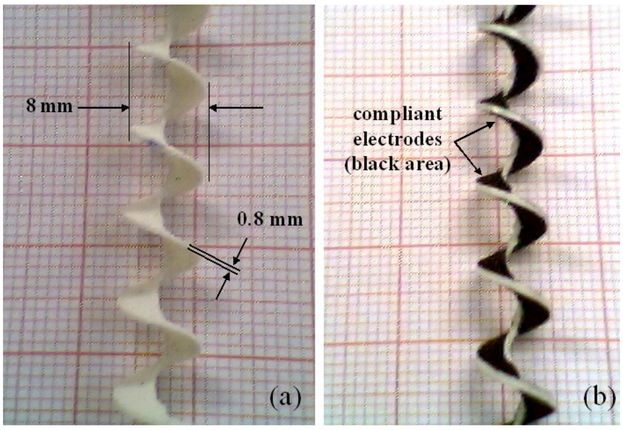

Figure 4. Photographs of a dielectric elastomer helix before (a) and after (b) the deposition of the two electrodes.

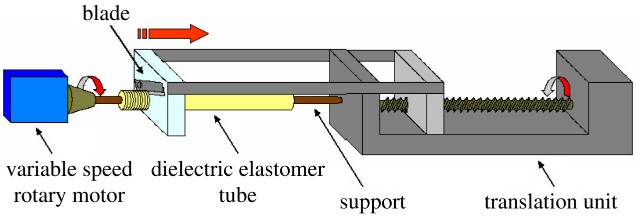

Figure 5. Experimental set-up for a blade helical cutting of a dielectric elastomer tube.

ceramic (PMN-38, TRS Ceramics, USA) was used, which has a nominal room-temperature relative dielectric constant of 19 000 at 1 kHz, according to the product datasheet [21].

Air-bubble-free samples were obtained by subjecting the material to a vacuum treatment for about 30 min. The elastomer was then cured at room temperature for approximately 12 h in the moulds shown in figure 3, which then allowed tubes with internal and external diameters of 2 and 8 mm, respectively, and length of 80 mm to be obtained (figure 3).

Step II. Cutting of dielectric elastomer helices. Elastomer tubes fabricated as described in step I were used to obtain dielectric elastomer helices (figures 2(b) and 4(a)) by means of a blade cutting, as described below.

A customized machine able to couple rotary and translation movements was built in order to implement such a helical cutting of a tube (figure 5). It is based on a variable speed rotary motor (RW16 basic, IKA-Werke, Germany) and a modified automatic injector (100, Kd Scientific, USA). The rotary motor provides rotation to a stick, which supports the elastomer tube. Furthermore, a metal blade is fixed to an aluminium holder mounted on the modified injector, which acts as a translation unit. By combining the rotation of the tube with the translation of the blade, helical cuts are obtained. This set-up permits the selection of the rotation and translation speeds, and therefore the definition of the resulting pitch of the helical cut.

By using this machine, dielectric elastomer helices with several thickness values down to 0.5 mm were obtained. The typical thickness of samples used for the realization of prototype actuators was of 0.8–1 mm (figure 4(a)).

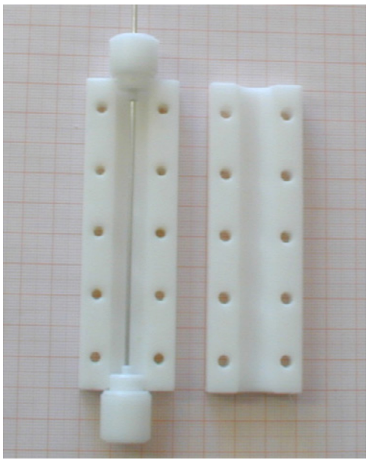

Figure 6. Photograph of a mould employed for the final assembly of the actuator.

Step III. Deposition of the electrodes and application of the electric contacts. Two faces of one elastomer helix were coated with compliant electrodes, consisting of a silicone/carbon-black mixture (figure 4(b)). In particular, a silicone matrix (CAF 4, Rhodorsil, France), previously solved in trichloroethylene, was loaded with a carbon-black powder (Vulcan XC 72 R, Carbocrom, Italy) with a weight ratio 1:1. The mixture was subject to an ultrasound treatment for 3 min, to avoid agglomerate formation.

This electrode material was applied to the helix by use of an airbrush (Millennium, Paasche, USA). In order to prevent the undesired coating of the inner and outer small surfaces of the helix, they were reversibly masked. Following the deposition of the electrode mixture, cured at a temperature of 50 °C for about 6 h, and the subsequent removal of the mask, the main surfaces of the helix ended up covered by two isolated and continuous electrodes (figures 2(c) and 4(b)).

Moreover, ring-shaped thin metal foils working as electric contacts were applied to both the electrodes at the opposite extremities of the helix (figure 2(c)).

Step IV. Device assembling. In order to complete the structure of the device, an electroded helix was coupled with a naked one (figure 2(d)), previously smeared with the dielectric material itself in degassed fluid state (i.e. not yet cross-linked).

The two helices were compacted and the ‘soldering’ material was cured at room temperature for about 12 h. The material curing was carried out by placing the coupled helices into cylindrical moulds (figure 6), filled with an additional amount of the fluid dielectric and subject to a degassing phase. This operation constituted not only the ‘soldering’ of the two helices (figure 2(e)), but also their external coating with a protective layer (figure 2(f)).

The coating works as an outer insulation of the electrodes, such that their air discharge during actuation is prevented. Nevertheless, such a passive layer results in a disadvantageous mechanical resistance, which stiffens the overall structure and limits its deformation. The effect of this drawback was reduced by processing the coating elastomer with a higher amount of softener in comparison with the helix material. In this regard, table 1 lists the materials used to fabricate two different types of samples of the actuator.

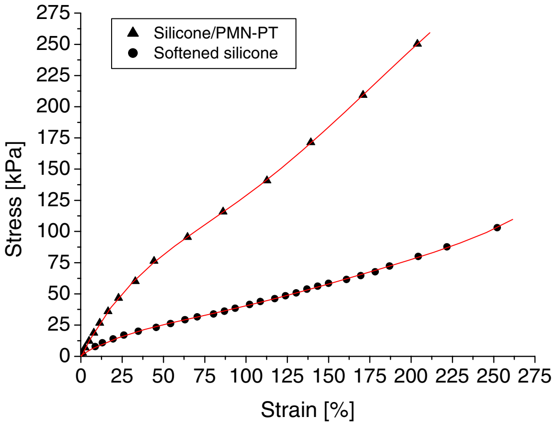

Figure 7. Pseudo-static stress–strain characteristics (fitting curves are inserted as a guide for the eye) of the two elastomers tested for realization of the dielectric helices (see table 1 for details).

Table 1. Dielectric elastomers employed in prototype samples.

Sample	Dielectric helices	External coating
Silicone/PMN–PT	Silicone (softener: 10 wt%) + 10 vol% PMN–PT	Silicone (softener: 15 wt%) + 10 vol% PMN–PT
Softened silicone	Silicone (softener: 20 wt%)	Silicone (softener: 35 wt%)

Air discharge of the electrodes at the inner cylindrical surface of the device was prevented, by using a suitable insulation material. However, in order to avoid the introduction of a further mechanical resistance due to the use of an eventual solid-state internal coating, a different solution was adopted: the inner cavity of the actuator was filled with a dielectric silicone oil and sealed. The use of such a liquid-state insulator enables an electrical protection with a negligible mechanical effect.

2.2. *Mechanical testing*

The mechanical properties under elastic loading of the dielectric elastomer constituting the helices were assessed by subjecting a sample of the material to a test under uniaxial extension. Increasing the forces applied (up to the material's fracture), the pseudo-static elongation corresponding to each force was recorded 3 min after the load had been applied. This allowed to derive the engineering stress–strain characteristic of the elastomer.

2.3. *Electromechanical testing*

Actuators fabricated in accordance with the method mentioned above underwent a preliminary testing procedure where the electromechanical strain generated along the axial direction was measured. This was achieved by using an isotonic displacement transducer (7006, Ugo Basile, Italy). It was connected to the upper end of an actuator placed in a vertical position with its lower end constrained. A DC high-voltage power supply (Bertan, USA, HV-DC 205A-30P) was used to generate the driving fields. During the application of several values of a step-wise high voltage difference between the electrodes (up to the dielectric breakdown of the material), the axial contraction of the device was measured by the transducers.

Figure 8. Pictures of a prototype of the new type of dielectric elastomer actuator.

3. Results

In accordance with the mechanical test specified, the considered dielectric elastomers exhibited the stress–strain curves shown in figure 7. Owing to such a typical non-linear trend provided by any rubbery material, the elastic modulus varies with the strain of the elastomer. Values of the tangent (local) modulus were calculated as the derivative of the stress–strain curve. An initial elastic modulus of about 275 and 90 kPa was respectively obtained for the silicone/PMN–PT elastomer and the softened silicone.

Figure 8 presents two photographs of a prototype actuator. The devices developed present the resulting shape of a soft hollow tube having the following typical dimensions: length of 60–80 mm, inner diameter of 2 mm and external diameter of 13 mm (including the coating layer).

As a result of the preliminary electromechanical testing of the prototype actuators developed so far, figure 9 shows values of the steady-state axial contraction strain measured following the application of the driving electric fields indicated. These preliminary data show that the new actuator is capable of contracting along its main axis, generating a strain which can vary, as expected, significantly with the particular elastomer used. A strain of about -3% in response to a driving field of 15 V $\mu\mathrm{m}^{-1}$ was obtained by adopting the considered silicone/PMN–PT mixture, while a maximum strain of about -5% was achieved at 14 V $\mu\mathrm{m}^{-1}$ with the softened silicone. Higher performances are expected with future improvements, as discussed in the following section.

4. Discussion

Results of this work have shown the feasibility of realizing a new dielectric elastomer actuator capable of linear contractions. The performance reported does not correspond

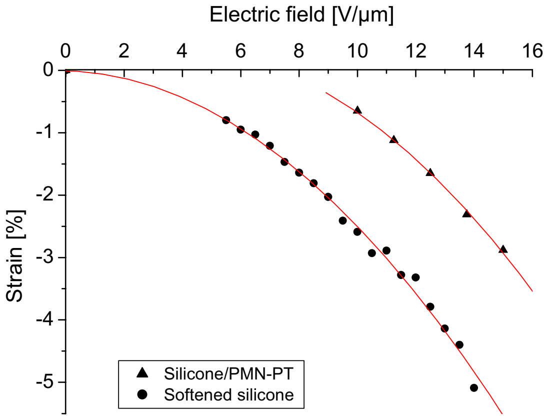

Figure 9. Preliminary data on the contraction strain generated by the new type of actuator in response to applied electric fields (fitting curves are inserted as a guide for the eye). The two plots refer to the different materials tested (see table 1 for details).

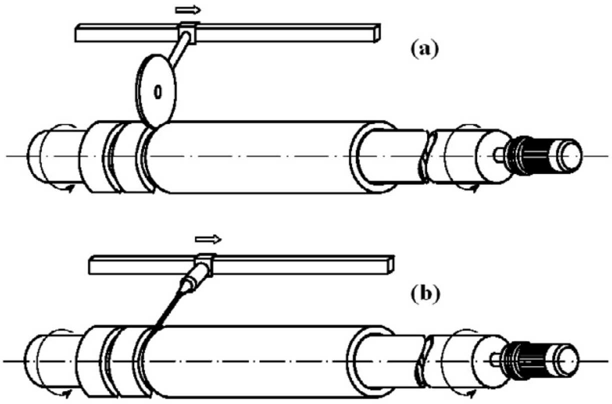

Figure 10. Helical cutting of a dielectric elastomer tube by means of a blade (a) or a laser beam (b).

to any intrinsic limitation of the proposed configuration and has thus to be regarded as the current ‘state of the art’, in accordance with the fabrication method adopted, the particular implementation and the elastomeric materials employed for such a new device. In order to achieve higher electromechanical properties, improvements are required in the fabrication technique, in the selection/development of suitable elastomers and in the identification of appropriate working conditions for the resulting actuator, as discussed below.

From the fabrication point view, one of the main issues is represented by the necessary decrease of the thickness of the helices. Thinner elastomers would have a double advantage: (1) they would consent the application of lower voltages; (2) they would require a thinner layer of lateral electrical insulation between the electrodes. This would reduce the undesired mechanical resistance of such a passive layer. However, in this and other respects, the fabrication method described here presents some limitations. In fact, besides the manual work required for several steps of the process, the realization of elastomeric helices through blade cutting is less effective with decreasing values of thickness. Thinner cuttings are in fact more difficult to obtain. Such a limitation, which is more evident with softer elastomers, can be ascribed to the material deformation under the stress applied by the blade while it is cutting. The set-up we currently use gives reliable cuttings with helical pitches not lower than 0.5 mm. In order to reduce these non-favourable deformations during the material cutting process, one could think of cooling it, such that a low-temperature cutting with a sort of freezing microtome would be implemented. However, the adoption of such a method could considerably complicate the fabrication process.

For these reasons, we are currently evaluating the feasibility of obtaining helices in different ways. Alternative solutions can arise from the use of different cutting tools. As an example, a laser beam may be employed for such a purpose (figure 10). A different strategy under evaluation foresees the direct fabrication of helices by means of mould casting. This would avoid the realization and cutting of tubes. Moulds can be obtained from different types of materials (either plastic or metallic) by using well established techniques such as stereolithographic processes or micromechanical manufacturing (including machining, laser working and electroerosion).

In addition to such technological issues, the choice of suitable materials is crucial for the performance to be achieved by the devices. In particular, the materials adopted for the lateral insulation of the electrodes have to exhibit a high dielectric strength, as well as a low elastic modulus, such that the effect of the introduced mechanical resistance is reduced. Therefore, while for the outer coating layer a soft silicone-based elastomer was used, the internal insulation was accomplished with a silicone oil. Nevertheless, it can be useful to consider that alternative materials for both the internal and the external insulation of the device may consist of gel-like compounds with a suitable dielectric strength. Concerning the helices, materials with a low elastic modulus and a high dielectric constant are obviously preferred in order to improve the actuation strain.

Despite these basic properties, the peculiarity of the configuration described in this paper determines additional material constraints, which may also be combined with constraints on preferable working conditions. Both of these types of constraints can be different from those related to other dielectric elastomer actuators. In particular, previous studies have documented well that several elastomers currently used for actuation show better performance at high pre-strains (pre-extensions). This results from an increased dielectric strength, which enables the application of higher electric fields [5]. For this reason, several actuators are usually subject to working conditions enabling the pre-strain of the material [5, 9, 10]. Moreover, figure 7 suggests that, as a consequence of the existence of an oblique flex point in the stress–strain curve of any elastomer, the material pre-strain up to such a point may reasonably be considered to increase the active strain achievable with a definite electric field. In fact, in this case the device would be operated around a point of minimum elastic modulus. However, material pre-straining before activation can be electrically disadvantageous for this new actuator. In fact, the distance between the electrodes of the device increases with pre-strain. This implies that, in order to impose any definite electric field, higher voltages are necessary. This is disadvantageous not only from a practical point of view but also for the lateral insulation of the electrodes, when considering the thinning of the coating layer as a consequence of pre-strain. Therefore, pre-strains appear to be unfavourable for this configuration from an electrical point of view. Accordingly, elastomers with a good elastic response and a suitable dielectric strength even at rest or low pre-strains seem to be the most suitable for the device.

These requirements determine the exclusion, from candidate dielectrics for the new actuator, of composite elastomers obtained by dispersing ceramic fillers in a polymer matrix, such as the silicone/PMN–PT samples which we tested in the first prototypes. In fact, such materials typically become stiffer at low strains, presenting a high initial Young's modulus, as shown in figure 7 and as confirmed by other studies [19]. This feature is reflected in the active strain achievable from the actuator. In this regard, figure 9 consistently indicates that the worst performance was obtained from the silicone/PMN–PT based samples, even though the better results recorded with the pure silicone have to be also ascribed to the concomitant use of a softer coating. This is why pure elastomers only have been used for the last generation of prototypes.

Moreover, in order to further increase the compliance of the actuator, the approach of softening the elastomer for the coating layer was also applied for the fabrication of the helices. However, in this case this approach cannot be pushed too much. In fact, the experimental set-up currently used for the fabrication does not give a reliable cutting of excessively soft elastomeric tubes. In fact, as previously discussed, in such a case the blade-based technique of cutting presents an inaccuracy arising from the excessive deformation of the soft elastomer while being cut. Accordingly, so far we have successfully obtained helices from elastomers containing an amount of softener up to 20 wt% (table 1). In contrast, the external coating does not require any further mechanical processing and, therefore, it can be moulded with more softener. In the latest samples we have used a proportion of 35 wt% (table 1).

As a final remark, it can be useful to consider the effect of pre-compressions, instead of pre-extensions, in this type of actuator. The thickness of the dielectric helices would be actually reduced before activation in a pre-compressed device. This would enable the use of lower voltages, with a benefit even in terms of electrode lateral insulation. Moreover, this would relax some dimensional constraints, reducing some fabrication drawbacks, since the cutting of very thin helixes would become less important. From a purely mechanical point of view, suitable pre-compressions are reasonably expected (as in the case of pre-strains) for strains around an eventual point of oblique flex in the stress–strain curve of compression of the material. In order to investigate such aspects, we are currently evaluating possible structural solutions enabling self-standing pre-compressions of the device. One method can be borrowed from the state of the art of roll-type dielectric elastomer actuators, which are fabricated with internal springs that provide the desired pre-elongation [9, 10]: dually, the new actuator may adopt an internal spring of pre-compression. As an alternative solution, it may be considered to relegate the function of support for the compression to the external coating layer. In particular, the coating may be realized on the surface of a couple of pre-compressed helices. Accordingly, in this case a coating material with a suitable elasticity should be selected, resulting from a compromise: highly compliant coatings would favour the desirable softness of the overall structure, while stiff coatings would advantageously attenuate the tendency of the elastomeric helices to passively recover the rest dimensions possessed before the imposed pre-compression.

5. Conclusions

The architecture, the principle of operation, a fabrication method and preliminary data on the electromechanical strains of a new dielectric elastomer actuator have been presented. The functionality of the actuator relies on electrodes with a helical configuration, so that the device is capable of generating electrically activated linear contractions.

Silicone-made prototypes of the new device have been realized and tested, showing a maximum axial contraction strain of -5% at about 14 V μm^{-1}.

Careful selections of appropriate materials, possible developments of the fabrication technique and eventual pre-compressions represent concomitant factors expected to enable potential improvements of the actuation performances of this promising new actuator.

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