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PVC gel based artificial muscles: Characterizations and actuation modular constructions

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ABSTRACT

Polymer materials based artificial muscles have the properties of being soft, lightweight, and flexible which are similar to the nature muscular actuators. In our previous study, we have developed a contraction type artificial muscle based on plasticized poly vinyl chloride (PVC) gel and meshed electrodes. And we have improved the characteristics to make it close to the level of natural muscle. It has many positive characteristics, such as stable actuation in the air, high output, notable response rate, and low power consumption. So a wide application is expected. However, for practical applications, it is necessary to consider some specific criteria, such as performance criteria and structural criteria. In this study, we introduced the most updated properties of PVC gel artificial muscles and proposed three types of mechanical actuation modular constructions for making the PVC gel artificial muscle as a robust actuation device for robotics and mechatronics. And we tested a prototype to examine the effectiveness of the proposed modules. Finally, an analytical model for the static characteristics of PVC gel artificial muscles at different applied voltages was derived and showed good agreement with experimental results measured by a prototype of modules.

1. Introduction

The most common actuators are combustion engines, electric motors and piezoelectrics. Combustion engines have high efficiency when operated continuously but not suitable for the intermittent motion like walking robots. Electric motors have high accuracy but low efficiency in torque to mass compared to biological muscles, which makes them very bulky for robotic, medical and fluidic applications. Piezoceramics have very high power densities but with a small strain of 0.1% which makes massive mechanical amplification necessary when significant displacements are required. These types of traditional actuators are not ideal for the applications in the mechatronics or biomimetics, such as rehabilitation devices, power assist suits and insect type micro robots. For these applications, the actuators that have the similar characteristics of biological muscles of light in weight, high strain and stress, soft and low noise are desirable.

Polymer material based artificial muscles have attracted great attention these years [1,2]. A variety of electronic, ionic, and photoactivated artificial muscles are proposed that exhibit large strain in length and volume, high response rate, and high output power, which is the primary similarity with muscle [3,4]. The pneumatic artificial muscles (PAMs) [5,6] have the advantages of high force to weight ratio, lightweight, low cost and flexibility. But generally a heavy and noisy energy resource (air or gas) equipment is needed. Shape memory polymers (SMPs) [7,8] can be developed into multifunctional materials actuated by various methods, such as thermal-induced, electro-activated and magnetic-actuated SMPs. They can achieve a high strain and stress but a low response rate (seconds to minutes). On the other hand, electro active polymers (EAPs) which exhibit large strain in response to electrical stimulation, are human made actuators that most closely emulate muscles. The most attractive feature of EAPs is their ability to emulate biological muscles offering resilience, toughness, large actuation strain and inherent vibration damping. Ionic polymer-metal composites (IPMCs) [9,10] are one type of EAP actuators that create a large bending motion under relatively low input voltage (1 ~ 3 V). However, the response rate is not notable and there is a need to maintain their wetness. Dielectric elastomer actuators (DEAs) are one of the most studied EAP actuators and numerous applications are being developed including electroactive fluid pumps, conformal skins for Braille screens and insect-like robots [11–13]. However, the challenge for this type of actuators is their use of a high voltage (>1 kV) due to the high electric fields that are needed (~ 100 V/μm).

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Among all the candidates of artificial muscles, PVC gel based artificial muscles showed a great potential for practical applications. Zulhash Uddin et al. [14] found the bending deformation of PVC gel under an electric field. However, to emulate nature's muscle, we think it is necessary to create a contraction and expansion movement. Based on the unique phenomenon and mechanism of PVC gel at the side of anode of electrode, we have developed a contraction and expansion type PVC gel artificial muscle, using the meshed anode and foil cathode [15]. And we evaluated and improved its characteristics [16,17], modeled it as a control element [18]. Also some applications, such as a motor brake [19] and walking assist gel spats [20] are implemented so far. The PVC gel artificial muscle has the advantages of stable movement in the air with a large strain and an output stress with a high response rate and stability on thermal influence. And a medium input electric field (~20 V/μm) and a low level of power consumption (~5 μW/μm) which also show the reasonability for practical applications. Furthermore, the durability (cycle life) under a continuous electric field driven is also confirmed sufficient for the practical applications, recently.

Since, each actuator is defined according to the physical theory on which its legitimacy is founded, a general theory of actuators does not exist. Each actuator has its own composition, mechanism, motion type, and mechanical structure. As an alternative among the artificial muscles or the traditional actuators in practical applications, it is necessary to consider some specific criteria, such as performance criteria and structural criteria. In this study, we introduced the composition, mechanism and present the most updated properties of PVC gel artificial muscles. And considering one step for various practical applications of PVC gel artificial muscles in the future, we proposed the actuation modular constructions with different functions to make the PVC gel artificial muscle as an useful soft actuator in practice. And we gave an example to show the effectiveness of the proposed modules and developed a model of static characteristics of PVC gel artificial muscles based on the experimental data measured by a prototype of mudules.

This paper is organized as follows: The composition and mechanism of PVC gels are introduced in Section 2. The structure and characteristics of PVC gel artificial muscles are described in Section 3, and the actuation modular constructions are proposed in Section 4. The fabricated module unit and experimental results are presented in Section 5. Finally, some discussions and conclusions are addressed in Sections 6 and 7, respectively.

2. Composition and deformation mechanism of PVC gels

2.1. Materials and fabrication of PVC gels

Plasticized PVC gel was made from commercial PVC powder (degree of polymerization = 3200), dibutyl adipate (DBA) plasticizer and tetrahydrofuran (THF) solvent with different weight ratios. The mixed solution was cast in a petri dish and the THF was evaporated at a constant temperature of 20 °C for two days to get a thin film gel, as one kind of soft dielectric elastomer with high transparency (Fig. 1). Stiffness of PVC gel can be adjusted by the weight ratio of PVC to DBA. The lower stiffness was achieved with the higher weight ratio of DBA. In this study, the weight ratio of PVC and DBA was adjusted to 1:4.

2.2. Deformation mechanism of PVC gels

As shown in Fig. 2, when PVC gel is sandwiched between electrodes, creep deformation takes place between the gel and the anode when the electric field is charged. And with the electric field is turned off, the gel returns to its original shape quickly by its own elasticity. A phenomenon that an accumulation of negative charges

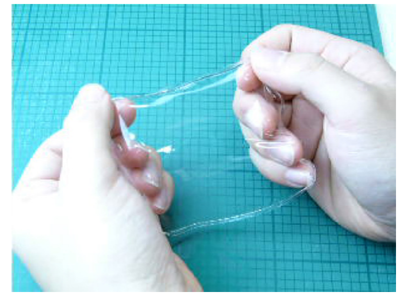

Fig. 1. A plasticized PVC gel film.

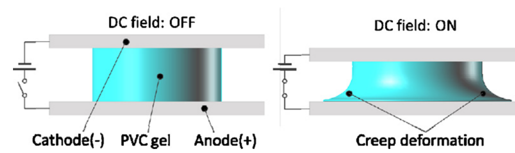

Fig. 2. Deformation mechanism of PVC gel.

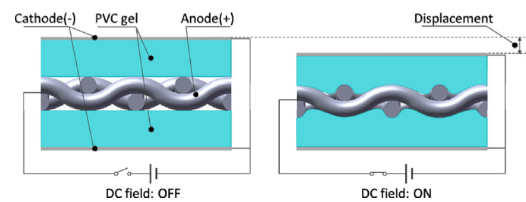

Fig. 3. Cross sectional deformation of a single layer PVC gel artificial muscle.

on the gel surface near the anode was confirmed by space-charge measurement [21]. It was also found that PVC gels were separated to two layers obviously after applied an electrical field, of which the layer near the anode was thinner and softer than other layer due to the transfer of plasticizer to the anode [22]. Therefore, we believe that when an electric field is turned on, electrons are injected from the cathode into the gel, and migrate toward the anode. Due to the Maxwell force, the PVC gel will be deformed asymmetrically and results in creep deformation along the anode. Based on this hypothesis, we simulated the deformation of PVC gel by finite element method (FEM) and got the same creep deformation [23].

3. Structure and properties of PVC gel artificial muscles

3.1. Structure of PVC gel artificial muscles

Considering the unique creep deformation near the anode, we proposed the structure of a contraction and expansion type PVC gel artificial muscle using a meshed electrode as the anode [15]. The PVC gel is sandwiched between a stainless mesh as an anode and a stainless foil as a cathode. Fig. 3 shows the deformation mechanism of the PVC gel artificial muscles. When the DC field is applied, the PVC gel creeps up the anode and moves into the mesh hole, and the actuator shrinks in the direction of thickness. When the DC field is turned off, it returns to its former shape very quickly because of its elasticity. Thus it performs as an expansion and contraction deformation similar to a human muscle. And by stacking in layers we can get a multilayered contraction and expansion type artificial muscle (see Fig. 4).

3.2. Characterizations

Fig. 5 shows an example of fabricated 10-layer multilayered PVC gel artificial muscles, which is sandwiched by two glass slides at