THE POTENTIAL OF DIELECTRIC ELASTOMERS IN UPPER LIMB PROSTHETICS

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INTRODUCTION

The pursuit of a comfortable hand prosthesis offering both life-like appearance and function is thwarted by limitations in current actuator technology. Electroactive polymers, particularly dielectric elastomers (DEs), have been suggested as a possible “artificial muscle” to counter current limitations of typical motors and gearing systems. Theoretically, DEs exhibit properties very similar to those of natural muscle particularly with respect to typical stress and strain, energy and power densities, peak strain rate, response speed, and efficiency [1]. For these reasons, DEs have been advocated for a number of applications including upper limb prosthetics [1-4]. This study explores the feasibility of DEs for this application specifically in terms of device durability.

DE actuators are comprised of a DE, typically silicone or acrylic based, coated on both sides with a compliant electrode. When a voltage potential is applied to the device, Maxwell stress caused by electrostatic attraction induces contraction in the thickness direction and consequently area expansion such that the volume of the incompressible elastomer is conserved. As evident by the governing equation (1), the effective pressure is a function of the applied voltage (V), the thickness of the elastomer film (t), and the dielectric permittivity of the elastomer (ε_r) multiplied by the permittivity of free space (ε_o).

$$P = \varepsilon_o \varepsilon_r (V/t)^2 \qquad (1)$$

The actual performance of a DE actuator depends on the material properties of the elastomer (e.g. the dielectric constant, viscoelasticity, modulus of elasticity), the configuration of the elastomer, and the electric field as applied to the compliant electrodes.

METHODS

DE planar film actuators were fabricated from VHB4910 acrylic foam tape (3M). A 1cm x 1cm square was marked on the unstretched elastomer. The elastomer film was then pre-strained symmetrically such that the area of the marked box was 25 times its original area. The thickness of the pre-strained elastomer was approximately 0.04mm. A small central area was coated on both sides with carbon conductive grease (MGChemicals). Carbon grease leads were painted from this central region to the edge of the film. A high voltage power converter (10A12-P4-C, Ultravolt Inc.) was used to activate the DE actuator. The applied electric field was controlled and monitored in LabView through the data acquisition board (NI PXI-6052E, National Instruments). System inputs included the maximum applied voltage, and the desired voltage step or ramping speed. System outputs included the number of cycles to failure. The response of the actuator was captured via a Sony camera (DFW-X710) at a rate of 5 frames per second. Figure 1 schematically depicts the experimental setup.

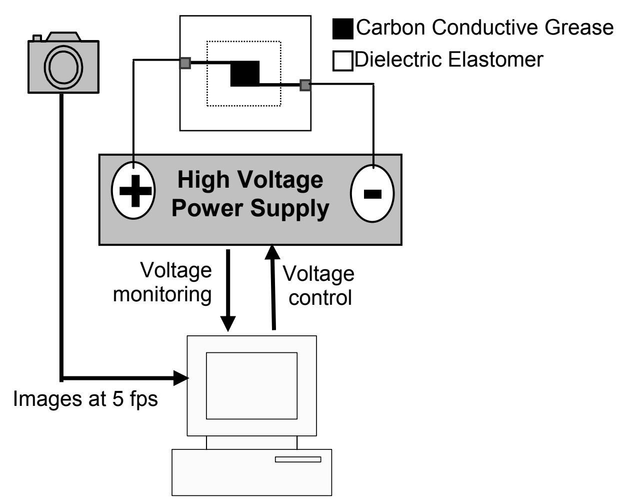


Figure 1: Experimental setup

Using the above experimental setup, DE planar actuators were activated for a range of applied electric fields and frequencies to explore the cycle life of the DE actuators and the modes of failure.

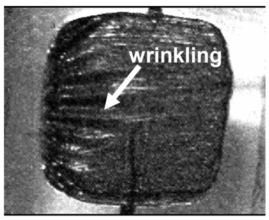
RESULTS

DE actuators are particularly susceptible to three primary failure modes as depicted in Figure 2. Specifically, these include:

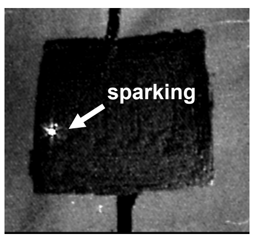
(a) *Pull-in failure* in which the Maxwell pressure exceeds the compressive stress of the film as evident by “wrinkling” of the elastomer material.

(b) *Dielectric breakdown* in which the elastomer fails as an electrical insulator as evident by small holes in the film and/or sparking.

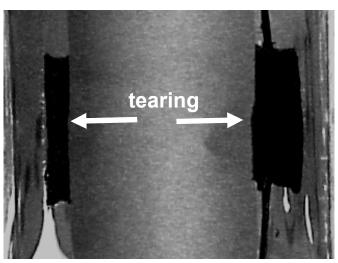
(c) *Material strength failure* as evident by tearing of the elastomer film, particularly at high degrees of stretch.



(a)



(b)



(c)

Figure 2: DE actuator failure modes including (a) pull-in failure, (b) dielectric breakdown and (c) material strength failure

Figure 3 depicts the typical cycle life of an unloaded, unencapsulated DE actuator for a range of applied electric fields and operating frequencies. Cycle life of the DE actuator decreased for higher applied electric fields and for lower frequencies of activation. Within the frequency range typical of upper limb prosthetics (0.1-1.5Hz), the DE actuator sustained less than 1000 cycles before failure occurred. In the majority of cases, the primary failure mode observed was dielectric breakdown.

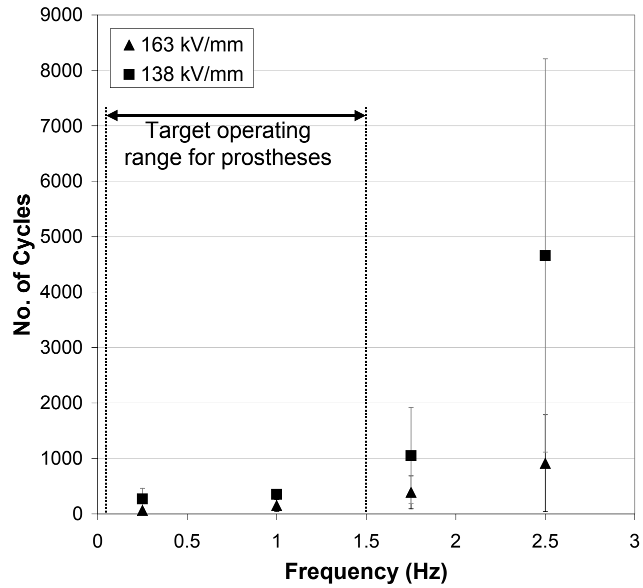


Figure 3: Cycle life of a DE actuator for a range of operating frequencies and applied electric fields.

Deterioration of the compliant electrode was also evident during these experiments as the carbon conductive grease dried and increased in porosity over time. Figure 4 depicts this deterioration.

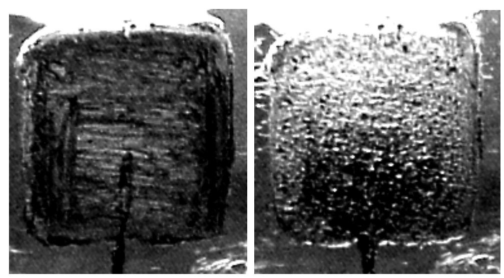


Figure 4. Deterioration of carbon conductive grease over a period of several hours due to evaporation.

DISCUSSION

Of note is the large variability in cycle life, particularly at high frequencies and applied electric fields. In ideal conditions (i.e. no dust particles, voids, inclusions etc.), a fatigue life greater than 500000 cycles was observed, considerably higher than the typical fatigue life of 150 cycles at an applied electric field of 163 kV/mm and a frequency of 1Hz as seen in Figure 3. This is to be expected as dielectric breakdown, which often occurs due to electrical and/or mechanical stress concentrations introduced by contaminants, was found to be the primary mode of failure. This emphasizes the necessity of a clean room for the fabrication of these actuators as well as the need for encapsulation techniques for practical implementation. Pull-in failure and material strength failure were also observed during the course of these experiments. Pull-in failure was most prevalent at low operating frequencies. At high frequencies, viscous forces prevent pull-in failure at a cost of generated stress and strain. Conversely, dielectric breakdown is more prevalent at high frequencies of activation. Although, a higher degree of pre-strain protects against dielectric breakdown to some extent, material strength failure becomes more common, particularly for pre-strains in area greater then 25 times [5]. In agreement with previous studies, the conflicting nature of these failure modes limits the range of frequencies within which reliable operation can be expected [5].

Previous reports on the fatigue life of DE actuators are also highly variable with one study reporting a typical operating life of 1500 cycles [3], while another reported a cycle life of over 4 million [5]. In this study the typical fatigue life ranged between 150 and 5000 cycles depending on the electric field and frequency of activation. It is probable that this variability is a function of the configuration of the actuator, the activation parameters (i.e. the frequency, the applied electric field), and the conditions under which the actuators were manufactured and operated. More research is needed to characterize the fatigue life of DE actuators, particularly when operating under load.

A typical prosthetic hand may undergo over 1200 cycles per day [6]. A recent consumer survey suggests that the frequency of major repairs should be limited to once every 3 years or less [7]. To meet with these design requirements, a suitable actuator for application in upper limb prosthetics should have a cycle life on the order of 10^6, which is evidently much higher than that observed for DE actuators in this study.

CONCLUSIONS

The results of this study suggest that DE actuators do not yet meet with design requirements with respect to device durability. Future design should focus on the development of actuators with a cycle life on the order of 10^6 within the frequency range typical of a prosthetic hand (0.1 – 1 Hz). The importance of a clean facility for the manufacture of DE actuators is emphasized as is the need for encapsulation techniques for practical implementation. Improvements in fundamental properties such as the dielectric constant and viscoelasticity of these materials are recommended in order to reduce the magnitude of electric fields need to generate useful stress and strain with increased reliability.

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