SMART DIELECTRIC ELASTOMERS AND THEIR POTENTIAL FOR BIODEVICES

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Abstract: Dielectric Elastomer (DE) actuators are compliant, ultra light-weight electromechanical devices that can be used as actuators, sensors, and power generators. While a relatively new technology, DE actuators can be produced using biocompatible materials and have already exhibited excellent performance in terms of strain, speed, pressure, specific energy density, and efficiency when compared to conventional actuation technologies and natural muscle. Further research is required in order for promising laboratory results to be translated into real-world applications, particularly in the areas of modelling and control, but the potential for multiple functions to be integrated into a single element is an exciting prospect for flexible smart structures and biodevices.

1 INTRODUCTION

Dielectric Elastomer (DE) actuators are compliant, ultra-light weight electromechanical devices that are emerging as an attractive emerging technology for a range of biomedical applications. They are fabricated from inexpensive biocompatible polymers that have highly tuneable material properties. They are also scale invariant, operate silently and efficiently over a range of speeds, and are capable of being used not only as actuators, but also as sensors and power generators (Kornbluh, 2004).

DE actuators have demonstrated remarkable performance characteristics in terms of active stress, strain, strain rate, energy density and electromechanical efficiency. Their unique properties offer a number of advantages with respect to weight, scalability, and simplicity of design over conventional transducer technologies such as electrostatics, piezoelectrics, electromagnetics, and shape memory alloys (Bar-Cohen, 2004; Kornbluh et al., 2004; Madden et al., 2004). They also compare very favourably with human skeletal muscle (Hunter and Lafontaine, 1992).

Table 1 compares the key performance figures of DE actuators with those of other tranducer technologies. While it is apparent that DEs do not excel in every category, it is clear that their key strength lies in their excellent overall performance.

2 DIELECTRIC ELASTOMER OPERATING PRINCIPLE

2.1 Basic DE Structure

A DE actuator is a compliant capacitor consisting of an incompressible soft polymer membrane dielectric with compliant electrodes applied on both sides.

When used as an actuator, the charge accumulated on the electrodes when a voltage is

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Table 1: Actuator Technology Comparison.

Characteristic	DEA* (Madden et al., 2004)	Skeletal Muscle (Hunter and Lafontaine, 1992)	Piezoelectric (Kornbluh et al., 2004)	Electro-magnetic (Kornbluh et al., 2004)	Electrostatic (Kornbluh et al., 2004)	Shape Memory Alloy (Hunter and Lafontaine, 1992)
Stress (MPa)	7.7	0.35	131	0.1	0.03	200
Strain (%)	380	>40	1.7	50	50	5
Relative Strain Rate	Medium	Medium	Fast	Fast	Fast	Slow
Energy Density (kJ/m^3)	34,000	40	0.13	0.003	0.003	10,000
Efficiency (%)	60-80	35	>90	>90	>90	2-3

**figures taken for a VHB dielectric membrane (see section 2.4). Stress, strain, strain rate and energy density figures vary depending on membrane material.*

applied gives rise to electrostatic forces that generate deformation in the DE. The opposite charges act to draw the positive and negative electrodes together while the like charges on each electrode act to expand the area of the electrode. When the charge is removed, the elastic energy stored in the dielectric returns it to its original shape (Fig. 1). The linear motion produced by this electromechanical response can be used for actuation purposes.

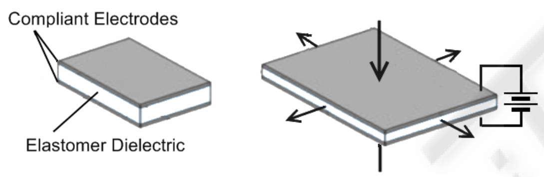

Figure 1: Deactivated (left) and activated (right) states of a simple DE actuator.

2.2 Pressure Capabilities

DEs are driven by electric fields. The pressure that can be generated in a DE is widely accepted to be defined by the following equation (Kofod, 2001):

$$P = \varepsilon_r \varepsilon_0 (V/d)^2 \quad (1)$$

Where P is the electrostatic Maxwell pressure, ε_r is the relative permittivity of the dielectric material, ε_0 is the permittivity of free space (ε_0 = 8.854 x 10^{-12} F/m), V is the voltage and d is the thickness of the dielectric membrane. This is twice the pressure generated by a rigid plate electrostatic device due to the addition of the area expansion to thickness compression upon activation. The level of deformation achieved at any given electric field is dependent on the combined stiffness of the polymer dielectric and electrode materials. The peak field that can be applied is limited by the dielectric breakdown strength of the DE membrane.

2.3 Power Generation

The phase difference between the electrical and mechanical stimulus applied to a DE determines whether it acts as an actuator or a generator. When the mechanical deformation leads the electrical excitation the DE will generate electrical power.

The electrical charge stored on a DE device (Q), the capacitance of the device (C), and the voltage difference between the electrodes (V) are related by the following equation:

$$Q = CV \quad (2)$$

And the electrical energy, $e_{electrical}$, stored in the DE is defined by:

$$e_{electrical} = ½CV^2 \quad (3)$$

Assuming, for simplicity, charge is kept constant (i.e. the DE is electrically isolated) work done by an external force acting to increase the separation between the electrodes against the electrostatic forces is converted to electrical energy and stored in the DE. This is because the capacitance of the device will decrease as the electrode separation increases and the electrode area decreases, thereby causing the voltage to increase. As the electrical energy stored in the DE is related to the voltage squared a net increase in the electrical energy is achieved; energy that can then be used to power other electrical devices.

2.4 Materials

Silicone and polyacrylate polymers have garnered much attention in the field of DE research due to their highly elastomeric nature and high breakdown strengths. Silicones typically exhibit low viscous losses and some can operate in temperatures ranging from -100ºC to 260ºC, making them well suited to dynamic, high speed applications in harsh environments. Their availability in monomer form (e.g. NuSil CF19-2186, Dow Corning Sylgard 184) enables the tuning of material properties (e.g. stiffness, elongation at break, and geometry) and facilitates the creation of silicone based composites through the incorporation of additional material prior to polymerization.

3M's commercially available VHB4905 double-sided polyacrylate tape has a high degree of viscoelasticity, but at low speeds is capable of the highest reported active displacement (380%) and energy density (3.4MJ/m^3) of any DE polymer. Fig. 2 illustrates a simple, easily fabricated DE made from a prestrained, partially electroded VHB membrane at rest (Fig. 2 left), and activated with an electric field of 252V/µm (Fig. 2 right). The electroded area expands by 125% at this field.

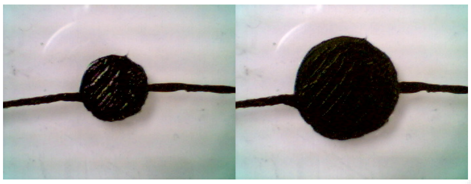

Figure 2: A VHB DE actuator at rest (left), and actuated with an electric field of 252V/µm (right).

While silicone and VHB4905 are popular choices for DE materials, a wide variety of other materials can be used and which is appropriate is highly dependent on the application. It is convenient therefore to define a relationship between the key properties of a material that results in an index value that can then be used to compare materials. The DE "Figure of Merit" relates a material's dielectric constant (ε_r), the breakdown strength (E_b), and the Young's modulus (Y), using the following formula (Sommer-Larsen and Larsen, 2004):

$$\textit{Figure of Merit.} = 3\varepsilon_r E_b^2/Y \qquad (4)$$

It is important to note that typical polymers with suitably low stiffness and high dielectric breakdown strengths have low dielectric constants (typically <5). Substituting this value into Equation (1) it is clear that high electric fields (~50-150V/µm) are required to generate enough pressure to deform a DE more than a few percent.

3 DIELECTRIC ELASTOMERS IN BIODEVICES

DEs acting either in an actuator, sensor, or power generator mode show great promise for a number of biomedical applications. The key strength of DE technology however is the ability for a single lightweight device to operate in multiple modes., thereby reducing device volume, complexity, and component count. This ability, coupled with their biocompatibility, opens up a number of possibilities not only for implantable or prosthetic devices, but also for tools to assist both surgeons and patients during operative and post-operative procedures.

3.1 Artificial Muscles

With performance metrics that exceed that of natural muscle, DEs show great promise as artificial muscles. Like natural muscle, DEs can be controlled in terms of position, speed and stiffness. Controlling the charge stored on a DE results in stable position control. By controlling the rate of charging the speed of actuation can be controlled. Similarly, utilising the geometry of the device and the level of charge stored on the DE, it is possible to determine the electroactive forces, which in conjunction with knowledge of the mechanical behaviour of the DE itself, can be used to control stiffness.

To achieve accurate control in terms of any these parameters it is necessary to obtain feedback data from which a physical aspect of the device can be inferred. Conventionally an external sensor is required to obtain this data but applying such an approach to DEs adds to the complexity, volume, mass, cost and power requirements of the device. Instead, self-sensing using inherent characteristics of the DE eliminates the constraints an external sensor implies and enables the creation of entirely compliant smart devices. Such devices, with an overall texture and consistency comparable to natural muscle, will have a natural look and feel; a factor that has been found to have a significant impact on patient acceptance of such devices (Popovic et al., 2002).

DE device properties such as electrode resistance (O'Brien et al., 2007), capacitance (Toth and Goldenberg, 2002), and electrical current (Bauer and Paajanen, 2006) have all been used to infer the physical state of a DE actuator subject to specific operating conditions. As self-sensing develops further and the richness of the feedback information increases, so too will the accuracy with which DE devices can be made to respond to a control signal.

In the case of artificial muscles this control signal should be derived from human nerve signals, and already basic proportional control of a DE device has been achieved with the magnitude of a variety of electrophysiological signals as the input signal (Carpi et al., 2006). Further development of not only artificial muscles but also of the human-device interface, including enabling bi-directional information flow between artificial muscle and human, could eventually lead to a true artificial muscle capable of being fully integrated into the human body.

3.2 Bio-sensors

Self-sensing and the ability of a DE device to convert mechanical energy into electrical energy enable DEs to be used in the monitoring of various biological functions. As discussed previously, various electrical characteristics of a DE will change when the DE is deformed from its rest state. These characteristic features have been used to demonstrate simple, highly compliant, low voltage strain and pressure sensors (Kornbluh, 2004).

The highly tuneable nature of the mechanical impedance and elongation of DE sensors can be exploited to enable strains of several hundred percent to be monitored without adding significant mechanical resistance to the movement itself. This would make them suitable for devices that monitor activities such as respiration, muscle movement, or limb articulation. For monitoring muscle movement in particular, feedback data from lightweight conformable sensors synchronised with relevant electrophysiological signals could be used to analyse the dynamic stress-strain-time behaviour of muscles. Biocompatible DE sensors could also potentially be used to monitor stresses/strains in vivo, whether this is in conjunction with another implanted device or simply to generate data that a sensor external to the body would be incapable of providing.

3.3 Surgical Tools

Compliant smart devices offer an ideal solution for procedures where "soft" manipulation is appropriate. In invasive surgeries such as endoscopic procedures, DE devices could fulfil multiple roles: they could operate as a multiple-degree-of-freedom actuator for directing/propelling sensory devices or fibre-optic cables whilst also providing a compliant interface between the patient and the device that serves to protect both.

Lightweight accurate sensors and actuators could be incorporated into portable glove-type devices with built in force feedback for surgical training or performing remote surgery. Already a prototype device has been devised that has been used to provide force feedback for a virtual reality simulation of grasping an object (Fig. 3)(Zhang et al., 2006). Low device mass and volume would ensure the device is portable and able to be used for extended periods without user fatigue.

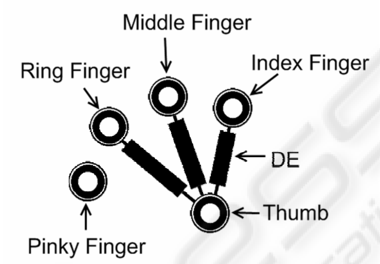

Figure 3: Lightweight compliant actuators for virtual reality feedback of grasping related hand gestures.

Furthermore, a smart device with the dexterity and flexibility of a human hand could be used as the manipulator in remote surgical operations. With feedback from pressure sensors embedded in the manipulator used as a control input for a DE force feedback device a complete DE solution could be created. An inherently muscle like actuator combined with realistic haptic feedback would result in an apparatus with an intuitive feel that could offer advantages in terms of flexibility and patient safety in comparison to heavy and rigid surgical robots driven by electromagnetics or hydraulics.

Other features of DE actuators such as their low current requirements and non-magnetic nature also provide advantages with regard to surgical tools. A prototype serpentine, DE based manipulator for needle positioning in close proximity to an MRI machine has been developed (Fig. 4)(Plante, 2006). Similar devices incorporating ferromagnetic materials or that use high currents would degrade the quality of the MRI scan.

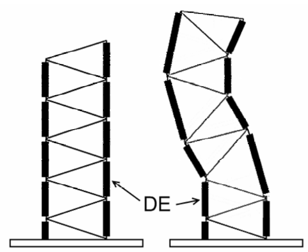

Figure 4: A conceptual design for a serpentine needle positioning device.

In the longer term there is the possibility of using nanoscale DE actuators in biology to stimulate the growth, migration and differentiation of stem cells. Mechanically deforming these cells can expose or activate different functional sites on their proteins, thereby affecting the biochemical reactions and intracellular pathways that ultimately regulate cell development (Vogel, 2006). Such a process may even create new opportunities for the treatment of diseases associated with mechanical cell dysfunction such as cancer, cardiac hypertrophy, genetic malformation, and immune disorders.

3.4 Power Generators

DEs are capable of operating as highly efficient generators. With appropriate driving circuitry DEs can be used to harvest energy from vibrations and motions inherently present in the environment. Already a heel-strike generator embedded in the heel of a boot (Fig. 5), is capable of generating up to 1W by using the downwards pressure of each footfall to stretch a DE membrane (Kornbluh, 2004).

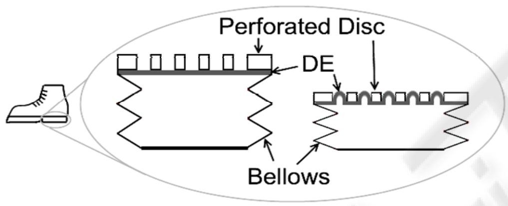

Figure 5: Heel strike generator capable of generating up to 1W.

The implication for biodevices is that lightweight power generators could be used to trickle charge or perhaps even directly power other low power devices on or within the body. A DE based prosthetic device subjected to intermittent usage patterns could make use of a DE generator combined with an energy storage device such that it would need recharging less frequently, if at all. Alternatively the energy storage device (e.g. battery pack) could be downsized.

The conformable and compact nature of DE generators means initially they could be strategically integrated into fabrics so as to take advantage of naturally occurring stretching as a result of human ambulation. In the future these generators may eventually be able to be implanted within the body itself, enabling a completely encapsulated, low maintenance power supply. Such a generator could be used to power wireless implantable sensors.

4 FUTURE DIRECTIONS FOR DIELECTRIC ELASTOMERS

As a smart material, a single DE element offers a multi-functional platform from which devices suited to a variety of applications can be developed. There are a number of hurdles yet to be overcome however and at the Biomimetics Laboratory we are actively investigating key issues that are currently limiting the practical implementation of DEs in biodevices.

DEs exhibit complex non-linear and hysteretic behaviours in both the mechanical and electrical domains that make modelling and precision control of these devices difficult. Current models can accurately predict behaviours based on specific parameters (e.g. the instantaneous uniaxial stress-strain response of a material subjected to a constant strain rate deformation), but have such a narrow scope that their accuracy degrades significantly if one or more of the parameters change (e.g. strain rate, mode of deformation, external loads, temperature). The ability to accurately describe the transient response of a DE device is especially limited. Improved modelling, particularly with respect to the electrical subsystem will greatly facilitate the development of more robust devices.

Improved modelling and self-sensing techniques will result in an increased understanding of the behaviour of a DE system that will greatly facilitate optimisation in terms of control, feedback, and device efficiency. In artificial muscles especially, owing to the desirability of ultra-thin dielectrics, devices will consist of large arrays of micro/nanoscale DE actuators in order to amplify force and displacement. It will be of critical importance therefore to develop a balance between the volume of feedback information and the control methodology such that the computational requirements are not prohibitively high.

The use of high electric fields (~50-150V/µm) in DEs also presents an issue given that current prototype membrane thicknesses typically range from 10µm to 50µm. While this is primarily a limitation of current fabrication techniques it nevertheless necessitates operating voltages in the kilovolt range. The impact of these high electric fields in proximity to the human body, including the efficacy of a soft polymer insulative layer encapsulating the device is being investigated.

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