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Novel Electroactive Polymer Actuator Materials

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Conducting Polymers and Carbon Nanotubes as Electromechanical Actuators and Strain Sensors

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ABSTRACT

Electromechanical actuators are being investigated for a wide range of applications in medical, electronics and industrial areas. There is a wide range of electromechanical actuator materials but both conducting polymers and carbon nanotubes are attractive because of their low voltage operation. For practical applications, the strain generated by the actuator must be known under different applied loads. Unfortunately, there is very little information about the performance of polymer actuators at different loads: most studies report the strain generated at zero, or near zero, loads. We have measured the isotonic strain for both polypyrrole films and carbon nanotube sheets at increasing applied loads and found a linear change in strain with increasing stress. Analysis of the deformation induced during electrochemical charging and discharging of the materials shows that a change in strain with increasing load can be attributed to a change in the elastic modulus of the material during charging (doping). Thus, the polypyrrole modulus changes significantly between the oxidized (high modulus) and reduced (low modulus) states. The difference in modulus can be as much as 100% for these materials, which correlates with the rapid decrease in actuator strain with increasing applied stress.

Another aspect of the practical use of actuator materials is their control. We have developed simple strain sensors based on conducting polymer – coated stretch fabrics. Calibration of these materials shows a wide linear range and high gauge factor. Combining fabric strain gauges with polymer actuators is a convenient means for providing feedback control to the actuating element.

INTRODUCTION

Much of the inspiration for actuator research comes from nature, where muscles (skeletal and smooth) and other systems generate a profoundly diverse range of mechanical movement: animals that walk/run/climb, birds and insects that fly, pumping systems, the rotary "motor" of the flagella and so on. To date, it has not been possible to match the performance of natural muscles (eg. skeletal muscle) with synthetic actuators, or "artificial muscles". The synthetic systems have the great advantage in being electrically driven and so have a convenient and familiar power source. However in comparison with skeletal muscle, the synthetic systems usually fall short either in terms of strain generated or strain rate achievable (Fig. 1). In nature, stress generation is compromised for speed and strain highlighting the importance of the latter to animal-like mobility.

The performance requirements needed by synthetic actuators are obviously dictated by the particular application. In some instances it is desirable to use low voltages for safety and convenience in terms of smaller, less expensive power supplies. In such cases, the candidate actuator materials (of those known to date) are conducting polymers, carbon nanotubes, hydrogel

polymers and shape memory alloys. The latter are the most well-developed of these low-voltage actuators, however they operate through a thermal cycle (resistive heating causes actuation) which can be undesirable in some applications. Hydrogel polymers suffer mainly from their slowness (although microgels have been shown to operate somewhat faster [1]) and their low stress generation. Conducting polymers have been extensively studied and been shown to generate useful strains (around 3%) and stresses (up to 10 MPa). The strain rate of conducting polymers is lower than skeletal muscle, although many researchers claim that this can be increased by building micro-actuators [2]. Carbon nanotubes have only recently been discovered as actuators [3] and produce reasonable strain (0.7%) and stress (25 MPa) at present. However, nanotubes offer much greater stress generation capabilities (perhaps up to several hundred MPa) because of the inherent stiffness of the nanotubes (640 GPa [4]).

In our laboratories, we have been improving the basic actuator performance (stress, strain, strain-rate) of conducting polymer and carbon nanotubes for a range of applications. In this paper, we describe these results with reference to an actuating glove designed to move the human hand. Although such a glove would have applicability in virtual reality and as prosthetic devices, we were purely interested in design concepts. As such, the speed of response was not considered important at this stage (and in some applications, a hand that can slowly open and close is considered useful, for example, in medical rehabilitations).

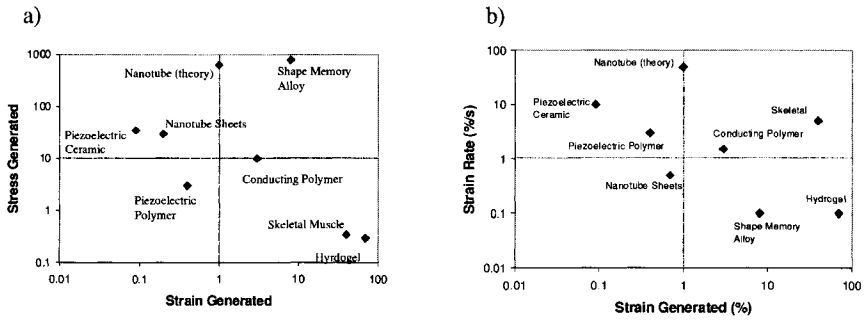

Figure 1 Approximate performance characteristics reported for various actuator materials.

The first stage of the project involved a biomechanical analysis of the movement of the human hand (Fig. 2). Table 1 summarises the performance data for full movement of all the finger joints with definitions given in Figure 2. Comparing these data with those presented in Figure 1, it appears as though the conducting polymer actuators can match the full performance of some joints and partially match the performance of others (with actuator lengths of 30cm and cross-sectional area of ~ 0.4 mm^2. However, the data given in Figure 1a) are taken from separate isometric (to give maximum stress) and isotonic (to give maximum strain when near-zero loads are used) experiments. Little is known about the effect of increasing load on the strain response of conducting polymer actuators. Two recent reports suggest that either the strain is unchanged [5] or decreases sharply [6], while it is well accepted that skeletal muscle shows much reduced strain as the load applied increases [7]. Considering the lack of design data, we instigated a study of the effect of applied loads on the strain generated and strain rate of polypyrrole and carbon nanotube actuators.

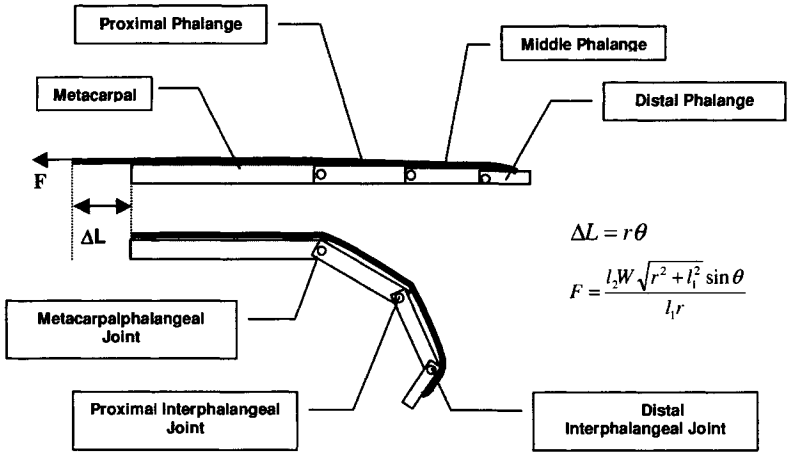

Figure 2 Approximate 2-dimensional biomechanical analysis of finger flexion in the human hand: F is the muscle force (l_2 = distance from knuckle to center of mass of joint; W = weight of joint; r= radius of rotation around knucle; l_1=distance from knuckle to tendon attachment point; θ= angle of rotation of joint) and ΔL is the excursion of the tendon required to straighten the finger.

Table 1 Muscle force and tendon excursion required to cause bending of the fingers on an adult human hand.

Finger	Joint	Tendon Movement Required for full flexion (mm)	Force Required for full flexion (N)
Digit 2 (Index)	Proximal Phalange	15.7	2.1
	Middle Phalange	13.1	1.4
	Distal Phalange	7.8	0.5
Digit 3 (Middle)	Proximal Phalange	15.7	2.9
	Middle Phalange	13.1	1.4
	Distal Phalange	7.8	0.6
Digit 4 (Ring)	Proximal Phalange	15.7	2.8
	Middle Phalange	13.1	1.2
	Distal Phalange	7.8	0.6
Digit 5 (Little)	Proximal Phalange	15.7	1.6
	Middle Phalange	13.1	0.8
	Distal Phalange	7.8	0.4

Finally, we are also interested in control systems for mechanical actuators. Fabric strain gauges are interesting devices that may be useful in providing direct feedback control to actuators. The operation of fabric strain gauges are briefly described in this paper.

EXPERIMENTAL

Polypyrrole films and fibres were prepared by electropolymerisation using platinum working electrodes in an electrolyte containing 0.06M pyrrole, 0.05M tetrabutylammonium hexafluorophosphate ($TBA.PF_6$) in propylene carbonate. Polymer was electrodeposited on the electrode using galvanostatic conditions (current density of $0.15mA/cm^2$) and at -28^oC. Carbon nanotube sheets were prepared by filtering as-received nanotube suspensions (Carbon Nanotechnologies Inc) to give entangled mats of nanotube ropes consisting of single wall nanotubes with an average diameter of 1.4nm. The sheets were thoroughly washed and then further purified by slow heating in argon to 1050^oC. Coated fabrics for strain gauge applications were prepared by first soaking the fabric (eg nylon/polyurethane) in a solution containg ferric chloride oxidant and then exposing the soaked fabric to pyrrole vapour.

Actuator testing was conducted by attaching samples to one side of a balance beam and fixing at the bottom of a container for electrolyte. The tension applied to the sample could be adjusted by changing the weights on either side of the balance beam. The test apparatus is illustrated in Figure 3. Various testing conditions were used, but in most cases the electrolyte was 0.25M $TBA.PF_6$ in propylene carbonate. Fabrics were tested by stretching in an Instron testing machine with the resistance change in the fabric measured using a Wheatstone Bridge circuit.

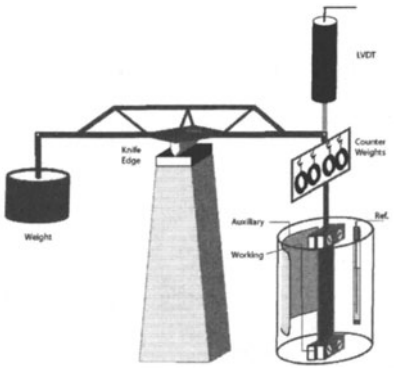

Figure 3 Test apparatus for isotonic (constant load) measurement of actuator strain: the linear variable distance transducer (LVDT) provides direct measurement of the actuator movement.

RESULTS

Polypyrrole Strain Under Load

For practicality it is beneficial to operate actuators in a two-electrode arrangement using a simple DC power supply. Figure 4a) shows how the strain (at constant stress) changes with increasing applied potential between a polypyrrole film and a stainless steel counter electrode.

The actuation strain increases with increasing voltage, but the maximum voltage (in this case 5V) is limited by the stability of the polymer. In Figure 4b) the inherent slowness of the actuation process in polypyrrole (dominated by ion-diffusion kinetics) is illustrated by the rapid decrease in actuation strain as the voltage scan rate is increased.

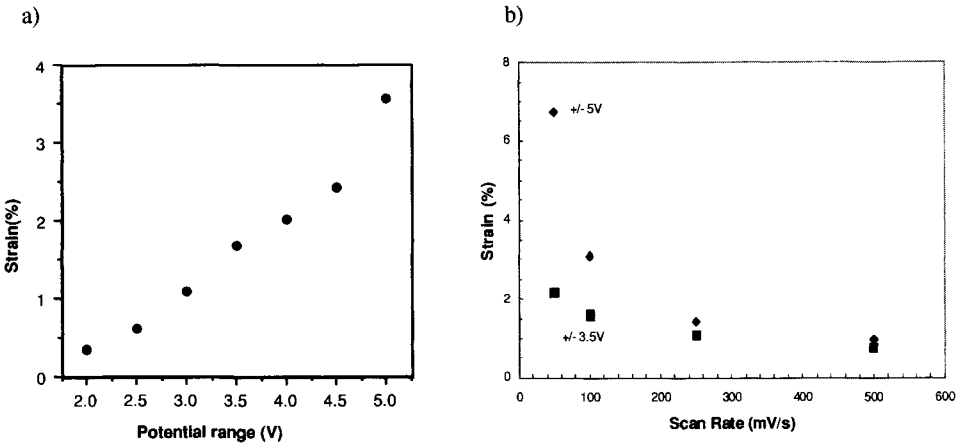

Figure 4 Isotonic strain (near-zero load) for polypyrrole films actuated under different electrical stimuli: a) applied DC potential between PPy and stainless steel counter electrode increased from 2V to 5V; b) scan rate between two different potential limits increased from 100 mV/s to 500 mV/s.

The effect of increasing applied load on the actuation strain under two different stimulation conditions is shown in Figure 5. In both cases the strain decreases approximately linearly as the load increases, although the rate of decrease is more pronounced when a wider voltage window (+/- 5V) was used.

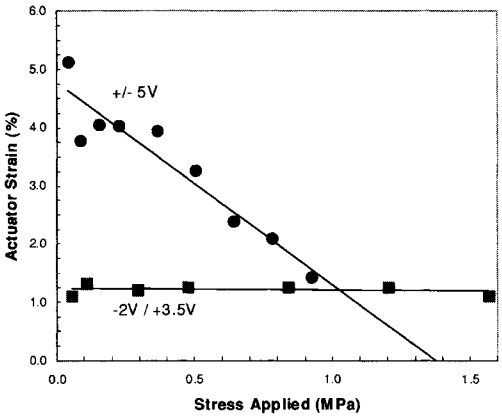

Figure 5 Isotonic actuator strain for polypyrrole films decreases as the applied stress increases.

Carbon Nanotubes Strain Under Load

Carbon nanotube sheets produce actuator strains approaching 1% in the axial direction of the sheet when the applied electrochemical potential is decreased to around –2V (vs. SCE). As shown in Figure 6, the strain generated from nanotube sheets increases roughly parabolically in both directions from the minimum strain (which occurs at approximately +0.5V). In contrast, the behaviour of conducting polymer actuators with respect to applied potential is more complex and depends on the mobility of the dopant anion [8]. The behaviour of the PPy/PF_6 films is also shown in Figure 6 and contrasts with carbon nanotubes in that a contraction occurs in the PPy at negative potentials, while the nanotube sheets expand at the negative potientials.

In Figure 7, the actuator strain from carbon nanotube sheets is seen to increase with increasing applied loads under pulse potential conditions.

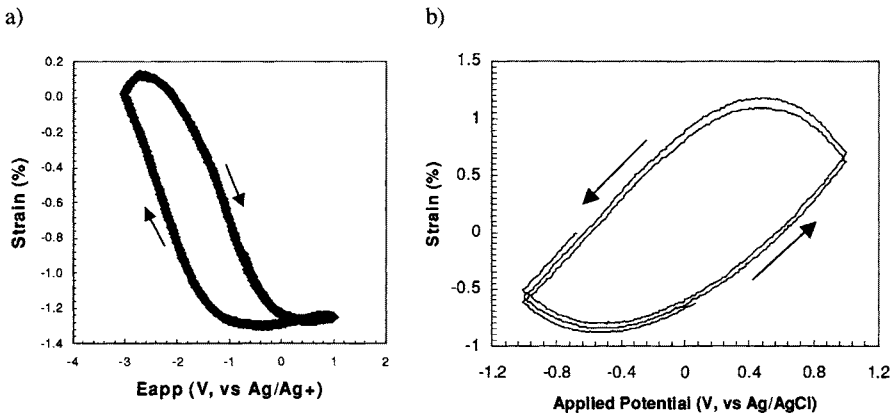

Figure 6 Actuator strain as a function of applied potential for a) carbon nanotube sheets and b) polypyrrole film. In both cases the potential was applied as a triangular waveform at 50 mV/s.