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Conducting Polymers Electromechanical Actuators and Strain Sensors

Geoffrey M. Spinks, Gordon G. Wallace, Lu Liu, Dezhi Zhou*

Intelligent Polymer Research Institute, University of Wollongong, NSW 2522, Australia
E-mail: gspinks@uow.edu.au

Summary. Electromechanical actuators are being investigated for a wide range of applications in medical, electronics and industrial areas. One attractive application is to incorporate conducting polymer fibre actuators into fabrics for use in prosthetic applications. In this paper, the design of polypyrrole fibre actuators for use in a glove to open and close the human hand (for assisting those with paralysis or hand injuries) is described. The key requirements for this application are the simultaneous generation of 16 mm of contractile movement and 2.9 N of force. Although not critical in the first prototypes, eventually it will also be necessary to produce a rate of movement of around 10 mm sec^{-1}. The effect of the geometry of polypyrrole actuators is examined in this paper and it is shown that a tubular geometry is superior to conventional flat films. Another aspect of the practical use of actuator materials is their control. Fabric strain gauges with polymer actuators is a convenient means for providing feedback control to the actuating element. The fabric strain gauges ideally articulate with fibre actuators to give both the actuating and sensing function in the same fabric structure.

Introduction

In this paper we describe two essential features needed for practical movement systems using polymer actuators: the actuator materials, based on polypyrrole (PPy); and a displacement sensor based on a conducting stretch-fabric material. The two elements work together in as much as the actuators produce motion and the fabric provides a feedback system to control the motion. We focus here on an actuating glove that can be used to open and close the human hand. This kind of device would be greatly beneficial to persons with paralysis, hand injuries or when recovering from hand surgery. A simple biomechanical analysis of the muscle displacement and force needed to lift the human fingers through their full motion (up to 100^{o}) shows that the "artificial muscle" needs to simultaneously produce a contraction of 16mm and 2.9 N force, Table 1 [1]. Ideally, this motion should be completed within ~1-2 seconds (giving a displacement rate of ~10mm sec^{-1}) although in first prototypes a much slower rate of

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movement is acceptable.

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

Finger	Joint	Muscle Contraction 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

Conducting polymers have been extensively studied as actuators and been shown to generate useful strains (around 3%) and stresses (up to 10 MPa) [2]. The strain rate of conducting polymers has been reported to be as high as 3.2% sec^{-1} [3]. Using these performance characteristics as design parameters, it is possible to design actuators for the glove application: length = 533mm; cross-sectional area = 0.29 mm^2 (corresponding to a film 5 mm wide and 58 μm thick). The problem with this design is that the available length (from the knuckle to the elbow) is only ~ 350mm in an adult male. This limitation means that the strain needed from the artificial muscle should be at least 4.5%.

Analysis of the data from the literature reveals that the reported stress and strains from polypyrrole materials are not for simultaneous conditions. That is, the strains are usually reported for near-zero loads and the stresses are for isometric (zero strain) conditions. We have recently shown [4] that the strain generated by PPy actuators decreases when the applied isotonic stress increases. Although it is possible to generate 5% strains, this only occurs at stress levels < 0.1 MPa. To provide full movement for the human fingers, a parallel stack of 100 films (5mm x 350mm x 58 μm) would be required. Obviously, it is a considerable technical challenge to build such a device.

In this paper we report improvements to PPy actuator performance by adopting a hollow fibre (tube) geometry. The method of preparation of the tubes is described as is the actuator performance in terms of strain under load and strain rate.

Finally, we are also interested in control systems for mechanical actuators. Fabric strain gauges [5] are interesting devices that may be useful in providing direct feedback control to actuators. The operation of fabric strain gauges is also 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. The polymer was electrodeposited on the electrode using galvanostatic conditions (current density of $0.15 mA/cm^2$) and at $-28^{\circ}C$. The hollow fibres were prepared by electrodeposition on Pt wire (125-250 μm in diameter) to give a coating thickness of ~50 μm. The Pt wire was removed after the electrodeposition to give a free-standing hollow tube of PPy. Flat films prepared in the same fashion were thicker, in the range 120-140 μm. Mechanical and electrical properties of the film and tube samples are given in Table 2.

Table 2 Basic electrical and mechanical properties of tube and film samples of PPy/PF_6.

	Tube(1)	**Flat Film**(2)
Conductivity (Scm^{-1})	170 Scm^{-1}	85
Tensile strength	19.6 ~ 27.3	6.0
Elongation to break	15.4 ~ 19.0	8.5
Electrolytic efficiency	10%	5.0%

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 1. Various testing conditions were used, but in most cases the electrolyte was 0.25M $TBA.PF_6$ in propylene carbonate. For practicality it is beneficial to operate actuators in a two-electrode arrangement using a simple DC power supply.

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. Fabrics were tested by stretching in an Instron testing machine with the resistance change in the fabric measured using a Wheatstone Bridge circuit.

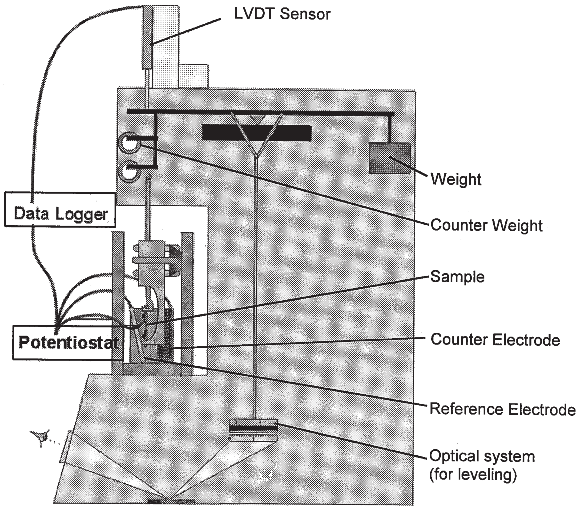

Figure 1 Balance beam apparatus for isotonic actuator measurements: the actuator displacement is determined by the linear variable distance transducer (sensor) for fixed isotonic loads. The load can be varied by removing counter-weights.

Results

Actuators

Figure 2 shows how the strain (at constant stress) changes with increasing applied potential for polypyrrole films and tubes. The actuation strain increases with increasing voltage, but the maximum voltage is limited by the stability of the polymer. For the tube geometry the maximum voltage range was +/- 3.5 V, while for the film a wider range of +/-5V could be applied. The higher conductivity of the tube accounts for its lower voltage stability range, since the electrochemical potential achieved at the polymer working electrode (E) depends upon the polymer resistance:

$$E = Eapp - iR_T$$
$$R_T = R_s + R_p$$

[R_T = total resistance, R_s = solution resistance, R_p = polymer resistance]

where Eapp is the potential applied by the external power source and *i* is the current. Since the tube has a lower resistance (R_p) than the film, a smaller external voltage (E_{app}) is needed to ensure that the polymer reaches the breakdown potential (E).

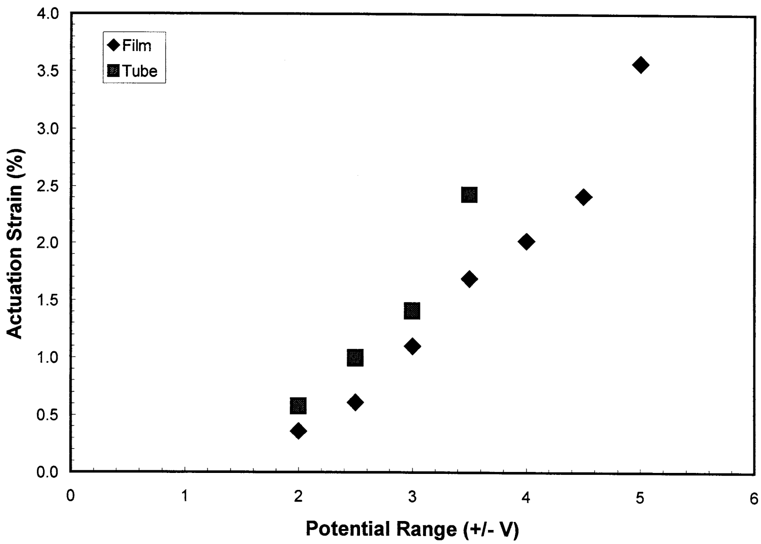

Figure 2 Isotonic actuator strain measured for polypyrrole film and tube geometries for different applied potential limits using a voltage scan rate of 50 mV/s (stress = 0.05 MPa for the film and 0.72 MPa for the tube).

In Figure 3 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. The kinetics appear to be similar for the two geometries, with the tube slightly less affected by increasing scan rates compared with the film. Again, this observation can be explained by the higher conductivity of the tube compared with the film.

The effect of increasing applied load on the actuation strain for the two different geometries is shown in Figure 4. At all loads the tube produces substantially higher strains due to its higher electrical conductivity, so that the polymer potential (E) for the tube is higher than for the film. The tube can also be tested to higher isotonic stress levels than the film. Mechanical failure limits the stress that can be applied and the higher tensile strength of the tubes compared with the films means that actuation can be measured up to 3.5 MPa for the tubes compared to <1.5 MPa for the films.

Finally, the strain rate achieved by the tubes is significantly higher than that produced by the films under the same stimulus conditions. As shown in Figure 4, the tubes produce a strain rate in the order of 0.05 % sec^{-1} compared to the films with 0.01% sec^{-1}.

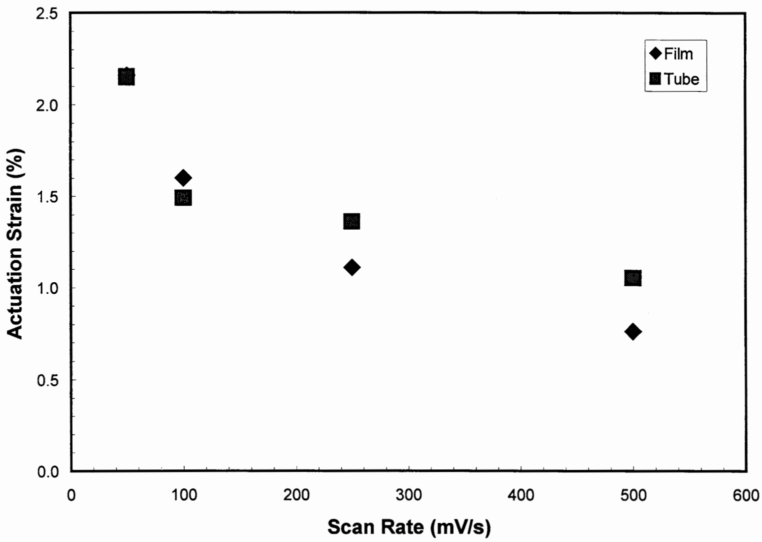

Figure 3 Isotonic actuator strain for $PPyPF_6$ film and tube samples tested at different voltage scan rates between the limits of +/- 3.5V (stress = 0.10 MPa for the film and 1.0 MPa for the tube).

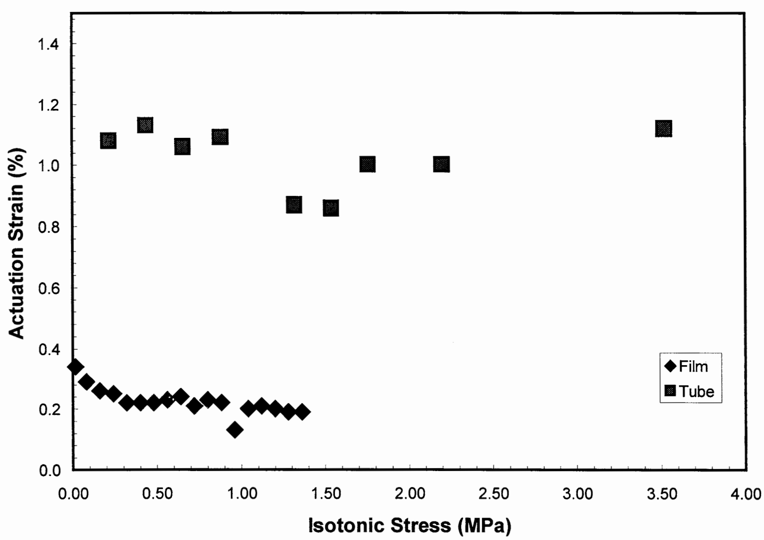

Figure 4 Actuator strain obtained isotonically at different applied stress levels for $PPyPF_6$ films and fibres. A cyclic voltage signal of +/-2.5V at 50 mV/s was used in both cases.

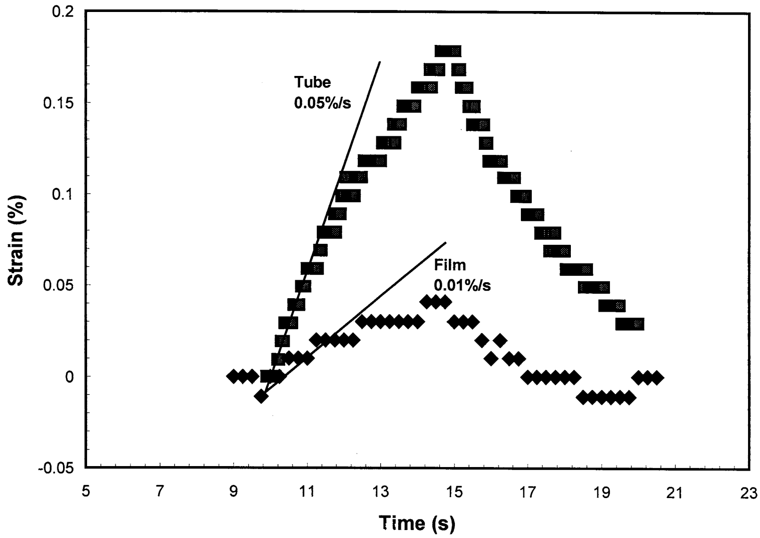

Figure 5 isotonic strains induced by a square wave voltage cycle at +/-1.5V at 0.1 Hz.

Fabric Strain Gauges

Polypyrrole coated stretch fabrics have been shown to act as useful strain gauges having a wide dynamic range [5]. The resistivity of the fabric changes dramatically when the fabric is stretched (Figure 6). The direction of stretch produces different strain gauge response; with a more linear change in resistance occurring when stretching is conducted in the course direction. The gauge factor of these fabrics is approximately 2, which is similar to conventional strain gauges. However, the dynamic range is up to 100%, which is an order of magnitude greater than conventional strain gauges. Examination of the deformation process (Figure 7) for stretch fabrics shows that the weave structure opens up as stress is applied. The opening of the weave changes the number of interfibre contacts and this is most probably the reason for the change in resistance with stretch.

The combination of strain gauge functionality with wearable fabrics opens up the possibility of manufacturing garments for monitoring human movement. In Figure 8 a prototype sensor glove is shown. Coated fabric strips are sewn across the proximal interphalangeal joint in this example and bending of the finger causes a measurable change in fabric resistance.

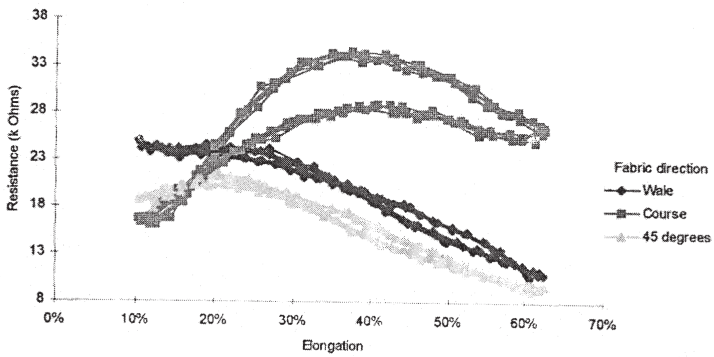

Figure 6 Change in resistance of polypyrrole coated fabric as a function of elongation when stretched in different directions.

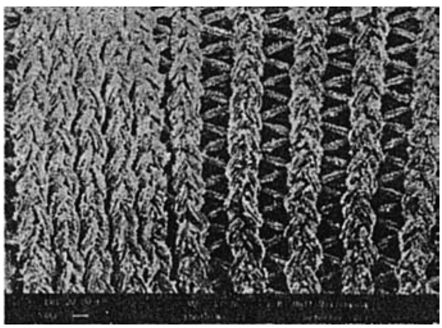

Figure 7 Scanning electron micrograph of coated fabric with the right side under tension in the course direction.

Figure 8 Prototype sensor glove with stretch fabric strain gauges attached to the metacarpo-phalangeal joints of each finger.

Conclusions

This study has focused primarily on the effect of geometry of PPy actuators on the (isotonic) actuator strain produced. The strain increased for hollow tubes compared with flat films, as did the strain rate. The increase in performance is attributed to the higher electrical conductivity of the tubes. Strains were obtained at higher isotonic stresses in the tubes compared with the films and this was attributed to the higher tensile strength of the former. Despite these performance improvements, the tube actuators still do not meet the requirements necessary to produce full movement of human fingers. We are now working on improving the electrical connection to the tube geometry in order to address the current limitations.

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