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Polypyrrole artificial muscles: a new rhombic element. Construction and electrochemomechanical characterization

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Abstract

A novel rhombus-shaped electrochemomechanical unit constituted by 4 polypyrrole bilayer (conducting polymer/tape) muscles and two plastic hinges, able to transform reversible angular movements from the basic bilayers into longitudinal movements, has been successfully constructed and electrochemically characterized. During operation two of the bilayers act as anode and the other two as cathode. Thus, all the electrical energy is used, avoiding an additional metallic counterelectrode and the subsequent generation of products able to degrade the muscle. The reference electrode is short-circuited to the counterelectrode in order to monitor the muscle potential along the galvanostatic experiments and the sensing abilities of the device. The devices were checked by repetitive galvanostatic contraction/extension of up to 20% of the original length. About 50% of the devices produced irregular movements, due to different ohmic resistances in the electrical contacts between the wires and polymeric films. Once the contacts were improved, the new devices showed good reproducibility. The influence of electrolyte concentration, experimental current and weight trailed by the device indicates that the complex device maintains most of the sensing properties of the basic bilayer muscles. Then checking the life-time of the device, contact failures and fissures around the metal/polymer joint were immediately detected from the chronopotentiometric noises which appeared after several cycles. Such failures must be solved before the device can be miniaturized and in order to construct different shapes, and three-dimensional sensing muscles for robotics from combinations of basic units.

1. Introduction

In 1992, artificial muscles based on conducting polymers (CPs) were constructed with the ability to describe very large and macroscopic angular movements [1, 2] when the applied potential is shifted along a potential range lower than 1 V. Baughman et al. and DeRossi et al. [3–5] suggested that electrochemically induced volume changes in conducting polymers could be applied to the construction of actuators, similarly to the way in which volume changes produced by high electric fields (10–10^4 V) in piezoelectric or electrostrictive inorganic or polymeric films have been applied to electromechanical actuators. The bending movements obtained by electrochemically induced movements in films of conducting polymer (electrochemomechanical devices) [6–9] described angles larger than 180 degrees, surpassing all expectations of the stated hypotheses.

The basic devices are constituted by CP/tape bilayers, or CP/tape/CP triple layers, to the top of which electrical contacts are fixed, and an electrolyte, which acts as counterion supplier for the electrochemical reactions and which supports the current flow during actuation. These reactions promote quite reproducible small changes of volume in the CP. The device translates length variations into large angular movements of its free end. The present state of the art was thoroughly reviewed in two recent papers [10, 11]. The devices show simultaneous actuating, sensing and tactile capabilities [12, 13] constituting a new paradigm for robotic applications and opening new technological possibilities.

Basic single elements, such as CP/tape bilayers, or CP/tape/CP triple layers, develop sufficient mechanical energy to control bending movements of probes for medical or industrial applications [10, 14–16]. Electrochemical procedures of synthesis are also suitable for micromachining processes. Micro-fabricated actuators have been successfully produced for different micro-robotic and bio-chemo-medical applications [10, 15, 16]. However, one of the most exciting perspectives was the possibility of reproducing compliant macroscopic biological muscle shapes and volumes in order to produce plastic robots.

To develop three-dimensional volumetric devices three main procedures are currently followed. Many groups including those of, DeRossi, Kaneto, Wallace, Yoshino, François, and others [10, 11] are engaged in synthesizing new polymers, generating polymer films, tubes or fibers on different conducting supports, able to produce large longitudinal variations during oxidation/reduction processes. The above mentioned length variations for the first electrochemical cycle of the individual elements are spectacular (greater than 20% the original length) in some cases. Nevertheless, when a macroscopic device composed of several elements was constructed, the good mechanical characteristics of the basic individual elements were lost due to increasing stiffness and the irregular distribution of the electric fields, e.g. cylindrical structures prevent the different elements from working simultaneously. Moreover, to date all the devices constructed required a metallic counterelectrode to allow the current to flow, thus losing about half the electrical energy to generate new chemicals (fast pH variations in aqueous media), which induces rapid degradation of the actuator.

Other groups are trying to develop a basic element using simple bilayers as working electrodes for the transformation of bending movements into lineal movements. The need for a metallic counterelectrode results in the same difficulties as described for the lineal elements. A third group is trying to produce basic elements including working, counter and reference electrodes in the constituent bilayers or triple layers of the device: in this way, both anodic and cathodic reactions are actuating reactions that transform electrical energy into mechanical energy, allowing the sensing muscle potential to be monitored simultaneously. Once a basic element is characterized, mechanically and electrochemically and the reproducibility, reliability and extended lifetime of the device have been proved, macroscopic devices of any shape able to produce *n* times the mechanical energy of the basic element (*n* being the number of basic elements) can be produced. In such devices, working, counter or reference electrodes are constituted by films of CP, while both anodic and cathodic reactions, are actuating reactions. This will considerably attenuate the loss of electrical energy consumed by the current flow through the metal/solution interface of the metallic counterelectrode for the first two actuator families, and the generation of reaction products that contribute to the rapid deterioration of the basic actuating element will be considerably attenuated. In such a device, all the simultaneous sensing (followed through the muscle potential) and actuating capabilities described for the basic bi or triple layer elements [12, 13, 17] could be maintained, with a perfect control of the movement by means of the driving current.

This is the route followed by our group and here we present and characterize a new basic element in an attempt to explore the origin of the difficulties that have been hindering the production of three dimensional electro-chemo-mechanical muscles of any volume and shape.

2. Experimental

2.1. *Synthesis of polypyrrole films*

The polypyrrole films used were electrogenerated from a 0.2 M pyrrole and 0.1 M $LiClO_4$, with 1% aqueous acetonitrile solution under a nitrogen atmosphere.

The monomer pyrrole was distilled at low pressure and then stored at −10 °C. An AISI 304 stainless steel plate with a surface area of $6.6 \times 2.5 = 16.5$ cm^2 was used as working electrode (WE) for the electropolymerization process. Two equally and parallel spaced polished steel plates of the same dimensions were used as counter electrodes. Two similar polypyrrole films, one each side of the WE, were obtained. A saturated Ag/AgCl electrode (Crison Instruments) served as reference electrode.

Electropolymerization was carried out at ambient temperature and pressure by submitting the working electrode to consecutive square waves of potential between −0.322 V (2 s) and 0.872 V (8 s) using a PAR M273A potentiostat/galvanostat. The electrical charge consumed during polymerisation was 135 C, which produced two 13 μm thick polypyrrole films (estimated from the polymer density and film dimensions, by electronic microscopy and from the polymerisation charge), each weighting 33 mg on average.

2.2. *Construction of a single muscle strip*

After generation, the coated electrode was rinsed with acetronitrile and dried, and double-sided plastic tape was stuck to the coated polypyrrole electrode film, slowly peeling off the new CP/tape bilayer from the steel plate. A protective plastic covered the second adhesive side of the tape. To prevent additional stiffness (resistance to movement), the protective plastic from the second side of the adhesive tape was removed and replaced by a covering layer of conventional nail-lacquer to avoid unwanted adherence.

The stripped polymer layer was then cut into strips of the desired dimensions. In our experiments we used bilayers of polypyrrole measuring 2 cm in length, 0.4–0.5 cm in width and 12–14 μm thick, each weighing 1.5–2 mg. One end of the muscle strip was kept adherent in order to stick the hinge-joint. At the other end a thin copper wire (diameter 90 μm) was fixed and sealed to the polypyrrole layer using a conductive carbon cement ("Leit-C", Neubauer Chemikalien).

2.3. *Construction of the basic muscle element*

We built a basic unit consisting of polypyrrole bilayer muscles and two plastic hinges that we hoped would be able to transform the reversible bending movements of the individual bilayers into a longitudinal movement of the device.

Figure 1 illustrates the assembly of the muscle device: four conventional bilayers and two hinges forming a rhombus. The two upper muscles were connected at the top to the working electrode (WE) of the potentiostat (1). The two bilayers from the lower part of the device were connected at their bottom to the counter electrode (CE) of the potentiostat (2). Two thin elastic plastic foils (3) were stuck to the lateral free ends of the bilayers as hinge joints.

In order to monitor the muscle potential (WE vs. CE) during the experiments the reference electrode (RE) was short-circuited to the CE. Finally the device was immersed in a 1 M $LiClO_4$ aqueous solution. The device was submitted to a constant current using a PAR M273A potentiostat/galvanostat. The oxidation/reduction processes generated swelling/shrinking effects (incorporation and expulsion of ClO_4^- -anions and water) in the polypyrrole films, resulting in bending movements due to stress gradients across the polypyrrole/tape interface [18–22].

2.4. *Model and functional description*

Two opposing forces are generated since the device is basically a composition of antagonistic electrochemomechanical movements. When the two upper muscles (1) act as anode of the direct current flowing through the device, the polypyrrole swells, bending the bilayers to a convex shape (the polypyrrole film at the external face). The resulting forces try to push the lower ends of the bilayers (2), and the two hinges, towards the centre of the device. The pair of muscles from the lower part of the device act as cathode. The polypyrrole shrinks and each bilayer bends to a concave shape, opening the rhombus.

By combining both bending movements by means of two floating hinges, a linear movement from bottom towards the top is obtained. At the same time the distance between hinges increases, broadening and shortening the rhombic shape, as illustrated by Figure 2. Reversing the direction of the current flow reverses the movements, producing a rhombus with a greater distance between electric contacts, the two upper bilayers acting as cathode and two lower bilayers being the anode.

Nevertheless, if the two upper muscles act as cathode and the two lower ones act as anode from the initial position, an analogous initial shortening (with reverse bending of each muscle) will be obtained. This initial shortening of the device, which is independent of the sense of the direct current flow, provides the device with a high degree of flexibility.

We underline that the design includes electrode and conterelectrode as simultaneous actuating components of the device and so most of the electrical energy is used to produce mechanical movements, avoiding the generation of water electrolysis products on the metallic counterelectrodes. The reference electrode was short-circuited to the counterelectrode in order to monitor the muscle potential, providing an integrated electrochemical element suitable for producing linear movements.

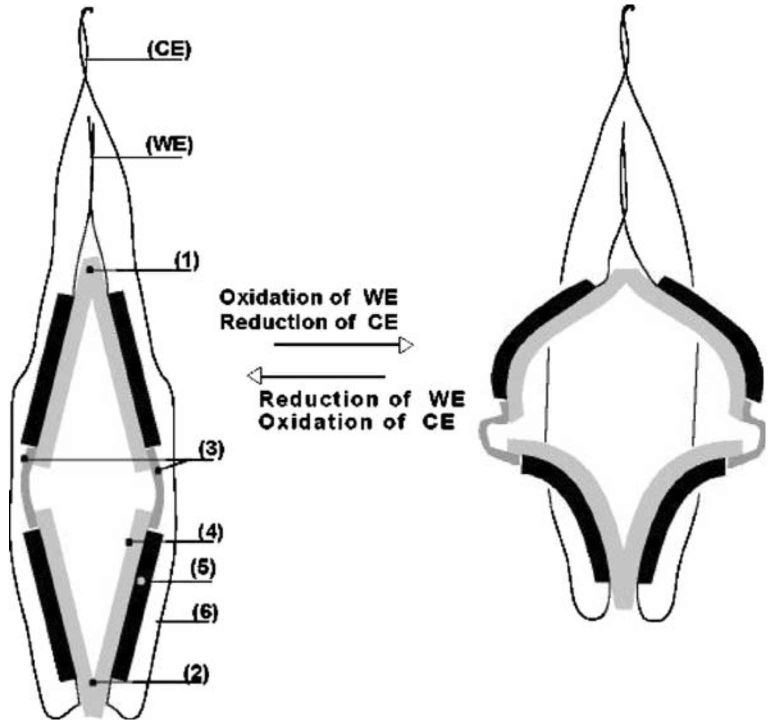

Fig. 1. Scheme of the proposed device.

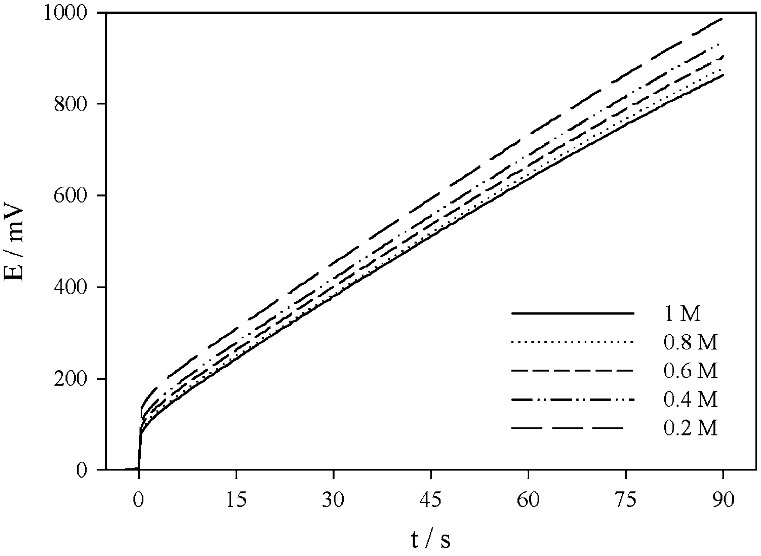

Fig. 2. Experimental chronopotentiograms obtained for the repetitive movement representing 20% of the device length in different concentrations of electrolyte (1, 0.8, 0.6, 0.4 and 0.2 M) by flow of a constant current of 2.5 mA for 90 s.

3. Results and discussion

3.1. *Operation*

The four polypyrrole films used to construct a given device were obtained by the same electropolymerization process. Different devices required independent electrosynthesis, under analogous chemical and electrical conditions.

Every device was initially tested in 1 M $LiClO_4$ aqueous solution under galvanostatic conditions with a flow of 1 mA for 90 s in order to gently condition the material. Then the influence of different experimental variables was studied: electrolyte concentrations (1, 0.8, 0.6, 0.4, 0.2 M $LiClO_4^-$), electric current (from 1 to 15 mA) or shifting different weights adhered to the bottom of the device.

3.2. *Influence of the electrolyte concentration*

The movement of the device was characterized in aqueous solutions (1, 0.8, 0.6, 0.4, 0.2 M) of $LiClO_4$ using a constant current of 2.5 mA for 90 s, the two upper muscles acting as anode and the two lower muscles acting as cathode, at ambient temperature and pressure. The distance between the top and the bottom of the rhombic device was shortened every time by 20% of the original length. The original shape of the device was recovered every time by reversing the direction of the current flow (2.5 mA) for 90 s.

As was obtained for bi and triple layer actuators [12, 13, 17], parallel chronopotentiograms showing increasing potentials for decreasing electrolyte concentrations were obtained (Figure 2). The results indicate that, despite the complexity of the device, the sensing ability of the constituent bilayers was maintained. The initial muscle potentials during the shortening of the device ranged between 106 and 225 mV for the different concentrations studied, or between −156 and −352 mV during device elongation by the current flowing in the opposite direction. The muscle potentials at the end of the 90 s of current flow ranged between 980 and 1256 mV (shortening), or between −988 and −1100 mV (elongation).

To check the reproducibility of the methodology, four different devices were constructed, each with a similar polypyrrole mass, from four separate polymerisation processes. Figure 3 shows the experimental responses obtained from the four devices in 0.2 and 1 M $LiClO_4$ (the two extreme concentrations) aqueous solutions. The electrical energies consumed per unit of polypyrrole mass as a function of the $LiClO_4$ concentration (1, 0.8, 0.6, 0.4, 0.2 M) are depicted in Figure 4. The consumed energies [mJ mg^{-1}] at a constant concentration for the different tested devices remained almost constant. A linear decrease in the energy consumed per unit of polypyrrole mass was observed for the four devices when the electrolyte concentration was increased, maintaining the same behaviour described (20) for individual bilayers polypyrrole/tape. Within the range of concentrations used, the consumed energy decreased by 50%. The consumed energy was defined as mJ per unit of polypyrrole mass, due to the electrochemical origin of the mechanical movement. A more precise expression would be mJ per unit of polypyrrole mass and surface area since this includes the possibility of comparing devices constructed with polypyrrole films having different thicknesses.

3.3. *Reproducibility*

Since one of the main problems associated with complex devices constructed of artificial muscles is the low reproducibility, we checked eight different devices obtained from eight independent polymerisation processes (under galvanostatic (±2.5 mA for 180 s per cycle conditions). Aluminium wires were used as the

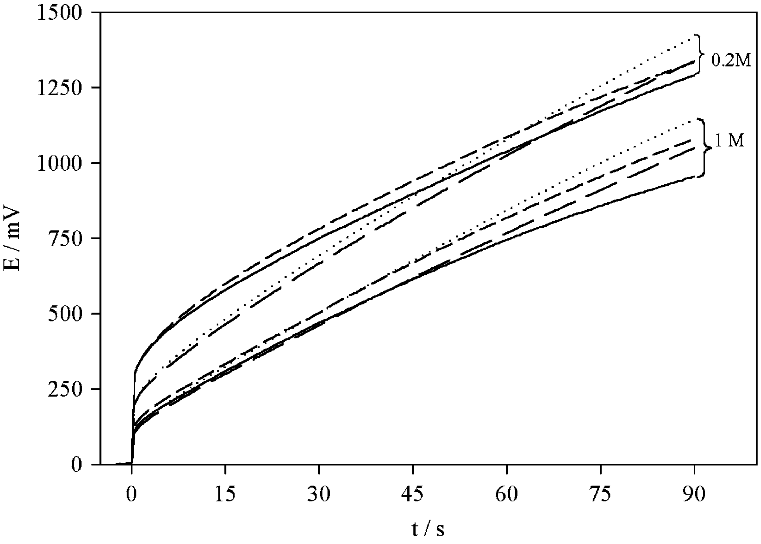

Fig. 3. Experimental chronopotentiograms obtained for four different devices, characterized by flows of 2.5 mA for 90 s in 1 and 0.2 M $LiClO_4$ aqueous solution, resulting in 20% average shortening of the muscle in order to check reproducibility.

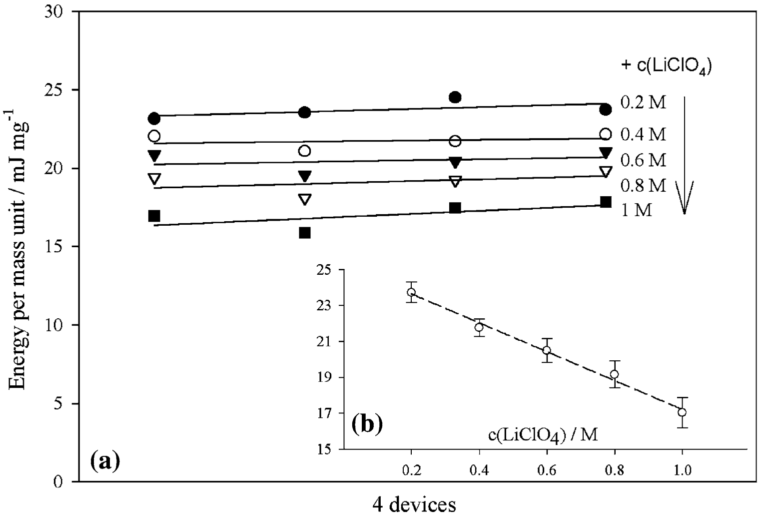

Fig. 4. (a) Electrical energies consumed per unit of polypyrrole mass by the four devices of Figure 3 checked in five different electrolyte concentrations (driven by 2.5 mA for 90 s). (b) Energy consumed as function of the electrolyte concentration.

electrical connections for device 7. Device no. 8 did not contain flexible hinges; a continuous double-sided tape supporting both polypyrrole films from the left side of the device, and another tape those from the right side. Table 1 shows the characteristics of the devices and the results obtained in 1 M $LiClO_4$ aqueous solution, giving an average contraction/elongation of 21% of the original length of the device, as seen in Figure 5. This means that we expend the same charge, Q (mC) = I (mA) t (s), for every experiment.

Device 2 was not considered for calculating the average displacement. Devices 7 (aluminium wires) and 8 (without hinges) were excluded from the energy calculations. The average deviation percentage of the polypyrrole content was close to 20%, which could be the origin of similar deviations obtained for either the consumed energy per surface area unit or the average lineal displacement. Moreover, similar deviations can be observed in the column of the energy consumed per unit

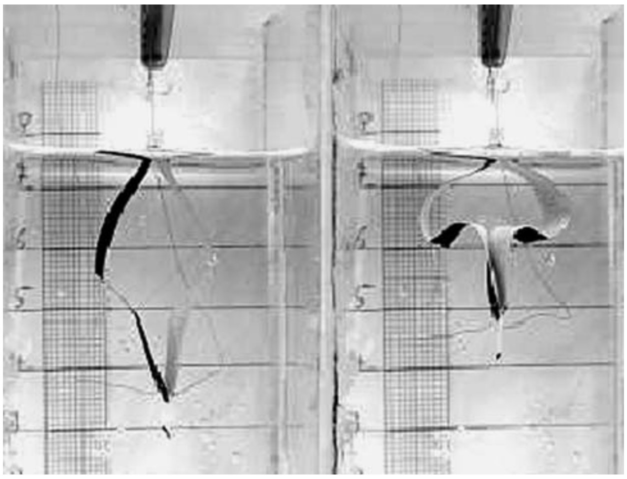

Fig. 5. In 1 M LiClO4-aqueous solution, under flow of 2.5 mA for 90 s, a contraction by 21% (12 mm) of the synthetic muscle from the relaxed state was reached.

Table 1. Comparison between 8 different devices, of given polypyrrole mass and thickness, characterized by flow of 2.5 mA for 90 s in 1 M $LiClO_4$ aqueous solution. Aluminum wires were used for electric contacts in device no. 7. Device no. 8 does not contain any hinge, but continuous tapes from the top to the bottom of the device

device	mass/mg	thickness/μm	E_{el}/mass/mJ mg^{-1}	E_{el}/area/mJ cm^{-2}	E_{el}/area_mass/mJ cm^{-2} mg^{-1}	Contraction in 90 s/%
1.	6.65	12	14.32	26.46	3.98	19
2.	5.93	12	18.68	34.64	5.84	52
3.	8.37	13.6	16.67	34.92	4.17	24
4.	6.6	13.4	17.09	35.25	5.34	16
5.	8.25	13.4	23.09	47.58	5.76	22
6.	8.07	13.1	16.95	34.21	4.24	20
7.	5.93	12	25.85	47.94	8.08	20
8.	5.03	13.6	24.85	52.08	10.35	25
Average	6.85 ± 24.4	1288 ± 6.2	17.8 ± 24.6	35.51 ± 30.1	4.89 ± 19	20.86 ± 21.5

weight. Nevertheless the average deviation decreases if we look at the most representative electrochemical magnitude of energy consumed per unit weight and per unit surface area. The observed deviations indicate the existence of mechanical and electrical aspects of the device which are more difficult to reproduce than the electrochemical aspects.

3.4. *Electric current*

The current is the driving force for producing volume changes in the polypyrrole and consequently for the movement of the artificial muscle. Previous studies using bi and triple layers [17–22] showed that increasing current densities promote faster angular movements at the same time as the muscle potential rises and higher electrical energies are consumed. To check whether similar interdependencies were maintained for complex devices constituted by four bilayers working simultaneously, a device including 8.25 mg of polypyrrole (4 films) with a thickness of 13.4 μm and a surface area of 4 cm^2 was immersed in a transparent plastic tank containing a 1 M $LiClO_4$ aqueous solution. It was then subjected to the flow of different currents between ± 2 and ± 7 mA. For every experiment, the current was allowed to flow for the time that the lower end of the device took to cover a constant distance of 10 mm, 22% of the device length. The experimental chronopotentiograms are depicted in Figure 6. Rising currents produced higher potential increments between anodic and cathodic polypyrrole films, in agreement with Ohm's law, resulting in increasing consumption of electrical energy.

A linear relationship was obtained between the rate of lineal movement and the applied current, corroborating the electrochemomechanical origin of the movement and the perfect control of the movement rate by the current. Variations in the volume of the polypyrrole films are produced by the electrochemical reaction: the applied current imposes the kinetics of the reaction and that of the volume variations. So, the bending movement rate of the constituent bilayers and the final lineal movement of the complex device, obtained by composition of the bilayer bending motions, are also under the kinetic control of the driving current.

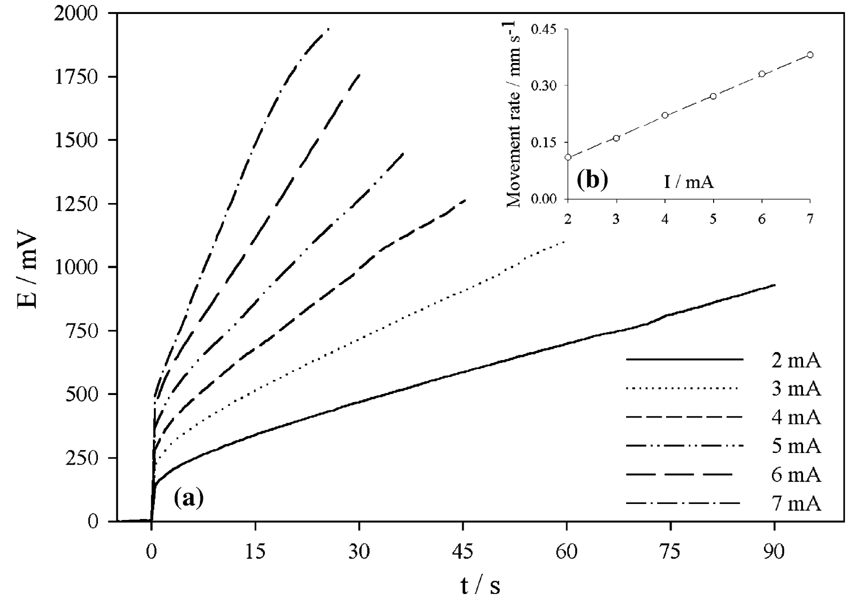

Fig. 6. (a) Evolution of the experimental chronopotentiograms when a device was characterized using different currents (2, 3, 4, 5, 6 and 7 mA), in 1 M $LiClO_4$ aqueous solution from periods of time required to produce a constant 22% contraction of the device length. (b) Evolution of the longitudinal movement with the applied current.

Figure 7 compares the reproducibility of the electric energy consumed per unit mass and per unit area for four similarly constructed devices with different masses of polypyrrole ranging from 6.6 to 8.25 mg and different total film areas, ranging from 3.2 to 4 cm^2. Each device was checked by currents ranging from ± 2 to ± 12.5 mA in 1 M $LiClO_4$ aqueous solution. Similar slopes and close energy consumptions rates, which increased linearly with current, were obtained. The device with the lowest polypyrrole content showed the lowest consumption. Higher masses of polypyrrole led to greater consumption of energy and increasing slopes.

3.5. *Different loaded weights*

Steel wires, clips or pins (up to 200 times the mass of the constituent polypyrrole films) were attached to the lower end of the device. Figure 8 shows the results obtained when the device ($m_{ppy} = 6.6$ mg, $area_{ppy} = 3.2$ cm^2, $thickness_{ppy} = 13.4$ μm) was checked by passing a current of 3 mA for 90 s in aqueous 1 M $LiClO_4$ solution, trailing steel masses weighing 5, 10, 13, 20 and 47 times the polypyrrole mass. Increasing weights promoted increasing potentials and consequently more electrical energy was consumed to lift the steel weights.

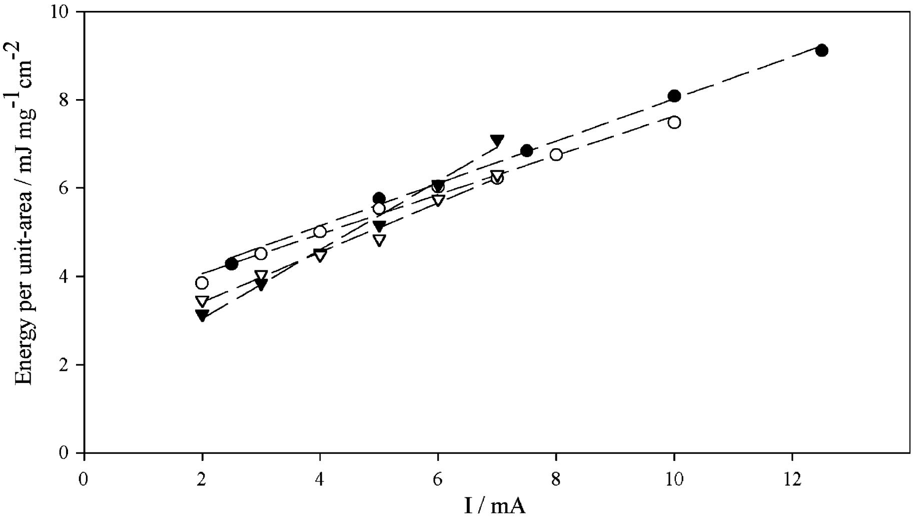

Fig. 7. Electrical energies consumed per unit of polypyrrole mass and per unit of polypyrrole surface for four different devices checked with electrical currents ranging between 2 and 12.5 mA, each flowing for 90 s in 1 M $LiClO_4$ aqueous solution. Experimental contractions were 18.5 ± 3% of the extended length of the device.

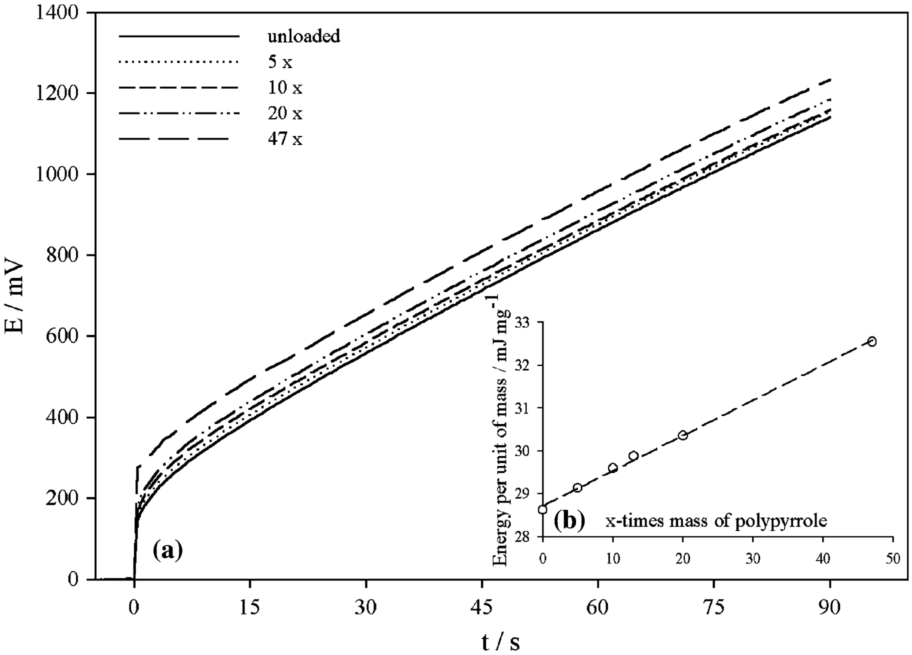

Fig. 8. (a) Experimental chonopotentiograms obtained when different steel pieces, weighing 5, 10, 20 or 47 times the polypyrrole content (6.6 mg) of the device, were suspended from the bottom of the device and then lifted by a flow of 3 mA for 90 s in a 1 M molar $LiClO_4$ aqueous solution. (b) Evolution of the consumed electrical energy per unit of polypyrrole as a function of the lifted weight.

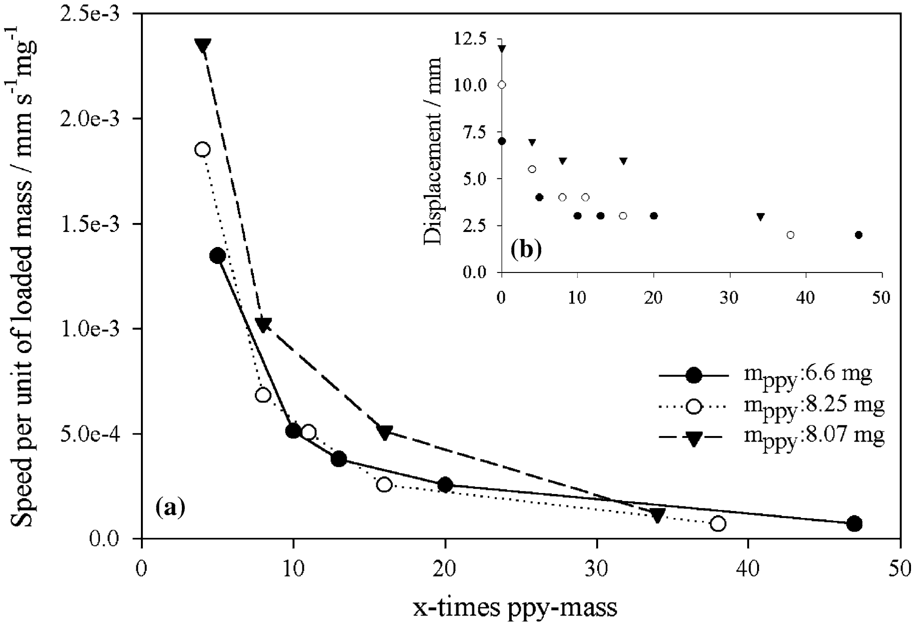

Fig. 9. (a) Evolution of the lineal rates as a function of the lifted mass by using a current of 2.5 mA for 90 s in a 1 M $LiClO_4$ solution. (b) Evolution of the maximum displacement attained by the device bottom under those experimental conditions.

Loaded with increasing weights, the vertical distance covered by the device for a constant time (90 s) of current flow (constant consumed charge) diminished, producing lower movement rates, as Figure 9 shows. It was also observed that the movement rates of 3 different devices of different polypyrrole masses (6.6, 8.07, 8.25 mg), with different surface areas, gave a similar variation under load. This complex device also maintained the behaviour of the basic bilayers when under load [12, 13, 17, 19].

In Figure 10 a pin of 20-times the polypyrrole mass is lifted under a muscular contraction of 12%. Nevertheless in this complex device higher loads produced plastic deformation and loss of hinge joint elasticity, diminishing the longitudinal movements. Loading weights higher than 400 mg led to the hinge becoming detached, as shown by Figure 11.

If very rigid tape or hinges with poor mechanical characteristics are used, the sensing abilities of the system easily detect the problems. Any consequence of poor mechanical characteristics, of poor transmission of the generated force or the existence of poor electrical contacts, whatever the origin, is detected by the chronopotentiometric responses, which are very irregular and show a lot of noise in the average potentials (Figure 12). Different plastic materials were checked as hinges and no significant improvement was attained.

Checking the device at different temperatures (−10 to 40 °C) also produced similar non-reproducible mechanical and chronopotentiometric results, with no significant problems of oxidation or reduction of the constituent polypyrrole films. Different points of electrical contact, different surfaces of tape and hinge adherence and the use of different materials (tape, hinges, conducting glue) resulted in a quite rigid device at low temperatures and adherence loss at high temperatures. Those results indicate the need for new experiments so that results from bilayers or triple layers can be applied to build more complex three dimensional devices: however extrapolation of bilayer results to complex structures is not straightforward.

3.6. *Difficulties*

Around 50% of the devices produced presented the above-described problems from the beginning of the checking process. The origin of most of the problems was attributed to failures of the electrical contacts between the copper wires and some of the polypyrrole films. Initially we tried to integrate the wires between the

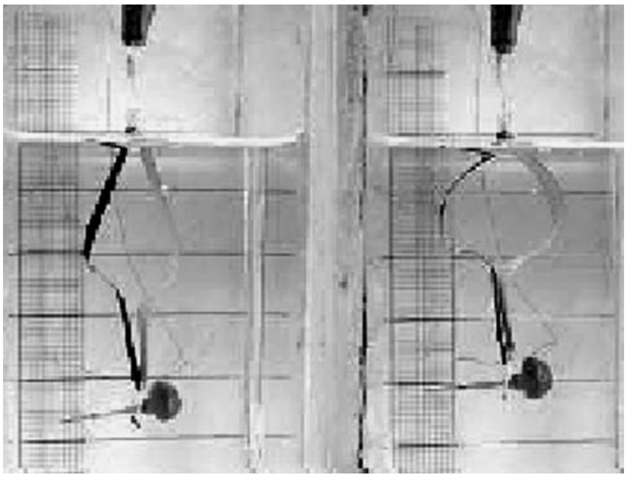

Fig. 10. A pin weighing 20-times the polypyrrole weight (8.07 mg) is lifted by flow of 2.5 mA for 90 s in a 1 M $LiClO_4$ solution producing a 12% contraction of the muscle extended length.

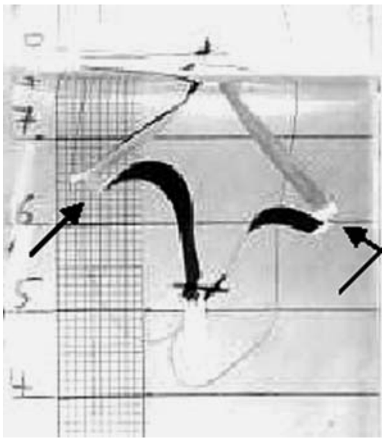

Fig. 11. Adherence loss of the hinge joints appeared due to overloading.

tape and the polymer. The electrochemically induced changes of volume during actuation resulted in fluctuations of the electric resistance, which was reflected as fluctuations in the chronopotentiograms (figure 12).

By fixing the wires directly to the polypyrrole films using conductive carbon cement, the contact was improved as deduced from the resulting smooth chronopotentiograms. The different devices now showed reasonable reproducibility and were used for the experiments described in this paper. During the checking experiments, peeling of the carbon cement was sometimes observed, probably induced by the volume changes in the polypyrrole film, and which again produced noise in the responses. Checking the life-time of the device by consecutive square cycles of current (a cycle: 2.5 mA for 90 s/−2.5 mA for 90 s) noisy responses were also obtained as fissures appeared in the constituent polypyrrole films and around the contact points due to material fatigue.

Moreover, from the experimental fluctuations in the chronopotentiograms, a lateral component appeared in the vertical movement of the device, indicating that one of the two muscles from that side was not working properly because it had some of the above described problems.

In summary, a careful design of the basic electro-chemo-mechanical elements, improving electrical contacts, hinge-materials and electric connections, should substantially increase the amplitude of movement, and decrease the consumption of electrical energy, opening up the possibility of miniaturization and of constructing three dimensional muscles of a variety of shapes and dimensions from combinations of basic units.

4. Conclusions

A basic rhombic electrochemomecanical actuator, composed of four CP/tape bilayers, the two upper bilayers acting as working electrode and the two lower ones acting as counterelectrode and shorcircuited to the counterelectrode, was successfully constructed and checked to transform the bending movement of the bilayers into longitudinal displacements. In this way, no metallic counterelectrode is required and both anodic and cathodic reactions produce mechanical energy. The muscle potential and the sensing capacities of the device can be followed during the actuation process from the same two connecting wires. Initial problems related to failures in the electrical contact were successfully overcome in order to improve the reproducibility of the complex device. The device thus maintains some of the simultaneous sensing and actuating properties of the basic bilayers, as verified using different electrolyte concentrations, different currents or different loaded weights. Some mechanical problems were identified when the complex element was

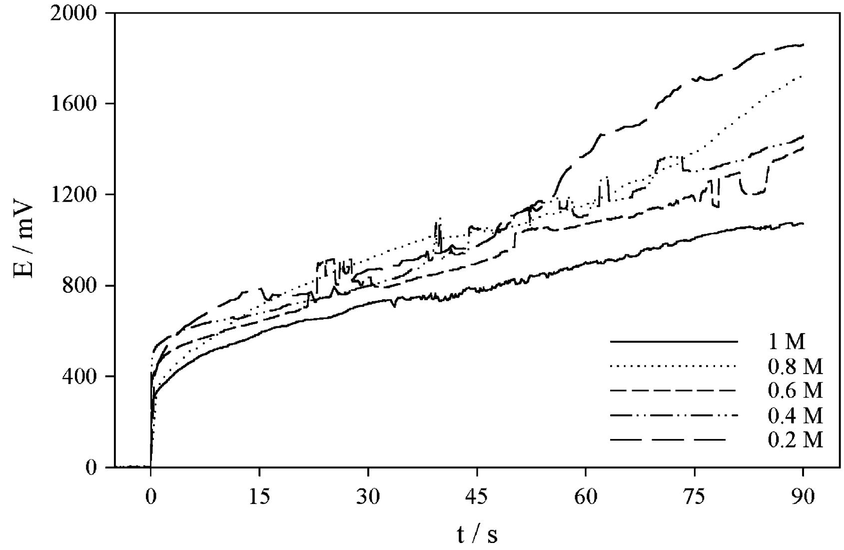

Fig. 12. Noisy and irregular potential curves obtained when contact failures or fissures across the polypyrrole film starts to appear during the characterization of a variable. The studied variable here was the electrolyte concentration (0.2–1 M), flowing as constant current of 2.5 mA for 90 s.

checked at different temperatures, probably due to the mechanical changes induced in the hinges and hinge adherence. Failures in the electrical contacts and the formation of transverse fissures on the polypyrrole film appeared after long cycling times. Identification of the origin of the cycling failure will allow development of improved devices using new materials and new adhesives for the hinges, by improving the mechanical resistance of the polypyrrole films against bending fatigue and by improving the electrical contacts between the polypyrrole films and the Cu wires. The possibility of constructing muscles of any shape and volume using spatial combinations of a basic unit will finally be opened up.

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