

# Ionic polymer–metal composites: IV. Industrial and medical applications

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## Abstract

This paper, the last in a series of four review papers to appear in this journal, presents some critical applications using ionic polymer–metal composites (IPMCs). Industrial and biomedical applications of IPMCs are identified and presented along with brief illustration.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

There are numerous potential applications using IPMCs as actuators, artificial muscles, and transducers. In this paper, some critical applications using ionic polymer–metal composites (IPMCs) are presented [1–30]. Industrial and biomedical applications are identified and presented along with brief illustration in the following sections. It is certainly clear that the extent of applications of IPMCs goes beyond the scope of this paper or the space allocated. However, it presents the breadth and the depth of all such applications of IPMCs as biomimetic robotic distributed sensors, actuators, transducers and artificial/synthetic muscles.

## 2. Industrial applications

### 2.1. Mechanical grippers

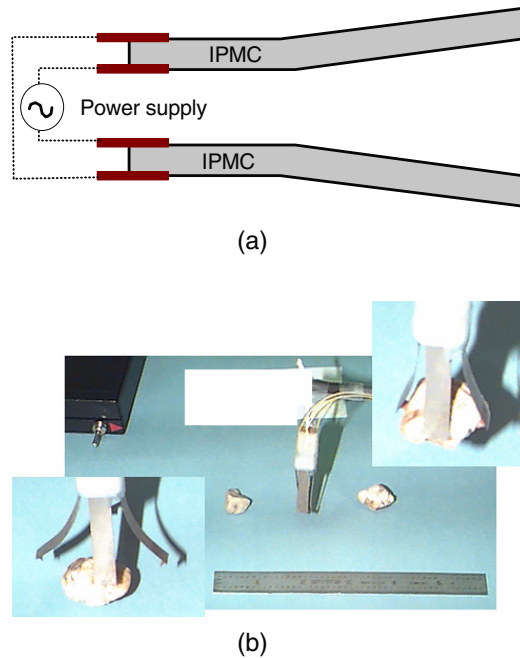
An IPMC can be fabricated to act as a micro- or macro-gripper, e.g., tweezers when two membranes are wired and sandwiched in a way such that they bend in opposing directions. Figure 1(a) is a perspective view of the mechanical gripper concept showing two treated IPMC actuators packaged as an electrically controlled gripper. The two IPMC actuators are placed parallel to each other with top surfaces facing each other. The terminals are attached to the top surface and the bottom surface of each actuator. Terminals are connected to

each other and to one pole of the power supply by electrical wire. The length of wire depends on the required gap between the two IPMC actuators, depending on application. The most important advantage of such IPMC grippers originates from their intrinsic material softness relative to conventional actuators.

As also seen in figure 1(b) the fingers are shown as vertical gray bars and the electrical wiring, where the films are connected back to back, can be seen in the middle portion of figure 1(b). Upon electrical activation, this wiring configuration allows the fingers to bend either inward or outward, similar to the operation of a hand, and thus close or open the gripper fingers as desired. The hooks at the end of the fingers represent the concept of nails and secure the gripped object that is encircled by the fingers.

To date, multi-finger grippers that consist of two, four, and eight fingers have been produced, where the four-finger gripper shown in figure 1(b) was able to lift 10.3 g mass. This gripper prototype was mounted on a 5 mm diameter graphite/epoxy composite rod to emulate a light weight robotic arm. This gripper was driven by a 5 V square wave signal at a frequency of 0.1 Hz to allow sufficient time to perform a desirable demonstration of the capability of the gripper (opening the gripper fingers, bringing the gripper near the collected object, closing the fingers and lifting an object with the arm). The demonstration of this gripper capability to lift a rock was intended to pave the way for a future potential application of the gripper to planetary sample collection tasks using an

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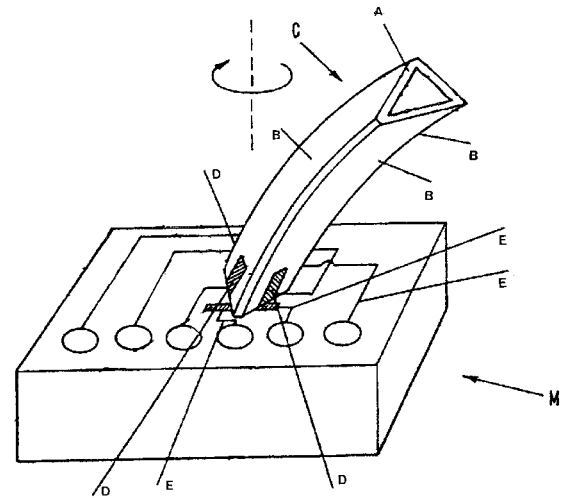


**Figure 1.** An illustration of the IPMC gripper concept (a) and a four-finger gripper (b).

ultra-dexterous and versatile end-effector or to handle soft biological objectives. Interestingly, the work at NASA/JPL reported that the actuation properties of IPMC muscles in a harsh space environment such as 1 Torr of pressure and  $-140^{\circ}\text{C}$  temperature are noticeable for space applications.

### 2.2. Three-dimensional actuator

Figure 2 shows an illustrative view of a three-dimensional IPMC actuator C packaged in three-dimensional form for use with a three-phase generator box M. IPMC actuator C is a hollow triangular tube configuration consisting of three independent membrane actuators A attached and electrically insulated along the long edges and having three external faces B. The tube is fixed to the generator box M. One pair of terminals D is located on each of the three actuators C for connection to electrodes E incorporated in generator box M. The IPMC actuator C is designed to produce a three-dimensional movement by positioning each of the actuators to be stimulated at a phase angle apart from the adjacent actuator by a low amplitude alternating signal, therefore inducing wobble-like motion around the long imaginary axis of the combined actuator tube in null position. Each IPMC actuator has its own terminal connections to each phase of a typical three-phase power generator (M) or a multi-phase power supply (programmable function generators/power supplies exist that have phase-separated outputs). Figure 2 details this arrangement. Each of these IPMC actuators has its external and internal faces similar to the top and bottom faces of the gripper shown in figure 1. Other configurations of three-dimensional motion actuators, such as the four-sided square rod shown in figure 3(a) and undulating and morphing actuators shown in figure 9(b), are also possible. Motion produced by any such device would be used to power soft mixers, production line feeders, and other task-specific equipment for many industrial



**Figure 2.** An illustration of the three-dimensional IPMC actuator concept.

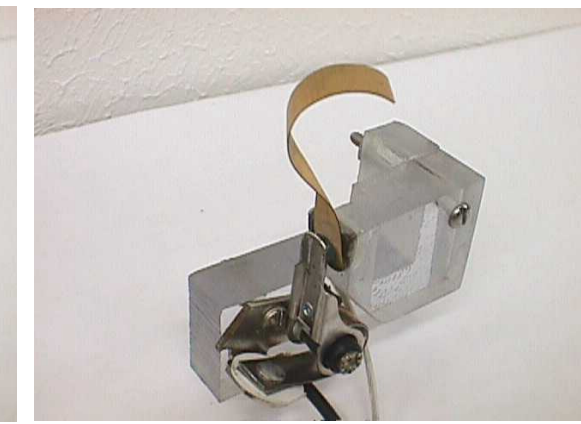
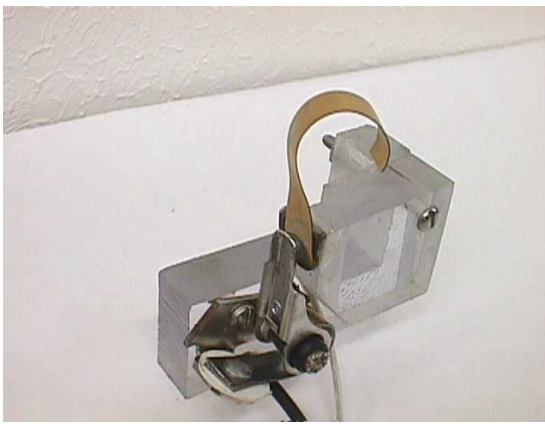
usages. Also, in sensing modes, they can be used as joysticks or X-Y locators.

### 2.3. Robotic swimming structure

Figure 4 shows one embodiment of a robotic swimming structure made by cutting and packaging strips of IPMCs A to the desired size and shape and consequently placing an alternating low voltage (a few volts-peak per strip) across the muscle assembly E. In this figure, muscle assembly E is formed of IPMC strips B, which is encapsulated into an elastic membrane C with electrodes D imprinted on each strip and with a first end and a second end. The second end F is attached to an appropriate electronics and wiring structure G for providing guidance and control to actuate the muscle assembly E. Structure G as shown comprises a sealed housing module H containing a means for generating a signal and a means for generating power J. The tail assembly consists of electrically actuated artificial muscles such as IPMCs cut into tiny fibers or strips. The tail is then encapsulated in an elastic membrane. The ends of fibers closer to the head assembly H are wired to a miniature printed circuit board (PCB) or like assembly to a signal generator assembly consisting of an oscillator circuit and batteries or other power source. The head assembly is preferably sealed to protect the circuitry and electronics from the elements. By varying the frequency of the applied voltage to the membrane muscle, the speed of muscle-bending oscillation of muscle assembly E, and therefore propulsion of the swimming structure, can be modulated. In this manner, robotic swimming fishes and submarine structures containing a sealed signal and power-generating module (preferably in the head assembly) can be made to swim at various depths by varying the buoyancy of the structure by conventional means. Remote commands via radio signals can then be sent to modulate propulsion speed and buoyancy. Based on such dynamic deformation design and observed characteristics, a noiseless swimming robotic structure, as shown in figure 4, was constructed and also tested for collective vibrational dynamics.

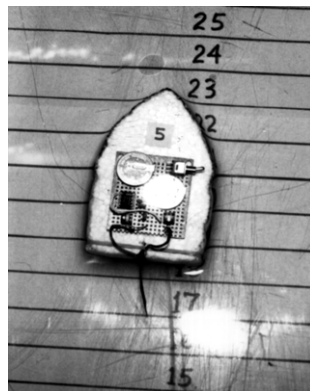
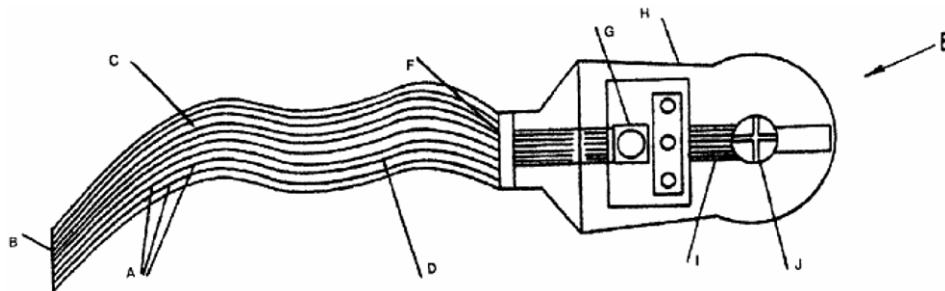


(a)



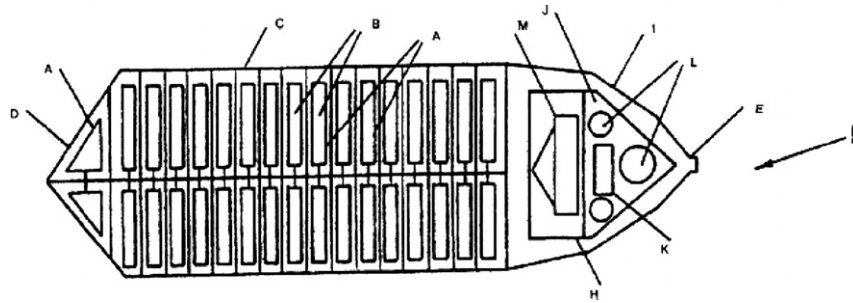
(b)

**Figure 3.** A photograph of the fabricated IPMC in a square rod form (a) and a photograph of the undulating and morphing actuator made with IPMC.



**Figure 4.** Robotic swimming structure (top) and swimmer with muscle (bottom). The scale shown is in cm [9].





**Figure 5.** An illustrative design of robotic fish.



**Figure 6.** A robotic fish equipped with a single IPMC tail fin [9].

Figure 5 is a plan view of another arrangement of the IPMC actuator showing an elastic construction with imprinted electrodes for use as a robotic swimming structure, more specifically a robotic fish. Figure 6 shows a robotic swimming structure made by cutting and packaging strips of IPMCs A in two rows of desired size and shape and imprinted with electrodes B spaced throughout and in a single structure. In this figure, muscle assembly structure F is formed of polymer gel strips A that are encapsulated into an elastic membrane C with multiple electrodes B imprinted therein and with a first end D (tail) and a second end E (head). Head assembly E contains appropriate electronics and wiring structure H for providing power, guidance and controls to the muscle assembly F. Structure H is contained in a sealed housing module I, containing a means for generating a signal M and a means for generating power. The power source J at end E places an alternating low voltage (a few volts-peak per strip) across the muscle assembly F as shown. Power source J includes an erasable, programmable chip K and batteries. Note the two rows of small actuators in parallel. Each has two terminals that are connected individually to the multi-phase signal generator M located in the head assembly E. There are also batteries (or another power source) housed in this section for required voltage input. By energizing one pair (across) of actuators at a time and then the consequent pairs downstream, one can produce a propagating or traveling wave downstream on each side of the fish. This will produce a sting-ray type of motion which propels the swimming structure forward. The middle terminals or spines act as conductors that connect the signal generator outputs in the head assembly to each actuator in the tail or wing assembly. By varying the frequency of the applied voltage, the speed of muscle-bending oscillation of

the membranes A, and therefore propulsion of the swimming structure F, can be modulated. In this manner, robotic swimming fishes and submarine structures containing a sealed signal and power-generating module in the head assembly can be made to swim at various depths by varying the buoyancy of the structure by conventional means. Remote commands via radio signals can then be sent to modulate propulsion speed and buoyancy by radio controls.

In figure 6 another robotic fish design is presented [9]. This robotic fish, equipped with a tail fin made from a single piece of IPMC material, has demonstrated that such a structure is feasible for mimicking biological fish locomotion. Furthermore, the noiseless propulsion is attractive in nature. A maximum speed of approximately  $2 \text{ m min}^{-1}$  was achieved under an applied voltage of 2 V.

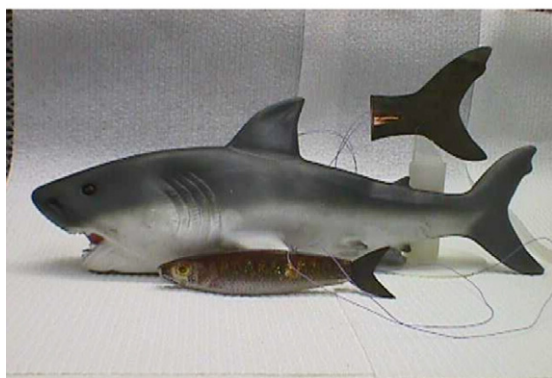
Electrically controllable caudal actuator fins (propulsion, and gross turning and maneuvering) and pectoral actuator fins (fine turning and maneuvering) and remotely controllable stealthy, noiseless, biomimetic swimming robotic fish made with IPMCs were designed and laboratory-tested. One of these is shown in figure 7.

It is also important to consider the optimal design of fish fin actuators such as the one shown in figure 7. The strategy here is to design different kinds of fins for noiseless fish propulsion. Note that there are five different kinds of fins:

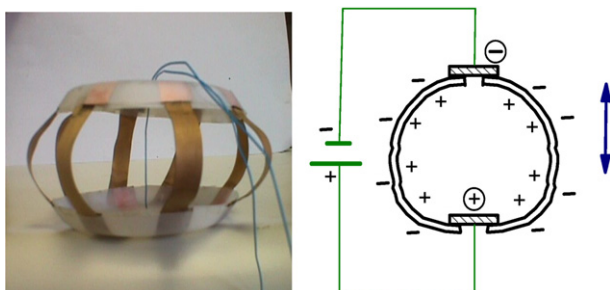
- (1) caudal or tail fin, which is primarily used for propulsion;
- (2) dorsal or back fin used for sudden turns and stability;
- (3) pectoral fins (paired) on the sides of a fish and primarily used for turning and stability;
- (4) pelvic fins (paired), on the sides, primarily used for braking or slowing down the propulsion;
- (5) anal fin, under the fish, near the belly and the tail, to add stability.

The main applications of these efforts are noiseless propulsion undulating fins and smart sonar evading skins made with IPMCs to be used in a noiseless biomimetic swimming robotic fish for naval applications. The requirements may be the following:

- (1) the IPMC fins must be water-survivable and must sustain the harsh ocean environment while performing sensing and actuation for propulsion;
- (2) the IPMC fins must have good force density for propulsion, i.e., for a typical caudal fin of  $20 \text{ cm}^2$  surface area an undulating force of 1 N or about 100 gm<sub>f</sub> will be required;
- (3) the IPMC undulating fin must have a good bandwidth to undulating frequencies of at least 10 Hz.



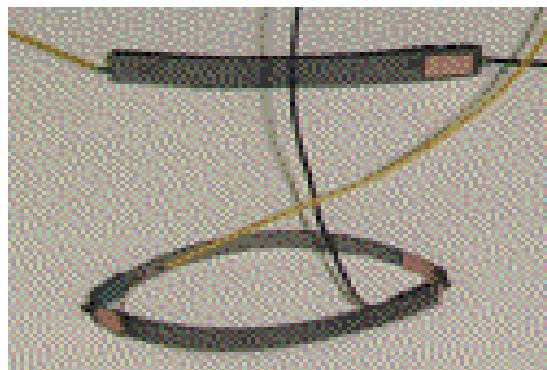
**Figure 7.** A designed and fabricated undulating caudal fin actuator and two robotic fish equipped with IPMC fin actuator.



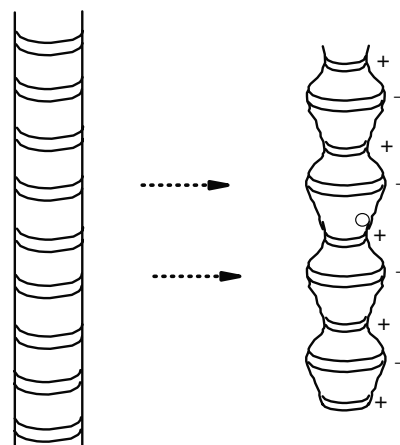
**Figure 8.** A photograph of a platform actuator driven by eight IPMCs. This design can feature two-dimensional motion of the platform. The operating principle is illustrated.

#### 2.4. Linear actuators

Linear actuators can be made to produce a variety of robotic manipulators including platform type or parallel platform IPMC actuators such as shown in figure 8 [9]. Also, multiple degrees of freedom of motion can be obtained by controlling each IPMC with a robotic controller. Since the base-polymeric material of IPMC is for the most part a three-dimensional network of macromolecules often cross-linked nonuniformly, the concentrations of certain ionic charge groups are also nonuniform within the polymer matrix. Based on dynamic deformation characteristics, linear and platform type actuators can be designed and made dynamically operational. One necessity of these IPMC linear actuators is to properly design the structure to produce enough force for required actuation.



**Figure 9.** IPMC film pair in expanded mode. A reference pair (top) and an activated pair (bottom).



**Figure 10.** Schematics of an IPMC cylindrical linear actuator with discretely arranged ring electrodes.

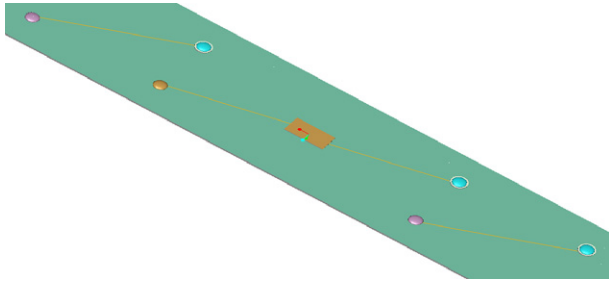
Other variations in design is also possible. The bi-strip type linear actuator shown in figure 9 is a simple version of such bi-strip actuators. A film pair weighing 0.2 g was configured as a linear actuator and using 5 V and 20 mW successfully induced more than 11% contraction displacement. Also, the film pair displayed a significant expansion capability, where a stack of two film pairs 0.2 cm thick expanded to about 2.5 cm wide. Also, transverse directional actuation of the IPMC may be possible.

Another possibility is to create long linear actuators by proper placement of electrodes on a cylindrical body of an IPMC such as the one shown in figure 10.

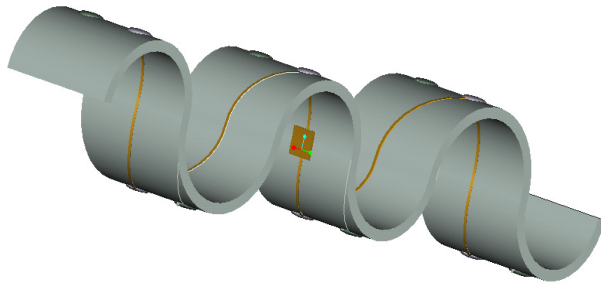
#### 2.5. IPMC contractile serpentine and slithering configurations

Some efforts were directed towards creating certain contractile serpentine and slithering artificial muscle configurations for the strips of IPMC by placing alternating electrodes on the surfaces of IPMC strips as illustrated in figures 11 and 12.

Some actual configurations of slithering IPMC strips were constructed, as shown in figures 13(a) and (b). However, the results were not yet very encouraging due to the fact that the stiffness of the strips prevented them from easy slithering. Efforts are underway to manufacture thinner IPMC strips and to repeat such experiments to observe more profound serpentine-like or snake-like slithering and maneuvering motions of IPMC strips.



**Figure 11.** Interdigitated electrode arrangement on an IPMC strip to create a serpentine-like contractile and slithering artificial muscle.



**Figure 12.** Another interdigitated electrode arrangement on a slithering IPMC strip to create a serpentine-like contractile and slithering artificial muscle.

## 2.6. Metering valves

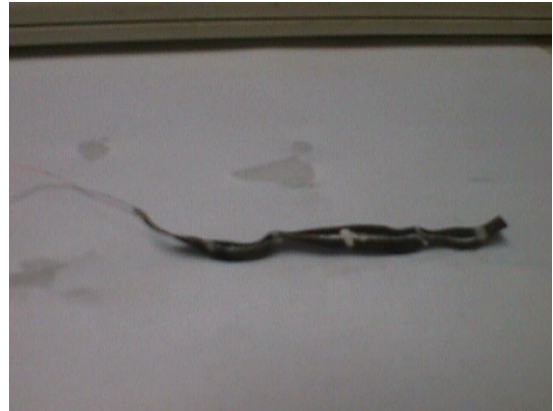
Metering valves can be manufactured from IPMC. By applying a calibrated amount of direct voltage/current to the IPMC metering valve attached to any tubes and, consequently, varying the degree of bending displacement of the IPMC, the control of aqueous fluid flow can be attained. Figure 14 depicts a set of preliminary data obtained in using an IPMC strip in a fluttering mode in a pipe flow. However, the calibration of such a device requires more work.

## 2.7. Diaphragm pumps using flexing IPMC strips and diaphragms

Bellows pumps can be made by attaching two planar sections of slightly different sizes of IPMC sections and properly placing electrodes on the resulting cavity. This permits modulation of the volume trapped between the IPMCs. The applied voltage amplitude and frequency can be adjusted to control the flow and volume of fluid being pumped.

IPMC diaphragm pumps can also be made in various ways. Single or multiple IPMCs can function as the diaphragms that create positive volume displacement. In figure 15 we present a miniaturized double-diaphragm pump constructed of IPMC. Such a pump produces no noise and has a controllable flow rate in the range of a few microliters per minute.

These pump systems can also be useful for biomedical applications. For example, each includes a pumping chamber having an anterior end attached to an implantable influent conduit in eye. In the case of an ocular pressure control device, the influent conduit is inserted into the anterior chamber of the eye. A flexing ionic polymer conductor composite IPMC artificial muscle functions as the primary actuator. The

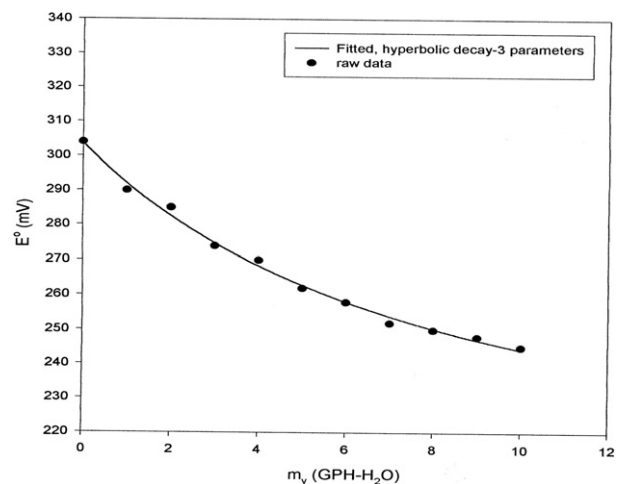


(a)



(b)

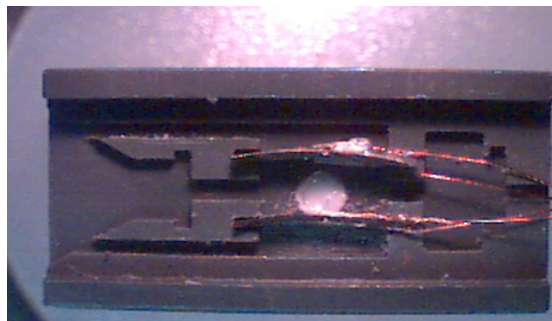
**Figure 13.** Actual interdigitated electrode arrangement on a slithering IPMC strip to create a serpentine-like contractile and slithering artificial muscle.



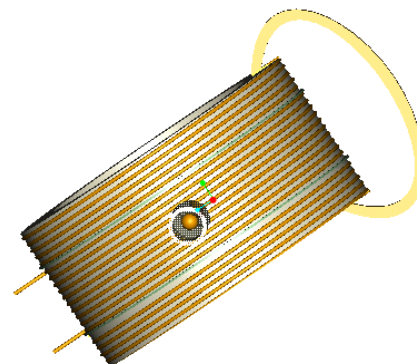
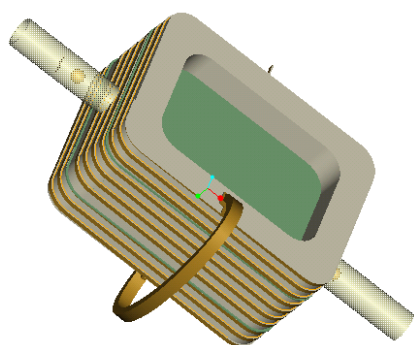
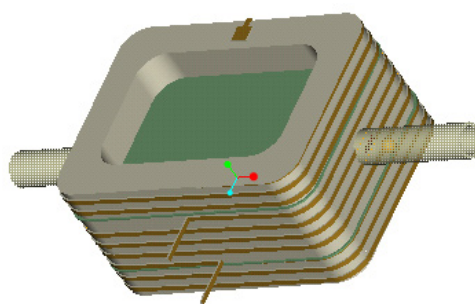
**Figure 14.** Metering valve data (open circuit) obtained by a strip of IPMC undulating in a pipe flow.

posterior end of the pumping chamber is connected to an effluent or drainage conduit, which may drain bodily fluids or dispense drugs to an area of the body. Figures 16–19 depict various configurations of such mini diaphragm pumps with rectangular and circular chambers. An alternative external power system includes a biocompatible induction coil with gold wire armature that can be transcutaneously

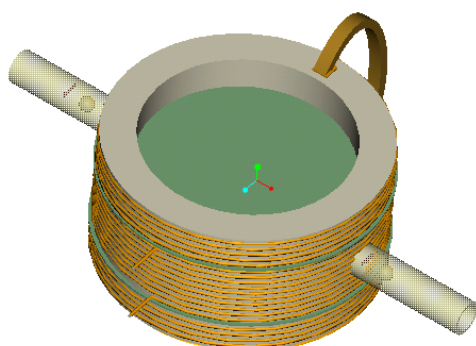




**Figure 15.** A photograph of the fabricated double-diaphragm pump. The size of the IPMC is 1 mm width  $\times$  5 mm length  $\times$  0.2 mm thickness [9].



**Figure 17.** Side view of the two double-diaphragm mini-pumps equipped with synthetic muscles and an inductive receiving coil.

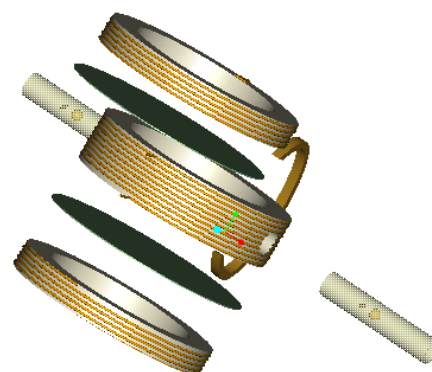
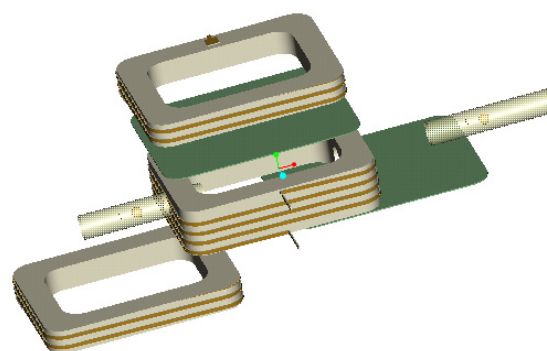


**Figure 16.** Perspective view of two (rectangular and circular chamber) double-diaphragm mini-pumps equipped with IPMC muscles and an inductive receiving coil.

activated, adjusted and computer interrogated and controlled by a surgeon. The device is further equipped with a pair of adjustable variable flow valves placed at the juncture of the inlet and effluent conduits with the pumping chamber.

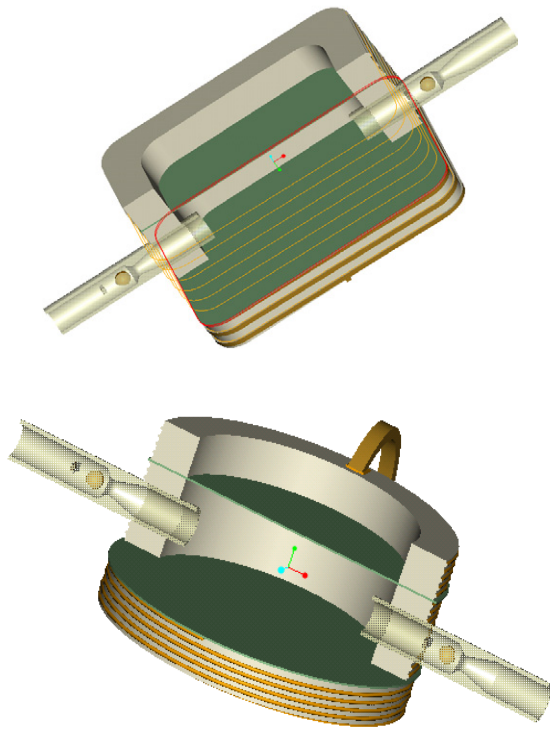
The valves are used to regulate fluid flow through the pumping chamber. A pressure regulating system including a pressure sensor and pump controlling microprocessor may also be used with the system.

Based on the designs presented in figures 16–19, a number of mini-pumps with rectangular and circular chamber configurations were built with flexing IPMC diaphragms. The IPMC diaphragms were sandwiched between two gold-plated ring electrodes which were either circular or rectangular. The ring electrodes were cut from either circular copper tubings or rectangular copper channel tubings and then gold plated.



**Figure 18.** Exploded view of the two double-diaphragm mini-pumps equipped with synthetic muscles and an inductive receiving coil.

The chambers were also equipped with gold-plated armature windings to act as receiving inductive coils to



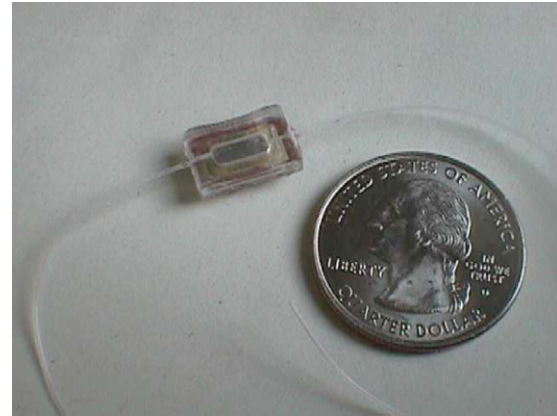
**Figure 19.** Cut-away view of the double-diaphragm mini-pumps equipped with synthetic muscles and an inductive receiving coil.

energize the mini-pump in case it is implanted in a patient's body or a remote location not easily accessible to a direct source of electricity.

Figure 20 depicts a double-diaphragm mini-pump for which a series of experiments for pumping characteristics were conducted.

The housing of the pump was PMMA (polymethyl methacrylate). The synthetic muscle (diaphragm) was 30  $\mu\text{m}$  thick IPMC, the ring electrodes are copper coated with gold, the tubings are Teflon and the inductive coil is enameled gold armature wire with the stripped ends gold plated with gold. It should be emphasized that implantable, pressure adjustable diaphragm pump systems can be fabricated with IPMCs. Furthermore, these mini-pumps are scalable and are characterized by a common type of actuating mechanism in the form of synthetic muscles made with IPMCs. The pumps may be inductively and transcutaneously powered via adjacent, mutually inductive electromagnetic coils. Alternatively, the pumps may be effectively 'self' powered using a synthetic muscle attached to a local bending or twisting force.

A key feature of the pump is the self or secondary power generation system in the form of a much larger piece of IPMC synthetic muscle, which, in the case of glaucoma prevention systems, may be placed on the globe surface (sclera) of the eye and attached to and secured by the extraocular muscles of the eye. An alternative external power system includes a biocompatible induction coil with gold wire armature that can be transcutaneously activated, adjusted and computer interrogated and controlled by a surgeon.



**Figure 20.** A fabricated double-diaphragm mini-pump equipped with IPMC diaphragms.

### 2.8. *Exo-skeletal human joint power augmentation (ESHPA)*

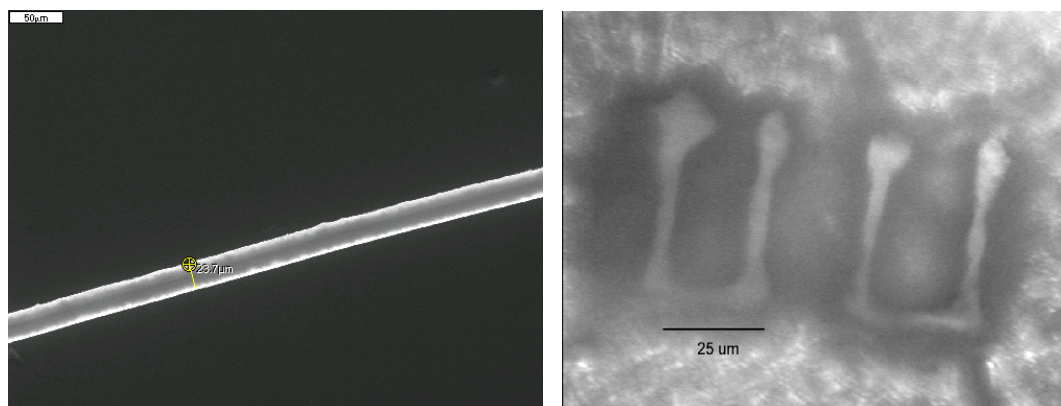
IPMC artificial muscles can be used in certain attire to augment human joint power. Human skeletons have on average 98 skeletal joints. Some of these joints, such as the jaw's temporomandibular joint and the hand's radiocarpal (wrist) joint, the fingers' interphalangeal (IP) joint or the thumb's carpo metacarpal (CM) joint, are highly active, while some, such as the foot's subtalar joint or transverse tarsal joint, are less active, and yet other joints are rather integrated joints, such as the spine cervical, thoracic or lumbar vertebrate joints. The human skeletal joints are exoskeletally powered by elaborate systems of skeletal muscles, some 4000 of them; mostly operating in an antagonist configuration in which families of pairs of contractile muscles perform articulated joint motions.

The powering sequence of skeletal muscles can start with an initial electrical polarization wave signal from the brain through the human spine and nervous system to cause an ATP-ADP release of chemical energy to power the muscles. Therefore, in order to fabricate the proposed family of ESHPA systems equipped with IPMC sensors and actuators, the full integration of triggering signals, energy sources, power converters, sensors and actuators into a complete exoskeleton system will not be discussed here as being beyond the scope of this paper.

### 2.9. *Microelectromechanical systems*

Microelectromechanical systems (MEMS) and microrobots made with electroactive polymers and in particular IPMCs represent an enabling technology for manufacturing sensor and actuator microarrays, disposable microbiosensors for real-time medical applications, and a variety of microfabrication processes requiring the manipulation of small objects. The IPMC actuator microarrays will have immediate applications in micromirror-based photonic optical fiber switches. Also, the IPMC microgrippers are actuated with low voltages ( $<0.5$  V), are fast (minimum of 50 Hz bandwidth), and can be cut arbitrarily small (see figure 21) from sheets of the IPMC material (a typical thickness of 30  $\mu\text{m}$ , see figure 21). As MEMS technology develops, the most obvious problem is how to build small devices. It is equally important to develop techniques to manipulate and assemble





**Figure 21.** A photograph of a manufactured, micron-scale IPMC that can be used for MEM applications (left). Assembly of micro-strips of IPPC cut in laser-microscope work station for micro-sensing and micro-actuation (right) [9].

the MEMS components into systems. Historically, grasping and manipulating objects of any size has been a challenge. As components become smaller, the problem becomes even more pronounced. For the most part, there are no suitable actuators for the range of around 10–100  $\mu\text{m}$ . Electroceramics (piezoelectric and electrostrictive) offer effective, compact, actuation materials to replace electromagnetic motors. A wide variety of electroactive ceramic (EAC) materials are incorporated into motors, translators and manipulators, in such devices as ultrasonic motors and inchworms. In contrast to electroceramics, IPMCs are emerging as new actuation materials with displacement capabilities that cannot be matched by the striction-limited and rigid ceramics. Table 1 shows a comparison between the capability of IPMC materials and both electroceramics and shape memory alloys (SMAs). As shown in table 1, IPMC materials are lighter and their potential striction capability can be as high as two orders of magnitude more than EAC materials. Further, their response time is significantly higher than that of SMAs. The current study is directed towards taking advantage of these polymers' resilience and the ability to engineer their properties to meet robotic microarticulation and MEMS requirements. The mass produceability of polymers and the fact that electroactive polymer materials do not require poling (in contrast to piezoelectric materials) help to reduce cost. IPMC materials can be easily formed in any desired shape and can be used to build MEMS-type mechanisms (actuators and sensors).

They can be designed to emulate the operation of biological muscles and they have unique characteristics of low density as well as high toughness, large actuation strain constant and inherent vibration damping.

When electroactive ceramics or shape memory alloys are applied to micromanipulation, a variety of creative approaches have been taken to compensate for each actuator's limitations. For example, many creative systems have been proposed including a non-linear, high ratio transmission systems made with a piezoelectric actuator and micromanipulation using shape memory alloys, and the use of temperature change to modify the pressure inside micro-holes on the surface of the end effector.

The current state of the art in MEMS technologies in connection with robotic micro-manipulation and assembly as well as sensing and actuation is that small micron

**Table 1.** Comparison of the properties of IPMCs, SMAs and EACs.

Property	Ionic polymer–metal composites (IPMCs)	Shape memory alloys (SMAs)	Electroactive ceramics (EACs)
Actuation displacement	>3%	<6% short fatigue life	0.1–0.3%
Force (MPa)	10–30	About 700	30–40
Reaction speed	$\mu\text{s}$ to s	s to min	$\mu\text{s}$ to s
Density ( $\text{g cm}^{-3}$ )	2.0–2.5	5–6	6–8
Drive voltage (V)	0.1–7	NA	50–800
Fracture toughness	Resilient, elastic	Elastic	Fragile

size components can be made by traditional micro-machining in the semiconductor industry. Sensors, valves, pumps, manipulators, filters, probes, connectors are just a few examples of MEMS-based devices. Fabrication processes involve silicon surface micromachining, silicon bulk micromachining and wafer bonding, LIGA, EDM (electro-discharge machining) and single-point diamond machining. Micro-electro-mechanical systems (MEMS) are the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through the utilization of the above microfabrication technology. Since MEMS devices are manufactured using batch fabrication techniques, similar to ICs, unprecedented levels of functionality, reliability and sophistication can be placed on a small silicon chip at a relatively low cost. The IPMC sensors and actuators can be naturally integrated with the current MEMS technology because they are easily batch processable and manufacturable and they can be made as small as desired and in any geometry that is desired, as we have proven. IPMC-MEMS technology will definitely become an enabling new technology to help in biotechnology as well. Technologies such as the polymerase chain reaction (PCR), microsystems for DNA amplification and identification, the micromachined scanning tunneling microscopes (STMs), biochips for detection of hazardous chemical and biological agents, and microsystems for high-throughput drug screening and selection will particularly benefit from IPMC-MEMS integration. IPMC-MEMS can also easily integrate into high output dynamic sensing systems such as accelerometers

and dynamic motion and force sensors as well. Although MEMS devices are extremely small, MEMS technology is not about size. Furthermore, MEMS is not about making things out of silicon but is a manufacturing technology; a new way of making complex electromechanical systems using batch fabrication techniques similar to the way integrated circuits are made and making these electromechanical elements along with electronics. It is, in this spirit, that ionic polymer-metal composite (IPMC) sensors and actuators can easily be integrated into MEMS technologies and manufacturing techniques. These new manufacturing technologies will have several distinct advantages. First, MEMS is an extremely diverse technology that potentially could significantly impact every category of commercial and military products. MEMS are currently used for everything ranging from in-dwelling blood pressure monitoring to active suspension systems for automobiles to airbag accelerometers. Historically, sensors and actuators are the most costly and unreliable part of a macroscale sensory-actuator-electronics system. In comparison, MEMS technology allows these complex electromechanical systems to be manufactured using batch fabrication methods. In this context, the use of IPMCs to make large MEMS-based microarrays of sensors and actuators for distributed type applications is quite promising. Examples of these applications are distributed microactuator arrays for photonic optical fiber switching and tactile biosensing. These new applications will allow the cost and reliability of the sensors and actuators to be put into parity with that of integrated circuits. IPMC-based microelectromechanical system (MEMS) switches have the potential to form low cost, high performance, ultra broadband quasi-optical control elements for advanced defense and commercial applications. IPMC-based MEMS quasi-optical switches offer numerous advantages over conventional switches. Another potential application will be in military and commercial microwave systems requiring monolithic solutions for the realization of low cost, compact systems. The IPMC-actuated micromachined switch has great potential for microwave applications due to its extremely high power handling capability and compatibility with other state-of-the-art fabrication technologies for higher level integrated circuits or systems.

The developments in state-of-the-art micro-electro-mechanical-system (MEMS) technology have made possible the design and fabrication of micro-machined control devices suitable for switching microwave signals. IPMC-MEMS switches will have low parasitics at microwave frequencies (due to their small size) and will be amenable to achieving low resistive switching or high on-capacitance (capacitive switching). It must also be mentioned that in MEMS technologies micro-manipulation has always been the most difficult problem.

The first and most obvious way to make a microgripper is to miniaturize an industrial size gripper. Unfortunately, this does not take into account the physics of changing the scale of the problem. Normally, gravity is the predominant force, and when a gripper opens (and sometimes sooner) the carried object falls to the floor. In the micro-world, gravity is no longer the predominant force. Adhesive forces, such as electrostatic, van der Waals and surface tension, dominate in

the small scale. It has been shown that, at a  $10\text{ }\mu\text{m}$  object radius, the attractive forces between a sphere and a plane are  $10^{-10}$ ,  $10^{-10}$ ,  $10^{-8}$  and  $10^{-5}$  N for gravity, electrostatic, van der Waals and surface tension forces, respectively. Given the challenges to micromanipulation, it is not surprising to find a wide variety of approaches to the problem.

Recent approaches to fabricate microgrippers attempt to use

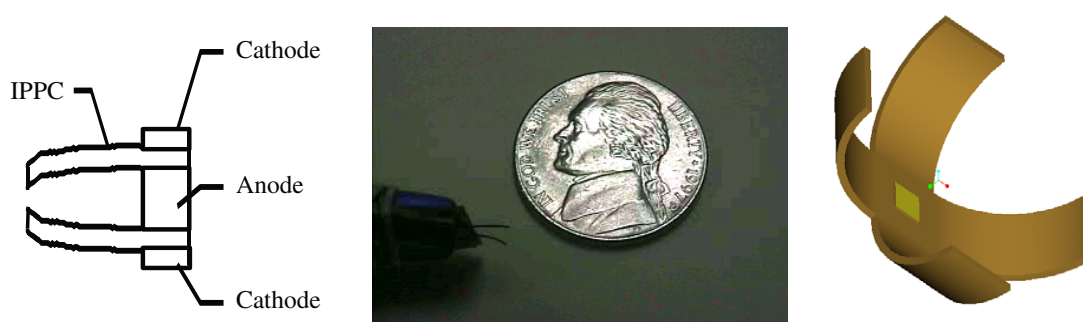
- (i) piezoresistive strain gauges (Hexsil process) for tactile feedback or the assembly of precision optical and magnetic components,
- (ii) a vacuum system with Lithographic Galvanoformung Abformung (LIGA) fabrication,
- (iii) temperature change causing a change in pressure,
- (iv) shape memory alloys, i.e., rotary micro-joint,
- (v) laser trapping or
- (vi) dielectrophoresis effects.

The technologies that have been applied to micromanipulation do not satisfy all of the requirements necessary for an economically viable approach. One would expect a material that is flexible rather than brittle, has long life rather than short life, reacts quickly rather than slowly, and is simple rather than complex. IPMCs are believed to satisfy such requirements of MEMS microactuation technologies. Since these muscles can be cut as small as one desires, they present a tremendous potential to micro-electro-mechanical system (MEMS) sensing and actuation applications. Figure 21 also displays a micron size array of IPMC muscles cut in a laser microscope work station.

A variety of microelectromechanical systems (MEMS) can be made by packaging and fabricating IPMCs in small, miniature, and micro sizes. Some examples include micro-propulsion engines for material transport in liquid media and biomedical applications such as active microsurgical tools. Other applications involve micro-pumps, micro-valves and micro-actuators. Flagella and cilia type IPMC actuators fall into this category. Figure 21 shows a manufactured IPMC with a thickness of  $25\text{ }\mu\text{m}$ . Note that an effective way of manufacturing such micro-sized IPMCs is to incorporate solution-recasting techniques.

As noted, IPMCs have shown remarkable displacement under a relatively low voltage drive, using a very low power. However, these ionomers have demonstrated a relatively low force actuation capability. Since the IPMCs are made of a relatively strong material with a large displacement capability, we investigated their application to emulate fingers. As seen in figure 22, a gripper is shown that uses IPMC fingers in the form of an end-effector of a miniature low mass robotic arm. The fingers are shown as vertical gray bars. Upon electrical activation, this wiring configuration allows the fingers to bend either inward or outward similar to the operation of a hand and thus close or open the gripper fingers as desired. The hooks at the end of the fingers are representing the concept of nails and allow securing the gripped object that is encircled by the fingers.

A 2D schematic diagram of the microgripper is provided in figure 22. The gripper would normally be attached to a gross manipulation device, e.g., a small robot, and the artificial muscles are actuated under voltage control. When actuated, the



**Figure 22.** An illustration of the microgripper concept (left), a photograph of a fabricated microgripper (middle) and a design of the four-finger gripper.

muscles will move together and grip the object in a compliant manner. By increasing the control voltage, the amount of gripping force is increased, and a firmer grasp is achieved. Since the artificial muscle also can act as a sensor, gluing muscles together provides an interesting mechanism to explore how closed-loop controlled microgripping is best achieved. It is envisaged using the sensing capabilities of the muscle to provide feedback for gripper closure. A variety of experiments need to be performed to determine the best shape for the muscles to achieve grasping various sized objects from about 10 to 100  $\mu\text{m}$ . One can vary the number of fingers on the microgripper as well as the artificial muscle sensors attached to the mechanism.

#### 2.10. Electromechanical relay switches

Non-magnetic, self-contained, electromechanical relay switches can be made from IPMCs by utilizing their good conductivity and bending characteristics in small applied voltages to close a circuit. In this manner, several of these IPMC actuators can be arranged to make a multipole–multithrow relay switch.

#### 2.11. Continuous variable aperture mirrors and antenna dishes

Continuous variable aperture mirrors and antenna dishes can be made by cutting circular sections of the IPMC and placing electrodes at strategic locations. The focal point of the resulting parabolic dish can be controlled by varying the amplitude of the applied voltage to selected electrodes.

#### 2.12. Slithering device

Snake-like locomotion can be accomplished by arranging appropriate segments of the IPMC in series and controlling each segment's bending by applying sequential input power to each segment in a cascade mode.

#### 2.13. Part orientation/feeding

Soft part orientors or feeders for delicate handling of parts in a manufacturing assembly line can be made from flaps made out of IPMC membrane. Figure 23 shows a various shape of manufactured IPMCs.

#### 2.14. Musical instruments

Because of the fact that mechanical flexing of IPMC materials generates a voltage and the fact that if these materials are already stretched they create different frequency output signal, one can use them as a musical instrument. Figure 24 depicts a one-string musical instrument that operates like a cello or a double-bass and generates very low frequency musical tones.

#### 2.15. Composite wing-flap

Figure 25 is a view showing multiple, IPMC actuators in a stacked (sandwiched), configuration D which is designed to accommodate more power for specific actuations. IPMC actuators A–a, b, c, d and e are each independent planar IPMC actuators of different lengths (to provide different stiffnesses, and therefore resonant frequencies, of the composite wing) manufactured according to the prescribed process and formed in a stacked configuration D which as a whole comprises a top surface and a bottom surface. Terminals B are connected to the top surface and bottom surface, respectively, at the first end of IPMC actuator D. Terminals are also connected by electrical wires C respectively, to a power source E. Electrical wire C contains an on–off switch F. Several of these IPMC actuators A can be assembled in series and multiple amounts of voltage applied to increase power in the composite actuator. IPMC actuators A–a–e act as series resistor elements, especially at higher frequencies.

The IPMC actuator of figure 25 is a resistive element by nature. Therefore, as one stacks several of the actuators, in effect one increases the overall resistance of the combined system. This in turn can allow for higher input voltages. The variation in length of each actuator is due to the desired stiffness of the wing as a whole. Since each actuator has conductivity through its thickness, there is no need to connect wires to faces. By just stacking them one can produce a thicker and more powerful actuator that can handle higher loads. The only necessary terminal connections are on the top face of the top layer A–a and the bottom face of the bottom layer A–e to an alternating (oscillating) source of voltage.

#### 2.16. Resonant flying machine

Figure 26 is a perspective view of the IPMC actuator showing a flying machine G constructed from IPMC actuator B formed in a single sheet having a top surface A and a central axis C.





An eight finger synthetic muscle.  
It has a thickness of approximately  
2 mm.



A rod shape synthetic muscle.  
It has a rectangular cross-section of  
approximately 8 mm x 8 mm.

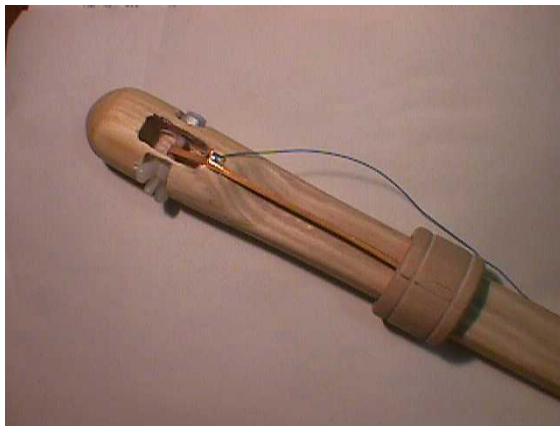


A coil type synthetic muscle.

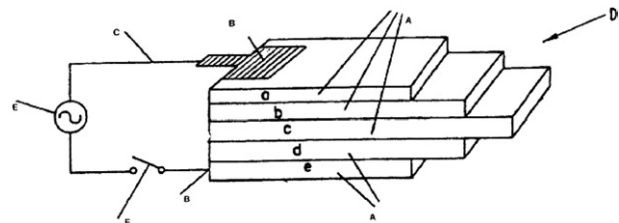


A circular shape synthetic muscle.

**Figure 23.** Various shapes of IPMCs having three-dimensional shapes.



**Figure 24.** One-string musical instrument.

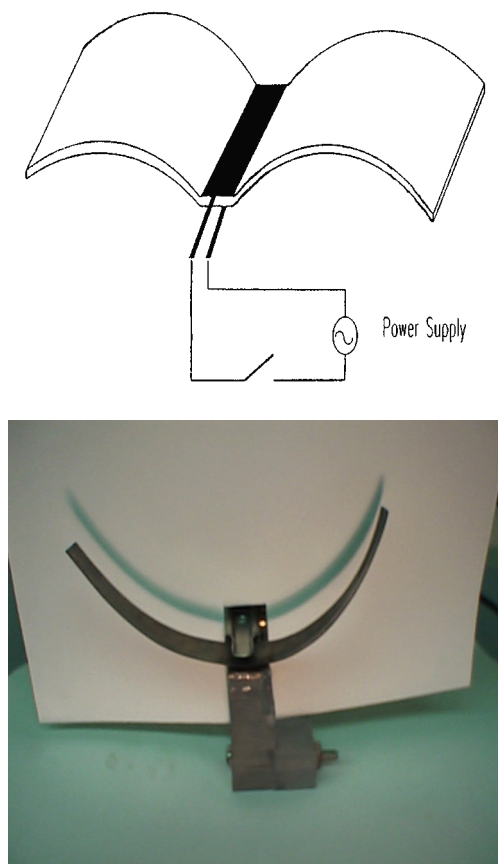


**Figure 25.** Composite wing-flap made with IPMCs.

The terminal D, attached to the top surface, extends along the central axis C of the membrane B.

Terminals D are connected at their ends to a power supply H by the electric wire E. As shown, wire E connecting terminal D to power supply H, includes an on-off switch F. The IPMC is packaged in this form for application as a resonant flying machine. In this configuration, the treated IPMCs ('muscles') can flap like a pair of wings and create a flying machine. 'Resonant' means excitation at the resonant frequency of the

membrane, which causes the most violent vibration of the membrane. Each body of mass has a resonant frequency at which it will attain its maximum displacement when shaken by some input force or power. To obtain large displacements of the actuator, one should apply oscillating signals at a frequency close to its body resonant frequency. In figure 39 one sees a fabricated large IPMC actuator strip with a pair of electrodes (terminals) in the middle fixed to the actuator surfaces of top and bottom. By connecting the circuit to an AC-power source (alternating current signal generator), one can produce oscillating motion of the membrane actuator similar to a hummingbird's or insect's wing-flap motion. Furthermore, if one applies the input voltage signal at or near the resonant frequency of the wing structure, large deformations can be obtained which will vibrate the wing structure in a resonant mode. The wing assembly can be preferably encapsulated in a



**Figure 26.** An illustrative view of the IPMC actuator showing a flying machine.

thin elastic wrap to prevent dehydration of the IPMC actuator. Also, solid-state polyelectrolytes can be incorporated.

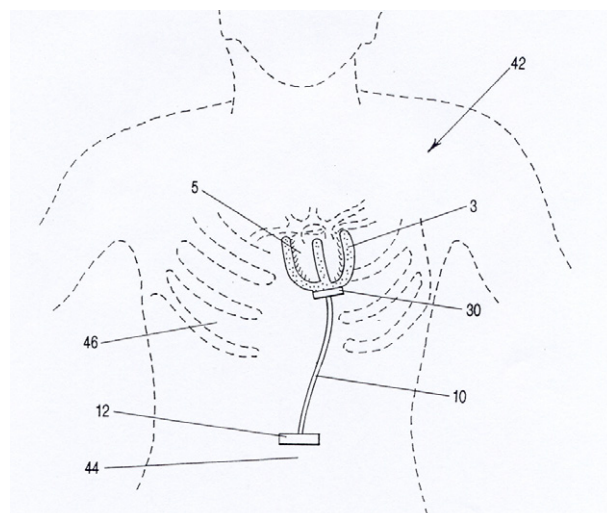
In reality, the possible wake capture mechanism in typical flies requires nonlinear wing operation to mimic biological locomotion. Therefore, the IPMCs should be controlled in a similar manner to carry out such locomotion either actively or possibly.

### 3. Biomedical applications

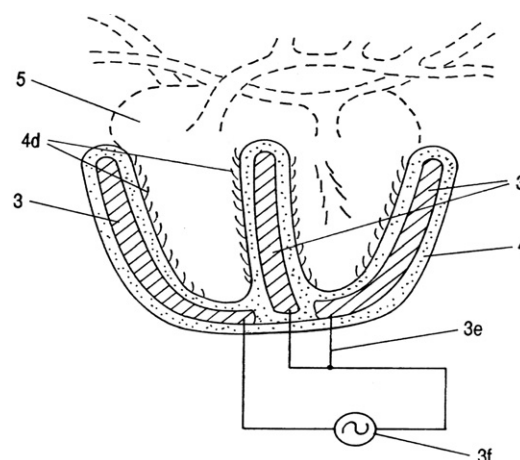
The softness and flexibility of IPMCs are definite advantages that can be used in biomedical applications. In this section, we present a number of potential biomedical applications that have been or are currently being developed.

#### 3.1. Artificial ventricular or cardiac-assist muscles

Artificial ventricular assist type muscles can be made for heart patients with heart abnormalities associated with cardiac muscle functions. We present the broad category of heart compression and assist and arrhythmia control devices, in particular ionic polymeric metal composite (IPMC) biomimetic sensors, actuators and artificial muscles integrated as a heart compression device which can be implanted external to the patient's heart, and partly sutured to the heart without contacting or interfering with the internal blood circulation. Thus, the potential IPMC device thereby can avoid thrombosis and similar complications, which are common to current



**Figure 27.** General configuration for the proposed heart compression device.

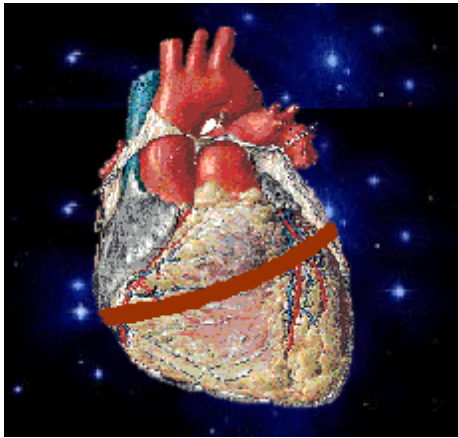


**Figure 28.** Heart compression device equipped with IPMC fingers.

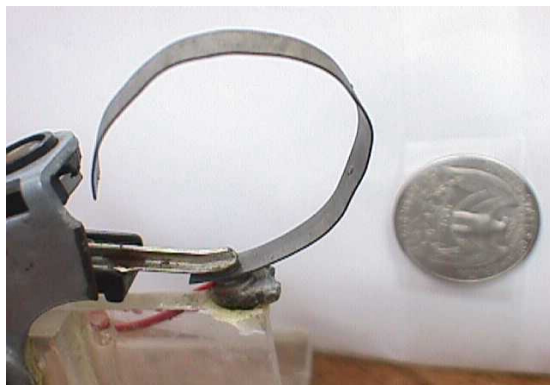
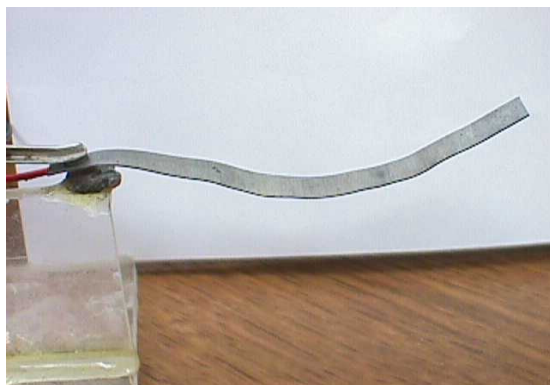
artificial heart, or heart-assist devices, which may arise when the blood flow makes repeated contacts with non-biological or non-self surfaces. In compressing a heart ventricle the device must be soft and electronically robust in order not to damage the ventricle. This means that the device should contain control means such as bradycardic (pacing) and tachyarrhythmic (cardioverting/defibrillating) to facilitate device operation in synchronism with the left ventricular contraction, and should be capable of transcutaneous recharging of the implanted batteries. The general idea is presented in figure 27. Note that the device is implanted essentially in the ribcage of the patient but is supported on a slender flexible stem that extends to the abdomen. The stem allows the systolic and diastolic cycles of the heart to continue and yet allows the body of the heart to make swinging motions to one side or the other without unnecessary restriction. It is also possible to place the supporting structure of the heart compression device on the diaphragm muscle. These details can be worked out during the clinical testing and operation of such devices.

Note in figure 27 that 42 is the patient body, 44 is the abdomen area, 46 is the rib-cage, 5 is the heart, 3 is the polymeric compression finger made with IPMCs, 30 is the base





**Figure 29.** A heart with an IPMC compression band.



**Figure 30.** An IPMC compression band in open and closed configurations.

of the compression device, 10 is a slender conduit carrying the electronic wires to the muscle and acting as a flexible support column as well and 12 is the power/microprocessor housing placed in the abdomen. Figure 28 depicts a more detailed drawing of the compression device itself.

Again, 3 denotes the compression fingers made with IPMCs, 5 is the heart itself, 4 depicts an encapsulated enclosure filled with water to create a soft cushion for the compression fingers, 4d are IPMC-based sensor cilia to continuously monitor the compression forces applied to the heart and 3e and 3f are the associated wiring and electronics. As designed, this device produces assisting or soft compression of the left ventricle of a weak heart to produce more internal pressure and



(a)



(b)

**Figure 31.** Four-fingered heart-compression device equipped with thick IPMCs: (a) before compression; (b) after compression.

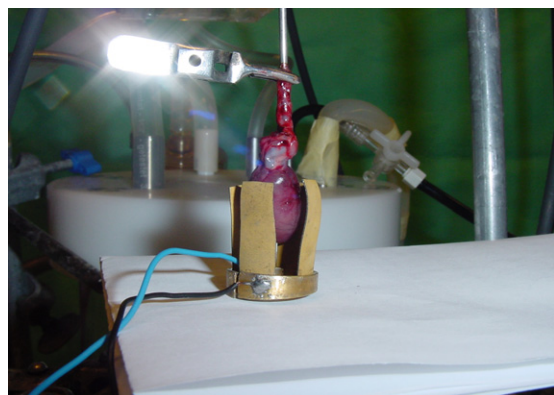


**Figure 32.** The upright configuration of the heart-compression device.

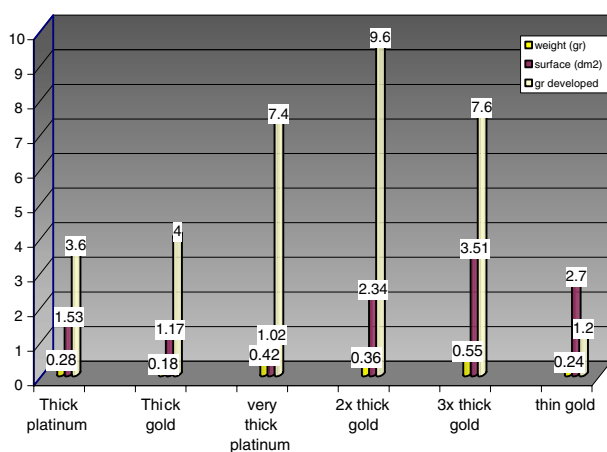
to pump more blood from one or more sides in synchrony with the natural systolic contraction of the ventricle. Additionally, the system can also provide arrhythmia control of the beating heart. The soft fingers incorporate suitably located electrodes for monitoring the ventricular stroke volume and pressure. A simpler design configuration uses a compression band to assist the heart in its systolic and diastolic cycles of compression–decompression as shown in figure 29.

Also, the compression band can be designed such that it can encircle the heart as shown in figure 30. Other configurations are depicted in figures 31 and 32.





**Figure 33.** Mini heart compression device equipped with IPMC muscles.



**Figure 34.** Pressure generation versus electrode thickness.

Compression devices shown in figures 31 and 32 were designed and fabricated from thick (2 mm thick) ionic polymer metal composites and were subsequently gold plated.

Here are presented some preliminary data concerning a mini heart compression device equipped with IPMCs. First the force generated by each strip at 5 V is measured, then the pressure generated when squeezing a small balloon or the rat's heart is measured (see figure 33).

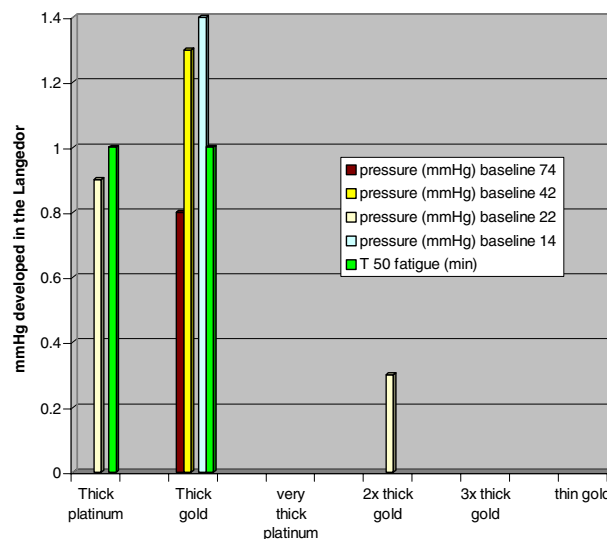
Figures 34 and 35 depict the variation of pressure generated in mm Hg with the voltage applied.

### 3.2. Surgical tool

The IPMC actuator can be adopted for use as a guide wire or a micro-catheter in biomedical applications for intra-cavity endoscopic surgery and diagnostics. Small internal cavities in the body can be navigated by using small strip or fiber-like IPMC actuators.

### 3.3. Peristaltic pumps

Peristaltic pumps can be made from tubular sections of the membrane of IPMC and placement of the electrodes in appropriate locations. Modulating the volume trapped in the tube is possible by applying appropriate input voltage at the proper frequency.



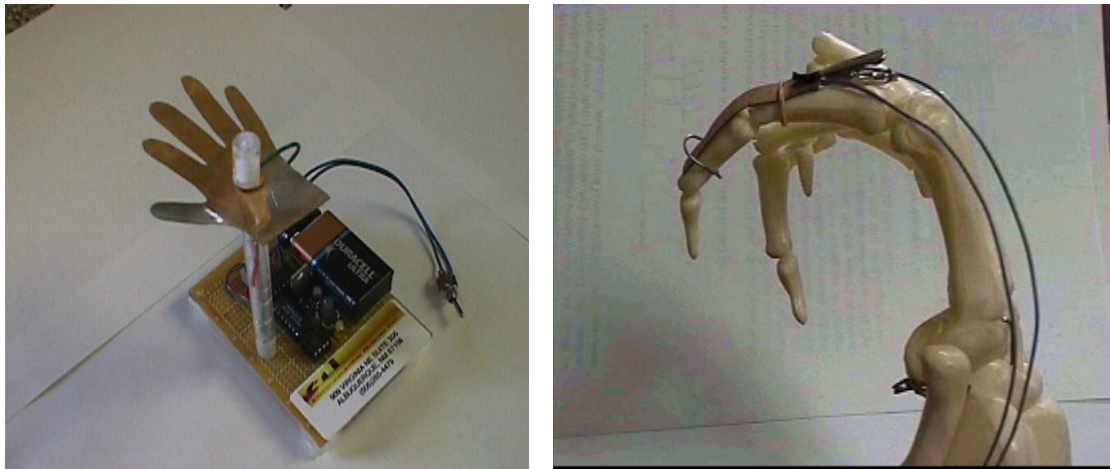
**Figure 35.** Pressure generation versus electrode thickness.

### 3.4. Artificial smooth muscle actuators

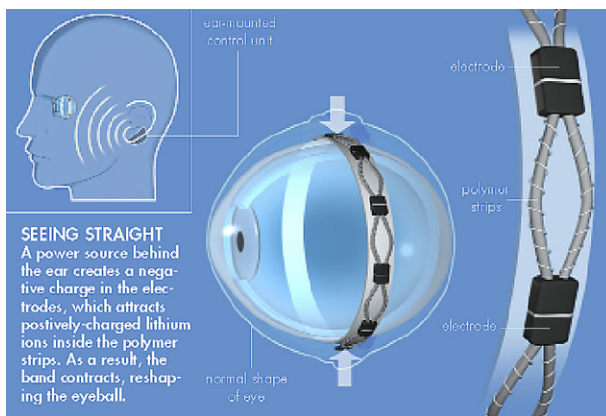
Artificial smooth muscle actuators similar to biological smooth muscles can be made by attaching several segments of tubular sections of IPMC and employing a simple control scheme to sequentially activate each segment to produce a traveling wave of volume change in the combined tube sections. This motion can be used to transport material or liquid contained in the tube volume. The activation of each segment is similar to the peristaltic pump, above. Artificial veins, arteries, intestines made with the IPMC can be fabricated and packaged in variety of sizes depending on the application. Figure 36 shows an artificial smooth muscle actuator that mimics a human hand. It is made with IPMC.

Another method of using IPMC actuators is to package them as human skeletal joint mobility and power augmentation systems in the form of wearable, electrically self-powered, exoskeletal prostheses, orthoses and integrated muscle fabric system components such as jackets, trousers, gloves and boots. These features are intended to improve the quality of a human system and can be extended to power augmentation of attire for advanced soldier and astronaut systems, and prosthetic devices which would empower paraplegics, quadriplegics and disabled and elderly people, as well as a variety of other robotic and medical applications. The essence of the operation of such prostheses, orthoses and wearable attire (smart muscle fabric) is that, for example, a skeletal joint such as the elbow will be equipped with a flexible strip-like bending muscle made from a family of IPMCs. As noted, IPMCs have the ability to sense any dynamic motion imparted to them by generating tens of millivolts of electricity (for a 10 mm × 40 mm × 2 mm synthetic muscle bent by 1 cm in a cantilever configuration) and the same muscle can generate a torque of about 20 gramforce cm, with 9 V and 100 mA, to augment the bending power of a skeletal joint.

Thus, such prostheses, orthoses and smooth muscle fabric systems can be integrated devices equipped with both sensing and actuation that can be used for positive feedback robotic control for the mobility of any joint such as the knee, elbow, shoulder, neck, hip or fingers. Integrated



**Figure 36.** An artificial smooth muscle actuator that mimics a human hand (left) and a fabricated human joint mobility and power augmentation system equipped with IPMCs (right).



**Figure 37.** The essential operation of the active scleral band to create bionic vision.

smooth muscle systems shown in figure 36 as integrated joint power augmentation muscle systems are capable of carrying distributed loads.

### 3.5. Artificial sphincter and ocular muscles

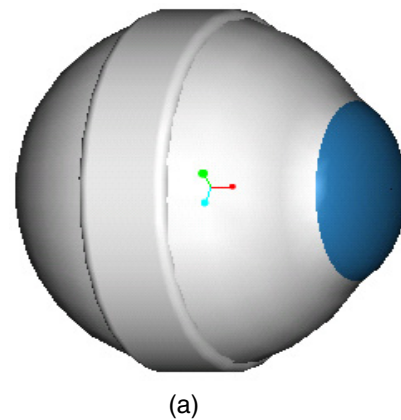
Artificial sphincter and ocular muscles can also be made from the IPMC by incorporating thin strips of the actuators in a bundle form similar to the parallel actuator configuration.

### 3.6. Incontinence assist devices

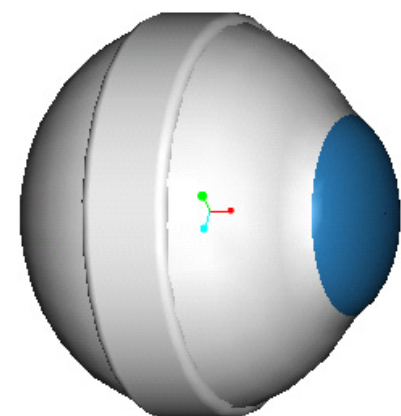
Various configurations of IPMC may be used in medical applications involving incontinence. In these systems, a patient can activate the muscles by means of a push-button switch or the like to prevent leakage, and control discharge by pressing a switch, which is preferably battery operated.

### 3.7. Correction of refractive errors of the human eyes and bionic eyes and vision

Various configurations of IPMC may be used in medical applications involving dynamic or static surgical corrections of the refractive errors of the mammalian eyes.



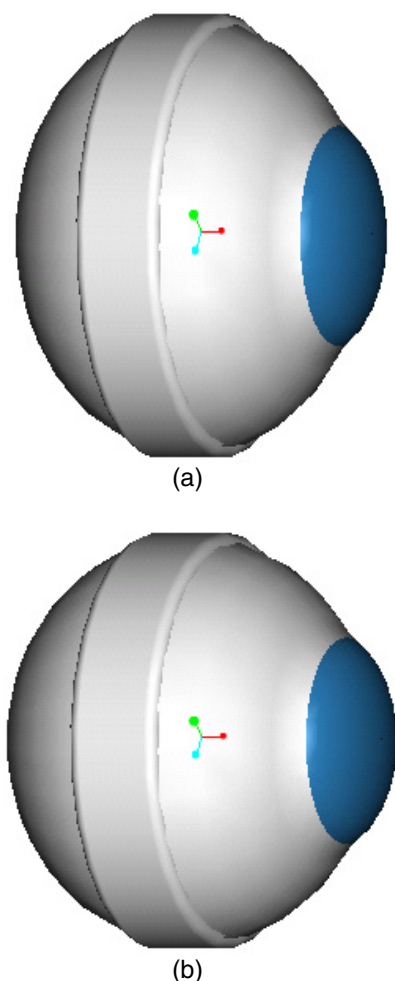
(a)



(b)

**Figure 38.** The eye in (a) is myopic (long and thus short-sighted; the image is formed inside the eye and does not reach the macula). The band expands the sclera outward to correct myopia (shorten the eye length and decrease corneal curvature) as in (b).

Described here is an apparatus and method to create either an automatic or on-demand correction of refractive errors in the eye by the use of an active and smart (computer-controllable) scleral band equipped with composite IPMC artificial muscles. The scleral band is an encircling band around the middle of the



**Figure 39.** The eye in (a) is hyperopic (short and thus far-sighted; the image is formed outside and beyond the eye and does not reach the macula). The band contracts the sclera inward to correct hyperopia (increase the eye length and increase corneal curvature) as in (b).

eye's globe to provide relief of intraretinal tractional forces, in the case of retinal detachment or buckle surgery, by indentation of the sclera as well as repositioning of the retina and choroids. It can also induce myopia, depending on how much tension is placed on the buckle, by increasing the length of the eye globe in the direction of the optical axis and changing the corneal curvature. By using the same kind of encircling scleral band, even in the absence of retinal detachment, one can actively change the axial length of the scleral globe and the corneal curvature in order to induce refractive error correction.

Figure 37 depicts the proposed surgical correction of refractive errors by active scleral bands to create bionic eyes. The band has a built-in coil to be energized remotely by magnetic induction and thus provide power for the activation of IPMC muscles.

The active composite artificial muscle will deactivate on command, returning the axial length to its original position and vision back to normal (emmetropic vision). Figure 38 depicts the general configuration for surgical correction of myopia while figure 39 depicts the general configuration for surgical correction of hyperopia or prebyopia.

#### 4. Concluding remarks

As the demand for energy grows, the need for more efficient and convenient energy conversion devices increases. One area of improvement is the use of direct energy conversion processes and devices. Smart materials are the foundation of current state-of-the-art devices to convert energy from chemical or electrical into mechanical energy to perform useful work. In the field of sensing, these devices can provide an efficient way of converting mechanical energy into electrical or chemical forms. The work presented in this paper summarizes efforts on a number of potential applications of ionic polymer–metal composite that have proven to be a viable alternative to conventional means. The application of these materials shows great promise as alternatives for use in robotics, biotechnology and industrial applications.

#### Acknowledgments

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