Artificial muscles driven by the cooperative actuation of electrochemical molecular machines. Persistent discrepancies and challenges

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ABSTRACT
Here we review the persisting conceptual discrepancies between different research groups working on artificial muscles based on conducting polymers and other electroactive material. The basic question is if they can be treated as traditional electro-mechanical (physical) actuators driven by electric fields and described by some adaptation of their physical models or if, replicating natural muscles, they are electro-chemo-mechanical actuators driven by electrochemical reaction of the constitutive molecular machines: the polymeric chains. In that case the charge consumed by the reaction will control the volume variation of the muscular material and the motor displacement, following the basic and single Faraday’s laws: the charge consumed by the reaction determines the number of exchanged ions and solvent, the film volume variation to lodge/expel them and the amplitude of the movement. Deviations from the linear relationships are due to the osmotic exchange of solvent and to the presence of parallel reactions from the electrolyte, which originate creeping effects. Challenges and limitations are underlined.

Introduction
Most of the technological expectancies to develop soft robotics using artificial muscles from conducting polymers and other electroactive materials working at low, or very low, voltages have advanced very slowly. Here electroactive means that the muscular material follows reversible electrochemical reactions in presence of an electrolyte, liquid or solid. In this review we present some of the persisting conceptual discrepancies between different research groups that could be the origin of this slow development.

Natural muscles
Natural muscles are elegant natural devices developed through millions of years of biological evolution to transform chemical energy into mechanical energy and heat. The muscle contraction is a result of the cooperative actuation of molecular (macromolecular) machines...
(actin-myosin) driven by a chemical reaction, the hydrolysis of ATP to ADP, and triggered by an electric pulse arriving from the brain (brain order) and liberating Ca\(^{2+}\) ions inside the sarcomere: natural muscles are electro-chemo-mechanical devices. The basic actuating unit of a muscular cell (the sarcomere) is a dense gel constituted by molecular chemical machines working in aqueous solution. The actuation of a natural muscle involves: a) aqueous media, b) an electric pulse arriving from the brain (the pulse generator) to the muscle through the nervous system, c) liberation of calcium ions inside the sarcomere (ionic exchange), d) chemical reactions, e) reaction-driven conformational changes of the natural polymeric chains (actin and myosin) and d) water exchange for osmotic balance [1,2].

The human technology has been trying to reproduce those movements using electromagnetic motors, internal explosion devices, steam engines, hydraulic devices or solid-state physical actuators. Any machine containing those motors produces quite rudimentary movements and a lot of noise (acoustic and electromagnetic), when compared with animal movements, or movements of low amplitude from physical actuators.

Polymeric actuators: multielectronic molecular machines

In order to replicate natural muscles we need, in a first stage, an electroactive dense gel constituted by molecular chemical machines driven by electric pulses replicating, in its simplest expression, the intracellular matrix (ICM) of the muscular cell. At the moment our knowledge and control of actin gels and myosin actuators doesn´t allow the construction of macroscopic motors [2–5]. The discovery of artificial molecular machines driven by electrical, chemical, optical, and other energetic pulses from the eighties of the past century has received the Nobel Prize of chemistry 2016 [6–11]. In parallel new carbon based materials: conducting polymers, fullerenes, carbon nanotubes or graphenes, were discovered. Films from those materials are electronic conductors and electroactive: when used as a working electrode in liquid electrolytes they can be oxidized and reduced in a reversible way by extraction, or injection, of consecutive electrons (one by one) from/towards every polymeric chain or carbonaceous structure. Thus, during the material oxidation consecutive positive charges (radical cations, using the chemical terminology, or polarons, using the physical terminology) are generated on every chain by extraction of consecutive electrons. The reaction changes the conformational structure of the chain: the σ bonds between every two consecutive monomeric units, allowing their free rotation to get different conformational states, change to a planar π conjugated structure (the polaron or radical cation) involving several (3–5) monomeric units. The extraction of consecutive electrons from an independent chain drives consecutive conformational movements of the chain from a coil-like structure to a stick like structure (Figure 1). Increasing energies corresponding to the first, second, third… nth ionization potentials of the chain are required to extract the consecutive electrons. Simultaneously consecutive anions are attracted from the solution to surround the chain for charge compensation. The final result of the reaction is similar to the presence of a linear electrical double layer (EDL), positive charges distributed along the chain and anions in solution around the chain. By electrochemical reduction with injection of consecutive electrons to the chain reverse events and conformational movements of the chain are
produced. The chain becomes a reversible electrochemical (multielectronic) molecular machine (Figure 1) [12–14].

**Reaction-driven cooperative actuation of molecular machines in a film**

Inside the film electrode the cooperative actuation, driven by oxidation (or reduction) of the entangled constitutive molecular machines generates (or destroys) the required free volume to lodge (or expel) the number of monovalent anions, penetrating from (or expelled towards) the solution, needed to compensate the generated (or annihilated), respectively, polaronic charges on chains. The driving reaction 1 only can happen if both, electronic and ionic exchanges occur simultaneously:

\[
[\text{Pol}^{\ast}] + n\text{A}^-_{\text{solv}} + p\text{S}_{\text{solv}} \iff [(\text{Pol})^{n\ast}](\text{A}^-)_n (\text{S})_{p\text{gel}} + n(e^-)_{\text{metal}}
\]

Where *Pol* represents every active center on the film polymeric chains where a positive charge will be generated by extraction of one electron after oxidation; \( \text{A}^-_{\text{solv}} \) are the anions from the salt, solved (solv subindex) and dissociated, present in the electrolyte; \( \text{S}_{\text{solv}} \) are solvent molecules present in the electrolyte; \( e^- \) represents the exchanged electrons, the subindex *gel* indicates a dense gel structure and the subindex *metal* means that the electronic exchange from the polymer chains and imposed by the potentiostat-galvanostat occurs through the connecting metal wire.

The presence of those charges (polarons and counterions) inside the film breaks the osmotic balance between the film and the solution. The generated osmotic pressure drives the entrance of solvent molecules (S) from the solution in order to reestablish the osmotic balance. This is a physical process driven by the electrochemical generation/destruction of charges in the film.
The material becomes a dense reactive gel constituted by electrochemical molecular machines (every polymeric chain), water and ions replicating, in its simplest version, the basic content of the intracellular matrix (ICM) of a muscular cell [15,16].

**Reaction-driven structural changes of the material: swelling/shrinking**

The cooperative actuation of the film molecular machines during the electrochemical reactions drives macroscopic structural changes of the film: shrinking by expulsion of counterions and solvent towards the solution, structural closing and counterion trapping when the average distance between chains during the material shrinking becomes equal to the diameter of the counterions, conformational compaction by slow expulsion of counterions beyond the closing potential through the soft material, conformational relaxation of the compacted structure to begin the entrance of counterions from the solution and final structural swelling with entrance of counterions and solvent from the solution [17–20].

Summarizing the reaction drives conformational movements of the polymeric chains giving molecular (polymeric) electrochemical machines, and the cooperative actuation of those molecular machines originates macroscopic structural responses. Under electrochemical control they give structural electrochemical (voltammetric, chronoamperometric, chronopotentiometric or coulovoltammetric) responses from conducting polymers [21–25], carbon nanotubes [26,27] or graphenes [28–31].

By similitude with natural muscles the reaction-driven material shrinking/swelling (Figure 2) is being used from the nineties of the past century to produce electrochemo-mechanical actuators: macroscopic and microscopic, giving linear or bending movements [32–67]. The reaction-driven macroscopic changes of volume (Figure 2), the material content (molecular machines, water and ions) and the consecutive event during actuation (electric pulse, chemical reaction, conformational movements, ionic and...
aqueous exchange and macroscopic volume variation) replicate those taking place inside the sarcomere in natural muscles: the devices were named artificial muscles [32].

**Working between nanometric and molecular dimensions**

The final result of the electrochemical reaction 1 driving the movement of the artificial muscles is that counterions and solvent form some kind of linear electrical double layer surrounding every polymeric chain taking part of the reactive gel: an entangled three-dimensional structure of lineal EDLs expands across the full polymer gel. The dimensions of the basic electrode moved beyond micro and nanoelectrodes to the cooperative manipulation of individual molecular machines: every film polymeric chain acts as an individual molecular electrode.

During the last decades through the synthesis, control and manipulation of nanoparticles we have learned that new and unexpected properties are linked to the surface/volume relationship of the materials: new and unexpected properties can merge now by cooperative manipulation and control of electrochemical molecular machines [16]. The molecular dimensions of artificial reactive gels overlap those selected by the biological evolution to develop life and life functions: most of the new properties will replicate those changing in natural organs when move form the rest to the actuation state. One of those properties, the reaction-driven volume variation, gives artificial muscles [46,68–77].

**Persisting conceptual discrepancies**

The above-presented picture only is partially accepted nowadays by the scientific community there involved. Most of the scientists working in the area have a physical or engineering background. In addition electro-mechanical actuators, as solid-state inorganic physical actuators responding to electric fields and not including any chemical reaction, have been developed for over one century. During the last 25 years the field of the electro-chemo-mechanical polymeric actuators (involving chemical reactions) grew in parallel to that of the electro-mechanical polymeric actuators (dry or gels, but never including chemical reactions) [78–81]. The actuation of the electromechanical actuators, that means the generated strains and forces, are proportional to the applied electric field: to $E^2$ for electrostrictive polymers; to $E$, for piezoelectric or ferroelectric polymers, for electrokinetic polymeric gels (electrophoretic or electroosmotic) and for polymeric solutions of salts in solid polymers (coulombic). The charge there involved during actuation of any reversible bending tri-layer actuator (electrode/polymer/electrode) when submitted to consecutive square potential waves is employed to charge/discharge the electrical double layers (EDL) at each of the two electrode/polymer interfaces supporting the potential gradient applied between both electrodes.

A solid theoretical background has been accumulated during the last century to describe those electro-mechanical (physical-driven) actuators. The concomitant physical and mathematical models have been profusely checked by experimental results and technological applications. The temptation is high to treat electro-chemo-mechanical devices as singular cases of electro-mechanical actuators driven by electric fields and described by adaptation of electro-mechanical physical models [36,56,82–101].

Those models try to integrate applied electric fields and mechanical deformations. The charge consumed by electro-chemo-mechanical actuators is included in most of the
cases as a capacitive parameter. Neither the electrochemical reaction driven the volume variation nor the polymeric nature of the reaction occurring through consecutive energetic steps fitting the first, second, third...ionization potentials inducing reversible conformational movement of the polymeric chains are considered there.

**Electro-chemo-mechanical actuators: the charge consumed by reactions of the muscular material drives the actuation**

Nevertheless, for electro-chemo-mechanical actuators the film volume variation is driven, through reaction 1, by the number of ions penetrating from the solution per unit of time altogether the number of solvent molecules following the ionic exchange to restore the osmotic pressure. The balanced reaction 1, quantifies the rate of the ionic (A\(^-\), Ms\(^-1\)) exchange as number of moles, \(n\), exchanged per unit of time, \(t\) (s), which equals (see reaction 1) both, the number of moles \(n\) of positive charges, \(Pol^+\), generated on the polymer chains per unit of time and the number moles \(n\) of electrons, \(e^-\), extracted from the chains per unit of time. Those number of moles \(n\) are obtained from the charge \((Q, C)\) consumed by the reaction and flowing through the system per unit of time; the current \((I, C\text{s}^{-1} = A)\) [102]:

\[
n = \frac{Q}{Ft} = \frac{I}{F} \text{ (M s}^{-1})
\]  

(2)

Where \((Q, C)\) is the charge consumed to drive the reaction 1 during a time \((t, s)\), \((F, C \text{ M}^{-1})\), the charge per electron’s mole is the Faraday constant. Equation (2) states that the rate of the ionic exchange, therefore the rate of the film volume variation required to lodge those ions, occurs under Faradaic control through reaction 1.

Thus, electro-chemo-mechanical actuators or artificial muscles are Faradaic devices: the volume variation (required to lodge/expel exchanged ions and solvent molecules) and the concomitant strain is expected to be a linear function (through Equation (2)) of the charge, \(Q\), consumed by the reaction. The movement rate to go every time from the same initial position to a final position (always the same) must be a function of the ions and solvent exchange rate, controlled (Equation (2)) by the flowing current \((I)\) [103–107]. Therefore the influence of different experimental conditions (temperature, ionic concentration, concentration of active centers, pressure or mechanical conditions) on the muscular actuation will be described by the electrochemical kinetics, i.e. by the Buttler-Volmer equation. As a consequence artificial muscles driven by electrochemical or chemical reactions will respond, during actuation, to any change of the experimental working conditions: they will sense the working conditions.[108, and references therein] One reaction (reaction 1) originates two simultaneous functions: actuation and sensing, mimicking haptic muscles.

**Coulovoltammetric (charge/potential) and dynamovoltammetric (angle/potential responses**

The control of the muscular movement by the charge is unequivocally clarified by checking a bilayer or a triple layer bending artificial muscles by potential cycles (by application of a linear variation of the electric field, one of the methodologies used to check electro-mechanical physical devices) with simultaneous video-recording of the
muscle angular displacements. The coulovoltammetric (evolution of the consumed charge with the applied potential) response, obtained by integration of the voltammetric response (Figure 3(a)), follows the dynamovoltammetric (evolution of the angular displacements with the applied potential) response (Figure 3(b)). Reversing the potential scan rate (Point 1, Figure 3(a)) does not reverse the direction of the bending movement (Figure 3(b)) as expected for an electro-mechanical device: the bending movement goes on, following the persisting increase of the oxidation charge (electrochemical inertia), at the beginning of the cathodic potential sweep. In a similar way after the cathodic potential limit the film reduction-compaction (and the parallel reaction-driven angular displacement of the muscle, Figure 3(b)) goes on, for over 1V, at the beginning of the anodic potential sweep (electrochemical inertia). Due to the slow ionic and conformational movements in the film the system is, at any potential, outside its electrochemical equilibrium described by reaction 1: oxidation and reduction reactions, and the concomitant movements of the artificial muscles, present great electrochemical inertia. The movement of the Faradaic muscles does not follow the changes of the applied potential, they follow the evolution of the consumed charge as described by Equation (2).

As conclusion electro-chemo-mechanical actuators, or artificial muscles, are Faradaic motors transducing electrical energy to mechanical energy through electrochemical

![Figure 3](image-url)

Figure 3. A PPy/tape bilayer muscle was submitted to consecutive potential sweeps from 1.00 V to −2.50 V, at 5 mVs⁻¹ in 0.1 M LiClO₄ aqueous solution. (a) Stationary voltammetric response after three consecutive potential cycles. (b) Parallel evolution of the consumed charge, coulovoltammetric response (black line), and parallel evolution of the angle described by the muscle, voltamodynamics response (dotted red line). (c) Amplitude of the described angle for different consumed charges: coulo-dynamic response. Pictures 1–6 show the bending position of the muscle for the same points, 1 to 6, on figures 2a, 2b and 2c. The last picture overlaps pictures 3, 4 and 5. Reproduced with permission from Ref [109]. Elsevier.
reactions as reaction 1. The movement rate can be characterized by their responses to the flowing current (reaction rate) and the amplitude of the movement is characterized by the muscle response to the charge (reaction extension) consumed by the driving electrochemical reaction 1 (Figure 3(c)). Thus, even when the electro-chemo-mechanical actuator is checked by application of electric fields the mechanical responses must be analyzed as a function of the consumed charge.

How the presence of the material chemical reactions can be unequivocally detected and quantified

Both, electro-mechanical and electro-chemo-mechanical processes consume charge during reversible actuation. Determining the empirical chemical kinetics of the electro-dic material (i.e. conducting polymer) reaction unequivocally identifies the presence of a chemical reaction. Thus, for the driving reaction 1, the oxidation rate ($r_o$ for the forward reaction) is the number of positive charges $n$ (Equation (2)) generated in the polymeric film per unit of volume $(V, L)$ and per unit of time is:

$$r_o = \frac{d[Pol^{+}]}{dt} = \frac{Q}{FtV} = \frac{l}{FV} = k[Pol]^{\alpha}[A]^{\beta} = Ae^{-\frac{E_a}{RT}}[Pol]^{\alpha}[A]^{\beta} (\text{ML}^{-1} \text{s}^{-1}) \quad (3)$$

Where $V$ is the volume of the film reacting inside the solution, $k$ is the reaction coefficient, $\alpha$ and $\beta$ are the reaction orders related to the concentration of active centers on chains inside the polymer film and to the concentration of anions in solution, respectively, and $E_a$ is the activation energy of the reaction. Thus by applying any of the methodologies from the chemical kinetics those magnitudes are attained working at different electrolyte concentrations ($\beta$), different concentrations of the active centers in the film ($\alpha$) and different temperatures ($E_a$) [110,111]. If the material follows Equation (3) any artificial muscle including those materials is, unequivocally, a Faradaic muscle driven by a chemical reaction. The charge of the EDL in electro-mechanical devices never responds to Equation (3).

Overlapping irreversible reactions: hydrogen and/or oxygen evolution from moisture

The charge above considered is, of course, the reversible charge involved in the reversible oxidation/reduction described by reaction 1 for the constitutive conducting polymer. The main problem is that in order to get deeper oxidation states, that means higher reaction charges, by different experimental methodologies used to check the polymeric actuators (consecutive square potential waves, consecutive square current waves or cyclic voltammetry) researchers move the applied potential beyond the water splitting potential range (0 to 1430 mV vs. HRE).

When any artificial muscle is checked in air, the presence of moisture in the ambient is enough, taking into account the great interaction of water vapors with conducting polymers, to be absorbed in the film[60,112–120] or in the checking electrolyte (organic or ionic liquid). Most researchers use intermediate gold or platinum sputtered metal films trying to get most uniform electric fields in the muscle, but those metals are excellent catalyst for both, hydrogen or oxygen production at low cathodic or anodic, respectively, overpotentials [121,122]. Thus, in addition to the reversible reactions
driving the muscle actuation other irreversible reactions as hydrogen evolution, oxygen evolution, or both of them if the experimental potential range is large enough, are present. They consume charge and produce radical intermediates without any contribution to the film volume variation.

Coulomvotammetric (consumed charge-potential) responses from films of conducting polymers or from artificial muscles allow (Figure 4) detecting the presence of those irreversible reactions, the quantification of the charge consumed by each of those reactions and the determination of the cathodic and anodic potentials where the evolution of hydrogen or oxygen, respectively, begins [19]. The artificial muscle is submitted to consecutive potential sweeps from a different cathodic potential limits every time to the same anodic potential limit [123]. Then, keeping a constant cathodic potential limit by changing the anodic potential limit for every experiment. When the anodic and cathodic potential limits do not include hydrogen and oxygen release the coulovoltammetric response is a closed loop (Figure 4(a) QE, response from −0.5 to 0.3 V): the oxidation charge equals the reduction charge. When the cathodic potential limit goes beyond the hydrogen release the coulovoltammetric responses present a closed loop (polymer oxidation/reduction reversible charge) and an open part at the higher cathodic potentials (Figure 4(a), −1.4/0.3 V). The charge difference between both ends \( Q_i \) is the charge consumed by irreversible reduction reactions (hydrogen evolution here). Thus, the hydrogen release begins at the first experimental cathodic potential limit showing the open part of the coulovoltammetric response related to this irreversible reaction. When the anodic potential limit is higher than the oxygen release the QE response is an open loop (Figure 4(b), −0.9/0.8): the charge difference between both ends is the charge consumed by the irreversible oxygen release. Thus, the oxygen release begins at the first experimental anodic potential limit giving the open coulovoltammetric response related to the oxygen evolution.

Figure 4. (a) Closed coulovoltammetric response from a polypyrrole film coating a Pt electrode in 0.1 M NaCl aqueous solution to a potential sweep at 50 mV s\(^{-1}\) from −0.5 to 0.3 V; and open coulovoltammetric response from −1.35 to 0.3 V. \( Q_{\text{redox}} \) is the film reduction/oxidation reversible charge and \( Q_i \), the irreversible cathodic charge consumed by parallel irreversible reduction reactions. (b1) The open loop curve shows the charge involved in a new irreversible oxidation process \( Q_i \) plus the film redox charge; (b2) The closed loop shows the film reversible redox film charge, \( Q_{\text{redox}} \). Reproduced with permission from Ref [19], Wiley.
**Creeping effects**

During both irreversible reactions intermediate radicals are generated, which attack the polymer promoting partial degradation and/or polymeric crosslinking. Any of them modify the polymeric electroactivity: the amplitude of the muscle displacement for the same reaction charge is always the same (is a function of the number of exchanged ions) but shifting the beginning of the displacement between consecutive control cycles: creeping effect [67,124–128]. It doesn’t matter if they are potentiostatic or galvanostatic cycles.

**Both, coulovoltammetric and coulodynamic responses present hysteresis loops: osmotic effects**

The responses charge/displacement or movement rate/current plots are not fully linear (Figure 3(c)), as expected for a Faradaic process controlled by Equation (2). Reaction 1 summarizes two consecutive processes: the Faradaic exchange of ions followed by the osmotic (physical) exchange of solvent [107,129–131]. Due to the slow osmotic process the system is far from the equilibrium and the osmotic exchange of solvent goes on when the flowing charge was stopped or reversed (from anodic to cathodic or vice versa). This fact has been used to quantify the number of solvent molecules exchanged per reaction unit (per electron transfer) [129,132–134]. Developing new methodologies in this area can help to solve in the next future the parallel pending point in biological reactions: determining the number of water molecules exchanged between the cell and the extracellular matrix (ECM) per reaction unit under normal conditions or outside those conditions, i.e. to produce hematomas.

**Technological and biological challenges**

The excellent control of the attained muscular position by the consumed charge and of the muscle movement rate by the applied current makes electro-chemo-mechanical artificial muscles (polymeric motors) one the most promising polymeric actuators for robotic applications. The motors are ready to be used for the development or different mechanical tools for soft robots. They will work, like natural muscles do, driven by chemical or electrochemical reactions of the constitutive molecular machines given so elegant and quite movements as natural muscles do. They will work at constant temperature: not submitted to the Carnots’s servitude of thermal machines.

A new technological world of soft, wet and chemical-driven machines replicating biological organs is envisaged. New products, new companies and high quality jobs are waiting there.

In parallel some of the new results could provide information for a better understanding of how biological organs, working by cooperative actuation of molecular chemical machines, work and how they intercommunicate with brain.

The Faradaic nature of the device allows a mutual benefit from results attained from the studies performed to improve scientific or technological aspects of different Faradaic devices constituted by conducting polymers, carbon nanotubes or graphenes (batteries, smart windows, smart membranes, drug delivery devices and so on). In parallel simultaneous improvements of those device efficiencies, life-time and performances can be attained by using quantitative results related to the electrode volume variations,
reaction-driven conformational and structural changes or solvent exchange, among others, got from the electrochemical characterization of artificial muscles.

**Limitations**

The great experimental and theoretical efforts performed by many research groups to attain technological applications have not attained the expected results. Here we have reviewed one of the possible origins of those scarce practical results. Most of the researchers in the field use for the characterization of the electro-chemo-mechanical artificial muscles the same experimental methodologies used during the last century for electromechanical (physical) actuators. The theoretical description of the attained results was, form most of the laboratories, an extension of those models developed for electromechanical actuators. The models try to integrate Electricity (applied electric fields) and Mechanics (generated deformations); from electrochemical reactions (Electrochemistry) only the consumed charge (without separation of reversible and irreversible) is included (usually as a capacitive parameter). The polymeric nature of the material (Polymer Science) and the osmotic exchange of solvent are avoided. From the personal point of view of this author those facts have complicated the theoretical description and the scientific comprehension of those Faradaic (very single) devices deviating the interest of most of the young researcher towards electro-mechanical polymeric devices and loosing thus most of the efforts needed to overcome the new scientific and technological limitations.

The presence of parallel irreversible reactions during the actuation originates parallel degradation processes and creeping effects, decreasing the mechanical control of the muscles and diminishing their lifetime. Those irreversible reactions need to be identified and characterized in order to develop the concomitant methodologies to eliminate, or to inhibit, them.

The exchanged solvent increases the volume variation per unit of consumed charge: it increases the charge efficiency. It acts as a transducer from the ambient energy to mechanical energy just for free: not consuming charge. Few efforts have been paid for its quantification, characterization and technological exploitation. Even worst, suspecting that it can be the origin of some of the problems most researchers try to eliminate it going towards full solid-state devices. Most of the solvents are, in addition, good plasticizers increasing the rate of the conformational movement, the reaction rate and the movement rate.

The increase of the movement rate by applying rising currents is limited by conformational, structural (polymeric) and diffusional (ionic) rates inside the polymer film. Nevertheless the literature uses to attribute those limitations to polymer/electrolyte surface effects and few efforts have been paid for the characterization of conformational and structural changes as a function of different experimental variables. The present state is that electro-chemo-mechanical actuators are very slow when compared with electro-mechanical (physical) actuators or with chemical-driven natural muscles.

Finally most of those limitations are related to the scientist’s background. The development of new tools and products and the construction of zoomorphic and anthropomorphic tools and robots requires a new generation of scientists (chemists, physicists, engineers, robot designers) having a solid background on those new reactive materials constituted by chemical or electrochemical molecular machines for the manipulation of their biomimetic chemical and physical properties. Universities, colleges and research institutions must implement the concomitant merging courses.
Conclusions

Artificial muscles based on conducting polymers, and other reactive materials (carbon nanotubes, graphenes, fullerenes or synthetic electrochemical molecular machines) work by cooperative actuation of the constitutive electrochemical molecular machines. They are electro-chemo-mechanical actuators: their displacement is controlled by the charge consumed by the electrochemical reaction and the driving current (charge consumed per unit of time) controls the rate of the movement. They are Faradaic devices: according with the Faraday’s law the consumed charge determines, simultaneously, de number of counterions exchanged with the electrolyte for charge balance, the volume variation of the film required to lodge/expel ions and solvent and the concomitant muscular displacement. Deviations from the expected linear relationships (charge/displacement and current/displacement rate) are due to: the osmotic exchange of solvent, a physical effect following the ionic exchange, and to the simultaneous presence of irreversible reactions from the electrolyte, which also originate creeping effects. Scientists having a solid background on the chemical nature of those devices are required to accelerate the development of technological tools and bioreplicating zoomorphic and anthropomorphic electrochemical-driven robots.

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