Sensors and Actuators B 195 (2014) 365–372

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Mechanical awareness from sensing artificial muscles: Experiments and modeling[☆]

Jose G. Martinez, Toribio F. Otero*

Universidad Politécnica de Cartagena (UPCT), Center for Electrochemistry and Intelligent Materials, ETSII, Campus Alfonso XIII, Aulario II, E-30203 Cartagena, Spain

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form
21 December 2013
Accepted 23 December 2013
Available online 24 January 2014

Keywords:
Conducting polymers
Sensing-actuators
Haptic artificial muscles
Theoretical models
Mechanical awareness

ABSTRACT

The theoretical description of electrochemical artificial muscles sensing while working any mechanical perturbation is presented and corroborated by experimental results. The polymeric motors sense (haptic motors) any variable acting on the driving chemical reaction rate. Only two connecting wires contain, and the computer reads at any time of the movement, actuating (current) and sensing (potential or energy) magnitudes. The computer/generator/muscle system mimics brain/muscles feedback communication. Based on electrochemical and polymeric principles, a multifunctional sensing-actuating equation is attained, including information about: the movement rate, the muscle position, the chemical ambient, the working temperature and the mechanical perturbations. The equation describes the artificial experimental mechanical awareness and proprioception and the quantitative relationships between actuating and sensing variables. Most intelligent and simplest zoomorphic and anthropomorphic tools and robots are envisaged.

1. Introduction

Any human being trailing an object grasped in his hand is aware at any time (even if he cannot see it) of: the weight of the object; the force required to keep it grasped without breaking it; how transferring it the required mechanical energy and direction to get a goal located at a distance; the magnitude of the transferred energy; the exact position, at any moment and related to any other body's part, of the hand; the rate and direction of the movement; the fatigue state of the arm muscles, or the presence of obstacles in the arm's way during the movement (Fig. 1A). The feedback communication between muscles and brain originates the human (and mammals) mechanical awareness: the brain proprioception of the body–arm–surroundings mechanical interactions during the movement [1–3].

Today artificial haptic devices, haptic virtual interfaces and haptic artificial skins, are constituted by separated sensors and actuators, each requiring two connecting wires [4,5]. Engineers and robot designers have been dreaming for decades with the availability of motors sensing, by themselves, physical and chemical ambient variables (as natural muscles do) for the construction of smarter and simpler tools and robots. Despite continuous and clever advances, powerful-limiting barriers persist. On one side our technological motors and sensors are constituted by solid and dry components that keep a constant composition during actuation: they are thermo-mechanical motors submitted to the Carnot's efficiency servitude. On the other side soft and wet materials (dense gels) constitute the functional cells of natural muscles, nerves and brain working at the constant body's temperature (outside the Carnot's servitude). They are driven by chemical reactions, triggered by electrical (ionic) nervous signals and they sense (haptic) the working mechanical, thermal and chemical conditions: they are sensing chemical motors.

A plethora of inorganic and organic actuators have been developed during the last 30 years [6–8]. The artificial muscles based on polymeric materials are the closest ones to natural muscles [9–16]. Among those, conducting polymers include ions and water exchange under actuation driven by electrochemical reactions. Their mechanical performance [17] is being improved by the use of interpenetrated polymer networks [18], by using polyelectrolytes or plasticizers [19] or by studying the influence of ions and solvents [20–23] on the actuation.

Here our aim is to demonstrate, theoretically and empirically, that artificial muscles [24,25] constituted by dense gels of conducting polymers and driven by electrochemical reactions (polymeric electrical motors) can sense by themselves while working (not requiring additional sensors) any mechanical perturbation: they can mimic haptic natural muscles (Fig. 1B). Starting from basic

---

[☆] This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-No Derivative Works License, which permits non-commercial use, distribution, and reproduction in any medium, provided the original author and source are credited.

* Corresponding author. Tel.: +34 968325519; fax: +34 968325915.
E-mail address: toribio.fotero@upct.es (T.F. Otero).

0925-4005/$ – see front matter © 2014 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.snb.2013.12.099

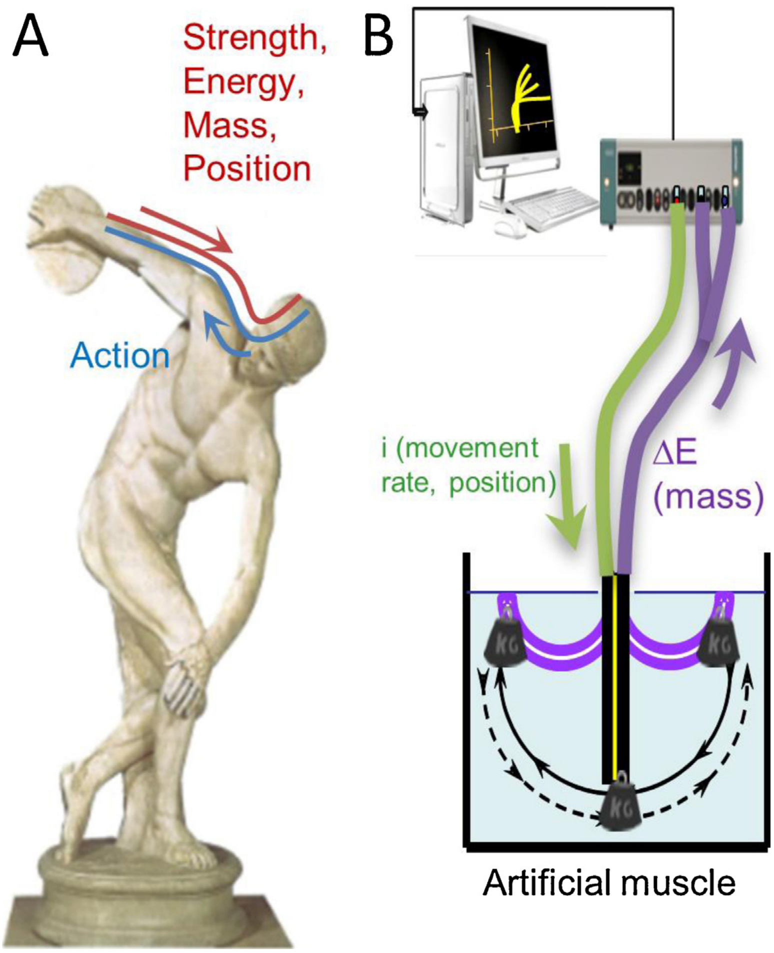

Fig. 1. (A) Human mechanical awareness and (B) artificial expected mechanical awareness from artificial muscles.

electrochemical and polymeric principles we will try to get a physical–chemical equation able to describe the multifunctional system including the characteristic magnitudes of the working motor and those of the mechanical sensors, constituting a mathematical description of the artificial mechanical awareness.

1.1. Driving chemical reaction

Artificial muscles based on the electrochemistry of the constitutive chains of conducting polymers (Pol) exchanging anions (A^-) with the solution (sol) for charge balance in the film are driven by the reaction:

$$(\mathrm{Pol}^*)_s + n(A^-)_{\mathrm{sol}} + m(S) \underset{\mathrm{red}}{\overset{\mathrm{ox}}{\rightleftarrows}} [(\mathrm{Pol})^{n+}(A^-)_n(S)_m]_{\mathrm{gel}} + ne^- \qquad (1)$$

where Pol* represents the active centers of the polymeric chains that will store a positive charge after oxidation, subindex *s* means solid, the exchanged solvent (*S*, water in this case) balance the osmotic pressure in the gel. Forwards and backwards reactions drive molecular (conformations) or macroscopic (relaxation, swelling, shrinking and compaction) structural changes [26,27].

1.2. Gel reactions sense physical and chemical ambient

The Le-Chatelier principle [28] can be applied to the chemical equilibrium 1 that, after reformulation, can be applied outside the chemical equilibrium to the forwards or backwards reaction: any chemical or physical (mechanical here) perturbation of the electrochemical reaction rate (driving here the muscle movement rate) shifts the reaction overpotential (energy of the electrons in reaction (1)) to fit the new imposed energetic requirements. This new formulation is deduced from the empirical responses got in the past decade from artificial muscles driven by constant currents and recently reviewed [29,30]: the muscle potential at any described position (or the electrical energy consumed to attain that position) senses while working, electrolyte concentration, temperature, driving current, obstacles or trailed weight.

1.3. Artificial reactive muscles are faradaic polymeric sensing-motors

Bending artificial muscles constituted by active conducting polymers are faradaic devices [27,31,32]: the driving specific current, i ($\mathrm{A\,g^{-1}}$), controls the rate of the angular movement, $\omega = k{\cdot}i$ ($\mathrm{rad\,s^{-1}}$), and the consumed specific charge during the movement controls both, the angular position and the amplitude of the displacement, $\alpha = k_1{\cdot}q$ (rad), where k ($\mathrm{rad\,A^{-1}\,s^{-1}}$) and k_1 ($\mathrm{rad\,C^{-1}}$, or $\mathrm{rad\,A^{-1}\,s}$) are characteristic constants of the system being q the consumed specific charge ($\mathrm{C\,g^{-1}}$).

Both, actuating (current, i) and sensing (muscle potential, E) magnitudes are present (and can be read by the computer at any time) in the two connecting wires needed to close the electrical circuit. The system computer/generator/artificial muscle mimics the brain/muscles feedback sensing/actuating communication [33,34].

Our aim now is to provide engineers, materials scientists, biologists and robot designers with a theoretical description of