

# Artificial Muscles

## Applications of Advanced Polymeric Nanocomposites

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# Prologue

In this book, thorough reviews of existing knowledge in connection with ionic polymeric conductor nanocomposites (IPCNCs)—including ionic polymeric metal nanocomposites (IPMNCs) as biomimetic distributed nanosensors, nanoactuators, nanotransducers, nanorobots, artificial muscles, and electrically controllable intelligent polymeric network structures—are presented. Two brief introductory appendices on biological muscles are also presented to offer short reviews of how biological muscles work, how biomimetic actuator materials in general have been developed based on biological muscles, and how the latter are limited in their performance compared with biological muscles. This is intended to help provide motivation to understanding as well as a means of comparison for artificial muscle materials to be discussed and analyzed in this book.

Where possible, comparisons have been made with biological muscles and applications in noiseless, biomimetic marine propulsion and unmanned aerial vehicles (UAVs) and flapping-wing systems using such electroactive polymeric materials. Furthermore, the book introduces and discusses in detail methods of fabrication and manufacturing of several electrically and chemically active ionic polymeric sensors, actuators, and artificial muscles, such as polyacrylonitrile (PAN), poly(2-acrylamido-2-methyl-1-propanesulfonic) acid (PAMPS), and polyacrylic-acid-*bis*-acrylamide (PAAM), as well as a new class of electrically active composite muscles such as IPCNCs or IPMNCs. These discoveries have resulted in seven U.S. patents regarding their fabrication and application capabilities as distributed biomimetic nanoactuators, nanosensors, nanotransducers, nanorobots, and artificial muscles.

In this book, various methods of IPMNC manufacturing and fabrication are reported. In addition, manufacturing and characterization of PAN muscles are discussed. Conversion of chemical activation to electrical activation of artificial muscles using chemical plating techniques is described. Furthermore, other methodologies, such as physical/chemical vapor deposition methods or physical loading of a conductor phase into near boundary of such materials, are briefly discussed. The technologies associated with pH-activated muscles like PAN fibers have also been detailed. Experimental methods are described to characterize contraction, expansion, and bending of various actuators using isometric, isoionic, and isotonic characterization methods.

Several apparatuses for modeling and testing the various artificial muscles have been described to show the viability of application of chemoactive as well as electroactive muscles. Furthermore, fabrication methods of PAN fiber muscles in different configurations (such as spring-loaded fiber bundles, biceps, triceps, ribbon-type muscles, and segmented fiber bundles) to make a variety of biomimetic nanosensors and nanoactuators have been reported here.

Theories, modeling, and numerical simulations associated with ionic polymeric artificial muscles' electrodynamics and chemodynamics have been discussed, analyzed,

and modeled for the manufactured material. The book concludes with an extensive chapter on all current industrial and medical applications of IPMNCs as distributed biomimetic nanosensors, nanoactuators, nanotransducers, nanorobots, and artificial muscles.

**Mohsen Shahinpoor  
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# Symbols

<b>a</b>	Maximum swelled distance from the center of the gel
<b>B</b>	Reduced electric potential
<b>b</b>	Polyion separation distance
<b>b<sub>i</sub></b>	Spacing between <i>i</i> th row of polyion segments
<b>C</b>	Total ion-exchange capacity, mL/g dry membrane; also, gel cylindrical sample half radial thickness
<b>C<sub>p</sub></b>	Power coefficient
<b>C<sub>T</sub></b>	Thrust coefficient
<b>C<sub>g</sub></b>	Specific capacitance of the gel, F/g
<b>C<sub>mi</sub></b>	Fourier coefficients
<b>C<sub>oi</sub></b>	Fourier coefficients
<b>c<sub>i</sub></b>	Concentration of the <i>i</i> th species
<b>D</b>	Dielectric constant of the liquid phase; also, drag force
<b>D<sub>eff</sub></b>	Effective diffusivity coefficient in cm <sup>2</sup> /sec
<b>D<sub>0</sub></b>	Diameter of cylindrical polymer sample
<b>ΔE</b>	Driving force pumping ions; also, gradient of electric field
<b>e</b>	Electron charge, $1.602 \times 10^{-19}$ C
<b>E</b>	Young's modulus
<b>F</b>	Total free energy; also, force performing mechanical work; also, force produced in the gel; also, mean coulomb attraction/repulsion forces associated with $R^*$
<b>F<sub>0</sub></b>	Force during isometric contraction
<b>ΔF</b>	Free energy decrease as a result of contact between two polymer networks
<b>F<sub>e</sub></b>	Free energy due to work done against electric field
<b>F<sub>g</sub></b>	Free energy due to gel deformation
<b>f</b>	Frequency, Hz; also, number of ionized segments out of $N_0$ total; also, friction coefficient between polymer network and liquid medium
<b>G</b>	Shear modulus
<b>g</b>	Local gravity acceleration, 9.81 m/s <sup>2</sup>
<b>H</b>	Total amount of hydrogen ions (including undissociated)
<b>h</b>	Hydrogen ion concentration
<b>h̄</b>	Hydrogen ion concentration inside the membrane
<b>I</b>	Electric current, A
<b>i</b>	Current density of the gel
<b>K</b>	Dissociation constant; also, modified Bessel function
<b>k</b>	Proportionality constant; also, Boltzmann constant, $1.381 \times 10^{-23}$ J/K; also, bulk elastic modulus of the gel polymeric component
<b>L</b>	Gel length when fully swollen
<b>L<sub>0</sub></b>	Length of cylindrical polymer sample

<b>I</b>	Uniaxial elongation of muscle fiber
<b><math>N_0</math></b>	Number of freely jointed segments of polymer
<b>n</b>	Number density of counter-ions; also, number of polyions
<b><math>n_i</math></b>	Number density of ions for the <i>i</i> th species
<b>P</b>	Pressure term, N/m <sup>2</sup> ; also, hydrostatic pressure term
<b>pH</b>	A measure of acidity or alkalinity of solution
<b>Q</b>	Electric charge, C; also, charge per unit mass or specific charge of the gel, C/g
<b>q</b>	Electric charge, C; also, degree of swelling
<b><math>q_n</math></b>	Quantity of mobile ions
<b>R</b>	Electric potential field per unit charge
<b><math>R_+</math></b>	Electric potential field corresponding to positive charges
<b><math>R_-</math></b>	Electric potential field corresponding to negative charges
<b><math>R^*</math></b>	Total electric field due to all strands of polymer network
<b><math>R_g</math></b>	Specific resistance of the gel, Ω/g
<b>Re</b>	Reynolds number
<b>r</b>	Hydrodynamic frictional coefficient; also, radius of ionic gel sample
<b><math>r^*</math></b>	Mean radius of ionic gel sample
<b><math>r_i</math></b>	Inner radius of elemental cylinder in gel fiber; also, cylindrical polar coordinate
<b><math>r_o</math></b>	Outer radius of elemental cylinder in gel fiber
<b>S</b>	Total amount of salt cation; also, entropy in thermodynamic context; also, wetted surface area in fluid mechanics
<b><math>S_w</math></b>	Linear swelling ratio
<b>s</b>	Concentration of salt cation
<b><math>\bar{s}</math></b>	Concentration of salt cation inside the membrane
<b>T</b>	Absolute temperature, K; also, thrust force, N
<b>t</b>	Time, s
<b><math>t^*</math></b>	Thickness of gel cylindrical sample
<b>U</b>	Total internal energy, J; also, steady-state velocity term
<b><math>u_0</math></b>	Percent change of sample dimension at final state
<b><math>u_{ij}</math></b>	Displacement vector of the gel elemental volume from its position when the swelling process has gone to completion
<b>V</b>	Water volume; also, volume in thermodynamic sense; also, velocity of contraction
<b><math>V_p</math></b>	Volume of the dry polymer sample
<b><math>V_T</math></b>	Total volume
<b><math>\bar{V}</math></b>	Water volume inside the membrane
<b>v</b>	Voltage across the thickness of the gel, V
<b>W</b>	Dry weight of the muscle membrane or gel
<b><math>w_0</math></b>	Water content of the muscle membrane, ml/g
<b>X</b>	Total concentration (dissociated and undissociated) of weak acid groups in the membrane
<b>Z</b>	Distance of an element from free end of the gel; also, number of ionizable groups
<b><math>Z_i</math></b>	Cylindrical polar coordinate

$\Delta Z_0$	Elemental disk thickness before applied electricity
$z$	Valance number
$z_i$	Valance of the $i$ th species
$\alpha$	Degree of dissociation; also, degree of ionization; also, factor increasing $D_0$ after application of electricity
$\beta$	Factor increasing $\Delta Z_0$ after application of electricity; also, chemical stress term
$\beta_m$	Positive root of Bessel function of order zero
$\Gamma$	Modified Bessel function
$\Delta$	Thickness term
$\delta_{ij}$	Mechanical strain
$\epsilon$	Dielectric constant; also, electric field energy; also, average electric charge
$\eta$	Fish propulsion efficiency
$\theta$	Cylindrical polar coordinate angle
$\Phi$	Contraction rate of the gel
$\phi$	Volume fraction of the polymer network
$\phi_0$	Concentration of polymer (no interaction between segments or reference states)
$\kappa$	Inverse of Debye length or effective thickness of the ionic layer surrounding the charge sites of the individual fibrils; also, phenomenological coefficient
$\lambda$	Dimensionless parameter relating to $\beta$
$\mu$	Shear modulus; also, average mobility of the medium in the gel; also, solvent viscosity
$\mu_h, \mu_s$	Hydrogen-ion and salt-cation mobility
$\mu_i$	Chemical potential (energy) for the $i$ th species
$\xi$	Positive root of Bessel function of order zero
$\rho$	Density of liquid solvent
$\rho^*$	Charge density
$\sigma_{ij}$	Tensile stress, $\text{N}/\text{m}^2$
$\tau$	Reduced temperature
$v$	Number of polymers cross-linked in the network; also, velocity of contraction of the gel; also, three-dimensional liquid velocity vector
$\psi$	Local electrostatic potential

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# Acronyms

<b>AMPS</b>	2-Acrylamido-2-methyl-1-propanesulfonic acid monomer
<b>CAM</b>	Composite artificial muscles
<b>DLVO</b>	Combination double-layer forces and Van der Waals forces in ionic gels
<b>HEMA</b>	2-Hydroxyethyl methacrylate
<b>IEM</b>	Ion-exchange membrane
<b>IEM-Pt</b>	Ion-exchange membrane platinum
<b>IEMMC</b>	Ion-exchange membrane metal composite
<b>IEMPC</b>	Ion-exchange membrane platinum composite
<b>IPCC</b>	Ionic polymeric conductor composite
<b>IPCNC</b>	Ionic polymeric conductor nanocomposite
<b>IPMC</b>	Ionic polymeric metal composite
<b>IPMNC</b>	Ionic polymer–metal nanocomposite
<b>MBAA</b>	N, N'-Methylene- <i>bis</i> -acrylamide
<b>PAAM</b>	Polyacrylic acid <i>bis</i> -acrylamide
<b>PAM</b>	Polyacrylamide
<b>PAMPS</b>	Poly2-acrylamido-2-methyl-1-propanesulfonic acid
<b>PAN</b>	Polyacrylonitrile
<b>PANI</b>	Polyaniline
<b>PPy</b>	Polypyrrol

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