Artificial Muscles

Applications of Advanced Polymeric Nanocomposites

Mohsen Shahinpoor
School of Engineering and School of Medicine
University of New Mexico
Albuquerque, New Mexico, USA

Kwang J. Kim
College of Engineering
University of Nevada-Reno
Reno, Nevada, USA

Mehran Mojarrad
Pharmaceutical Delivery Systems
Eli Lilly & Company
Indianapolis, Indiana, USA

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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
Kwang J. Kim
Mehran Mojarrad

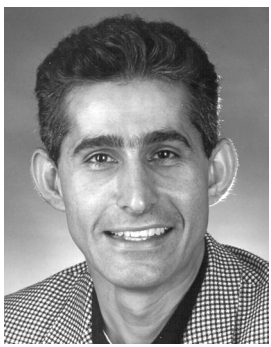
The Authors

Mohsen Shahinpoor is the chief scientist and director of biomedical products at Environmental Robots Incorporated. He is a Regents Professor for Life at the University of New Mexico's School of Engineering and School of Medicine, Neurological Surgery Department. He graduated from the Abadan Institute of Technology with a B.Sc. degree in chemical and materials engineering and received his M.Sc. and Ph.D. degrees in mechanical and aerospace engineering from the University of Delaware. Currently, Dr. Shahinpoor is also director of the Artificial Muscles Research Institute (AMRI). He is the former director of the Intelligent Materials, Structures and Systems Laboratory and the CAD/CAM, CIM and Robotics Laboratories in the University of New Mexico School of Engineering, where he served as chairman of the Mechanical Engineering Department and associate dean of engineering.

Dr. Shahinpoor has served as principal research scientist at the Johns Hopkins and Northwestern Universities and as visiting professor at the California Institute of Technology. He is a fellow of ASME, fellow of the Institute of Physics (IOP), licensed professional engineer, senior member of SME, and member of the New York Academy of Sciences. Professor Shahinpoor has been involved with the field of intelligent robotic systems for the past 22 years and the field of smart/intelligent materials, structures, and systems for the past 15 years. He has made significant advances in the area of electrically controllable artificial muscles for medical and industrial applications using ionic polymeric metal or conductor nanocomposites, as well as distributed nanosensors, nanoactuators, and artificial muscles. He has produced numerous publications and patents on these subjects.

Kwang J. (Jin) Kim is associate professor in the Mechanical Engineering Department and director of the Active Materials and Processing Laboratory (AMPL) at the University of Nevada, Reno (UNR). He graduated from Yonsei University, Korea, in 1987 and received his M.S. and Ph.D. degrees from Arizona State University in 1989 and 1992, respectively. Later, he completed postdoctoral study at the University of Maryland, College Park (1993–1995). His industrial experience includes senior research engineer at Thermal Electric Devices, Inc. (1995–1997) and chief scientist at Environmental Robots, Inc. (1997–2001), Albuquerque, New Mexico. From 1996 to 2001, he also was an adjunct professor at University of New Mexico (1996–2001). His research interests are in

active materials/sensors and energy systems. He has authored or coauthored more than 180 technical papers. He is a recipient of the 2006 UNR Lemelson Award for Innovation and Entrepreneurship, the 2002 Ralph E. Powe Junior Faculty Enhancement Award from Oak Ridge Associated Universities, and the 1997 Best Paper Award of ASME/Advanced Energy Systems/HPTC.



Mehran Mojarrad is a project management consultant for Eli Lilly and Company, where, as a member of the advanced development team, he has supported development of new devices for large and small molecule drug delivery for a variety of therapeutics markets. Dr. Mojarrad is the technical lead in advanced drug delivery technologies including nanotechnology application in targeted drug delivery, transdermal delivery, infusion pumps, injection pens, needle-free injection pens, mucosal delivery, lingual delivery, pulmonary drug delivery, ophthalmic delivery, implants, and MEMS based drug delivery technologies. He graduated from the University of Maryland, College Park, with a B.S. in mechanical engineering and received his M.S. and Ph.D. degrees in mechanical engineering from the University of New Mexico, Albuquerque.

Dr. Mojarrad has more than 18 years of industrial and 6 years of academic research and teaching experience including smart materials, biomimetic robotics, biomedical devices, naval propulsion, semiconductor device manufacturing, and rapid prototyping. He also founded two high-technology materials and robotics companies supporting advanced materials applications in robotics, propulsion, and medical devices. Dr. Mojarrad is coauthor of *Ionic Polymer Conductor Composite Artificial Muscles* (ERI/AMRI Press, 2004) and has published more than 13 articles in professional journals. He is a member of ASME, AIAA, SPIE, Sigma Xi, and SVC.

List of Figures

Symbols

a	Maximum swelled distance from the center of the gel
B	Reduced electric potential
b	Polyion separation distance
$\mathbf{b_i}$	Spacing between *i*th row of polyion segments
C	Total ion-exchange capacity, mL/g dry membrane; also, gel cylindrical sample half radial thickness
$\mathbf{C_p}$	Power coefficient
$\mathbf{C_T}$	Thrust coefficient
$\mathbf{C_g}$	Specific capacitance of the gel, F/g
$\mathbf{C_{mi}}$	Fourier coefficients
$\mathbf{C_{oi}}$	Fourier coefficients
$\mathbf{c_i}$	Concentration of the *i*th species
D	Dielectric constant of the liquid phase; also, drag force
$\mathbf{D_{eff}}$	Effective diffusivity coefficient in cm^2/sec
$\boldsymbol{D_0}$	Diameter of cylindrical polymer sample
$\boldsymbol{\Delta E}$	Driving force pumping ions; also, gradient of electric field
e	Electron charge, 1.602×10^{-19} C
E	Young's modulus
F	Total free energy; also, force performing mechanical work; also, force produced in the gel; also, mean coulomb attraction/repulsion forces associated with R^*
$\boldsymbol{F_0}$	Force during isometric contraction
$\boldsymbol{\Delta F}$	Free energy decrease as a result of contact between two polymer networks
$\mathbf{F_e}$	Free energy due to work done against electric field
$\mathbf{F_g}$	Free energy due to gel deformation
f	Frequency, Hz; also, number of ionized segments out of N_0 total; also, friction coefficient between polymer network and liquid medium
G	Shear modulus
g	Local gravity acceleration, 9.81 m/s^2
H	Total amount of hydrogen ions (including undissociated)
h	Hydrogen ion concentration
$\boldsymbol{\bar{h}}$	Hydrogen ion concentration inside the membrane
I	Electric current, *A*
i	Current density of the gel
K	Dissociation constant; also, modified Bessel function
k	Proportionality constant; also, Boltzmann constant, 1.381×10^{23} J/K; also, bulk elastic modulus of the gel polymeric component
L	Gel length when fully swollen
$\boldsymbol{L_0}$	Length of cylindrical polymer sample

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

ΔZ_0 Elemental disk thickness before applied electricity
z Valance number
z_i Valance of the ith species
α Degree of dissociation; also, degree of ionization; also, factor increasing D_0 after application of electricity
β Factor increasing ΔZ_0 after application of electricity; also, chemical stress term
β_m Positive root of Bessel function of order zero
Γ Modified Bessel function
Δ Thickness term
δ_{ij} Mechanical strain
ε Dielectric constant; also, electric field energy; also, average electric charge
η Fish propulsion efficiency
θ Cylindrical polar coordinate angle
Φ Contraction rate of the gel
ϕ Volume fraction of the polymer network
ϕ_0 Concentration of polymer (no interaction between segments or reference states)
κ Inverse of Debye length or effective thickness of the ionic layer surrounding the charge sites of the individual fibrils; also, phenomenological coefficient
λ Dimensionless parameter relating to β
μ Shear modulus; also, average mobility of the medium in the gel; also, solvent viscosity
μ_h, μ_s Hydrogen-ion and salt-cation mobility
μ_i Chemical potential (energy) for the ith species
ξ Positive root of Bessel function of order zero
ρ Density of liquid solvent
ρ^* Charge density
σ_{ij} Tensile stress, N/m^2
τ Reduced temperature
ν Number of polymers cross-linked in the network; also, velocity of contraction of the gel; also, three-dimensional liquid velocity vector
ψ Local electrostatic potential

Acronyms

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

Contents