

Contents

About the Editors	xiii
List of Contributors	xv
Foreword	xix
Series Preface	xxi
Preface	xxiii

Part One BIOLOGICAL PHENOMENA

1	Cell–Receptor Interactions	3
	<i>David Lepzelter and Muhammad Zaman</i>	
1.1	Introduction	3
1.2	Mechanics of Integrins	4
1.3	Two-Dimensional Adhesion	7
1.4	Two-Dimensional Motility	9
1.5	Three-Dimensional Adhesion	11
1.6	Three-Dimensional Motility	12
1.7	Apoptosis and Survival Signaling	13
1.8	Cell Differentiation Signaling	13
1.9	Conclusions	14
	References	15
2	Regulatory Mechanisms of Kinesin and Myosin Motor Proteins: Inspiration for Improved Control of Nanomachines	19
	<i>Sarah Rice</i>	
2.1	Introduction	19
2.2	Generalized Mechanism of Cytoskeletal Motors	19
2.3	Switch I: A Controller of Motor Protein and G Protein Activation	21
2.4	Calcium-Binding Regulators of Myosins and Kinesins	23
2.5	Phospho-Regulation of Kinesin and Myosin Motors	26

2.6	Cooperative Action of Kinesin and Myosin Motors as a “Regulator”	28
2.7	Conclusion	29
	References	30
3	Neuromechanics: The Role of Tension in Neuronal Growth and Memory	35
	<i>Wylie W. Ahmed, Jagannathan Rajagopalan, Alireza Tofangchi, and Taher A. Saif</i>	
3.1	Introduction	35
3.1.1	<i>What is a Neuron?</i>	36
3.1.2	<i>How Does a Neuron Function?</i>	38
3.1.3	<i>How Does a Neuron Grow?</i>	40
3.2	Tension in Neuronal Growth	41
3.2.1	<i>In Vitro Measurements of Tension in Neurons</i>	41
3.2.2	<i>In Vivo Measurements of Tension in Neurons</i>	43
3.2.3	<i>Role of Tension in Structural Development</i>	45
3.3	Tension in Neuron Function	48
3.3.1	<i>Tension Increases Neurotransmission</i>	48
3.3.2	<i>Tension Affects Vesicle Dynamics</i>	48
3.4	Modeling the Mechanical Behavior of Axons	52
3.5	Outlook	58
	References	58

Part Two NANOSCALE PHENOMENA

4	Fundamentals of Roughness-Induced Superhydrophobicity	65
	<i>Neelesh A. Patankar</i>	
4.1	Background and Motivation	65
4.2	Thermodynamic Analysis: Classical Problem (Hydrophobic to Superhydrophobic)	67
4.2.1	<i>Problem Formulation</i>	68
4.2.2	<i>The Cassie–Baxter State</i>	71
4.2.3	<i>Predicting Transition from Cassie–Baxter to Wenzel State</i>	73
4.2.4	<i>The Apparent Contact Angle of the Drop</i>	77
4.2.5	<i>Modeling Hysteresis</i>	79
4.3	Thermodynamic Analysis: Classical Problem (Hydrophilic to Superhydrophobic)	84
4.4	Thermodynamic Analysis: Vapor Stabilization	86
4.5	Applications and Future Challenges	90
	Acknowledgments	91
	References	91
5	Multiscale Experimental Mechanics of Hierarchical Carbon-Based Materials	95
	<i>Horacio D. Espinosa, Tobin Filleter, and Mohammad Naraghi</i>	
5.1	Introduction	95

5.2	Multiscale Experimental Tools	97
5.2.1	<i>Revealing Atomic-Level Mechanics: In-Situ TEM Methods</i>	98
5.2.2	<i>Measuring Ultralow Forces: AFM Methods</i>	101
5.2.3	<i>Investigating Shear Interactions: In-Situ SEM/AFM Methods</i>	102
5.2.4	<i>Collective and Local Behavior: Micromechanical Testing Methods</i>	103
5.3	Hierarchical Carbon-Based Materials	106
5.3.1	<i>Weak Shear Interactions between Adjacent Graphitic Layers</i>	106
5.3.2	<i>Cross-linking Adjacent Graphitic Layers</i>	110
5.3.3	<i>Local Mechanical Properties of CNT/Graphene Composites</i>	113
5.3.4	<i>High Volume Fraction CNT Fibers and Composites</i>	115
5.4	Concluding Remarks	120
	References	123
6	Mechanics of Nanotwinned Hierarchical Metals	129
	<i>Xiaoyan Li and Huaqian Gao</i>	
6.1	Introduction and Overview	129
6.1.1	<i>Nanotwinned Materials</i>	130
6.1.2	<i>Numerical Modeling of Nanotwinned Metals</i>	132
6.2	Microstructural Characterization and Mechanical Properties of Nanotwinned Materials	134
6.2.1	<i>Structure of Coherent Twin Boundary</i>	134
6.2.2	<i>Microstructures of Nanotwinned Materials</i>	135
6.2.3	<i>Mechanical and Physical Properties of Nanotwinned Metals</i>	137
6.3	Deformation Mechanisms in Nanotwinned Metals	145
6.3.1	<i>Interaction between Dislocations and Twin Boundaries</i>	146
6.3.2	<i>Strengthening and Softening Mechanisms in Nanotwinned Metals</i>	147
6.3.3	<i>Fracture of Nanotwinned Copper</i>	155
6.4	Concluding Remarks	156
	References	157
7	Size-Dependent Strength in Single-Crystalline Metallic Nanostructures	163
	<i>Julia R. Greer</i>	
7.1	Introduction	163
7.2	Background	164
7.2.1	<i>Experimental Foundation</i>	164
7.2.2	<i>Models</i>	167
7.3	Sample Fabrication	170
7.3.1	<i>FIB Approach</i>	170
7.3.2	<i>Directional Solidification and Etching</i>	172

7.3.3	<i>Templated Electroplating</i>	173
7.3.4	<i>Nanoimprinting</i>	173
7.3.5	<i>Vapor-Liquid-Solid Growth</i>	174
7.3.6	<i>Nanowire Growth</i>	175
7.4	Uniaxial Deformation Experiments	175
7.4.1	<i>Nanoindenter-Based Systems (Ex Situ)</i>	176
7.4.2	<i>In-Situ Systems</i>	176
7.5	Discussion and Outlook on Size-Dependent Strength in Single-Crystalline Metals	178
7.5.1	<i>Cubic Crystals</i>	178
7.5.2	<i>Non-Cubic Single Crystals</i>	183
7.6	Conclusions and Outlook	184
	References	185

Part Three EXPERIMENTATION

8	<i>In-Situ TEM Electromechanical Testing of Nanowires and Nanotubes</i>	193
	<i>Horacio D. Espinosa, Rodrigo A. Bernal, and Tobin Filleter</i>	
8.1	Introduction	193
8.1.1	<i>Relevance of Mechanical and Electromechanical Testing for One-Dimensional Nanostructures</i>	194
8.1.2	<i>Mechanical and Electromechanical Characterization of Nanostructures: The Need for In-Situ TEM</i>	196
8.2	In-Situ TEM Experimental Methods	197
8.2.1	<i>Overview of TEM Specimen Holders</i>	199
8.2.2	<i>Methods for Mechanical and Electromechanical Testing of Nanowires and Nanotubes</i>	200
8.2.3	<i>Sample Preparation for TEM of One-Dimensional Nanostructures</i>	208
8.3	Capabilities of In-Situ TEM Applied to One-Dimensional Nanostructures	212
8.3.1	<i>HRTEM</i>	212
8.3.2	<i>Diffraction</i>	216
8.3.3	<i>Analytical Techniques</i>	217
8.3.4	<i>In-Situ Specimen Modification</i>	218
8.4	Summary and Outlook	220
	Acknowledgments	221
	References	221
9	<i>Engineering Nano-Probes for Live-Cell Imaging of Gene Expression</i>	227
	<i>Gang Bao, Brian Wile, and Andrew Tsourkas</i>	
9.1	Introduction	227
9.2	Molecular Probes for RNA Detection	229
9.2.1	<i>Fluorescent Linear Probes</i>	229
9.2.2	<i>Linear FRET Probes</i>	232

9.2.3	<i>Quenched Auto-ligation Probes</i>	233
9.2.4	<i>Molecular Beacons</i>	234
9.2.5	<i>Dual-FRET Molecular Beacons</i>	236
9.2.6	<i>Fluorescent Protein-Based Probes</i>	237
9.3	Probe Design, Imaging, and Biological Issues	239
9.3.1	<i>Specificity of Molecular Beacons</i>	239
9.3.2	<i>Fluorophores, Quenchers, and Signal-to-Background</i>	241
9.3.3	<i>Target Accessibility</i>	242
9.4	Delivery of Molecular Beacons	244
9.4.1	<i>Microinjection</i>	245
9.4.2	<i>Cationic Transfection Agents</i>	245
9.4.3	<i>Electroporation</i>	245
9.4.4	<i>Chemical Permeabilization</i>	246
9.4.5	<i>Cell-Penetrating Peptide</i>	246
9.5	Engineering Challenges and Future Directions	248
	Acknowledgments	249
	References	249
10	Towards High-Throughput Cell Mechanics Assays for Research and Clinical Applications	255
	<i>David R. Myers, Daniel A. Fletcher, and Wilbur A. Lam</i>	
10.1	Cell Mechanics Overview	255
10.1.1	<i>Cell Cytoskeleton and Cell-Sensing Overview</i>	256
10.1.2	<i>Forces Applied by Cells</i>	259
10.1.3	<i>Cell Responses to Force and Environment</i>	260
10.1.4	<i>General Principles of Combined Mechanical and Biological Measurements</i>	261
10.2	Bulk Assays	262
10.2.1	<i>Microfiltration</i>	262
10.2.2	<i>Rheometry</i>	264
10.2.3	<i>Ektacytometry</i>	266
10.2.4	<i>Parallel-Plate Flow Chambers</i>	267
10.3	Single-Cell Techniques	268
10.3.1	<i>Micropipette Aspiration</i>	268
10.3.2	<i>Atomic Force Microscopy</i>	270
10.3.3	<i>Microplate Stretcher</i>	272
10.3.4	<i>Optical Tweezers</i>	273
10.4	Existing High-Throughput Cell Mechanical-Based Assays	274
10.4.1	<i>Optical Stretchers</i>	274
10.4.2	<i>Traction Force Microscopy via Bead-Embedded Gels</i>	275
10.4.3	<i>Traction Force Microscopy via Micropost Arrays</i>	275
10.4.4	<i>Substrate Stretching Assays</i>	277
10.4.5	<i>Magnetic Twisting Cytometry</i>	277
10.4.6	<i>Microfluidic Pore and Deformation Assays</i>	278
10.5	Cell Mechanical Properties and Diseases	280
	References	284

11	Microfabricated Technologies for Cell Mechanics Studies	293
	<i>Sri Ram K. Vedula, Man C. Leong, and Chwee T. Lim</i>	
11.1	Introduction	293
11.2	Microfabrication Techniques	294
11.2.1	<i>Photolithography and Soft Lithography</i>	294
11.2.2	<i>Microphotopatterning (μPP)</i>	297
11.3	Applications to Cell Mechanics	298
11.3.1	<i>Micropatterned Substrates</i>	298
11.3.2	<i>Micropillared Substrates</i>	301
11.3.3	<i>Microfluidic Devices</i>	304
11.4	Conclusions	307
	References	307

Part Four MODELING

12	Atomistic Reaction Pathway Sampling: The Nudged Elastic Band Method and Nanomechanics Applications	313
	<i>Ting Zhu, Ju Li, and Sidney Yip</i>	
12.1	Introduction	313
12.1.1	<i>Reaction Pathway Sampling in Nanomechanics</i>	314
12.1.2	<i>Extending the Time Scale in Atomistic Simulation</i>	314
12.1.3	<i>Transition-State Theory</i>	315
12.2	The NEB Method for Stress-Driven Problems	315
12.2.1	<i>The NEB method</i>	315
12.2.2	<i>The Free-End NEB Method</i>	317
12.2.3	<i>Stress-Dependent Activation Energy and Activation Volume</i>	320
12.2.4	<i>Activation Entropy and Meyer–Neldel Compensation Rule</i>	322
12.3	Nanomechanics Case Studies	324
12.3.1	<i>Crack Tip Dislocation Emission</i>	324
12.3.2	<i>Stress-Mediated Chemical Reactions</i>	326
12.3.3	<i>Bridging Modeling with Experiment</i>	327
12.3.4	<i>Temperature and Strain-Rate Dependence of Dislocation Nucleation</i>	329
12.3.5	<i>Size and Loading Effects on Fracture</i>	330
12.4	A Perspective on Microstructure Evolution at Long Times	332
12.4.1	<i>Sampling TSP Trajectories</i>	333
12.4.2	<i>Nanomechanics in Problems of Materials Ageing</i>	334
	References	336
13	Mechanics of Curvilinear Electronics	339
	<i>Shuodao Wang, Jianliang Xiao, Jizhou Song, Yonggang Huang, and John A. Rogers</i>	
13.1	Introduction	339

13.2	Deformation of Elastomeric Transfer Elements during Wrapping Processes	342
13.2.1	<i>Strain Distribution in Stretched Elastomeric Transfer Elements</i>	342
13.2.2	<i>Deformed Shape of Elastomeric Transfer Elements</i>	344
13.3	Buckling of Interconnect Bridges	347
13.4	Maximum Strain in the Circuit Mesh	351
13.5	Concluding Remarks	355
	Acknowledgments	355
	References	355
14	Single-Molecule Pulling: Phenomenology and Interpretation	359
	<i>Ignacio Franco, Mark A. Ratner, and George C. Schatz</i>	
14.1	Introduction	359
14.2	Force–Extension Behavior of Single Molecules	360
14.3	Single-Molecule Thermodynamics	364
14.3.1	<i>Free Energy Profile of the Molecule Plus Cantilever</i>	365
14.3.2	<i>Extracting the Molecular Potential of Mean Force $\phi(\xi)$</i>	366
14.3.3	<i>Estimating Force–Extension Behavior from $\phi(\xi)$</i>	369
14.4	Modeling Single-Molecule Pulling Using Molecular Dynamics	370
14.4.1	<i>Basic Computational Setup</i>	370
14.4.2	<i>Modeling Strategies</i>	371
14.4.3	<i>Examples</i>	373
14.5	Interpretation of Pulling Phenomenology	376
14.5.1	<i>Basic Structure of the Molecular Potential of Mean Force</i>	377
14.5.2	<i>Mechanical Instability</i>	378
14.5.3	<i>Dynamical Bistability</i>	381
14.6	Summary	384
	Acknowledgments	385
	References	385
15	Modeling and Simulation of Hierarchical Protein Materials	389
	<i>Tristan Giesa, Graham Bratzel, and Markus J. Buehler</i>	
15.1	Introduction	389
15.2	Computational and Theoretical Tools	391
15.2.1	<i>Molecular Simulation from Chemistry Upwards</i>	391
15.2.2	<i>Mesoscale Methods for Modeling Larger Length and Time Scales</i>	392
15.2.3	<i>Mathematical Approaches to Biomateriomics</i>	394
15.3	Case Studies	400
15.3.1	<i>Atomistic and Mesoscale Protein Folding and Deformation in Spider Silk</i>	400
15.3.2	<i>Coarse-Grained Modeling of Actin Filaments</i>	402
15.3.3	<i>Category Theoretical Abstraction of a Protein Material and Analogy to an Office Network</i>	403

15.4	Discussion and Conclusion	406
	Acknowledgments	406
	References	406
16	Geometric Models of Protein Secondary-Structure Formation	411
	<i>Hendrik Hansen-Goos and Seth Lichter</i>	
16.1	Introduction	411
16.2	Hydrophobic Effect	412
	16.2.1 <i>Variable Hydrogen-Bond Strength</i>	415
16.3	Prior Numerical and Coarse-Grained Models	415
16.4	Geometry-Based Modeling: The Tube Model	416
	16.4.1 <i>Motivation</i>	416
	16.4.2 <i>Impenetrable Tube Models</i>	417
	16.4.3 <i>Including Finite-Sized Particles Surrounding the Protein</i>	419
	16.4.4 <i>Models Using Real Protein Structure</i>	421
16.5	Morphometric Approach to Solvation Effects	422
	16.5.1 <i>Hadwiger's Theorem</i>	422
	16.5.2 <i>Applications</i>	424
16.6	Discussion, Conclusions, Future Work	429
	16.6.1 <i>Results</i>	429
	16.6.2 <i>Discussion and Speculations</i>	430
	Acknowledgments	433
	References	433
17	Multiscale Modeling for the Vascular Transport of Nanoparticles	437
	<i>Shaolie S. Hossain, Adrian M. Kopacz, Yongjie Zhang, Sei-Young Lee, Tae-Rin Lee, Mauro Ferrari, Thomas J.R. Hughes, Wing Kam Liu, and Paolo Decuzzi</i>	
17.1	Introduction	437
17.2	Modeling the Dynamics of NPs in the Macrocirculation	438
	17.2.1 <i>The 3D Reconstruction of the Patient-Specific Vasculature</i>	439
	17.2.2 <i>Modeling the Vascular Flow and Wall Adhesion of NPs</i>	440
	17.2.3 <i>Modeling NP Transport across the Arterial Wall and Drug Release</i>	440
17.3	Modeling the NP Dynamics in the Microcirculation	448
	17.3.1 <i>Semi-analytical Models for the NP Transport</i>	449
	17.3.2 <i>An IFEM for NP and Cell Transport</i>	452
17.4	Conclusions	456
	Acknowledgments	456
	References	457
	Index	461