

Contents

Foreword	xi
Author	xiii
Chapter 1 Force Generation Mechanism of Skeletal Muscle Contraction.....	1
1.1 Anatomy of Skeletal Muscle.....	1
1.1.1 Macrostructure	1
1.1.2 Mesostructure.....	2
1.1.3 Microstructure	2
1.2 Force Generation Mechanism of Skeletal Muscle Contraction:	
The Excitation–Contraction Coupling	3
1.2.1 Motoneuron and Neuromuscular Junction	3
1.2.1.1 Action Potential	3
1.2.1.2 The Acceleration of Ion Diffusion Due to	
Electromagnetic Effects of Ion Currents in Ion Channels.....	7
1.2.1.3 Postsynaptic Response on Sarcolemma.....	13
1.2.2 T-Tubule and SR	14
1.2.2.1 Contraction Drive: RyR Channel and DHPR	14
1.2.2.2 Ca^{2+} Dynamics in Sarcoplasm	15
1.2.3 Myosin Motor	16
1.2.3.1 Operation Mechanism of Single Molecular Motor:	
Lymn–Taylor Cycle.....	16
1.2.3.2 Collective Working Mechanism of Molecular Motors	16
1.2.4 Receptor	17
1.2.4.1 Muscle Spindle.....	17
1.2.4.2 Tendon Organ	18
1.2.5 A Dynamical System: Markov Model for Active Postsynaptic	
Responses of Muscle Spindle Afferent Nerve.....	18
1.2.5.1 The Synapse of Ia Afferent Nerve	19
1.2.5.2 The Dynamical System Model for Membrane Potential	20
1.2.5.3 The Kinetic Model for Postsynaptic Receptors	22
1.2.5.4 The Model for Postsynaptic Responses	25
References	30
Chapter 2 Biomechanical Modeling of Muscular Contraction	33
2.1 Modeling of Driving and Control Processes	35
2.1.1 Bioelectrochemical Control Model with Variable-Frequency	
Regulation for Sarcomere Contraction.....	36
2.1.1.1 Modeling of Action Potentials on Sarcolemma.....	37
2.1.1.2 $[\text{Ca}^{2+}]$ Variation Inside Sarcomeres Caused by AP	40
2.1.1.3 Regulation of $[\text{Ca}^{2+}]$ Inside Sarcomeres by AP	42
2.1.1.4 The Application of the Variable-Frequency Regulation	
Model in Muscle Force Estimation.....	45
2.2 Modeling the Force-Producing Mechanism of Skeletal Muscle	50
2.2.1 Classical Models.....	50
2.2.1.1 Hill-Type Model.....	50
2.2.1.2 Conformational Change Model	53

- 2.2.1.3 Statistical Thermodynamical Model 55
 - 2.2.2 Coupling Mechanism of Multi-Force Interactions of a Single Myosin Motor 56
 - 2.2.2.1 Forces Involved in the Approaching Process 57
 - 2.2.2.2 Calculation of the Main Interaction Force..... 60
 - 2.2.2.3 Monte Carlo Simulation..... 63
 - 2.2.3 The 4M Model of Muscular Contraction 64
 - 2.2.3.1 Modeling of Sarcomere Activation..... 64
 - 2.2.3.2 Modeling of Sarcomere Contraction 66
 - 2.2.3.3 Sarcomere in Series and in Parallel..... 67
 - 2.2.3.4 Generalization to the Macroscopic Model 68
 - 2.2.3.5 Numerical Analysis and Simulation 69
 - 2.2.4 The New Semiphenomenological Model of Sarcomere..... 73
 - 2.2.4.1 Modeling Principles..... 74
- 2.3 Results 82
 - 2.3.1 The Development of Isometric Force 82
 - 2.3.2 Isotonic Contraction and the Force–Velocity Relationship..... 82
 - 2.3.3 Step-Length Change with Finite Velocities during Activation 83
 - 2.3.4 Cyclic Contractions under Periodic Burst Activations..... 84
- 2.4 Discussion..... 85
- References 87

- Chapter 3** Estimation of Skeletal Muscle Activation and Contraction Force Based on EMG Signals..... 91
 - 3.1 Generation Mechanism of sEMG Signals 91
 - 3.2 Real-Time Feature Extraction and Contraction Force Estimation of sEMG Signals 92
 - 3.2.1 Traditional Extraction Methods 92
 - 3.2.2 Differentiated Extraction Method 95
 - 3.2.3 Real-Time Signal Feature Extraction Experiment and Effect Comparison of the Different Methods 96
 - 3.2.3.1 Artificial Synthesis of Signals 96
 - 3.2.3.2 Real-Time Feature Extraction of sEMG Signals and Comparison of Results..... 100
 - 3.2.4 Phase-Portrait–Based Energy Kernel Method for Feature Extraction and Contraction Force Estimation 101
 - 3.2.4.1 The Oscillator Model of EMG Signal 102
 - 3.2.4.2 Algorithm..... 105
 - 3.2.4.3 Extraction Effects’ Validation 107
 - References 114

- Chapter 4** Human–Machine Force Interactive Interface and Exoskeleton Robot Techniques Based on Biomechanical Model of Skeletal Muscle..... 117
 - 4.1 Lower-Extremity Exoskeleton Robot 119
 - 4.1.1 State of the Art 120
 - 4.1.1.1 Early Exoskeleton Robot 120
 - 4.1.1.2 Exoskeleton Project by DARPA 121
 - 4.1.1.3 Other Exoskeleton Robots 123
 - 4.1.1.4 Exoskeleton Robot for Rehabilitation 125

- 4.1.2 Key Technologies 126
 - 4.1.2.1 Control System for Exoskeleton 126
 - 4.1.2.2 Human–Machine Interface Technology 131
 - 4.1.2.3 IoT-Based Rehabilitation System..... 132
- 4.1.3 Anatomical Structure and Gait Feature of Human Lower Limbs..... 133
 - 4.1.3.1 Datum Plane and Datum Axis of Humans 134
 - 4.1.3.2 Joints and Muscle Groups of Human Lower Extremity 134
 - 4.1.3.3 Gait Features of Human Motion..... 137
- 4.1.4 Bionic Design of the Lower-Extremity Exoskeleton Robot 141
 - 4.1.4.1 Requirements of Lower-Extremity Rehabilitation and Design Key Points 142
 - 4.1.4.2 Configuration Design for Exoskeleton Robot..... 143
 - 4.1.4.3 Static/Dynamic Analysis of Exoskeleton 149
- 4.1.5 Hardware System for Lower-Extremity Exoskeleton Robot 161
 - 4.1.5.1 EMG Signal Amplifier..... 161
 - 4.1.5.2 EMG Signal DAQ Instrument 163
 - 4.1.5.3 Motion Controller 165
- 4.1.6 Software System for Lower-Extremity Exoskeleton Robot 168
 - 4.1.6.1 Software for EMG Signal Collection..... 168
 - 4.1.6.2 Software for Lower-Extremity Rehabilitation System 170
- 4.2 Multi-Source-Signal–Based Bioelectromechanical Human–Machine Interface and Active Compliance Control..... 171
 - 4.2.1 Research Object..... 173
 - 4.2.2 Musculoskeletal System of Knee Joint..... 174
 - 4.2.2.1 Geometric Parameter Computation of Muscles..... 175
 - 4.2.2.2 Dynamic Analysis of Knee Joint..... 177
 - 4.2.3 Multi-Source Information Fusion Based on Force Interaction 179
 - 4.2.3.1 Multi-Source Biosignal Acquisition 179
 - 4.2.3.2 The Neurofuzzy-Network–Based Multi-Source Information Fusion and Movement Intention Identification 180
 - 4.2.4 Human–Machine Coordinated Control Mechanism..... 187
 - 4.2.4.1 Local Closed-Loop Control Mechanism in Motorium..... 190
 - 4.2.4.2 Closed-Loop Control Mechanism for Exoskeleton Robot 191
 - 4.2.4.3 Requirement Analysis of Bioelectromechanical Integration..... 191
 - 4.2.5 Bioelectromechanical Integrated Coordination Control Strategy.... 192
 - 4.2.5.1 Bidirectional Interaction Interface Based on EPP and sEMG 192
 - 4.2.5.2 Human–Machine Coordinated Control Strategy..... 193
 - 4.2.5.3 Human–Machine Integrated System Modeling..... 193
 - 4.2.6 Experimental Results of Active Compliance Control 195
 - 4.2.6.1 Experiment 1..... 195
 - 4.2.6.2 Experiment 2..... 200
- 4.3 Improving the Transparency of the Exoskeleton Knee Joint Based on Energy Kernel Method of EMG 208
 - 4.3.1 Real-Time Extraction Algorithm of Energy Kernel of EMG..... 209
 - 4.3.2 HMIM and Adaptive Prediction Scheme..... 210
 - 4.3.2.1 HMIM..... 210
 - 4.3.2.2 Adaptive Prediction Scheme Using FTDNN..... 211

	4.3.2.3	Iterative Prediction–Compensation Control Loop	212
4.3.3		Initial Experiment and Results	214
	4.3.3.1	Lower-Limb Robotic Exoskeleton	214
	4.3.3.2	EMG and Force Signal Acquisition	214
	4.3.3.3	Data Collection and Control System	214
	4.3.3.4	Results	216
		References	220
Chapter 5		Clinical Rehabilitation Technologies for Force-Control–Based Exoskeleton Robot	227
5.1		System Integration for Lower-Extremity Exoskeleton Rehabilitation Robot	227
	5.1.1	Mechanical Structure of Rehabilitation Robot	228
	5.1.2	Rehabilitation Robot Control System	229
	5.1.3	Rehabilitation Strategy Generation	231
	5.1.4	Rehabilitation Robot System Software	232
5.2		Compound Rehabilitation Strategy	234
	5.2.1	Passive Rehabilitation Strategy	234
	5.2.2	Active Rehabilitation Strategy	236
	5.2.3	Progressive Rehabilitation Strategy	236
	5.2.4	IoT-Based Remote Rehabilitation Strategy	238
5.3		Clinical Rehabilitation Experiments	241
	5.3.1	Zero-Load Check of Exoskeleton Robot	241
	5.3.2	Application Experiment of Exoskeleton Rehabilitation Robot	242
		5.3.2.1 Joint F/E Training	242
		5.3.2.2 Lower-Extremity Gait Training	242
		5.3.2.3 Active Muscle Force Training	243
		5.3.2.4 Active Control Training	246
	5.3.3	Experiment Device and Patient Selection	248
	5.3.4	Aim, Process, and Method of Clinical Experiment	249
	5.3.5	Evaluation Index and Statistical Method	249
5.4		Experimental Results and Analysis	250
	5.4.1	Clinical Experimental Results and Cases	250
	5.4.2	Results' Analysis	253
		References	254
Chapter 6		Bionic Design of Artificial Muscle Based on Biomechanical Models of Skeletal Muscle	257
6.1		Brief Introduction of Skeletal Muscle Bionics	258
	6.1.1	Bionic Design Concept Evolution	258
		6.1.1.1 Mechanical AM	259
		6.1.1.2 Pneumatic AM	261
		6.1.1.3 AM with Smart Material	264
	6.1.2	BID Bionic Design Methodology	268
		6.1.2.1 Framework of BID	269
		6.1.2.2 Sub-Conceptual Design Principles	270
6.2		Skeletal Muscle Character Identification and Modeling	273
	6.2.1	Biological Character Identification of Skeletal Muscle	273
		6.2.1.1 Structure and Function Properties of Skeletal Muscle	273

6.2.1.2 Biomechanical Property of Skeletal Muscle..... 275

6.2.2 Contraction Property Modelling of Skeletal Muscle 277

6.2.2.1 Isometric Contraction Modeling..... 277

6.2.2.2 Isotonic Contraction Modeling..... 280

6.3 SMA Artificial Skeletal Muscle Integrating Actuation, Sensing, and Structure 282

6.3.1 Key Technologies of SMA 283

6.3.1.1 Low Strain and Low Response Time of SMA 283

6.3.1.2 SMA Self-Sensing Character Analysis..... 284

6.3.1.3 Hysteresis Nonlinearity Analysis and Control of SMA 285

6.3.2 SMA-Based AM Design Realization 286

6.3.2.1 Bionic Design of Active Elements 288

6.3.2.2 Design of AM Passive Element 290

6.3.2.3 Bionic Structure Verification 291

6.3.3 Self-Sensing Properties of SMA 292

6.3.3.1 SMA Resistivity Phase Transformation Dynamics 292

6.3.3.2 Electro-Thermomechanical Coupling Properties..... 297

6.3.3.3 SMA Self-Sensing Model 304

6.3.4 Application of SMA Self-Sensing Model..... 306

6.4 Hysteresis Properties of SMA-AM..... 309

6.4.1 SMA Hysteresis Properties and Research Survey 310

6.4.1.1 Description of Hysteresis Property 310

6.4.1.2 Hysteresis Model 315

6.4.1.3 SBH Model of SMA 320

6.4.1.4 Inverse SBH Model and Feedforward Compensation 322

6.5 SMA-AM Application in Ankle-Foot Rehabilitation System..... 327

6.5.1 SMA-AFO 328

6.5.1.1 Actuating-Sensing System 329

6.5.1.2 AFO 329

6.5.1.3 Control System..... 329

6.5.2 Comprehensive Dynamic Model of SMA-AFO System..... 330

6.5.2.1 Thermoelectric Property..... 330

6.5.2.2 SMA Physics-Based Property..... 331

6.5.2.3 Hysteresis Properties 331

6.5.2.4 Mechanical Properties 332

6.5.3 Sliding-Mode Control of SMA-AFO System..... 332

6.5.3.1 Mechanism of Sliding-Mode Control 332

6.5.3.2 Controller Design..... 333

6.5.3.3 Stability Analysis..... 336

6.5.4 Experimental Study 337

Appendix 6.A 341

References 342

Conclusion 349

Index..... 353