

# CONTENTS

---

Preface xiii

Acknowledgments xvi

## **Part I Muscle Architecture and Mechanics 1**

### **■ Chapter 1 Muscle Architecture 3**

---

#### **1.1 Muscle Fascicles and Their Arrangements 8**

1.1.1 Parallel Fibered and Fusiform Muscles 10

1.1.2 Pennate Muscles 10

1.1.2.1 Planar Models of Pennate Muscles 12

1.1.2.2 Pennation in Three Dimensions 17

1.1.3 Convergent and Circular Muscles 19

#### **1.2 Muscle Fascicle Curvature: Frenet Frames 20**

#### **1.3 Fiber Architecture in the Fascicles 25**

#### **1.4 Muscle as a Fiber-Reinforced Composite 30**

#### **1.5 Fiber, Fascicle, and Muscle Length: Length–Length Ratios 33**

1.5.1 Fiber and Fascicle Length 33

1.5.2 Length–Length Ratios 34

#### **1.6 Muscle Path: Muscle Centroids 37**

1.6.1 Straight-Line Representation of Muscle Path 38

1.6.2 Centroid Model of Muscle Path 39

1.6.3 Curved and Wrapping Muscles 41

1.6.4 Twisted Muscles 47

1.6.5 Muscles Attaching to More Than Two Bones 48

#### **1.7 Cross-Sectional Area, Physiological and Anatomical 49**

#### **1.8 Muscle Attachment Area 56**

#### **1.9 Summary 62**

#### **1.10 Questions for Review 64**

#### **1.11 Literature List 65**

### **■ Chapter 2 Properties of Tendons and Passive Muscles 69**

---

#### **2.1 Biomechanics of Tendons and Aponeuroses 72**

2.1.1 Elastic Behavior 72

2.1.1.1	Stress–Strain Relations	74
2.1.1.1.1	<i>Stress–Strain Relations in the Toe Region</i>	76
2.1.1.1.2	<i>Stress–Strain Relations in the Linear Region</i>	78
2.1.1.2	Tendon Forces	80
2.1.1.3	Tension and Elongation in Tendons and Aponeuroses	81
2.1.1.4	Constitutive Equations for Tendons and Ligaments	85
2.1.2	Viscoelastic Behavior of Tendons	86
2.1.2.1	Basic Concepts of Viscoelasticity	86
2.1.2.2	Viscoelastic Properties of Tendons	90
2.1.2.2.1	<i>Computational Models of the Tendons</i>	90
2.1.2.2.2	<i>Factors Affecting Mechanical Properties of the Tendons</i>	91
2.1.3	Tendon Interaction With Surrounding Tissues	92
2.1.3.1	Intertendinous Shear Force and Lateral Force Transfer	92
2.1.3.2	Interfinger Connection Matrices	95
2.1.3.3	Gliding Resistance Between the Tendons and Surrounding Tissues	98
2.1.3.4	Tendon Wrapping	99
2.1.3.5	Bowstringing	103
2.1.3.6	Tendon Properties and Muscle Function	105
2.1.3.7	Musculotendinous Architectural Indices	107
<b>2.2</b>	<b>Mechanical Properties of Passive Muscles</b>	<b>108</b>
2.2.1	Muscle Tone: Equitonometry	109
2.2.2	Mechanical Properties of Relaxed Muscles	111
2.2.2.1	Elastic Properties	111
2.2.2.2	Viscoelastic Properties of Passive Muscles: Passive Mechanical Resistance in Joints	114
<b>2.3</b>	<b>On Joint Flexibility</b>	<b>117</b>
<b>2.4</b>	<b>Summary</b>	<b>120</b>
<b>2.5</b>	<b>Questions for Review</b>	<b>124</b>
<b>2.6</b>	<b>Literature List</b>	<b>125</b>
<b>■ Chapter 3</b>	<b>Mechanics of Active Muscle</b>	<b>131</b>
<b>3.1</b>	<b>Muscle Force Production and Transmission</b>	<b>131</b>
3.1.1	Experimental Methods	132
3.1.2	Transition From Rest to Activity	132

3.1.2.1 Muscle Active State	135
3.1.2.2 Force Development in Humans: Rate of Force Development	137
3.1.3 Transition From Activity to Rest: Muscle Relaxation	140
3.1.4 Constancy of the Muscle Volume	143
3.1.5 Force Transmission and Internal Deformations (Strain)	146
3.1.5.1 Force Transmission in Muscle Fibers	146
3.1.5.2 Force Transmission in Muscles: Summation of Muscle Fiber Forces	149
3.1.5.2.1 <i>Parallel-Fibered and Fusiform Muscles</i>	149
3.1.5.2.1.1 Nonuniform Shortening of Muscle Fibers	149
3.1.5.2.1.2 Nonlinear Summation of Fiber Forces	153
3.1.5.2.2 <i>Pennate Muscles</i>	153
3.1.5.2.2.1 Force Transmission	154
3.1.5.2.2.2 Speed Transmission: Architectural Gear Ratio	155
3.1.6 Intramuscular Stress and Pressure	159
3.1.6.1 Specific Muscle Force	159
3.1.6.2 Stress Tensors	161
3.1.6.3 Intramuscular Fluid Pressure	163
3.1.6.3.1 <i>Hydrostatic and Osmotic Pressure</i>	163
3.1.6.3.2 <i>Factors Affecting Intramuscular Pressure: Application of the Laplace Law</i>	165
3.1.6.3.3 <i>Biological Function of Intramuscular Pressure: The Compartment Syndrome</i>	167
<b>3.2 Functional Relations</b>	<b>170</b>
3.2.1 Force–Length Relations	170
3.2.1.1 Force–Length Curves	170
3.2.1.2 Mechanisms Behind the Active Force–Length Curve	174
3.2.1.3 Problem of Muscle Stability	177
3.2.1.4 Submaximal Force–Length Curve	179
3.2.1.5 Muscle Lengths in the Body: Expressed Sections of the Force–Length Curve	181
3.2.2 Force–Velocity Relations	186
3.2.2.1 A Piece of History: Muscle Viscosity Theory and Heat Production	186
3.2.2.2 Hill's Force–Velocity Curve	190

3.2.2.3 Other Types of the Force–Velocity Curves	193
3.2.2.3.1 <i>Force–Velocity Relations in Single Movement</i>	193
3.2.2.3.2 <i>Nonparametric Force–Velocity Relations</i>	196
3.2.2.4 Mathematical Description of the Force–Velocity Curve: The Hill Characteristic Equation	198
3.2.2.5 Power–Velocity Relations	200
3.2.3 Force–Length–Velocity Relations	202
<b>3.3 History Effects in Muscle Mechanics</b>	<b>203</b>
3.3.1 Force Depression After Muscle Shortening	203
3.3.2 Effects of Muscle Release: Quick-Release and Controlled-Release Methods: Series Muscle Components	205
<b>3.4 Summary</b>	<b>208</b>
<b>3.5 Questions for Review</b>	<b>213</b>
<b>3.6 Literature List</b>	<b>215</b>
<b>■ Chapter 4 Muscles as Force and Energy Absorbers</b>	
<b>Muscle Models</b>	<b>223</b>
<b>4.1 Muscle Mechanical Behavior During Stretch</b>	<b>225</b>
4.1.1 Dynamic Force Enhancement	226
4.1.1.1 Force–Velocity Relation for Lengthening Muscle	227
4.1.1.2 Give Effects	228
4.1.2 Residual Force Enhancement	229
<b>4.2 Muscle Shortening After Stretch</b>	<b>231</b>
4.2.1 Work and Power During Shortening After Stretch	231
4.2.2 Energy Consumption During Stretch and Efficiency of the Muscle Shortening After Stretch	233
<b>4.3 Dissipation of Energy</b>	<b>235</b>
<b>4.4 Mechanical Muscle Models</b>	<b>237</b>
4.4.1 Hill-Type Model	238
4.4.2 Model Scaling	240
<b>4.5 Summary</b>	<b>242</b>
<b>4.6 Questions for Review</b>	<b>244</b>
<b>4.7 Literature List</b>	<b>245</b>

## **Part II Muscles in the Body 249**

### **■ Chapter 5 From Muscle Forces to Joint Moments 251**

#### **5.1 Force Transmission: From Muscle to Bone 252**

5.1.1 From Muscle to Tendon 252

5.1.2 From Tendon to Bone 255

5.1.3 Tendon Elasticity and Isometric Force–Length Relation 258

#### **5.2 Force Transmission via Soft Tissue Skeleton (Fascia) 261**

5.2.1 Structure of Fascia 261

5.2.2 Muscle–Tendon–Fascia Attachments 263

5.2.3 Fascia as Soft Tissue Skeleton (Ectoskeleton) 264

5.2.3.1 Plantar Fascia and the Windlass Mechanism 265

5.2.3.2 Fascia Lata and Iliotibial Tract 267

#### **5.3 Muscle Moment Arms 268**

5.3.1 Muscle Moment Arm Vectors and Their Components 269

5.3.1.1 Moment Arms as Vectors 269

5.3.1.2 Muscle Moment Arms About Rotation Axes 272

5.3.1.3 Muscle Moment Arms About Anatomical Axes:  
Muscle Functions at a Joint 274

5.3.1.4 Moment Arms of Muscles With Curved Paths:  
Quadriceps Moment Arm 280

5.3.1.5 Moment Arms of Multijoint Muscles:  
Paradoxical Muscle Action 283

5.3.2 Methods for Determination of Muscle Moment Arms 285

5.3.2.1 Geometric Methods 285

5.3.2.1.1 *Anatomical Geometric Methods* 286

5.3.2.1.1.1 Planar Geometric Models 286

5.3.2.1.1.2 Three-Dimensional Geometric Models 290

5.3.2.1.2 *Imaging Geometric Methods* 291

5.3.2.2 Functional Methods 293

5.3.2.2.1 *Tendon Excursion Method (Kinematic Method)* 294

5.3.2.2.2 *Load Application Method (Static Method)* 299

5.3.3 Factors Affecting Muscle Moment Arm 301

5.3.3.1 Moment Arm as a Function of Joint Angles 301

5.3.3.2 Moment Arm as a Function of Exerted Muscle Force 305

5.3.3.3 Scaling of Moment Arms 307



- 5.3.4 Transformation of Muscle Forces to Joint Moments:  
Muscle Jacobian 311

## 5.4 Summary 313

## 5.5 Questions for Review 316

## 5.6 Literature List 318

# ■ Chapter 6 Two-Joint Muscles in Human Motion 325

---

## 6.1 Two-Joint Muscles:

### A Special Case of Multifunctional Muscles 325

#### 6.1.1 Functional Features of Two-Joint Muscles 326

#### 6.1.2 Anatomical and Morphological Features of Two-Joint Muscles 328

## 6.2 Functional Roles of Two-Joint Muscles 331

#### 6.2.1 Kinetic Analysis of Two-Joint Muscles: Lombard's Paradox 331

#### 6.2.2 Kinematic Analysis of Two-Joint Muscles: Solution of Lombard's Paradox 336

## 6.3 Mechanical Energy Transfer and Saving by Two-Joint Muscles 343

### 6.3.1 Tendon Action of Two-Joint Muscles 343

#### 6.3.1.1 Illustrative Examples of Tendon Action of Two-Joint Muscles 343

#### 6.3.1.2 Methods of Energy Transfer Estimation 350

##### 6.3.1.2.1 Energy Generated by Joint Moment and Muscles at a Joint 350

##### 6.3.1.2.2 Work Done by a Two-Joint Muscle at the Adjacent Joint 353

#### 6.3.1.3 Tendon Action and Jumping Performance 356

### 6.3.2 Saving Mechanical Energy by Two-Joint Muscles 357

## 6.4 Summary 361

## 6.5 Questions for Review 364

## 6.6 Literature List 366

# ■ Chapter 7 Eccentric Muscle Action in Human Motion 369

---

## 7.1 Joint Power and Work as Measures of Eccentric Muscle Action 370

### 7.1.1 Negative Power and Work at a Joint 370

7.1.2 Total Negative Power and Work in Several Joints	372
7.1.3 Negative Power of Center of Mass Motion	372
7.1.4 Two Ways of Mechanical Energy Dissipation: Softness of Landing	372
<b>7.2 Negative Work in Selected Activities</b>	<b>374</b>
7.2.1 Walking	375
7.2.2 Stair Descent and Ascent	377
7.2.3 Level, Downhill, and Uphill Running	378
7.2.4 Landing	381
<b>7.3 Joint Moments During Eccentric Actions</b>	<b>383</b>
7.3.1 Maximal Joint Moments During Eccentric Actions	383
7.3.2 Force Changes During and After Stretch	386
7.3.2.1 Dynamic Force Enhancement	387
7.3.2.2 Short-Range Stiffness	389
7.3.2.3 Decay of Dynamic Force Enhancement	391
7.3.3 Residual Force Enhancement in Humans	392
<b>7.4 Muscle Activity During Eccentric Actions</b>	<b>394</b>
7.4.1 Surface Electromyographic Activity During Eccentric Actions	395
7.4.2 Motor Unit Activity During Eccentric Actions	396
7.4.3 Electromechanical Delay	397
<b>7.5 Physiological Cost of Eccentric Action</b>	<b>398</b>
7.5.1 Oxygen Consumption During Eccentric and Concentric Exercise	398
7.5.2 Fatigue and Perceived Exertion During Eccentric Action	400
7.5.3 Muscle Soreness After Eccentric Exercise	401
<b>7.6 Reversible Muscle Action: Stretch–Shortening Cycle</b>	<b>402</b>
7.6.1 Enhancement of Positive Work and Power Production	404
7.6.2 Mechanisms of the Performance Enhancement in the Stretch–Shortening Cycle	407
7.6.3 Efficiency of Positive Work in Stretch–Shortening Cycle	411
<b>7.7 Summary</b>	<b>416</b>
<b>7.8 Questions for Review</b>	<b>420</b>
<b>7.9 Literature List</b>	<b>422</b>

## ■ Chapter 8 Muscle Coordination in Human Motion 429

### 8.1 Kinematic Redundancy and Kinematic Invariant

#### Characteristics of Limb Movements 430

8.1.1 Straight-Line Limb Endpoint Trajectory 434

8.1.2 Bell-Shaped Velocity Profile 437

8.1.3 Power Law 440

8.1.4 Fitts' Law 444

8.1.5 Principle of Least Action 446

### 8.2 Kinetic Invariant Characteristics of Limb Movements 447

8.2.1 Elbow–Shoulder Joint

Moment Covariation During Arm Reaching 448

8.2.2 Minimum Joint Moment Change 449

8.2.3 Orientation and Shape  
of the Arm Apparent Stiffness Ellipses 451

### 8.3 Muscle Redundancy 455

8.3.1 Sources of Muscle Redundancy 455

8.3.2 Invariant Features of Muscle Activity Patterns 457

### 8.4 The Distribution Problem 460

8.4.1 Static Optimization 460

8.4.1.1 Problem Formulation 460

8.4.1.2 Cost Functions 461

8.4.1.3 Accuracy of the Static Optimization Methods:  
How Well Do the Methods Work? 464

8.4.2 Dynamic Optimization 467

8.4.2.1 Basic Concepts 467

8.4.2.2 Forward Dynamics Problem 468

8.4.3 Inverse Optimization 472

8.4.4 On Optimization Methods  
in Human Biomechanics and Motor Control 476

### 8.5 Summary 478

### 8.6 Questions for Review 482

### 8.7 Literature List 483

Glossary 491

Index 511

About the Authors 519