# CONTENTS

Preface xiii Acknowledgments xvi

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	toy J. Brouley
1.4 Muscle as a Fiber-Reinforced Composite 30	
1.5 Fiber, Fascicle, and Muscle Length: Length-Length Ratio	os 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	9
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 Muse	cles 69

2.1.1.1 Stress–Strain Relations 74 2.1.1.1.1 Stress–Strain Relations in the Toe Region 76 2.1.1.1.2 Stress–Strain Relations in the Linear Region 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 Computational Models of the Tendons 90 2.1.2.2.2 Factors Affecting Mechanical Properties of the Tendons 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 2.2 Mechanical Properties of Passive Muscles 108 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 2.3 On Joint Flexibility 117 2.4 Summary 120 124 bold and in address of allow M 2.1.2.8 2.5 Questions for Review 2.6 Literature List 125 Chapter 3 Mechanics of Active Muscle 131 3.1 Muscle Force Production and Transmission 131 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 Parallel-Fibered and Fusiform Muscles 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 Pennate Muscles 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 Hydrostatic and Osmotic Pressure 163

3.1.6.3.2 Factors Affecting Intramuscular Pressure: Application of the Laplace Law 165

3.1.6.3.3 Biological Function of Intramuscular Pressure: The Compartment Syndrome 167

#### 3.2 Functional Relations 170

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

Part	II Muscles in the Body 249
Cha	pter 5 From Muscle Forces to Joint Moments 251
5.1 F	orce 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 F	orce Transmission via Soft Tissue Skeleton (Fascia) 261
	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 M	Iuscle 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 :	5.3.2.2.2 Load Application Method (Static Method) 299 3.3 Factors Affecting Muscle Moment Arm 301
0.0	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 Mile Power of Center of Miles

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
7.2 Negative Work in Selected Activities 374
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
7.3 Joint Moments During Eccentric Actions 383
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
7.4 Muscle Activity During Eccentric Actions 394
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
7.5 Physiological Cost of Eccentric Action 398
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
7.6 Reversible Muscle Action: Stretch–Shortening Cycle 402
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
7.7 Summary 416
7.8 Questions for Review 420
7.9 Literature List 422

### 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