Biomechanics of Movement

The Science of Sports, Robotics, and Rehabilitation

Thomas K. Uchida and Scott L. Delp illustrations by David Delp

THE MIT PRESS CAMBRIDGE, MASSACHUSETTS LONDON, ENGLAND

Contents

Preface XI

1

First Steps 1 Why we study movement 4 The Cybathlon 8 Tools to study movement 11 Overview of this book 15 Language of movement 16

2 Walking 25

The walking gait cycle 26 Ground reaction forces 28 Ballistic walking model 33 The Froude number 34 Cost of transport 37 Dynamic walking model 39 Arm swing 42 Skeletal model for gait analysis 44 Kinematics of walking 46 Ground reaction forces and walking speed 48 Atypical gait 49 Changes in walking under various conditions 52

3 Running 55

The running gait cycle 56 Ground reaction forces 57 Elastic mechanisms in hopping and running 61 Hopping robots 64 Tuned track 66 Elastic mechanisms to improve running shoes 69 Leg stiffness changes with body mass 70 Gait transitions 72 Bipedal mass-spring model 74 Kinematics of running 75 Ground reaction forces and running speed 77

Part I *Locomotion* Part II Production of Movement 4 Muscle Biology and Force 81

Muscle structure 83 The cross-bridge cycle 85 Sarcomere structure 86 Force-length relationship 88 Force-velocity relationship 90 Muscle activation 93 Rate encoding 95 Motor unit recruitment 96 Electromyography 98 Modeling muscle activation dynamics 100 Modeling the force-length-velocity-activation relationship 102

5 Muscle Architecture and Dynamics 105

Optimal muscle fiber length, ℓ_o^M 107 Muscle fiber pennation angle at optimal fiber length, ϕ_o 109 Maximum isometric muscle force, F_o^M 111 Maximum muscle contraction velocity, v_{max}^M 112 Tendon slack length, ℓ_s^T 114 Measuring muscle-specific parameters 117 Hill-type model of muscle-tendon dynamics 121 Dimensionless curves 123 Computing muscle force with a rigid tendon 124 Computing muscle force with a compliant tendon 126 Other models of muscle force generation 128

6 Musculoskeletal Geometry 133

Muscle mechanical advantage 134 Definition of a muscle moment arm 137 Tendon-excursion definition of a moment arm 138 Muscle moment arms affect muscle lengths and velocities 143 Moment arms of multi-joint muscles 145 Measurement and modeling of maximum joint moments 148 Muscle architecture, moment arms, and tendon transfer surgery 152 Moment arms of muscles with complex actions 154 Wrapping up 156

7 Quantifying Movement 161

Measurement techniques 162 Optical motion capture 166 Unconstrained inverse kinematics 171

Part III Analysis of Movement Transformation matrices 174 Calculating joint angles with unconstrained inverse kinematics 181 Constrained inverse kinematics 183 Kinematic model of the shoulder 186 Assessing anterior cruciate ligament injury risk 188

8 Inverse Dynamics 193

Measuring external forces 195 Center of pressure 197 Inverse dynamics algorithms 199 Inverse dynamics with ground reaction forces 201 Inverse dynamics without ground reaction forces 207 Verifying dynamic consistency 208 Joint moments during walking and running 209 Gait retraining to reduce knee loads and pain 212

9 Muscle Force Optimization 217

Biological and numerical optimizers 220 Static optimization problems solved by inspection 223 Local methods to solve static optimization problems 226 Global methods to solve static optimization problems 228 Muscle forces during walking and running 230 Estimating joint loads 238 Dynamic optimization 239 Muscle coordination during a standing long jump 242

Part IV Muscle-Driven Locomotion

10 Muscle-Driven Simulation 249

Understanding muscle actions during movement is challenging 251 Creating muscle-driven simulations 254 Stage 1: Modeling musculoskeletal system dynamics 255 Stage 2: Simulating movement 259 Stage 3: Testing the accuracy of dynamic simulations 262 Stage 4: Analyzing muscle-driven simulations 269 Software for creating muscle-driven simulations 270

11 Muscle-Driven Walking 273

Building and testing simulations of walking 275 Muscle contributions to ground reaction forces 275 Muscle actions during the swing phase 280 Muscle actions in stiff-knee gait 282 Muscle actions over a range of walking speeds 287 Muscle actions in crouch gait 292 Heel-walking and toe-walking 297 Device-assisted walking 299

12 Muscle-Driven Running 305

Building and testing simulations of running 307 Muscle contributions to ground reaction forces 310 Muscle activity during running 310 Changes with running speed 312 Run-to-sprint transition 314 Muscle actions during the walk-to-run transition 315 Interaction of arm and leg dynamics 317 Swinging the legs in running 317 Foot-strike patterns 318 Device-assisted running 323 Springs to enhance running 326

13 Moving Forward 331

Wearable technology 332 Physical rehabilitation everywhere 335 Large-scale experiments 336 Modern statistics and machine learning 338 Modeling neuromuscular control to predict movement 340 Motivating movement 342 Open science 343 Taking the baton 347

Symbols 349 References 353 Image Credits 363 Index 365