

Contents

Acknowledgments xiii

Preface xv

I

PRELIMINARIES

1. Introduction

Understanding Human Motor Control 2

Levels of Analysis 4

Fields Contributing to Research on Human Motor Control 6

Physics 6

Engineering 6

Statistics 7

Behavioral Science, Cognitive Science, and Human Factors 7

Physiology, Neuroscience, Medicine, and Allied Fields 7

Organization of the Book 7

Summary 9

2. Core Problems

The Degrees of Freedom Problem 12

Whose Problem Is the Degrees of Freedom Problem? 13

Why the Term “Degrees of Freedom”? 14

Synergies 14

Relying on Mechanics 18

Efficiency 18

The Sequencing and Timing Problem 20

Speech Errors 20

Coarticulation 22

Timing 23

The Perceptual-Motor Integration Problem 25

Feedback 25

Feedforward 26

Movement Enhances Perception 28

Movement Informs Perception 29

Mirror Neurons 31

The Learning Problem 32

Learning by Doing 33

Learning by Practicing Deliberately 34

Learning Through Specificity of Practice 35

Learning Through Neural Plasticity 37

Summary	39
Further Reading	41

3. Physiological Foundations

Muscle	46
<i>The Length-Tension Relation</i>	47
<i>Motor Units and Recruitment</i>	49
Proprioception	50
<i>Muscle Spindles</i>	51
<i>Golgi Tendon Organs</i>	53
<i>Joint Receptors</i>	54
<i>Cutaneous Receptors</i>	54
Spinal Cord	55
<i>Spinal Reflexes</i>	55
<i>Servo Theory</i>	55
<i>α-γ Coactivation</i>	57
<i>Recurrent Inhibition</i>	57
<i>Reciprocal Inhibition</i>	58
<i>The Smart Spinal Cord</i>	60
<i>Tuning of Spinal Reflexes</i>	61
Cerebellum	61
<i>Regulation of Muscle Tone</i>	62
<i>Coordination</i>	63
<i>Timing</i>	63
<i>Learning</i>	65
Basal Ganglia	65
<i>Huntington's Disease</i>	66
<i>Parkinson's Disease</i>	66
<i>Theories of Basal Ganglia Function</i>	67
Motor Cortex	69
<i>Force and Direction Control</i>	71
<i>Whole-Body Movement</i>	73
<i>Long-Loop Reflexes</i>	74
Premotor Cortex	75
Supplementary Motor Area	76
Parietal Cortex	80
<i>Apraxia</i>	81
<i>Cross-Modal Integration</i>	82
Disconnections	84
Concluding Remarks	85
Summary	86
Further Reading	89

4. Psychological Foundations

Theories of Sequencing and Timing	94
<i>Response Chaining</i>	94
<i>Element-to-Position Associations</i>	97
<i>Inter-Element Inhibition</i>	98
<i>Hierarchies</i>	99

Skill Acquisition	101
<i>Closed-Loop Theory</i>	101
<i>Generalized Programs</i>	103
<i>Hierarchical Learning</i>	106
<i>Mental Practice and Imagery</i>	109
<i>Stage Theory</i>	110
<i>Physical Changes in Skill Acquisition</i>	112
Codes and Stores	115
<i>Codes</i>	115
<i>Procedural and Declarative Knowledge</i>	116
<i>Long-Term Memory</i>	118
<i>Short-Term Memory</i>	119
<i>History Effects</i>	122
<i>Motor Programs</i>	124
<i>The Motor Output Buffer</i>	125
States of Mind	127
<i>Attention</i>	127
<i>Intention</i>	128
<i>Ideo-Motor Theory</i>	129
Summary	131
Further Reading	134

II

THE ACTIVITY SYSTEMS

5. Walking

Descriptions of Walking	136
<i>Gait Patterns at Different Speeds</i>	136
<i>Regularities in Gait Patterns</i>	139
Neural Control of Locomotion	141
<i>Neural Circuits for Locomotion</i>	143
<i>The Role of Sensory Feedback</i>	146
<i>Descending Effects</i>	147
<i>Anticipatory Postural Adjustments</i>	150
Walking Machines	151
The Development of Walking	154
<i>Neonatal Reflexes</i>	155
<i>Disappearance and Reappearance of Stepping</i>	156
Models of Motor Development	158
Navigating	161
<i>Visual Kinesthesia</i>	161
<i>Development of Visual Guidance</i>	163
Memory	164
<i>Route Maps and Survey Maps</i>	165
<i>Memory and Feedback</i>	166
Summary	168
Further Reading	171

6. Looking

Blinking	174
Accommodation	177
Pupil Constriction and Dilation	177
General Features of Eye Movements	179
<i>Why Moveable Eyes?</i>	179
<i>Physical Dynamics</i>	180
<i>Activation of the Extra-Ocular Muscles</i>	182
<i>Conjugate and Disjunctive Eye Movements</i>	184
<i>Miniature Eye Movements</i>	184
Saccades	187
<i>Saccadic Suppression</i>	191
<i>Saccades and Attention</i>	192
Smooth Pursuit Movements	194
<i>Optokinetic Nystagmus</i>	195
<i>Vestibular-Oculo-Motor Reflex</i>	197
Vergence Movements	200
Eye Movements and Space Constancy	201
Development and Plasticity of Oculo-Motor Control	205
Summary	206
Further Reading	209

7. Reaching and Grasping

The Development of Reaching and Grasping	214
<i>Direction</i>	215
<i>Distance</i>	215
<i>Orientation</i>	215
<i>Size</i>	216
<i>Functional Tuning of Grasps in Infancy</i>	216
Visual Guidance	217
<i>Vision and Touch</i>	219
<i>Vision for Action</i>	221
<i>Eye-Hand Coordination</i>	222
Aiming	225
<i>Woodworth's Pioneering Study</i>	227
<i>Fitts' Law</i>	229
<i>Iterative Corrections Model</i>	230
<i>Impulse Variability Model</i>	231
<i>Optimized Initial Impulse Model</i>	232
Equilibrium Point Hypothesis	233
Discrete Versus Continuous Movements	237
Intersegmental Coordination	238
<i>Transport and Grasp Phases</i>	240
<i>Hand-Space versus Joint-Space Planning</i>	241
<i>Moving Two Hands at Once</i>	244
Summary	248
Further Reading	249

8. Drawing and Writing

Drawing	254
<i>Planning of Strokes</i>	254
<i>The Isogony Principle</i>	257
<i>Two-Third Power Law</i>	258
<i>Drawing Smoothly</i>	262
Control of Writing	263
<i>Error Analyses</i>	263
<i>Dysgraphia</i>	263
<i>Reaction Time Evidence for Grapheme Selection</i>	265
<i>Reaction Time Evidence for Allograph Selection</i>	265
<i>Writing Size, Relative Timing, and Absolute Timing</i>	266
<i>Context Effects</i>	268
<i>Writing and Handedness</i>	270
The Dynamic Dominance Hypothesis	272
Summary	273
Further Reading	275

9. Keyboarding

Reaction Time	279
<i>Simple Reaction Time</i>	279
<i>Choice Reaction Time</i>	280
<i>Stimulus-Response Compatibility</i>	282
<i>Ideo-Motor Accounts of Stimulus-Response Compatibility</i>	284
<i>The SNARC Effect</i>	285
<i>The Simon Effect</i>	286
<i>The Stroop Effect</i>	286
<i>Response-Response Compatibility</i>	287
Simultaneous and Sequential Finger Presses	288
<i>Simultaneous Keystrokes</i>	288
<i>Sequences of Keypresses</i>	289
<i>Learning Keyboard Sequences</i>	293
<i>Control of Rhythm and Timing</i>	294
<i>Hierarchical Time Keepers</i>	296
<i>Event Timing</i>	297
<i>Amodality of Timing</i>	299
<i>Integration of Serial Order and Timing</i>	300
<i>Adjusting the Rate of Production for Entire Sequences</i>	301
Typing	303
<i>Historical Issues</i>	304
<i>Units of Typing Control</i>	306
<i>Typing Errors</i>	307
<i>Timing of Keystrokes in Typewriting</i>	307
<i>Rumelhart and Norman's Model of Typewriting</i>	312
Piano Playing	314
Summary	317
Further Reading	321

10. Speaking and Singing

The Issues	324
Overview of the Chapter	326
The Vocal Tract and Articulatory Dynamics	328
<i>The Respiratory System</i>	328
<i>Laryngeal Mechanisms</i>	329
<i>Articulatory Mechanisms</i>	331
<i>The Pharynx</i>	332
<i>Vowels</i>	332
<i>Consonants</i>	333
Variability	335
<i>The Motor Theory of Speech Perception</i>	336
<i>The Target Hypothesis</i>	337
<i>Relative Positions and Acoustic Targets</i>	339
<i>A Mechanism for Relative Positioning</i>	341
<i>A Parallel Distributed Processing System for Coarticulation</i>	343
High-Level Control of Speech	346
<i>Word Games</i>	346
<i>Laboratory Studies of Speaking Speed</i>	347
<i>Speech Errors</i>	349
Brain Mechanisms Underlying Speech	353
Bird Song	354
Motor Resonance	357
Summary	359
Further Reading	362

11. Smiling

Physical Control of the Face	364
Neural Control of the Face	366
<i>Control of the Upper and Lower Face</i>	366
<i>Volitional and Emotional Control</i>	366
<i>Left-Right Differences</i>	368
Origins of Emotional Expression	369
<i>Innateness and Universality</i>	369
<i>Causal Connections Between Expressions and Emotions</i>	370
<i>Associations Between Expressions and Emotions</i>	371
Social Interaction	374
<i>Imitation in Newborns</i>	375
<i>Imitation in Married Couples</i>	375
Summary	377
Further Reading	378

III

PRINCIPLES AND PROSPECTS

12. Moving On

Integration	379
<i>Hitting Oncoming Balls</i>	380
<i>Golf Putting</i>	383
<i>Walking and Reaching</i>	385
<i>Enactive Cognition</i>	386
<i>More Subtle Manifestations of Cognition in Action</i>	388
<i>Moving with Others</i>	391
<i>Motion and Emotion</i>	392
Individual Differences	395
Theories of Human Motor Control	397
<i>Dynamical Systems Theory</i>	400
<i>Optimization</i>	405
Innovations	412
<i>Genetics</i>	412
<i>Technology</i>	415
Concluding Remarks	418
Summary	421
Further Reading	423
References	425
Author Index	467
Subject Index	485