

---

# CONTENTS

---

Introduction	xv
Contributors	xxi
<b>1 BASIC PHYSIOLOGY AND BIOPHYSICS OF EMG</b>	
<b>SIGNAL GENERATION</b>	<b>1</b>
<i>T. Moritani, D. Stegeman, R. Merletti</i>	
1.1 Introduction	1
1.2 Basic Physiology of Motor Control and Muscle Contraction	2
1.2.1 Motor Unit	2
1.2.2 Motor Unit Recruitment and Firing Frequency (Rate Coding)	6
1.2.3 Factors Affecting Motor Unit Recruitment and Firing Frequency	9
1.2.4 Peripheral Motor Control System	11
1.2.5 Muscle Energetics and Neuromuscular Regulation	15
1.3 Basic Electrophysiology of the Muscle Cell Membrane	17
1.3.1 The Hodgkin-Huxley Model	17
1.3.2 Propagation of the Action Potential along the Muscle Fiber	19
References	20
<b>2 NEEDLE AND WIRE DETECTION TECHNIQUES</b>	<b>27</b>
<i>J. V. Trontelj, J. Jabre, M. Mihelin</i>	
2.1 Anatomical and Physiological Background of Intramuscular Recording	27
2.2 Recording Characteristics of Needle Electrodes	29
2.3 Conventional Needle EMG	30
2.3.1 MUAP Parameters and Their Changes in Disease	32
2.3.2 Needle EMG at Increasing Voluntary Contraction	34
2.3.3 The Concentric Needle Electrode	34
2.3.4 The Monopolar Needle Electrode	35
2.4 Special Needle Recording Techniques	36
2.4.1 Single-Fiber EMG	36
2.4.2 Macro EMG	39
2.4.3 EMG Decomposition Technique with Quadrifilar Needle Electrode	41
2.4.4 Scanning EMG	41
2.5 Physical Characteristics of Needle EMG Signals	42

2.6	Recording Equipment	43
2.6.1	Principles of Instrumentation	43
2.6.2	Features of EMG Equipment	43
2.6.3	Features of Digitized Signals	45
2.6.4	Data Format	45
	References	45
<b>3</b>	<b>DECOMPOSITION OF INTRAMUSCULAR EMG SIGNALS</b>	<b>47</b>
	<i>D. W. Stashuk, D. Farina, K. Sjøgaard</i>	
3.1	Introduction	47
3.2	Basic Steps for EMG Signal Decomposition	48
3.2.1	EMG Signal Acquisition	49
3.2.2	Detecting MUAPs or Signal Segmentation	50
3.2.3	Feature Extraction for Pattern Recognition	52
3.2.4	Clustering of Detected MUAPs	53
3.2.5	Supervised Classification of Detected MUAPs	58
3.2.6	Resolving Superimposed MUAPs	63
3.2.7	Uncovering Temporal Relationships between MUAPs	64
3.3	Evaluation of Performance of EMG Signal Decomposition Algorithms	67
3.3.1	Association between Reference and Detected MUs	67
3.3.2	Indexes of Performance	68
3.3.3	Evaluation of the Segmentation Phase Performance	68
3.3.4	Evaluation of the Classification Phase Performance	69
3.3.5	Reference Decomposition	70
3.4	Applications of Results of the Decomposition of an Intramuscular EMG Signal	70
3.4.1	Firing Pattern Analysis	71
3.4.2	Investigation of Correlation between MU Firing Patterns	74
3.4.3	Spike-Triggered Averaging of the Force Signal	75
3.4.4	Macro EMG	75
3.4.5	Spike-Triggered Averaging of the Surface EMG Signal	76
3.5	Conclusions	77
	References	77
<b>4</b>	<b>BIOPHYSICS OF THE GENERATION OF EMG SIGNALS</b>	<b>81</b>
	<i>D. Farina, R. Merletti, D. F. Stegeman</i>	
4.1	Introduction	81
4.2	EMG Signal Generation	82
4.2.1	Signal Source	82
4.2.2	Generation and Extinction of the Intracellular Action Potential	85
4.2.3	Volume Conductor	87
4.2.4	EMG Detection, Electrode Montages and Electrode Size	89

4.3 Crosstalk	91
4.3.1 Crosstalk Muscle Signals	91
4.3.2 Crosstalk and Detection System Selectivity	92
4.4 Relationships between Surface EMG Features and Developed Force	97
4.4.1 EMG Amplitude and Force	97
4.4.2 Estimated Conduction Velocity and Force	100
4.4.3 EMG Spectral Frequencies and Force	101
4.5 Conclusions	101
References	102

**5 DETECTION AND CONDITIONING OF THE SURFACE EMG SIGNAL 107**

*R. Merletti, H. Hermens*

5.1 Introduction	107
5.2 Electrodes: Their Transfer Function	108
5.3 Electrodes: Their Impedance, Noise, and dc Voltages	110
5.4 Electrode Configuration, Distance, Location	111
5.5 EMG Front-End Amplifiers	115
5.6 EMG Filters: Specifications	120
5.7 Sampling and A/D Conversion	121
5.8 European Recommendations on Electrodes and Electrode Locations	123
References	128

**6 SINGLE-CHANNEL TECHNIQUES FOR INFORMATION EXTRACTION FROM THE SURFACE EMG SIGNAL 133**

*E. A. Clancy, D. Farina, G. Filligoi*

6.1 Introduction	133
6.2 Spectral Estimation of Deterministic Signals and Stochastic Processes	134
6.2.1 Fourier-Based Spectral Estimators	134
6.2.2 Parametric Based Spectral Estimators	135
6.2.3 Estimation of the Time-Varying PSD of Nonstationary Stochastic Processes	137
6.3 Basic Surface EMG Signal Models	137
6.4 Surface EMG Amplitude Estimation	139
6.4.1 Measures of Amplitude Estimator Performance	141
6.4.2 EMG Amplitude Processing—Overview	141
6.4.3 Applications of EMG Amplitude Estimation	145
6.5 Extraction of Information in Frequency Domain from Surface EMG Signals	145
6.5.1 Estimation of PSD of the Surface EMG Signal Detected during Voluntary Contractions	146

6.5.2	Energy Spectral Density of the Surface EMG Signal Detected during Electrically Elicited Contractions	148
6.5.3	Descriptors of Spectral Compression	148
6.5.4	Other Approaches for Detecting Changes in Surface EMG Frequency Content during Voluntary Contractions	152
6.5.5	Applications of Spectral Analysis of the Surface EMG Signal	153
6.6	Joint Analysis of EMG Spectrum and Amplitude (JASA)	153
6.7	Recurrence Quantification Analysis of Surface EMG Signals	154
6.7.1	Mathematical Bases of RQA	155
6.7.2	Main Features of RQA	159
6.7.3	Application of RQA to Analysis of Surface EMG Signals	159
6.8	Conclusions	162
	References	163
<b>7</b>	<b>MULTI-CHANNEL TECHNIQUES FOR INFORMATION EXTRACTION FROM THE SURFACE EMG</b>	<b>169</b>
	<i>D. Farina, R. Merletti, C. Disselhorst-Klug</i>	
7.1	Introduction	169
7.2	Spatial Filtering	170
7.2.1	Idea Underlying Spatial Filtering	170
7.2.2	Mathematical Basis for the Description of Spatial Filters Comprised of Point Electrodes	173
7.2.3	Two-Dimensional Spatial Filters Comprised of Point Electrodes	174
7.2.4	Spatial Filters Comprised of Nonpoint Electrodes	177
7.2.5	Applications of Spatial Filtering Techniques	179
7.2.6	A Note on Crosstalk	180
7.3	Spatial Sampling	180
7.3.1	Linear Electrode Arrays	181
7.3.2	Two-Dimensional Spatial Sampling	183
7.4	Estimation of Muscle-Fiber Conduction Velocity	185
7.4.1	Two Channel-Based Methods for CV Estimation	186
7.4.2	Methods for CV Estimation Based on More Than Two Channels	190
7.4.3	Single MU CV Estimation	191
7.4.4	Influence of Anatomical, Physical, and Detection System Parameters on CV Estimates	196
7.5	Conclusions	196
	References	199
<b>8</b>	<b>EMG MODELING AND SIMULATION</b>	<b>205</b>
	<i>D. F. Stegeman, R. Merletti, H. J. Hermens</i>	
8.1	Introduction	205
8.2	Phenomenological Models of EMG	207



8.3	Elements of Structure-Based SEMG Models	207
8.4	Basic Assumptions	209
8.5	Elementary Sources of Bioelectric Muscle Activity	209
8.5.1	The Lowest Level: Intracellular Muscle-Fiber Action Potentials	209
8.5.2	The Highest Level: MU Action Potentials	210
8.6	Fiber Membrane Activity Profiles, Their Generation, Propagation, and Extinction	210
8.7	Structure of the Motor Unit	213
8.7.1	General Considerations	213
8.7.2	Inclusion of Force in Motor Unit Modeling	213
8.8	Volume Conduction	214
8.8.1	General Considerations	214
8.8.2	Basics Concepts	215
8.9	Modeling EMG Detection Systems	215
8.9.1	Electrode Configuration	216
8.9.2	Physical Dimensions of the Electrodes	216
8.10	Modeling Motor Unit Recruitment and Firing Behavior	218
8.10.1	MU Interpulse Intervals	220
8.10.2	Mean Interpulse Intervals across Motor Units	220
8.10.3	Synchronization	220
8.11	Inverse Modeling	222
8.12	Modeling of Muscle Fatigue	222
8.12.1	Myoelectric Manifestations of Muscle Fatigue during Voluntary Contractions	222
8.12.2	Myoelectric Manifestations of Muscle Fatigue during Electrically Elicited Contractions	224
8.13	Other Applications of Modeling	226
8.14	Conclusions	227
	References	227

## **9 MYOELECTRIC MANIFESTATIONS OF MUSCLE FATIGUE 233**

*R. Merletti, A. Rainoldi, D. Farina*

9.1	Introduction	233
9.2	Definitions and Sites of Neuromuscular Fatigue	234
9.3	Assessment of Muscle Fatigue	235
9.4	How Fatigue Is Reflected in Surface EMG Variables	236
9.5	Myoelectric Manifestations of Muscle Fatigue in Isometric Voluntary Contractions	238
9.6	Fiber Typing and Myoelectric Manifestations of Muscle Fatigue	242
9.7	Factors Affecting Surface EMG Variables	246
9.7.1	Isometric Contractions	246
9.7.2	Dynamic Contractions	251

9.8	Repeatability of Estimates of EMG Variables and Fatigue Indexes	251
9.9	Conclusions	252
	References	253

## **10 ADVANCED SIGNAL PROCESSING TECHNIQUES** **259**

*D. Zazula, S. Karlsson, C. Doncarli*

10.1	Introduction	259
10.1.1	Parametric Context	260
10.1.2	Nonparametric Context	260
10.1.3	Conclusion	261
10.2	Theoretical Background	261
10.2.1	Multichannel Models of Compound Signals	261
10.2.2	Stochastic Processes	264
10.2.3	Time-Frequency Representations	269
10.2.4	Wavelet Transform	272
10.2.5	Improving the PSD Estimation Using Wavelet Shrinkage	279
10.2.6	Spectral Shape Indicators	280
10.3	Decomposition of EMG Signals	281
10.3.1	Parametric Decomposition of EMG Signals Using Wavelet Transform	281
10.3.2	Decomposition of EMG Signal Using Higher Order Statistics	287
10.4	Applications to Monitoring Myoelectric Manifestations of Muscle Fatigue	292
10.4.1	Myoelectric Manifestations of Muscle Fatigue during Static Contractions	293
10.4.2	Myoelectric Manifestations of Muscle Fatigue during Dynamic Contraction	296
10.5	Conclusions	300
	Acknowledgment	302
	References	302

## **11 SURFACE MECHANOMYOGRAM** **305**

*C. Orizio*

11.1	The Mechanomyogram (MMG): General Aspects during Stimulated and Voluntary Contraction	305
11.2	Detection Techniques and Sensors Comparison	307
11.2.1	MMG Detected by Laser Distance Sensors	307
11.2.2	MMG Detected by Accelerometers	308
11.2.3	MMG Detected by Piezoelectric Contact Sensors	309
11.2.4	MMG Detected by Microphones	310
11.3	Comparison between Different Detectors	310
11.4	Simulation	312
11.5	MMG Versus Force: Joint and Adjunct Information Content	313

11.6 MMG Versus EMG: Joint and Adjunct Information Content	316
11.7 Area of Application	318
References	318

**12 SURFACE EMG APPLICATIONS IN NEUROLOGY 323**

<i>M. J. Zwarts, D. F. Stegeman, J. G. van Dijk</i>	
12.1 Introduction	323
12.2 Central Nervous System Disorders and SEMG	324
12.3 Compound Muscle Action Potential and Motor Nerve Conduction	326
12.4 CMAP Generation	328
12.4.1 CMAP as a Giant MUAP	328
12.4.2 Muscle Cartography	330
12.5 Clinical Applications	332
12.5.1 Amplitude: What Does It Stand For?	332
12.5.2 Deriving Conduction Properties from Two CMAPs	333
12.6 Pathological Fatigue	335
12.7 New Avenues: High-Density Multichannel Recording	338
12.8 Conclusion	341
References	341

**13 APPLICATIONS IN ERGONOMICS 343**

<i>G. M. Hägg, B. Melin, R. Kadefors</i>	
13.1 Historic Perspective	343
13.2 Basic Workload Concepts in Ergonomics	344
13.3 Basic Surface EMG Signal Processing	345
13.4 Load Estimation and SEMG Normalization and Calibration	346
13.5 Amplitude Data Reduction over Time	347
13.6 Electromyographic Signal Alterations Indicating Muscle Fatigue in Ergonomics	348
13.7 SEMG Biofeedback in Ergonomics	352
13.8 Surface EMG and Musculoskeletal Disorders	352
13.9 Psychological Effects on EMG	353
13.9.1 Definitions of Stress	354
13.9.2 Psychological and Physical Stress and the Total Workload on the Organism	354
13.9.3 Psychological Stress and Musculoskeletal Disorders	355
13.9.4 Two Neuroendocrine Systems Sensitive to Psychological Stress	355
13.9.5 Is It Justified to Include EMG in the Field of Stress?	355
13.9.6 Mental Stress Increases EMG Activity	356
13.9.7 Is the Trapezius Muscle Special in Its Response to Psychological Stress?	356

13.9.8	Psychological Factors and Possible Links to Musculoskeletal Tension	357
13.9.9	Conclusions	358
	References	358
<b>14</b>	<b>APPLICATIONS IN EXERCISE PHYSIOLOGY</b>	<b>365</b>
	<i>F. Felici</i>	
14.1	Introduction	365
14.2	A Few “Tips and Tricks”	366
14.3	Time and Frequency Domain Analysis of sEMG: What Are We Looking For?	368
14.4	Application of sEMG to the Study of Exercise	370
14.4.1	Walking versus Race Walking and Running	370
14.4.2	Gait Analysis Results	371
14.5	Strength and Power Training	372
14.6	Muscle Damage Studied by Means of sEMG	375
	References	377
<b>15</b>	<b>APPLICATIONS IN MOVEMENT AND GAIT ANALYSIS</b>	<b>381</b>
	<i>C. Frigo, R. Shiavi</i>	
15.1	Relevance of Electromyography in Kinesiology	381
15.2	Typical Acquisition Settings	382
15.3	Study of Motor Control Strategies	384
15.4	Investigation on the Mechanical Effect of Muscle Contraction	385
15.5	Gait Analysis	386
15.6	Identification of Pathophysiologic Factors	387
15.7	Workload Assessment in Occupational Biomechanics	388
15.8	Biofeedback	389
15.9	The Linear Envelope	389
15.9.1	Construction of the Linear Envelope	390
15.9.2	EMG Profiles	390
15.9.3	Repeatability	391
15.10	Information Enhancement through Multifactorial Analysis	393
15.10.1	Measured Variables	393
15.10.2	Measured and Derived Variables	397
	References	397
<b>16</b>	<b>APPLICATIONS IN REHABILITATION MEDICINE AND RELATED FIELDS</b>	<b>403</b>
	<i>A. Rainoldi, R. Casale, P. Hodges, G. Jull</i>	
16.1	Introduction	403
16.2	Electromyography as a Tool in Back and Neck Pain	404



16.2.1 Electromyography as a Tool to Investigate Motor Control of the Spine	404
16.2.2 Application to Neck Pain	409
16.2.3 Analysis in the Frequency Domain	410
16.3 EMG of the Pelvic Floor: A New Challenge in Neurological Rehabilitation	411
16.3.1 Introduction	411
16.3.2 Anatomy of the Pelvic Floor	412
16.3.3 Physiopathology of the Pelvic Floor	412
16.3.4 Routine Evaluation of the Pelvic Floor	412
16.4 Age-Related Effects on EMG Assessment of Muscle Physiology	417
16.4.1 Muscle Strength	417
16.4.2 Fiber Type Composition	418
16.4.3 Myoelectrical Manifestation of Muscle Fatigue	419
16.5 Surface EMG and Hypobaric Hypoxia	420
16.5.1 Physiological Modification Induced by Hypoxia	421
16.5.2 Modification of Mechanical Muscle Response Induced by Hypoxia	421
16.5.3 Modification of Fiber Type Induced by Hypoxia	421
16.5.4 Modification of Muscle Fatigue Induced by Hypoxia	421
16.5.5 The Role of Acclimatization	422
16.6 Microgravity Effects on Neuromuscular System	423
16.6.1 Postflight Effects on Humans	423
16.6.2 Postflight Effects on Animals	423
16.6.3 Models of Microgravity Effects	424
16.6.4 Microgravity Effect, Duration, and Countermeasures	425
References	425

## **17 BIOFEEDBACK APPLICATIONS 435**

<i>J. R. Cram</i>	
17.1 Introduction	435
17.2 Biofeedback Application to Impairment Syndromes	436
17.2.1 Psychophysiological, Stress-Related Hyperactivity	436
17.2.2 Simple Postural Dysfunction	437
17.2.3 Weakness/Deconditioning	438
17.2.4 Acute Reflexive Spasm/Inhibition	439
17.2.5 Learned Guarding/Bracing	439
17.2.6 Learned Inhibition/Weakness	440
17.2.7 Direct Compensation for Joint Hypermobility or Hypomobility	441
17.2.8 Chronic Faulty Motor Programs	442
17.3 SEMG Biofeedback Techniques	443
17.3.1 Isolation of Target Muscle Activity	443

17.3.2	Relaxation-Based Downtraining	444
17.3.3	Threshold-Based Uptraining or Downtraining	445
17.3.4	Threshold-Based Tension Recognition Training	445
17.3.5	Tension Discrimination Training	446
17.3.6	Deactivation Training	446
17.3.7	Generalization to Progressively Dynamic Movement	446
17.3.8	SEMG-Triggered Neuromuscular Electrical Stimulation (NMES)	448
17.3.9	Left/Right Equilibration Training	448
17.3.10	Motor Copy Training	449
17.3.11	Postural Training with SEMG Feedback	449
17.3.12	Body Mechanics Instruction	449
17.3.13	Therapeutic Exercise with SEMG Feedback	449
17.3.14	Functional Activity Performance with SEMG Feedback	450
17.4	Summary	450
	References	450

## **18 CONTROL OF POWERED UPPER LIMB PROSTHESES 453**

*P. A. Parker, K. B. Englehart, B. S. Hudgins*

18.1	Introduction	453
18.2	Myoelectric Signal as a Control Input	455
18.2.1	Single Myoelectric Channel Model	455
18.2.2	Single-Channel Control Information	457
18.2.3	Limitations of the Single-Channel Myoelectric Signal as Control Input	458
18.2.4	Multiple Myoelectric Channels	460
18.3	Conventional Myoelectric Control	460
18.4	Emerging MEC Strategies	463
18.4.1	Pattern Recognition Based Control	463
18.4.2	Intelligent Subsystems	468
18.5	Summary	471
	References	471

## **Index 477**