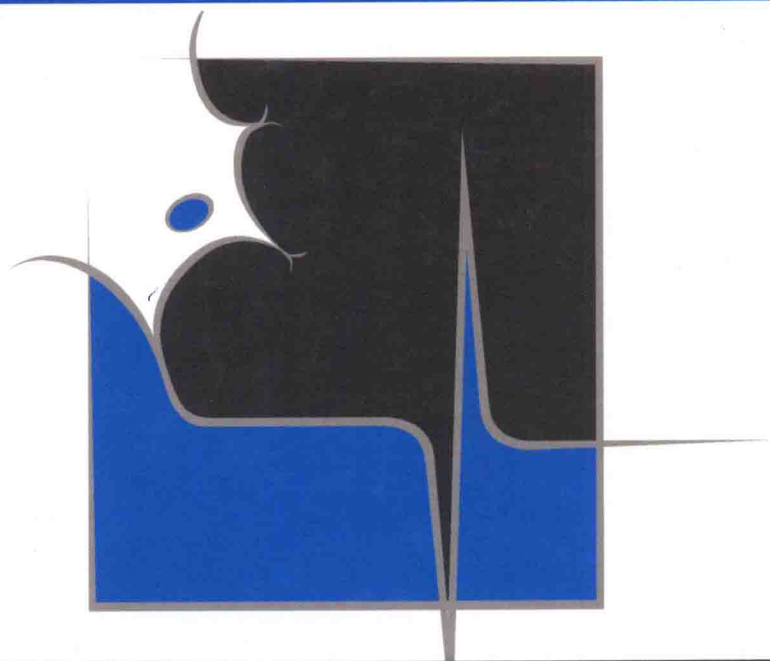


# Introduction to Neural Engineering for Motor Rehabilitation



EDITED BY  
DARIO FARINA, WINNIE JENSEN,  
AND METIN AKAY



IEEE Press Series in Biomedical Engineering  
Metin Akay, *Series Editor*



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# INTRODUCTION TO NEURAL ENGINEERING FOR MOTOR REHABILITATION

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EDITED BY

**DARIO FARINA**

Department of Neurorehabilitation Engineering, Bernstein Focus  
Neurotechnology Göttingen, Bernstein Center for Computational  
Neuroscience, University Medical Center Göttingen, Georg-August  
University, Göttingen, Germany

**WINNIE JENSEN**

Center for Sensory-Motor Interaction, Department of Health Science and  
Technology, Aalborg University, Aalborg, Denmark

**METIN AKAY**

Department of Biomedical Engineering, Cullen College of Engineering,  
University of Houston, Houston, TX, USA



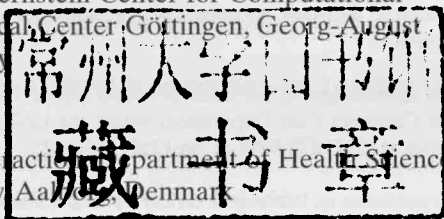
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# CONTRIBUTORS

**Ole K. Andersen**, Integrative Neuroscience Group, Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark

**Felix Biessmann**, Machine Learning Group, Technische Universität Berlin, Berlin, Germany

**Alberto Botter**, Laboratory for Engineering of the Neuromuscular System (LISiN), Politecnico di Torino, Torino, Italy

**Germana Cappellini**, Laboratory of Neuromotor Physiology, Santa Lucia Foundation, Rome, Italy

**Jacopo Carpaneto**, Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy

**Maura Casadio**, Department of Informatics, Systems and Telematics, University of Genoa, Italy; Sensory Motor Performance Program, Rehabilitation Institute of Chicago and Department of Physiology, Northwestern University Medical School, Chicago, IL, USA

**Luca Citi**, Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA; Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA; Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy

**Elaine A. Corbett**, Department of Biomedical Engineering, Northwestern University, Evanston, IL, USA

**Janis J. Daly**, Director, Brain Rehabilitation Research Center of Excellence, MR Gainesville DVA Medical Center; Research Career Scientist, DVA; Professor, Department of Neurology, College of Medicine, University of Florida, Gainesville, FL, USA; Director, Brain Rehabilitation Research Program, McKnight Brain Institute, University of Florida, Gainesville, FL, USA

**Peter Detemple**, Institut für Mikrotechnik Mainz GmbH, Mainz, Germany

**Hans Dietl**, Otto Bock HealthCare GmbH, Duderstadt, Germany; Otto Bock HealthCare Products GmbH, Vienna, Austria

**Omar Feix do Nascimento**, Center for Sensory–Motor Interaction, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark

**Strahinja Došen**, Department of Neurorehabilitation Engineering, University Medical Center, Georg-August University, Göttingen, Germany

**Kim Dremstrup**, Center for Sensory–Motor Interaction, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark

**Günter Edlinger**, g.tec medical engineering GmbH/Guger Technologies OG Schiedlberg, Austria

**Kevin Englehart**, Institute of Biomedical Engineering, University of New Brunswick, Fredericton, NB, Canada

**Christian Ethier**, Department of Physiology, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA

**Dario Farina**, Department of Neurorehabilitation Engineering, Bernstein Focus Neurotechnology Göttingen, Bernstein Center for Computational Neuroscience, University Medical Center Göttingen, Georg-August University, Göttingen, Germany

**Marco Gazzoni**, Laboratory for Engineering of the Neuromuscular System (LISiN), Politecnico di Torino, Torino, Italy

**Di Ge**, Glaizer Groupe, Malakoff, France

**Bernhard Graimann**, Otto Bock HealthCare GmbH, Duderstadt, Germany

**Ying Gu**, Center for Sensory–Motor Interaction, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark

**Christoph Guger**, g.tec medical engineering GmbH/Guger Technologies OG, Schiedlberg, Austria

**Levi Hargrove**, Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, IL, USA; Department of Physical Medicine and Rehabilitation, Northwestern University Feinberg School of Medicine, Chicago, IL, USA

**Kristian Rauhe Harreby**, Center for Sensory–Motor Interaction, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark

**Ulrich G. Hofmann**, Neuroelectronic Systems, Department for Neurosurgery, University Hospital Freiburg, Freiburg, Germany; Graduate School for Computing in Medicine and Life Sciences, University of Lübeck, Lübeck, Germany

**Yuri P. Ivanenko**, Laboratory of Neuromotor Physiology, Santa Lucia Foundation, Rome, Italy

**Winnie Jensen**, Center for Sensory–Motor Interaction, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark

**Konrad Kording**, Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA; Department of Physiology, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA

**Francesco Lacquaniti**, Department of Neuroscience and Centre of Space Biomedicine, University of Rome Tor Vergata, Rome, Italy; Laboratory of Neuromotor Physiology, Santa Lucia Foundation, Rome, Italy

**Birgit Larsen**, Neurodan A/S, Aalborg, Denmark

**Lorenzo Masia**, Department of Robotics, Brain and Cognitive Sciences, Italian Institute of Technology, Genoa, Italy

**Kevin A. Mauser**, Biomedical Engineering Department, Indiana University–Purdue University Indianapolis, Indianapolis, IN, USA

**Frank C. Meinecke**, Machine Learning Group, Technische Universität Berlin, Berlin, Germany

**Roberto Merletti**, Laboratory for Engineering of the Neuromuscular System (LISiN), Politecnico di Torino, Torino, Italy

**Silvestro Micera**, Biorobotics Institute, Scuola Superiore Sant’Anna, Pisa, Italy; Center for Neuroprosthetics and Institute of Bioengineering, School of Engineering, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

**José del R. Millán**, Center for Neuroprosthetics, School of Engineering, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

**Lee E. Miller**, Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA; Department of Physiology, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA; Department of Biomedical Engineering, Northwestern University, Evanston, IL, USA

**Marco Molinari**, Spinal Cord Unit, Santa Lucia Foundation, Rome, Italy

- Pietro G. Morasso**, Department of Robotics, Brain and Cognitive Sciences, Italian Institute of Technology, Genoa, Italy
- Juan C. Moreno**, Bioengineering Group, Spanish Research Council, CSIC, Arganda del Rey, Spain
- Natalie Mrachacz-Kersting**, Center for Sensory-Motor Interaction (SMI), Department of Health Science and Technology, Aalborg University, Aalborg, Denmark
- Klaus-Robert Müller**, Machine Learning Group, Technische Universität Berlin, Berlin, Germany
- Xavier Navarro**, Institute of Neurosciences and Department of Cell Biology, Physiology and Immunology, Universitat Autònoma de Barcelona; Centro de Investigación en Red sobre Enfermedades Neurodegenerativas (CIBER-NED), Spain
- Emily R. Oby**, Department of Physiology, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA
- António R.C. Paiva**, Scientific Computing and Imaging Institute, University of Utah, Salt Lake City, UT, USA; presently at ExxonMobil Upstream Research Company, Houston, TX, USA
- Il Park**, Center for Perceptual Systems and Institute for Neuroscience, University of Texas, Austin, TX, USA
- Andrei Patriciu**, Neurodan A/S, Aalborg, Denmark
- Eric J. Perreault**, Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago, IL, USA; Department of Biomedical Engineering, Northwestern University, Evanston, IL, USA
- José Luis Pons**, Bioengineering Group, Spanish Research Council, CSIC, Arganda del Rey, Spain
- Dejan B. Popović**, Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark; University of Belgrade, Faculty of Electrical Engineering, Belgrade, Serbia
- Mirjana B. Popović**, University of Belgrade, Faculty of Electrical Engineering, Belgrade, Serbia; Aalborg University, Department for Health Science and Engineering, Aalborg, Denmark; University of Belgrade, Institute for Multidisciplinary Research, Belgrade, Serbia
- José C. Príncipe**, Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL, USA
- Shaoyu Qiao**, Weldon School of Biomedical Engineering, Purdue University, West Lafayette, IN, USA

- Stanisa Raspopovic**, Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy; Center for Neuroprosthetics and Institute of Bioengineering, School of Engineering, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- Jacopo Rigosa**, Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
- Eduardo Rocon**, Bioengineering Group, Spanish Research Council, CSIC, Arganda del Rey, Spain
- Justin C. Sanchez**, Department of Biomedical Engineering, University of Miami, Coral Gables, FL, USA
- Vittorio Sanguineti**, Department of Informatics, Systems and Telematics, University of Genoa, Italy; Department of Robotics, Brain and Cognitive Sciences, Italian Institute of Technology, Genoa, Italy
- Erik Scheme**, Institute of Biomedical Engineering, University of New Brunswick, Fredericton, NB, Canada
- Thomas Sinkjær**, Center for Sensory–Motor Interaction, Aalborg University, Aalborg, Denmark
- Erika G. Spaich**, Integrative Neuroscience Group, Center for Sensory–Motor Interaction, Aalborg University, Aalborg, Denmark
- Valentina Squeri**, Department of Robotics, Brain and Cognitive Sciences, Italian Institute of Technology, Genoa, Italy
- Aiko K. Thompson**, Program for Translational Neurological Research, Helen Hayes Hospital and the Wadsworth Center, New York State Department of Health, New York, NY, USA
- Jonathan R. Wolpaw**, Program for Translational Neurological Research, Helen Hayes Hospital and the Wadsworth Center, New York State Department of Health, New York, NY, USA
- Yijing Xie**, Graduate School for Computing in Medicine and Life Sciences, University of Lübeck, Lübeck, Germany
- Ken Yoshida**, Biomedical Engineering Department, Indiana University–Purdue University Indianapolis, Indianapolis, IN, USA; Weldon School of Biomedical Engineering, Purdue University, West Lafayette, IN, USA; Center for Sensory–Motor Interaction, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark



## PREFACE

Neural engineering is an interdisciplinary research area that brings to bear methods from neuroscience and engineering to analyze neurological functions and to design solutions to problems associated with neurological limitations and dysfunctions (definition by the Editorial Board of the *Journal of Neural Engineering* [Durand, 2007]). Despite neural engineering's being a relatively new research area, the field is developing rapidly. This development requires continuously updated didactic material for the increasing number of undergraduate, graduate, and Ph.D. courses on the topic. The applications of neural engineering to rehabilitation of movement cover a broad range of engineering challenges, from electrode design to signal processing and from the neurophysiology of movement to robotics.

The three main approaches of neural engineering used for rehabilitation of impaired motor functions are restoration, replacement, and neuromodulation. Restoration consists in retaining existing neural and anatomical structures and in controlling them for reestablishing a motor function. An example of such an approach is functional electrical stimulation (FES). Replacement consists in substituting the impaired motor apparatus with an artificial one, controlled by residual, but still functional, neural or muscular structures. An example of these methods is the control of artificial limbs (active prostheses). The aim of neuromodulation is (re)training the central nervous system to induce plasticity through artificial stimulation of afferent pathways and/or by artificial enhancement of efferent neural and muscular signals provided as feedback. Examples of such an approach are the application of patterned peripheral electrical neuromuscular stimulation (e.g., transcutaneous electrical nerve stimulation, TENS), mechanical stimulation using robots,

or repetitive transcranial magnetic stimulation for retraining the diseased central nervous system.

The aim of this book is to present the state of the art in technologies for motor neurorehabilitation and to give an overview of the current challenges and recent advances within neural rehabilitation technology. The book is intended for undergraduate, graduate, and Ph.D. students as well as senior researchers who work in the field of biomedical engineering, and it is organized in five parts. Part I reviews aspects related to injuries of the nervous system that determine motor impairments. It is considered as a prerequisite that the reader is familiar with the physiology of the neuromuscular system, which is not included in this book. Part II reviews engineering methods for interfacing the neuromuscular system and for conditioning and processing neural and muscular signals. The methods described in Part II are also used in the last three parts of the book, which describe examples of neurotechnologies within the areas of restoration, replacement, and neuromodulation. The topics in each part are collected with the focus on the application (e.g., replacement of function) rather than on the principle on which such application is exploited. Therefore, for example, the principle of brain-interfacing is used in applications described in both Parts III (replacement) and V (neuromodulation), according to the different uses of brain-interfacing in these two sections. Each part begins with a short introduction that serves to put into perspective the topics addressed in that part and to guide the reader to the research areas detailed there. The book's parts comprise introductory chapters, which provide a broad perspective (review chapters), and chapters with a strong focus on more specialized topics (focused chapters), as indicated at the beginning of each chapter.

The book is intended to provide a broad perspective within the field of motor neurorehabilitation engineering by including several topics that in most other books are treated separately. At the same time, the book does not intend to provide an exhaustive treatment of all methods and approaches for motor neurorehabilitation. Rather, the topics presented have been selected to be representative of the field and thus to provide the reader with a general broad overview and understanding of the research area. Readers who approach neural rehabilitation engineering for the first time will find the review chapters as an overview of the state of the art, whereas senior researchers or experts within the field may have further interest in the focused chapters that provide a detailed analysis of specific topics with recent solutions. As indicated, the physiology of the neuromuscular system is not presented in this book, which has as its starting point the injuries of the system. Therefore, readers approaching neural engineering for the first time are advised to first consult references on human physiology.

The editors are very grateful to all the contributing authors for enthusiastically accepting the invitation to contribute to this project and to Dr. Antonietta Stango (University Medical Center Göttingen, Germany) for the important contribution of assisting with the editorial tasks.

Dario Farina thanks the European Research Council (ERC), which has awarded him the Advanced Research Grant DEMOVE (“Decoding the Neural Code of Human Movements for a New Generation of Man–Machine Interfaces”; contract #267888). This grant has supported Dario Farina for the time invested in editing this book.

DARIO FARINA  
WINNIE JENSEN  
METIN AKAY

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# CONTENTS

CONTRIBUTORS	ix
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PREFACE	xv
---------	----

PART I INJURIES OF THE NERVOUS SYSTEM	1
---------------------------------------	---

1 Diseases and Injuries of the Central Nervous System Leading to Sensory–Motor Impairment	3
<i>Dejan B. Popović and Thomas Sinkjær</i>	
2 Peripheral and Spinal Plasticity after Nerve Injuries	21
<i>Xavier Navarro</i>	
3 Motor Control Modules of Human Movement in Health and Disease	39
<i>Yuri P. Ivanenko, Germana Cappellini, Marco Molinari, and Francesco Lacquaniti</i>	

PART II SIGNAL DETECTION AND CONDITIONING	61
---	----

4 Progress in Peripheral Neural Interfaces	63
<i>Shaoyu Qiao, Kevin A. Mauser, and Ken Yoshida</i>	
5 Multimodal, Multisite Neuronal Recordings for Brain Research	95
<i>Ulrich G. Hofmann, Peter Detemple, and Yijing Xie</i>	
6 Surface Electromyogram Detection	113
<i>Alberto Botter, Marco Gazzoni, and Roberto Merletti</i>	

<b>7</b>	<b>Methods for Noninvasive Electroencephalogram Detection</b>	<b>137</b>
	<i>Christoph Guger and Günter Edlinger</i>	
<b>8</b>	<b>Spike Sorting</b>	<b>155</b>
	<i>Di Ge and Dario Farina</i>	
<b>9</b>	<b>Wavelet Denoising and Conditioning of Neural Recordings</b>	<b>173</b>
	<i>Luca Citi and Silvestro Micera</i>	
<b>10</b>	<b>Instantaneous Cross-Correlation Analysis of Neural Ensembles with High Temporal Resolution</b>	<b>183</b>
	<i>António R.C. Paiva, Il Park, José C. Príncipe, and Justin C. Sanchez</i>	
<b>11</b>	<b>Unsupervised Decomposition Methods for Analysis of Multimodal Neural Data</b>	<b>199</b>
	<i>Felix Biessmann, Frank C. Meinecke, and Klaus-Robert Müller</i>	
<b>PART III FUNCTION REPLACEMENT (PROSTHESES AND ORTHOSIS)</b>		<b>235</b>
<b>12</b>	<b>Brain-Computer Interfaces</b>	<b>237</b>
	<i>José del R. Millán</i>	
<b>13</b>	<b>Movement-Related Cortical Potentials and Their Application in Brain-Computer Interfacing</b>	<b>253</b>
	<i>Kim Dremstrup, Ying Gu, Omar Feix do Nascimento, and Dario Farina</i>	
<b>14</b>	<b>Introduction to Upper Limb Prosthetics</b>	<b>267</b>
	<i>Bernhard Graimann and Hans Dietl</i>	
<b>15</b>	<b>Myoelectric Prostheses and Targeted Reinnervation</b>	<b>291</b>
	<i>Levi Hargrove, Erik Scheme, and Kevin Englehart</i>	
<b>16</b>	<b>Controlling Prostheses Using PNS Invasive Interfaces for Amputees</b>	<b>311</b>
	<i>Jacopo Carpaneto, Luca Citi, Stanisa Raspopovic, Jacopo Rigosa, and Silvestro Micera</i>	
<b>17</b>	<b>Exoskeletal Robotics for Functional Substitution</b>	<b>327</b>
	<i>José Luis Pons, Juan C. Moreno, and Eduardo Rocon</i>	
<b>PART IV FUNCTION RESTORATION</b>		<b>349</b>
<b>18</b>	<b>Methods for Movement Restoration</b>	<b>351</b>
	<i>Dejan B. Popović, and Mirjana B. Popović</i>	

<b>19</b>	<b>Advanced User Interfaces for Upper Limb Functional Electrical Stimulation</b>	<b>377</b>
	<i>Elaine A. Corbett, Christian Ethier, Emily R. Oby, Konrad Kording, Eric J. Perreault, and Lee E. Miller</i>	
<b>20</b>	<b>Customized Modeling and Simulations for the Control of FES-Assisted Walking of Individuals with Hemiplegia</b>	<b>401</b>
	<i>Strahinja Došen and Dejan B. Popović</i>	
<b>21</b>	<b>ActiGait®: A Partly Implantable Drop-Foot Stimulator System</b>	<b>421</b>
	<i>Birgit Larsen and Andrei Patriciu</i>	
<b>22</b>	<b>Selectivity of Peripheral Neural Interfaces</b>	<b>433</b>
	<i>Winnie Jensen and Kristian Rauhe Harreby</i>	

## **PART V REHABILITATION THROUGH NEUROMODULATION**

<b>23</b>	<b>Brain-Computer Interface Applied to Motor Recovery after Brain Injury</b>	<b>463</b>
	<i>Janis J. Daly</i>	
<b>24</b>	<b>Functional Electrical Therapy of Upper Extremities</b>	<b>477</b>
	<i>Mirjana B. Popović and Dejan B. Popović</i>	
<b>25</b>	<b>Gait Rehabilitation Using Nociceptive Withdrawal Reflex-Based Functional Electrical Therapy in Stroke Patients</b>	<b>493</b>
	<i>Ole K. Andersen and Erika G. Spaich</i>	
<b>26</b>	<b>Robot-Assisted Neurorehabilitation</b>	<b>505</b>
	<i>Vittorio Sanguineti, Maura Casadio, Lorenzo Masia, Valentina Squeri, and Pietro G. Morasso</i>	
<b>27</b>	<b>Paired Associative Stimulation</b>	<b>529</b>
	<i>Natalie Mrachacz-Kersting</i>	
<b>28</b>	<b>Operant Conditioning of Spinal Reflexes for Motor Rehabilitation after CNS Damage</b>	<b>549</b>
	<i>Aiko K. Thompson and Jonathan R. Wolpaw</i>	

## **INDEX**

## **PART I**

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# **INJURIES OF THE NERVOUS SYSTEM**

Part I contains three chapters that examine the type of neural injuries that may lead to sensory–motor impairment, as well as aspects of plasticity, as a relatively novel conceptual theme in the field of neural rehabilitation. Damage to the nervous system is typically associated with the loss of motor drive and of afferent input to the central nervous system. The severity of the neural damage depends on the location of the injury, which may lead to adaptation of the movement pattern, paresis, or complete paralysis. Plasticity has been defined as changes in the strength, number, and location of synaptic connections in response to either an environmental stimulus or an alteration in synaptic activity in a network; our fundamental understanding of what underlies neural plasticity is believed to be one of the key elements in devising strategies for rehabilitation or repair of injuries.

Chapter 1, by Popović and Sinkjær, provides a review of the incidence and the pathology of major diseases and injuries within the central nervous system that lead to impairment of the sensory–motor system, such as stroke and spinal cord injury. The chapter also briefly introduces the types of injuries that lead to loss of sensory–motor functions at the peripheral level.

Chapter 2, by Navarro, more specifically examines injuries at the peripheral level that may result in partial or total loss of motor, sensory, and autonomic functions. Functional deficits may be compensated by reinnervation of denervated targets by regenerating the injured axons, by collateral branching of

undamaged axons, or by remodeling of nervous system circuitries. Plasticity of central connections may compensate functionally for the lack of adequate target reinnervation; however, plasticity has limited effects on disturbed sensory localization or fine motor control after injuries, and it may even result in maladaptive changes, such as neuropathic pain and hyperreflexia.

Obtaining evidence for spinal or cortical plasticity in the human is very difficult without using invasive recording techniques. Chapter 3, by Ivanenko and collaborators, reports on motor primitives to provide a novel perspective on how the neural control system operates under locomotion in healthy subjects and in patients. They find that building blocks with which the central nervous system constructs motor patterns can be preserved in patients with various motor disorders despite the fact that they often modify their muscle activity and adopt *motor equivalent* solutions. Our understanding of these motor primitives may be useful in driving neuroprostheses or entraining locomotor circuits in disabled people in the future.



# DISEASES AND INJURIES OF THE CENTRAL NERVOUS SYSTEM LEADING TO SENSORY–MOTOR IMPAIRMENT

DEJAN B. POPOVIĆ AND THOMAS SINKJÆR

*Center for Sensory–Motor Interaction, Aalborg University, Aalborg, Denmark*

## SUMMARY

Damage to the central and peripheral nervous systems is associated with a loss of motor drive and a defective afferent input to the central nervous system (CNS). Depending on the location and severity of the neural damage this leads to anything from a complete paralysis to a paresis and a maladaptation of the movement pattern. This chapter starts with a presentation of neuron injury. Such injuries are categorized based on the extent and type of damage to the nerve and the surrounding connective tissue. This chapter addresses sensory–motor deficits that are caused by neuron injury or disease: (a) cerebrovascular accident (CVA), or stroke, which causes impairments due to changes in blood supply to the brain; (b) spinal cord injuries (SCIs), which result in total or partial obstruction of flow of both sensory and motor information between the peripheral and central nervous systems; (c) nontraumatic disorders of the CNS (amyotrophic lateral sclerosis and multiple sclerosis); and (d) cerebral palsy. At the end of the chapter we present the incidence of CNS diseases.