Preface

There has been tremendous progress in the engineering of tools, which interact with the nervous systems—from signal detection and processing to restoration and enhancement of functions. Neural engineering (or its equivalent, neuroengineering) is a rapidly expanding interdisciplinary field bridging neuroscience and engineering. Neural engineering spans cellular, tissue, and systems level research and has become a core discipline within biomedical engineering and beyond. It is our intent to provide a comprehensive review of the principles, concepts, theories, methods, and state-of-the-art research in selected areas of neural engineering. This book is aimed at serving as a textbook for undergraduate and graduate level courses in neural engineering within a biomedical engineering or bioengineering curriculum. It is also suitable as an introduction to engineers or neuroscientists who are interested in entering the field of neural engineering or acquiring knowledge about the current state of the art in this rapidly developing field.

Chapter 1 provides a general introduction to human neuroanatomy and neurophysiology. The chapter was written mainly for readers with backgrounds in engineering and the physical sciences. Readers who are familiar with neuroanatomy and neurophysiology may skip this chapter, but this chapter will be useful for those who have not previously been exposed to these topics. The chapter includes over 60 original figures drawn for educational purposes.

Brain–computer interface or brain–machine interface technologies have been an important area of research in neural engineering and involve neural sensing, decoding, modeling, computation, and control. Chapter 2 provides an introduction and comprehensive review of the concepts, principles and methods of brain–computer interface technology. Using various recorded brain signals that reflect the "intention" of the brain, brain–computer interface systems have been shown to control an external device, a computer, or a robot. This chapter reviews the history, system structure, signal acquisition, signal processing, performance evaluation, and major applications of noninvasive brain–computer interface systems. Chapter 3 reviews the concept of neural prosthetic devices and recent developments in neurorobotics. These range from using the activity of peripheral nerves or muscles to acquire a control signal to implanting devices directly into the brain or central nervous system to extract command signals from populations of neurons. This chapter focuses on neuroprosthetic devices that use recording microelectrodes in the brain to capture information from populations of neurons to create a command signal for a device or machine that can then restore useful functions to the patient. Chapter 4 discusses the principles for model estimation that are relevant to brain–machine interface systems, as well as a review of successful implementations. This chapter specifically reviews methods and models that are based on a population of single-unit activity, where action potential timings from a single cell are used in estimating continuous kinematic variables.

An important aspect of neural engineering is to properly analyze and interpret the neural signals—a step that plays a vital role for sensing and controlling neural prostheses and other neural interfacing devices, as well as understanding the mechanisms of neural systems. Chapter 5 provides a comprehensive review of EEG signal processing. After a general overview of EEG, time, frequency, and wavelet signal processing techniques are reviewed in detail. These signal processing techniques are also applicable for processing other neural signals.

Computational models of neural systems provide a quantitative perspective in neurophysiology and neural engineering by coupling experimental observations to mathematical formulations. Chapters 6–8 deal with neural modeling, which is an important tool for understanding neural mechanisms. Chapter 6 provides an introduction to neural modeling, laying the foundation for several basic models and surveying key topics. These include the properties of electrically excitable membranes, the Hodgkin–Huxley model, and how such a model can be extended to describe a variety of excitable membrane behaviors, including axonal propagation, dendritic processing, and synaptic communication. Chapter 6 also covers mathematical models that replicate basic neural behaviors through more abstract mechanisms and explores efforts to extend single-neuron models to the network level. Chapter 7 discusses modeling techniques for neural information processing with selected application examples. Reviewed topics include: the known properties of neural information processes, ranging from cellular to system levels, generic multi-scale modeling techniques for the dynamics of neural systems, and selected model examples of a neural information process. The examples presented include sensory perception and neural control of baroreflex. Chapter 8 focuses on the bidomain modeling of excitable neural tissues. An understanding of the mechanisms of excitation and propagation of neural activation is desirable, and mathematical models of electrical stimulation can help predict localized activation in desirable regions of tissue, and conversely, regions where undesirable activation may occur.

Neuromodulation is one of the important areas in neuroengineering research and has rapidly become an important option in treating a variety of neurological and mental disorders. Chapter 9 provides an in-depth coverage of transcranial magnetic stimulation, a noninvasive neuromodulation technique that is based on electromagnetic induction principles. This technique creates electrical fields inside the body, which can depolarize neurons in the central nervous system and peripheral nervous system, leading to the firing of action potentials. Chapter 10 provides an overview of neurological disorders and various neuromodulation techniques, as well as the applications that are currently being used to treat clinical problems.

Neuroimaging has played an important role in understanding neural functions and aiding in clinical diagnoses and treatments. Recent developments in functional neuroimaging have led to important tools for better understanding, as well as aiding in the restoration of, neural functions. Chapters 11–13 cover three important approaches on neuroimaging. Chapter 11 provides an introduction to the principles of magnetic resonance imaging (MRI) and functional MRI, as well as a detailed look at the physiological source of the fMRI signal. This chapter covers the physics of nuclear magnetic resonance, image formation and contrast mechanisms; an overview of functional MRI; and experiment design, data analysis and modeling of the functional MRI. Chapter 12 reviews the basic principles and applications of electrophysiological neuroimaging. Applying the electromagnetic theory and signal processing techniques, electrophysiological neuroimaging provides spatio-temporal mapping of source distributions within the brain from noninvasive electrophysiological measurements, such as electroencephalogram (EEG) and magnetoencephalogram (MEG). Knowledge of such spatio-temporal dynamics of source distribution associated with neural activity aids in the understanding of the mechanisms of neural systems and provides a noninvasive probe of the complex central nervous system. Multimodal neuroimaging, which integrates functional MRI and EEG/MEG, is also discussed. Chapter 13 covers functional and causal connectivity analysis and imaging with the goal of not only discovering where brain activity occurs but also how neural information processing is performed. The concepts of functional and causal connectivity are introduced, and mathematic models behind the causality analysis are presented. Causal connectivity approaches using various signals are also introduced.

The retina represents an important component of the peripheral nervous system. Chapters 14 and 15 discuss retinal bioengineering and prostheses. The mathematical modeling of neural responses in the retinal microenvironment as well as the restoration of retinal function, is reviewed. The retina has long served as a model for understanding complex parts of the nervous system, but is also simpler than other parts of the brain due to the lack of significant feedback from the brain to the retina.

The translation of neuroscience discoveries to clinical applications represents one of the unique features of neural engineering research. The following chapters cover various medical aspects of neural engineering. Chapter 16 deals with peripheral neural interfacing. This chapter examines the possibility of detecting peripheral nerve signals and using these voluntary signals to restore function in patients with stroke, amputation or paralysis. Applying source localization and imaging techniques that were heavily developed in EEG/MEG source imaging, this chapter presents the capability of the estimation of electrical source signals from recordings made by an array of electrodes for peripheral neural interfacing. Chapter 17 discusses neural system prediction, in particular the prediction of epileptic seizures. It provides an overview of the various techniques for quantifying and predicting seizure activities, which may allow for proper intervention and control of the impending seizure. Chapter 18 provides a review of a cognitive prosthesis designed to restore the ability to form new long-term memories—a memory capability lost after damage to the hippocampal formation and surrounding temporal lobe brain structures. This chapter also describes recent studies demonstrating that the same device and procedures that are used to restore lost hippocampal memory function can also be used to enhance memory capability in otherwise normal animals.

Chapter 19 provides an overview of neural tissue engineering, which describes the potential for repairing injury to the nervous system. This chapter discusses the differences and challenges in treating injuries of central and peripheral nervous systems, and the current methodologies that are being employed to enhance the endogenous regenerative potential and plasticity. The discussion includes the state-of-the-art in facilitating repair and rehabilitation by means of biochemical and cellular therapies as well as by electrical stimulation of neuromuscular tissue.

Through this collection of carefully selected chapters, we wish to provide a general picture of neural engineering to outline the fundamental underpinnings that will make it a core discipline in biomedical engineering, as well as to convey the exciting aspects of neural engineering. Neural engineering not only represents an interface between neuroscience and engineering, but, more importantly, has led to great advancements in basic and clinical neurosciences which would not have been possible without the integration with engineering.

This book is a collective effort by researchers and educators who specialize in the field of neural engineering. I am very grateful to them for taking the time out of their busy schedules and for their patience during the entire process. It should be noted that the field of neural engineering is developing rapidly and there are many worthwhile topics that could not be included in this book, as the book aims to serve as textbook for a semester-long neural engineering course. Nevertheless, our intention is to provide a general overview that covers important areas of neural engineering research.

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