Chapter 13  
Design of Myocontrolled Neuroprosthesis: Tricks and Pitfalls

Emilia Ambrosini  
Politecnico di Milano, Italy

Simona Ferrante  
Politecnico di Milano, Italy

Alessandro Pedrocchi  
Politecnico di Milano, Italy

ABSTRACT

Recent studies suggest that the therapeutic effects of Functional Electrical Stimulation (FES) are maximized when the patterned electrical stimulation is delivered in close synchrony with the attempted voluntary movement. FES systems that modulate stimulation parameters based on the residual volitional muscle activity would assure this combination. However, the development of such a system might be not trivial, both from a hardware and a software point of view. This chapter provides an extensive overview of devices and filtering solutions proposed in the literature to estimate the residual volitional EMG signal in the presence of electrical stimulation. Different control strategies to modulate FES parameters as well as the results of the first studies involving neurological patients are also presented. This chapter provides some guidelines to help people who want to design innovative myocontrolled neuroprostheses and might favor the spread of these solutions in clinical environments.

INTRODUCTION

Functional Electrical Stimulation (FES) consists of the electrical stimulation of an intact lower motor neuron to activate paralyzed or paretic muscles in a precise sequence so as to directly accomplish or support functional tasks (Meo & Post, 1962). Functional tasks may include standing, walking, or cycling, upper limb activities, such as grasping or reaching, and control of respiration and bladder function. With the term neuroprosthesis we refer to a system or a device that provides FES.
FES systems have been covering a wide range of assistive and therapeutic applications in neurorehabilitation for the last forty years (Sheffler & Chae, 2007); they have been used to restore or replace impaired or lost motor functions in people affected by many neurological disorders, such as Spinal Cord Injury (SCI) (Gater, 2011), stroke (Ambrosini, 2012; Ambrosini, 2011a; Ferrante, 2008; Pomeroy, 2006; Popović, 2009), multiple sclerosis (Barrett, 2009), or cerebral palsy (Caucaugh, 2010; Trevisi, 2011).

When the muscles are not completely paralyzed it is possible to use the neural information extracted from the EMG signals of the paretic limb to control the timing and the intensity of the stimulation (Jiang, 2010). Such a control scheme seems to be a promising solution from a clinical perspective since it involves the physiological neural pathway in the recovery of the impaired motor functions. In support of this hypothesis, recent neurophysiological studies (Barsi, 2008; Iftime-Nielsen, 2012; Rushton, 2003; Gandolla, 2012) suggested that the use of electrical stimulation co-incidentally with the voluntary drive enhances the plasticity of the central nervous system (CNS), so as to improve motor relearning. First evidences about the efficacy of myocontrolled FES in improving upper limb motor performance have been shown in post-stroke patients (Fujiwara et al., 2009; Shindo et al., 2011). However, a full demonstration of the superiority of this approach compared to a more conventional use of FES is still missing, as well as a system ready to be transferred in clinical settings.

To design a control system that modulates FES parameters based on the residual volitional activation of the stimulated muscle, technological challenges, both from a software and a hardware point of view, need to be addressed. Indeed, when a muscle contraction is generated by two different activation sources, volitional and electrical stimulation, the overall EMG signal is due to the combination of these two components and the estimate of the volitional component might not be trivial.

This chapter focuses on FES systems that use the residual volitional EMG signal of the stimulated muscle to module the stimulation parameters. An extensive overview of the hardware and software solutions to estimate the volitional EMG in the presence of electrical stimulation, as well as the correspondent control strategies for FES are presented. Guidelines to support people who want to design innovative myocontrolled neuroprostheses are also provided. The Background section summarizes the neurophysiological principle and the therapeutic effects of FES both at peripheral and central level. The neurophysiological hypotheses that advocate the use of FES co-incidentally with the voluntary drive are also presented. The chapter is organized into five sections that guide the reader in the critical development of myocontrolled neuroprosthetic devices. The first section describes the characteristics of volitional and FES-induced EMG signals. The following section provides an overview of the current available hardware systems for EMG recording. The third section reviews digital signal processing methods for the estimate of the volitional EMG signal in the presence of FES-evoked EMG. The fourth section reviews the use of the volitional EMG as a control signal for modulating FES parameters. The final section of the chapter presents the results of early studies that tested myocontrolled neuroprostheses on people with neurological impairments. In closing, future and emerging research directions are presented.

BACKGROUND

When electrical pulses are delivered to the peripheral nervous tissue, repetitive depolarization of motor axons beneath the stimulation electrodes occurs and a muscle contraction is produced by signals travelling from the stimulation site to the neuromuscular junction. In this sense, FES substitutes for the normal voluntary drive...
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