

Chapter 9

Functional Electrical Stimulation (FES) Control for Restoration and Rehabilitation of Motor Function

Takashi Watanabe
Tohoku University, Japan

Naoto Miura
Tohoku University, Japan

ABSTRACT

Functional electrical stimulation (FES) has been studied and clinically applied to restoring or assisting motor functions lost due to spinal cord injury or cerebrovascular disease. Electrical stimulation without control of functional movements is also used for therapy or in rehabilitation training. In recent years, one of the main focuses of FES studies has been its application for rehabilitation of motor function. In this review, the authors first present the basics of applying electrical stimulation to the neuromuscular system for motor control. Then, two methods of FES control are discussed: controllers for FES based on feedback error learning (FEL) and on cycle-to-cycle control of limb movements. The FEL-FES controller can be practical in FES applications that need to control the musculoskeletal system that involves various nonlinear characteristics and delay in its responses to electrical stimulation. The cycle-to-cycle control is expected to be effective in controlling repetitive movements for rehabilitation training. Finally, a study on ankle dorsiflexion control during the swing phase using an integrated system of FES control and motion measurement with wearable sensors for rehabilitation is presented.

INTRODUCTION

Peripheral nerves and muscles can be activated by electrical stimulation. This makes it possible to restore or assist motor functions lost due to spinal cord injury or cerebrovascular disease by

applying appropriately regulated current or voltage pulses. This technique is known as Functional Electrical Stimulation (FES) and has been applied to various functions of the motor system, such as upper and lower limb control, respiratory control, assisting urination, and assisting the sensory system through auditory and visual prostheses and sensory substitution.

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Electrical stimulation that does not control functional movements is also used widely with the aim of producing therapeutic effects; such stimulation is called Therapeutic Electrical Stimulation (TES). TES has been applied clinically for various purposes such as strengthening muscles, reducing spasticity or pain, improving muscle atrophy due to disuse, improving range of motion (ROM), improving volitional movement and urinary incontinence, and preventing bedsores. TES has also been applied for motor rehabilitation.

Application of FES as an orthotic and therapeutic aid in the rehabilitation of upper and lower limb motor function has been one of main focuses of FES studies in recent years. Motor rehabilitation using FES to restore or assist motor function is called FES rehabilitation or FES therapy and has been studied by multiple groups. The therapeutic effects of rehabilitation with FES include improved muscle strength (Merletti et al., 1978; Granz et al., 1996; Yan et al., 2005) and muscle recruitment (Nwesam & Baker, 2004; Yan et al., 2005). Repetitive movement therapy mediated by electrical stimulation also has the potential to facilitate motor relearning (Sheffler & Chae, 2007).

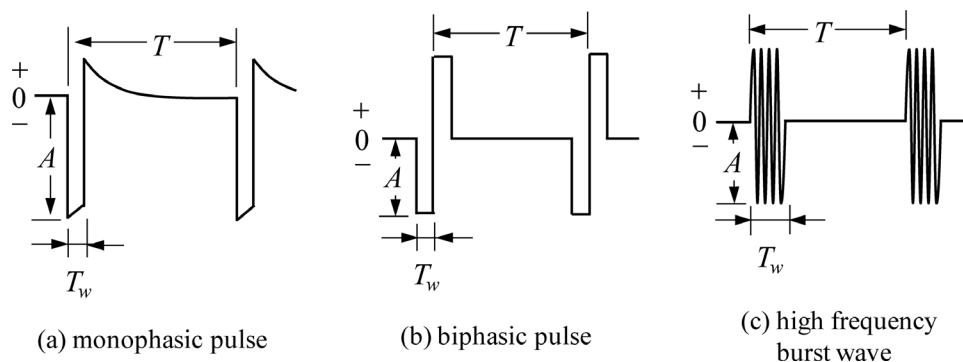
In this review, we first present the basics of applying electrical stimulation to the neuromuscular system in FES applications. Then, two methods of FES control, controllers for FES based on feedback error learning (FEL) and on cycle-to-cycle

control of limb movements, are considered in terms of their potential to restore motor functions and movement control during rehabilitation with FES. Finally, an integrated system of FES control and motion measurement using wearable sensors is presented and applied to evaluation of movements in ankle dorsiflexion control.

BASICS OF FES FOR ASSISTING AND RESTORING MOTOR FUNCTIONS

Waveforms of voltage or current stimulation, like those shown in Figure 1, are used in FES applications. When using a monophasic pulse (Figure 1a), the DC component of the pulse is eliminated by a capacitor or transformer to prevent the electrolyzation of stimulation electrodes and damage to the tissue. A charge-balanced biphasic pulse (Figure 1b) can also be used to eliminate the DC component. The biphasic pulse has the advantages that the stimulation effect is larger than that of a monophasic pulse of the same amplitude (A), and the biphasic pulse makes it possible to activate 2 different parts simultaneously in TES (Ogura et al., 2006). Figure 1c shows bursts from several kilohertz to 50 kHz carried by a sine or rectangular wave. Burst wave stimulation is sometimes used to reduce discomfort at the surface

Figure 1. Electrical stimulation waveforms used in assisting and restoring motor function with FES. A : pulse amplitude, T_w : pulse width, $1/T$: pulse frequency



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