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Review article

# Sensing motion and muscle activity for feedback control of functional electrical stimulation: Ten years of experience in Berlin

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ABSTRACT

After complete or partial paralysis due to stroke or spinal cord injury, electrical nerve stimulation can be used to artificially generate functional muscle contractions. This technique is known as Functional Electrical Stimulation (FES). In combination with appropriate sensor technology and feedback control, FES can be empowered to elicit also complex functional movements of everyday relevance. Depending on the degree and phase of impairment, the goal may be temporary support in a rehabilitation phase, e.g. during re-learning of gait after a stroke, or permanent replacement/support of lost motor functions in form of assistive devices often referred to as neuro-prostheses.

In this contribution a number of real-time capable and portable approaches for sensing muscle contractions and motions are reviewed that enable the realization of feedback control schemes. These include inertial measurement units (IMUs), electromyography (EMG), and bioimpedance (BI). This contribution further outlines recent concepts for movement control, which include e.g. cascaded control schemes. A fast inner control loop based on the FES-evoked EMG directly controls the amount of recruited motor units. The design and validation of various novel FES systems are then described that support cycling, walking, reaching, and swallowing. All methods and systems have been developed at the Technische Universität Berlin by the Control Systems Group within the last 10 years in close cooperation with clinical and industrial partners.

## Contents

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## 1. Introduction

### 1.1. Stroke and spinal cord injury

Stroke represents one of the major causes of long-term disability world wide (Mackay, Mensah, Mendis, & Greenlund, 2004). Population growth and aging play an important role in the recently observed increase in stroke burden (Feigin et al., 2015). According to the WHO estimates, the number of stroke events in the EU countries, Iceland, Norway, and Switzerland is likely to increase from 1.1 million per year in 2000 to more than 1.5 million per year in 2025 solely because of demographic changes (Truelsen et al., 2006).

A stroke is either caused by an interruption of the blood supply to the brain (ischemic strokes) or by rupture of a blood vessel or an abnormal vascular structure that lead to bleeding into or around the brain (hemorrhagic strokes). More than two-thirds of the strokes are ischemic.

Generally, stroke can result in five types of disabilities: paralysis or problems controlling movement (motor control); sensory disturbances including pain (loosing the ability to feel touch, pain, temperature, or position); problems using or understanding language (aphasia); problems with thinking and memory; and emotional disturbances.

The paralysis is generally on the side of the body opposite to the side of the brain injured by the stroke. It may have an effect on an arm, a leg, the face, or the entire side of the body. This one-sided paralysis is named hemiplegia (one-sided weakness is known as hemiparesis). Stroke survivors with hemiparesis or -plegia may have difficulty with everyday activities such as walking or grasping objects. About 25 to 50% of chronic stroke patients have additional problems with swallowing, called dysphagia (Singh & Hamdy, 2006). Damage to the cerebellum, the lower part of the brain, can impair the ability to coordinate movement. This disability is called ataxia and leads to problems with body posture, walking, and balance. Spasticity following a stroke occurs in about 30% of the cases and usually occurs within the first few days or weeks (Thibaut et al., 2013). According to Pandyan et al. (2005) it can be defined as “disordered sensory-motor control, resulting from an upper motor neuron lesion, presenting as intermittent or sustained involuntary activation of muscles”. In the upper limbs, the most frequent pattern of arm spasticity after stroke is internal rotation and adduction of the shoulder together with flexion at the elbow, the wrist and the fingers. In the lower limbs, adduction and extension of the knee with pointed foot and curling toes is often present (Thibaut et al., 2013). Spasticity in stroke patients may hinder functional movements like reaching and grasping but often enables walking after paralysis due to knee extension.

Another major cause of disabilities are injuries of the spinal cord that may result from physical trauma such as car accidents or from non-traumatic reasons such as tumors. The prevalence of traumatic spinal cord injuries (SCI) is highest in the United States of America (906 per million) (Singh, Tetreault, Kalsi-Ryan, Nouri, & Fehlings, 2014). Worldwide, the majority of studies on prevalence and incidence of traumatic spinal cord injury show a high male-to-female ratio and an age of peak incidence of younger than 30 years old. Traffic accidents were typically the most common cause of traumatic SCI, followed by falls in the elderly population and violence injuries (Singh et al., 2014). A damage of the spinal cord may lead to complete or incomplete loss of sensation and motor function below the level of lesion and often results in the immobilization of the patient and possible lifelong dependency on a wheelchair. Ranging from high to low levels of lesions, one can classify the following locations of SCI: cervical (vertebra C1–C8), thoracic (vertebra T1–T12), lumbar (vertebra L1–L5), or sacral (vertebra S1–S5). The consequences of a SCI are more severe for high levels. A damage at a C1–C8 level also affects respiratory function. A lesion at thoracic, lumbar, or sacral levels can result in paraplegia, which affects the control of both legs, while a damage at a cervical level will typically affect all four limbs (tetraplegia). A complete loss of bladder, bowel and sexual function is also common. In the course of time, the primary effects of a spinal cord injury lead to a range of secondary medical complications, e.g. atrophy of the paralyzed muscles and decreased cardiovascular fitness.

### 1.2. Functional electrical stimulation

Stroke and the majority of SCIs belong to the class of upper motor neuron lesions where the signal path from the Central Nervous System (CNS) to the muscles is interrupted above the anterior horn cell. The lower motor neuron which leaves the central nervous system from the spinal cord at the anterior horn cell to establish a functional connection with an effector (muscle) is still intact, and the muscles themselves retain their ability to contract and produce force. Functional Electrical Stimulation (FES) applied to the lower motor neurons can therefore be used to replace the lacking signals from the CNS (see Fig. 1).

The underlying neurophysiological principle of FES is the generation of action potentials in the intact peripheral neurons by application of low levels of pulsed electrical current to the nerves. Muscle contractions can be artificially induced by direct electrical stimulation of efferent (motor) nerves innervating the paralyzed muscles or indirectly by electrical stimulation of afferent (sensory) nerves provoking reflexes via intact reflex arcs. An example for using reflexes is the painful stimulation of the foot sole to elicit the so-called withdrawal reflex (flexing the leg of the stimulated body side and extending the opposite leg).

A neuro-prosthesis can be used to restore motor function in patients on the basis of functional electrical stimulation. Applications of FES in paraplegia with the aim of motor function restoration include walking (e.g. Graupe, 2002; Graupe, Cerrel-Bazo, Kern, & Carraro, 2008; Ho et al., 2014), cycling (e.g. Newham & Donaldson, 2007) and rowing (e.g. Hettinga & Andrews, 2007). The major aim in tetraplegia is to restore reaching and grasping function (e.g. Ho et al., 2014; Popovic, Popovic, & Keller, 2002; Mangold, Keller, Curt, & Dietz, 2005; Patil, Raza, Jamil, Caley, & O’Connor, 2014). Apart from provoking contractions of skeletal muscles, FES is used in other neuroprosthetic devices for SCI, e.g. the phrenic pacemaker and the sacral anterior root stimulator for bladder control (see (Ho et al., 2014; Peckham & Knutson, 2005; Rushton, 1997; Stein, Peckham, & Popovic, 1992) for an overview). Beyond the direct functional motor effects, therapeutic effects of FES on the secondary medical complications that arise from SCI have been reported (e.g. Hunt, Fang, Saengsuwan, Grob, & Laubacher, 2012; Janssen, Glaser, & Shuster, 1998; Daly et al., 1996; Davis, Hamzaid, & Fornusek, 2008). The benefits from FES may include for example improved muscle tone, bulk, and strength, reduced spasticity, improved limb blood flow, or a reduction in disuse osteoporosis. Additionally to these peripheral adaptations, central adaptations of

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