# Chapter 3
# Sensors for Motor Neuroprosthetics:
## Current Applications and Future Directions

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## ABSTRACT

*Clinical applications of Functional Electrical Stimulation (FES) provide both functional and therapeutic benefits. To enhance the functionality of FES systems and to improve the control of the activated muscles through open-loop or feedback controllers, solutions to gather information about the status of the system in real time and to easily detect the intention of the subject have to be optimized. This chapter summarizes the state of art of sensors used in motor neuroprostheses. These sensors can be classified in two categories: sensors of biological signals, such as electromyogram, electroencephalogram, electroneurogram, eye tracking, and voice control, and sensors of non-biological signals, such as sensors of force/pressure (e.g. force sensitive resistors and strain gauges) and sensors of movement (e.g. accelerometers, electrogoniometers, inertial measurement units, and motion capture systems). Definitions, advantages and disadvantages, and some example of applications are reported for each sensor. Finally, guidelines to compare sensors for the design of motor neuroprostheses are drawn.*

## INTRODUCTION

A neuroprosthesis is a device that uses electrical stimulation to activate the neuromuscular system in order to improve or substitute motor or sensory functions of an impaired central nervous system. This chapter is focused on motor neuroprostheses.

NeuroMuscular Electrical Stimulation (NMES) has been used for 50 years and has been well acknowledged to improve motor recovery and independence of people affected by neurological diseases. However, despite the significant technological progress of the last 20 years, many challenges remain to be resolved to provide a more

DOI: 10.4018/978-1-4666-6094-6.ch003

efficient functionality of NMES systems. Current commercial NMES systems still operate in an open-loop modality. This means that the stimulator's controller does not adapt the stimulation patterns based on a direct feedback of the actual state of the system (i.e., the spatiotemporal position of the limbs). In addition, a natural interaction with the system is not always made available to the subject. To improve the control of the stimulated muscles and the usability of these systems, solutions to gather information about the status of the system in real time and to easily detect the intention of the subject have to be optimized.

To promote the development of motor neuroprostheses and to favor their application outside the research environment, this chapter reviews the state of art of sensors used in FES systems to detect the intention of the user and/or to feed back information so as to develop closed-loop control systems. Some examples of sensors used to provide a quantitative assessment of the FES-induced movements are also reported.

The chapter is organized in three sections. The Background section provides an overall definition of NMES, sensors, and categories of sensors used in motor neuroprostheses. The central section lists the main sensors that have been used in literature to control NMES systems. This section is divided in two parts, one describing the biological sensors (such as electromyogram, electroencephalogram, eye tracking, etc) and one describing the non-biological sensors (force sensitive resistors, accelerometers, inertial measurements units, etc.). For each sensor, a brief description, advantages and disadvantages, and some examples of applications are provided. In the last section, future and emerging research directions are presented.

## BACKGROUND

NMES refers to the electrical stimulation of an intact lower motor neuron to activate paralyzed or paretic muscles. Clinical applications of NMES provide either functional or therapeutic benefits. Moe and Post (Moe & Post, 1962) introduced the term functional electrical stimulation (FES) to describe the use of NMES to activate paralyzed muscles in precise sequence and magnitude so as to directly accomplish functional tasks. FES was started with the simple and ingenious idea of Liberson et al. (1961) of lifting the drop-foot of a hemiplegic patient with a portable electronic stimulator (Liberson, 1961).

Restoration of motor functions based on FES has been widely studied since the first developments by Vodovnik and Grobelnik (Vodovnik & Grobelnik, 1977). Clinical application provides both therapeutic and functional benefits by re-training atrophied muscles. Once trained, the muscles can be used again to generate functional movements. NMES is also used for therapeutic purposes. NMES may lead to a specific effect that enhances function but does not directly provide function. One therapeutic effect is motor relearning, which is defined as "the recovery of previously learned motor skills that have been lost following localized damage to the central nervous system" (Lee & van Donkelaar, 1995). Indeed, in addition to the well-known peripheral effects on muscles themselves, FES is considered to have some central therapeutic effects. Some hemiplegic patients treated with FES for foot-drop correction during walking have shown a relearning effect that outlasts the period of stimulation. This was firstly observed by Liberson and colleagues (Liberson, 1961) and it is currently known in literature as "carryover effect" (Ambrosini, 2012; Ambrosini, 2011; Burridge, 2001). However, we know from literature (Burridge, 2001; Merletti, 1979) and from clinical practice that it is not possible to infer which patient will get the carryover effect from a peripheral evaluation. This further supports the hypothesis that FES induces some plasticity mechanisms in the reorganization of the central nervous system that allows maintaining recovery of motor control, whose mechanisms of action are still under investigation, although some