Clinical Biomechanics 30 (2015) 101–113

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Review

Technical developments of functional electrical stimulation to correct drop foot: Sensing, actuation and control strategies

P.L. Melo [a,b,*], M.T. Silva [a], J.M. Martins [a], D.J. Newman [b]

[a] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, Sala 1.02, 1049-001 Lisboa, Portugal
[b] Man-Vehicle Lab, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ARTICLE INFO

Article history:
Received 3 April 2014
Accepted 13 November 2014

Keywords:
Functional electrical stimulation
Drop foot
Neuroprosthesis
Gait
Closed-loop control
Open-loop control

ABSTRACT

This work presents a review on the technological advancements over the last decades of functional electrical stimulation based neuroprostheses to correct drop foot. Functional electrical stimulation is a technique that has been put into practice for several years now, and has been shown to functionally restore and rehabilitate individuals with movement disorders, such as stroke, multiple sclerosis and traumatic brain injury, among others. The purpose of this technical review is to bring together information from a variety of sources and shed light on the field's most important challenges, to help in identifying new research directions. The review covers the main causes of drop foot and its associated gait implications, along with several functional electrical stimulation-based neuroprostheses used to correct it, developed within academia and currently available in the market. These systems are thoroughly analyzed and discussed with particular emphasis on actuation, sensing and control of open- and closed-loop architectures. In the last part of this work, recommendations on future research directions are suggested.

1. Introduction

Stroke is among the four leading causes of death and disability worldwide, with about 15 million people suffering from stroke every year. Of these, one third die and another third become permanently disabled (WHO, 2004). Depending on the size and location of the lesion, stroke survivors can have their physical and/or mental capabilities impaired. Motor disabilities are often a consequence and can affect speech, grasp and gait, as well as other everyday functions. With a prevalence of about 20% amidst stroke survivors, drop foot (DF) is one of such disabilities that severely impair these persons' mobility (Johnson et al., 2004). Along with stroke, cerebral palsy (CP), multiple sclerosis (MS), traumatic brain injury (TBI) and spinal cord injury (SCI) are also neurological conditions that can lead to DF. This condition is often the result of a paralysis and/or weakness in the patient's dorsiflexor muscles, making him unable to clear the toes off the ground during the swing phase of gait. Due to this lack of proper muscle activation, compensatory mechanisms at other joints, such as the knee or the hip, are often present and result in a very typical steppage or hip hiking gait (Don et al., 2007). Slap foot is another condition that is often concurrent with DF. Characterized by an uncontrolled plantarflexion, right after initial contact (heel strike), slap foot can lead to chronic ulcers (Hanft et al., 2011). Additionally, muscle weakness and/or spasticity at the plantarflexors might also occur, resulting in an inability to support their own weight.

Often DF individuals still retain electrically excitable peripheral nerves and muscle tissues, which allows the use of techniques such as functional electrical stimulation (FES) to restore their lost mobility. FES is a technique that taps into the person's paralyzed muscles to produce movements that would not be possible otherwise. Over the years, FES has proven itself as a promising technique to restore lost motor functions, allowing neuromuscular impaired individuals to recover lost motor functions, positively impacting their quality of life (Sheffler et al., 2013). FES was first used to correct DF in the 1960s (Liberson et al., 1961). Since then, this research field kept growing and eventually the first FES-based DF neuroprostheses became commercially available (Acimović-Janezic et al., 1987; Malone et al., 2002; Waters et al., 1975). However, and despite continuous developments, there are still important challenges to be tackled, specifically on the control architecture aspects of these types of neuroprostheses (Lynch and Popovic, 2005; Lynch and Popovic, 2008). Essentially, a FES-based neuroprosthesis to properly correct DF, and its associated conditions, should at least provide foot clearance during the swing phase, minimize foot slap during controlled plantarflexion (loading response) and, if necessary, provide assistance to the plantarflexors during push-off.

* Corresponding author.
E-mail address: paulo.de.melo@tecnico.ulisboa.pt (P.L. Melo).

http://dx.doi.org/10.1016/j.clinbiomech.2014.11.007
0268-0033/

This work presents a comprehensive review of the latest FES-based DF developments to help in identifying new research directions, with emphasis on different actuation and sensing strategies, specifically focusing on open- and closed-loop (feedback) control architectures. Recommendations on future research directions are also discussed. A thorough review on earlier FES systems to correct DF since the 1960s up to 2001 can be found elsewhere (Lyons et al., 2002). Functional electrical stimulation as a rehabilitation tool has been reported to improve gait when combined with conventional therapies (Daly and Ruff, 2004; Kesar et al., 2011; McRae et al., 2009; Roche et al., 2009; Sabut et al., 2011), however it is not going to be addressed as a main topic, since it falls outside the scope of this article. Nonetheless, therapeutic effects of FES may be brought to discussion when necessary. The combined use of FES, as a neuroprosthesis, with orthoses, often named hybrid orthoses, will again not be the main focus of this review, despite its increasing and promising use in the last few years (Gharooni et al., 2001; Greene and Granat, 2003; Jailani et al., 2011), specifically when FES alone is not enough to provide the desired function or support, which most often occurs in more complex conditions than DF, such as paraplegia.

2. Using FES to correct drop foot

The typical architecture for a FES-based DF neuroprosthesis can be seen as an integration of a network of sensors, a control algorithm and a stimulation unit. The sensing network should always provide system information to the controller (Moore and Zouridakis, 2004). This controller should then be able to correctly adjust its inputs to the stimulation unit. Thus, optimal control strategies to correct DF should be sufficiently robust to the nonlinear, time-varying and coupled response of stimulated muscles (Lynch and Popovic, 2005). Furthermore, electrical stimulators should be portable, lightweight and flexible enough, in terms of specifications and parameters, to deal with different control strategy requirements. Tables 1 and 2, presented in Appendix A, show detailed information on the portability, types and stimulation characteristics of several research and commercial stimulators, respectively.

To stimulate nerve fibers and generate more efficient muscle contractions, a rectangular shaped electrical pulse has been suggested as optimal, since it overcomes the problem of the nerve fiber membrane accommodation (see Fig. 1, a typical stimulation pulse). Moreover, the pulse should provide an equal distribution of charges at the electrode locations during the stimulation period, so that no electrochemical imbalance occurs, eventually leading to body tissue damage (Robertson et al., 2006). This is usually achieved by having a pulse in one direction (positive phase) and another one in the opposite direction (negative phase), symmetric or not. Additionally, on a typical stimulation profile, there is often a ramping up and down of the stimulus, so that sudden responses are avoided and more physiological types of contractions are achieved (Stein et al., 2008). To a certain degree, prolonging the stimulus for a small amount of time after heel strike, has been used to help in controlling slap foot (Taylor et al., 1999a). The frequency of the pulse controls the type of muscle contraction and the amount of force produced. Pulse amplitude and width, represent how much, and for how long, current is needed to produce a minimal amount of ionic flow to trigger action potentials. Further information on these parameters can be found elsewhere (Robertson et al., 2006).

Currently, most existing ankle–foot orthoses are passive. The only active systems commercially available are FES-based. Mechanically-based active DF orthoses are still to surface outside the research setting (Blaya and Herr, 2004). Until now, all the commercially available FES systems have been solely based on open-loop architectures. Even though most of these systems use sensory feedback to switch between states (e.g. finite state machine (FSM) controllers), they should not be considered closed-loop controllers; instead, a closed-loop system should be defined as a system where the controller is sufficiently stable and robust to correct for model errors and external disturbances, such as an obstacle or muscle fatigue (Lynch and Popovic, 2008). Tables 3 and 4 summarize several approaches using open- and closed-loop strategies, respectively.

2.1. Open-loop systems

The first open-loop system to correct DF using FES was developed by Liberson et al. (1961). Liberson's system enabled dorsiflexion of the foot by synchronous stimulation of the tibialis anterior muscle during the swing phase (see Fig. 1). This type of system was a FSM, in this particular case with two states, stimulus *on* or *off*, which were detected by means of a shunt resistor to sense heel contact. To the present date, Liberson's concept has remained very popular among researchers and most of the systems built in the following decades were based on his FSM architecture.

2.1.1. Research prototypes

2.1.1.1. Constant preset stimulation control based on foot switches. The advent of microcontrollers in the 1970s made possible the continuous development of more flexible and smaller stimulation devices. One such example is the system developed by Malezic et al. (1992), where

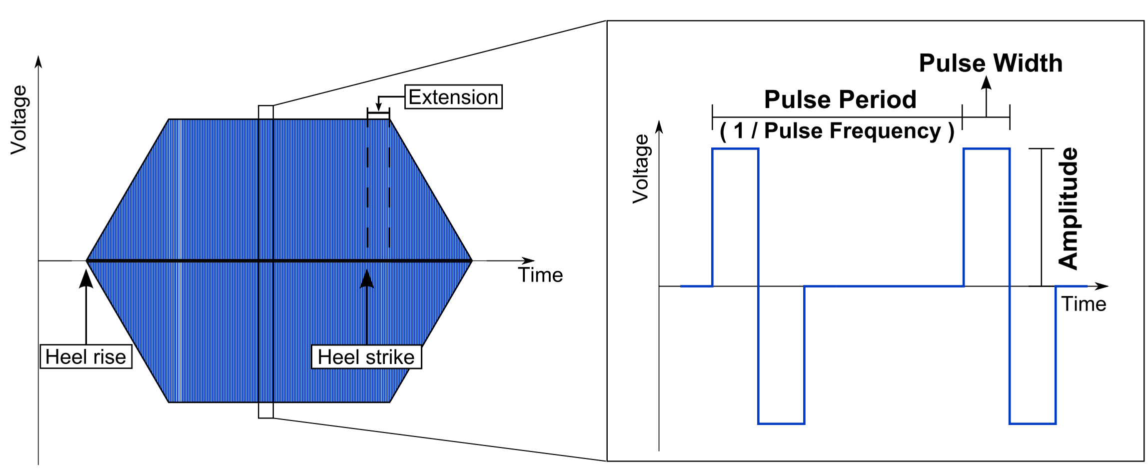

Fig. 1. Typical trapezoidal waveform used by most FES commercial systems, with balanced charges, posing no threat to tissue integrity. Note: Figure not drawn to scale.