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Iterative learning control of a drop foot neuroprosthesis — Generating physiological foot motion in paretic gait by automatic feedback control

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ABSTRACT

Many stroke patients suffer from the drop foot syndrome, which is characterized by a limited ability to lift the foot and leads to a pathological gait. We consider treatment of this syndrome via Functional Electrical Stimulation (FES) of the peroneal nerve during the swing phase of the paretic foot. We highlight the role of feedback control for addressing the challenges that result from the large individuality and time-variance of muscle response dynamics. Unlike many previous approaches, we do not reduce the control problem to the scalar case. Instead, the entire pitch angle trajectory of the paretic foot is measured by means of a 6D Inertial Measurement Unit (IMU) and controlled by an Iterative Learning Control (ILC) scheme for variable-pass-length systems. While previously suggested controllers were often validated for the strongly simplified case of sitting or lying subjects, we demonstrate the effectiveness of the proposed approach in experimental trials with walking drop foot patients. Our results reveal that conventional trapezoidal stimulation intensity profiles may produce a safe foot lift, but often at the cost of too high intensities and an unphysiological foot pitch motion. Starting from such conservative intensity profiles, the proposed learning controller automatically achieves a desired foot motion within one or two strides and keeps adjusting the stimulation to compensate time-variant muscle dynamics and disturbances.

1. Introduction

According to the World Health Organization, more than a million people suffer a stroke in Europe each year. Due to demographic changes and an increasing life expectancy, this number will rise as with the demand for efficient rehabilitation and medical devices. Stroke often leads to impaired motor function. Even after weeks of rehabilitation, many patients suffer from a limited ability to lift the foot by voluntary muscle contraction. This syndrome is known as drop foot (or foot drop), and it also appears in patients with other neurological disorders. Regardless of the cause, foot drop leads to a pathological gait with an increased risk of fall and injuries like ankle sprain.

A common treatment is to fix the foot in the lifted (dorsiflexed) position by a passive orthosis. This approach may improve safety and stability in the patient's gait, but it further promotes muscle atrophy and joint stiffness.

If the lesion affects the central nervous system and the peripheral nerves are still intact, then an alternative treatment can be provided by means of the technology known as Functional Electrical Stimulation (FES). FES facilitates the artificial activation of muscle contraction by applying tiny electrical pulses via skin electrodes with a conductive gel layer or via implanted electrodes. Due to the risk of complications associated with surgery and implants, we restrict our discussion to the former case. When using skin electrodes, 20–50 rectangular bi-phasic current pulses per second are applied, with each pulse having an amplitude of less than a tenth of an ampere and a pulse width of less than half a millisecond. If the current amplitude exceeds the range of a few milliamperes, each pulse triggers a bunch of action potentials in subcutaneous efferent nerves located near the electrodes. By modulating the frequency and/or dimensions of the pulses, one can control the contraction of paretic muscles and induce functional movements in the affected limbs. Unfortunately, FES may also trigger action potentials in afferent nerves, causing discomfort at medium and pain at high stimulation intensities. In most subjects, however, the sensation is weak enough to allow the generation of functional movements without discomfort. Abundant research demonstrates the potential of FES in neuroprosthesis

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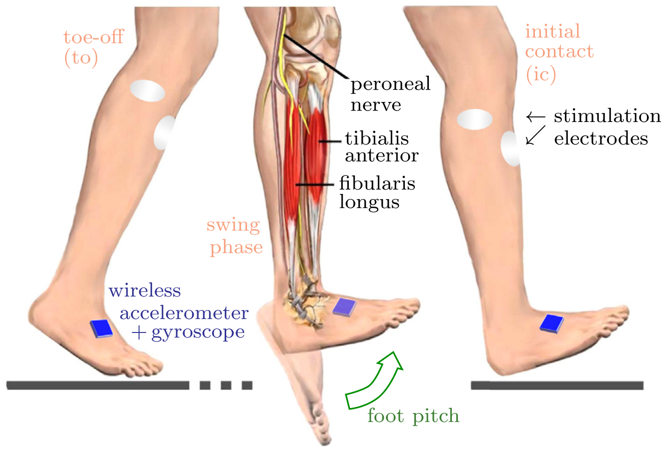

Fig. 1. A foot-mounted inertial sensor is used to obtain foot pitch angle measurements, which are used to adjust the intensity of FES applied to the shank muscles that lift the foot. By means of this feedback strategy, physiological foot motion can be achieved even in paretic limbs.

design beyond the application of drop foot treatment; see for example Peckham and Knutson (2005) and references therein.

Drop foot neuroprostheses, also known as peroneal stimulators, represent a drop foot treatment that aims at generating a natural foot lift via activation of the patient's shank muscles, cf. Ring, Treger, Gruendlinger, and Hausdorff (2009). To this end, the electrodes are placed on the skin near the peroneal nerve, whose branches innervate several shank muscles, as depicted in Fig. 1. When FES with well-chosen pulse dimensions is applied via well-positioned electrodes in a well-synchronized manner during gait, then the physiological motion of the foot can be restored even in paretic limbs.

1.1. *Challenges in FES-based drop foot treatment*

There are several challenges that need to be addressed when developing FES-based gait support systems for drop foot patients. Experiments show that the amount of foot lift that FES with a certain intensity triggers depends on the subject, varies with time, and is sensitive to small (~1 cm) changes in the electrode positions. This means that the gain (and dynamics) of the system we are aiming to control is not known a priori. Parameterizing the stimulation such that it yields a physiological foot lift in a paretic leg is a task that must be repeated every time the gait support system is used.

Another important issue is that FES-activated muscles fatigue rapidly[1] (see e.g. Lynch & Popovic, 2008), which means that large intensities make FES become ineffective. Therefore, it is essential to use the optimal stimulation parameters, i.e. the smallest intensities that achieve a safe and physiological foot lift. This optimum changes due to time-variant effects such as varying muscle tone (spasticity) and residual voluntary muscle activity. When patients cross a street, for example, residual muscle activity as well as the muscle tone (spasticity) often change significantly within less than ten seconds, i.e. less than about five strides. Therefore, once a physiological foot motion has been achieved, it is just as challenging to maintain it.

1.2. *State of the art in research and industry*

For drop foot treatment, a few commercially available solutions make use of FES, some via skin electrodes, others via implanted electrodes. The review articles by Lyons, Sinkjaer, Burridge, and Wilcox (2002) and Melo, Silva, Martins, and Newman (2015) provide an excellent overview of drop foot stimulators in research and industry and classify them in several ways. Until now, all commercially available devices have been solely based on open-loop architectures, they only use sensors to time the stimulation (Melo et al., 2015). Most of them employ heel switches to detect two gait phases: one when the heel of the paretic foot is on the ground and the other when it is not. In each stride, as soon as the heel is lifted, FES is applied with a fixed stimulation intensity profile over time, typically a trapezoidal shape tuned by an experienced clinician. Finding stimulation parameters that yield a physiological foot motion is cumbersome and, due to the described time-variant effects, requires repeated manual adaptations of the intensity profile. An obvious escape strategy that is often pursued is to choose larger stimulation intensities and accept exaggerated foot lift. While this strategy provides a certain amount of safety and functionality, it accelerates muscular fatigue and leads to a salient peculiarity in the patient's gait.

The challenges described in Section 1.1 can be met in a much more effective and elegant way by the use of feedback control. More precisely, the stimulation parameters can be adjusted automatically to avoid over-stimulation, to delay the onset of fatigue, and to induce the optimal level of foot lift. This requires measurement of the foot motion via, for example, an inertial sensor or a goniometer. When inertial sensors are attached to the shank and foot, the ankle dorsiflexion joint angle can be determined, as describe for example in Seel, Raisch, and Schauer (2014). If only the foot is equipped with an inertial sensor, the foot pitch angle with respect to the horizontal plane is assessable. Both quantities properly describe to which extent the applied FES compensates the foot drop.

Despite increasing efforts in the last decades to make closed-loop gait neuroprostheses a reality, it is still a challenging task to control paralyzed limbs with FES (Melo et al., 2015). Several control techniques have been proposed. Some respectable results have been obtained for the much simpler case of a sitting or lying subject, i.e. without the tight time constraints and the strong disturbances imposed by gait. For example, Kobravi and Erfanian (2009) and Valtin, Seel, Raisch, and Schauer (2014) proposed a fuzzy controller and an iterative learning controller, respectively, and performed experimental trials with sitting subjects. Hayashibe, Zhang, and Azevedo-Coste (2011) and Benedict and Ruiz (2002) suggested the use of predictive controllers and PID control, respectively, but tested their controllers in simulation studies only. Artificial neural networks were employed by Chang, Chen, Wang, and Kuo (1998) and Chen et al. (2004), who validated the controller in trials with subjects lying on a bed.

Besides those simplified in vitro studies, intense efforts have also been made to close the loop on FES during walking. Veltink et al. (2003) used an inertial sensor on the foot to tune an implantable drop foot stimulator such that a desired foot orientation just prior to initial contact was achieved. Negård (2009) proposed run-to-run control of the maximum foot pitch angle occurring during swing phase and tested the controller in trials with a walking drop foot patient. Previously, Mourselas and Granat (2000) had briefly reported similar results obtained with a bend sensor and a fuzzy logic algorithm.

While these latter results represent important improvements with respect to all commercially available stimulators, one major shortcoming remains: The entire foot motion is reduced to a single scalar measure, for example a minimum foot clearance with respect to ground or a desired foot pitch angle at initial contact. Obviously, this is a strong simplification of the control problem. As we will demonstrate, conventional stimulation intensity profiles

[1] I.e. when FES with the same intensity is applied repeatedly, the induced motion will become weaker with time.