Learning Neuroprosthesis for Automatic Compensation of Foot Drop and Inversion in Stroke Patients

Thomas Seel, Mirjana Ruppel, Boris Henckell, Thomas Schauer, Germany
seel@tu-berlin.de

Introduction

The human ankle joint exhibits two orthogonal rotational degrees of freedom, which can be described by the medical terms dorsi/plantarflexion and inversion/eversion. During the swing phase of gait, i.e. between toe-off and initial contact, these degrees of freedom correspond to the pitch and roll angle of the foot, respectively. In stroke patients who suffer from foot drop, a combination of weak dorsiflexion and inversion is often observed. These weaknesses can be compensated by functional electrical stimulation (FES) of the peroneal nerve. This nerve innervates m. tibialis anterior and m. fibularis longus, which cause dorsiflexion with inversion and dorsiflexion with eversion, respectively.

Common peroneal stimulators try to reduce this two-dimensional problem to a one-dimensional by either of the following three approaches: Some devices require a precise electrode placement that yields balanced activation of both muscles. Alternatively, the stimulation intensities are often increased above the required value to generate an over-eversion, which is safe but fatigue-promoting and not physiological. In the few approaches that employ two stimulation channels, a tuning of both channels yields a balanced activation, but only until, e.g., the muscles fatigue or the muscle tone changes. It remains an open research question, whether and how automatic adaption of the stimulation intensities and physiological foot motion can be achieved automatically.

Methods

We consider a stroke patient who suffers from chronic foot drop and spastic inversion during swing phase. A three-electrode array is attached to his paretic lower leg: two active electrodes on nervus peronaeus and on m. tibialis anterior, as well as a common counter electrode between them. Gait phase detection is facilitated by means of a foot-mounted inertial measurement unit (IMU). In pre-swing and swing phase, stimulation is applied to both channels with trapezoidal stimulation intensity profiles of variable height. Thereby, we determine the effect of each FES channel on foot pitch and roll angles that are measured by the IMU. We propose a nonlinear input transformation that facilitates decoupling of the system's input-output dynamics. Next, we design two decentralized iterative learning controllers, each of which adjusts one of the stimulation inputs during stance phase based on the foot pitch or roll trajectories of the previous step.

Results

In the participating patient, both strong dorsiflexion and strong eversion can be caused by FES via the proposed three-electrode array placement. Despite the paretic gait, four gait phases were detected on the paretic side in each step using the foot-mounted IMU. Each of the two FES channels' intensities had an influence on both the roll and pitch of the foot during swing phase. The decoupling approach reduced these couplings significantly. Even when starting from unreasonably low values, the iterative learning controllers for roll and pitch converge simultaneously within a few steps. Thereby, they compensate any undesired foot drop and inversion and precisely generate a predefined desired physiological foot motion.

Conclusion

We highlighted the multidimensionality of FES-support in drop foot patients. A learning neuroprosthesis employing a foot-mounted IMU and learning control methods was proposed. This approach yielded improved support by both quick and ongoing adaption to the patient's needs. With reasonably set initial stimulation profiles, foot drop and eversion are avoided from the very first step and a physiological gait is achieved and maintained.