A Strategy for Adaptive Tuning of a Two-Channel Peroneal Nerve Stimulator for Dropfoot

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Abstract
A strategy for adaptive tuning of a two-channel implantable peroneal nerve stimulator for dropfoot is proposed and analysed. The objective is to provide a well-balanced foot-movement during swing, providing adequate dorsiflexion and adequate orientation of the foot in the coronal plane. Preliminary experiments on one patient using the two-channel stimulator indicated that, on the cycle level, the relation between stimulation parameters (e.g. stimulation levels of both channels) and movement parameters (e.g. sagittal and coronal orientations in certain phases of the swing phase) can be conceived as nonlinear and static. An adaptive tuning strategy is proposed which constantly identifies the parameters of this nonlinear relation and updates the stimulation parameters on the basis of this model to achieve desired movement parameters. Simulations predict that this strategy is feasible. The identification requires noise to be added to the stimulation inputs in order to achieve persistent excitation.

1. Introduction
The stimulation of dorsiflexors for foot lift during the swing phase of gait in stroke patients with dropfoot has been proposed by Liberson already in the sixties [1]. There are major advantages in applying an implantable stimulator in the case of permanent use of such a system: it simplifies the use of the device and improves the selectivity and stability of stimulation. For these reasons a two-channel implantable drop foot stimulation system was developed [2] (figure 1). The deep and superficial branches of the peroneal nerve are stimulated separately, allowing electronic balancing of inversion and eversion of the foot.

In this paper, the possibility for automatic balancing of the two stimulation channels is explored. A strategy for adaptive tuning of the stimulator is proposed and analysed.

2. Methods

Figure 1. Dual channel dropfoot stimulator implant [2].

Figure 2. Strategy for cycle-to-cycle control of footbalance.

Adaptive tuning strategy
The proposed adaptive tuning strategy is depicted in figure 2. Movement criteria are defined on the level of a walking cycle, e.g. desired dorsiflexion angle before foot landing, foot lift during mid-swing. They are represented by \( \bar{m}_{\text{ref}} \). The realized movement parameters \( \bar{m}_{\text{ref}} \) are determined for each cycle using an inertial sensor module on the foot [3, 4]. For each new step, stimulation parameters are determined in advance
from the movement criteria using an inverse model of the relation between stimulation and movement parameters. This relation is assumed to be static and nonlinear. The parameters of this relation are recursively identified and updated, using the applied stimulation parameters and resulting movement parameters in every walking cycle [5]. Noise \( \tilde{v} \) is added to the stimulation parameters for persistent excitation, which is a requirement for adequate identification.

**Experimental assessment of relation between stimulation and movement parameters**

Experiments were performed on one hemiplegic stroke patient with a two-channel implant. He walked for several trials with several combinations of stimulation levels of both channels. The stimulation timing was derived from a heel switch. For each cycle, the complete foot movement was determined using an inertial sensor module placed on the foot at the stimulated side. The sagittal and coronal foot orientations just before foot landing were selected as movement parameters and were determined for all cycles [3, 4]. From this data, the relation between stimulation levels and the two movement parameters were determined.

**Simulation of adaptive tuning strategy**

The proposed adaptive tuning strategy was implemented in a simulation model, together with a static nonlinear model of the relation between stimulation and movement parameters. The performance of the strategy was predicted by simulations.

### 3. Results

**Relation between stimulation parameters and movement parameters**

As expected, the sagittal orientation before foot landing appeared to depend only on stimulation channel 1 (deep peroneal nerve), while coronal orientation depended on both channels (figure 3). The assumption of a static relation between stimulation and movement parameters appeared to be valid. However, some variation occurred in the movement parameters for the same stimulation parameters. It is assumed that, although measurement noise will contribute to the uncertainty, this is largely due to the variation of gait from step to step, being under the control of the user, as indicated by ‘physiological control’ in figure 2.

On the basis of these results, we modelled the relation between stimulation levels and movement parameters by the following nonlinear static model:

\[
\begin{align*}
    m_1 &= f_1(s_1) + \bar{w}_1 \\
    m_2 &= f_2(s_1, s_2) + \bar{w}_2
\end{align*}
\]

\[\text{(1)}\]

\( s_1 \) represents the stimulation level of channel 1 (deep peroneal nerve), \( s_2 \) stimulation level of channel 2 (superficial peroneal nerve), \( m_1 \) the sagittal and \( m_2 \) the coronal foot orientations just before foot landing. The stochastic variables \( \bar{w}_1 \) and \( \bar{w}_2 \) represent the variation from step to step due to user control.

**Simulation of adaptive tuning strategy**

The adaptive tuning strategy was simulated for the control of sagittal orientation (\( m_1 \)) by varying stimulation level of channel 1 (\( s_1 \)). A parabolic nonlinear static relation between \( s_1 \) and \( m_1 \) was
assumed as a system model. The performance of the identification and adaptive tuning (figure 4) depends on the learning factor $\lambda$, the variance of the added noise $\lambda$, to achieve persistent excitation, and the number of parameters to be identified. A learning factor of $\lambda=0.95$ was found to be optimal. The variance of $\lambda$ was chosen such that the induced variance in the movement parameters was the same as the variance due to user control (physiological noise). Recursive identification of the complete three parameter model resulted in very strong parameter estimation variations and slow adaptation of the stimulation level after a step change of the offset parameter of the system model (approximately 25 cycles). A two-parameter linearized model resulted in much faster adaptation of stimulation level (approx. 10 cycles), but still large variations in parameter estimates (figure 4). Apparently, the identification of the slope of the relation between stimulation level and movement parameter at the operating point was difficult due to the physiological noise, although the identification of the position of the operating point, determining the adjustment of the stimulation level, resulted in 10 steps. When the identified model was reduced to one parameter (line through origin), the estimated parameter value did not continuously vary, but adaptation of stimulation level required approximately 15 cycles.

4. Discussion

Only few stimulation and movement parameters were considered until now. More stimulation parameters (e.g. stimulation onset timing, varying stimulation frequency and envelope of the stimulation burst) and more relevant movement parameters in several phases of the step can be conceived. A minimal set of relevant and minimally dependent stimulation and movement parameters may be found through biomechanical modeling. Furthermore, the relation between stimulation parameters and movement parameters needs to be evaluated in more subjects and the proposed adaptive tuning procedure needs to be experimentally evaluated.

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References