OPTIMAL CONTROL OF FES–INDUCED CYCLICAL LEG MOVEMENTS

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ABSTRACT

An optimal control strategy for FES–induced cyclical movements is proposed. Optimal stimulation patterns are determined on the basis of a criterium, consisting of desired movement parameters and minimal stimulation burst duration, and a dynamic model of the system. Preliminary results of the identification and optimization are shown. Eventually, the optimal control will be combined with an adaptive scheme from cycle to cycle.

INTRODUCTION

Locomotion can be restored in paraplegic subjects [1,2]. However, upto now the required effort is too high and the functionality of the movement too low to be acceptable in common clinical practice. This is partly due to lacking stimulation methods and inadequate control. The objective of the research described in this paper is to develop improved control strategies.

A functional cyclical walking movement can be obtained if certain conditions are satisfied: the body should move foreward, while keeping balance. Preferably, these objectives should be reached with minimal effort and minimal fatigue, so the movement can be performed as long as possible.

STATEMENT OF THE PROBLEM

In this paper we consider the control of a cyclical movement of a freely swinging leg (Figure 1), which is a simplified problem compared to the control of walking. The movement is generated by stimulation of quadriceps and flexion reflex [2]. Stimulation of each channel is limited to one burst per cycle at constant recruitment level and stimulation frequency. The stimulation timing parameters for cycle i are expressed in the stimulation timing vector τ_i (dimension $n = 4$).

Objectives: The control problem is stated in terms of certain desired parameters, expressed in the parameter vector $\mathbf{p}_d$ (dimension m). This vector consists of parameters of the movement (e.g. hip angle range, foot clearance during forward swing, knee extension at heel strike), which ensure functionality of the movement, and parameters expressing the effort (in terms of stimulation burst durations), which should be minimized.

Criterion: The norm $\| \mathbf{p}_d - \mathbf{p}_i \|$, defined as the weighted absolute differences between the desired parameter values and the actual parameter values $\mathbf{p}_i$ in cycle i, should be minimized.

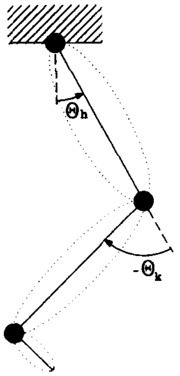

Figure 1. The considered test problem: control of cyclical movements of a leg, freely swinging in the sagital plane. The position of the hip is fixed.

MODEL OF THE NEUROMUSCULAR–SKELETAL SYSTEM

A dynamic model of the system is needed for deriving the optimal stimulation timing pattern τ_{opt}. We constructed a model (Figure 2) on the basis of literature [3–5] and preliminary experiments (Figure 3).

PRELIMINARY IDENTIFICATION

The model parameters were partly derived from literature ([3–4], etc), and partly from preliminary identification experiments on one paraplegic subject. As an example, the estimation of the delays of the flexion withdrawal reflex from experiments is illustrated in figure 3.

OPTIMAL CONTROL ASSESSMENT

Figure 4 illustrates the simulated influence of the stimulation timing on the movement parameters (vector $\mathbf{p}$). In first instance we considered the separate influences on each of the parameters. If the desired minimal hip angle value is taken to be – 10 deg [5], figure 4a indicates that the flexion reflex stimulation onset should lie between 0.6 and 0.8 s after the beginning of the cycle (i.e. maximal hip angle). The shortest sufficient burst time is predicted to lie around 0.1 s. At these timing values sufficient maximal hip angle is also obtained (35 deg [5]). The other movement parameters can be evaluated in the same way.

DISCUSSION

Further identification experiments have to be performed in order to identify the model in more detail, and assess the magnitude of modeling errors in the range of operation.

The optimal open–loop control illustrated in this paper will be combined with an adaptive control strategy, which adapts the stimulation patterns from cycle to cycle on the basis of the differences between the desired and actual movement parameters in the previous cycles [6].

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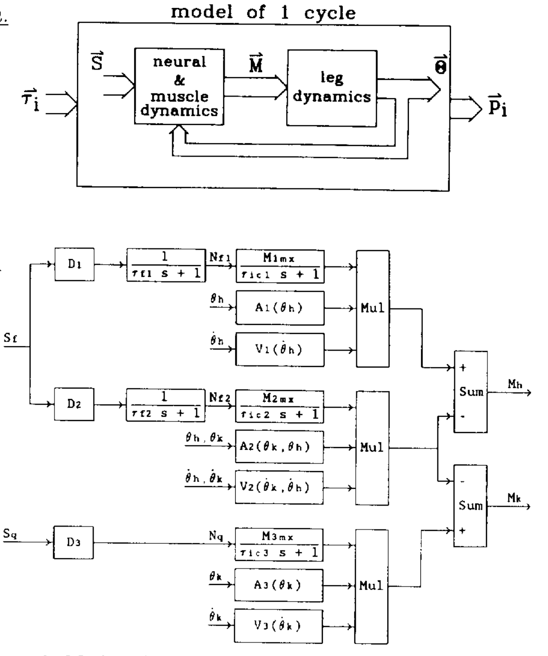

Figure 2. *Model of the freely swinging leg with stimulation of flexion reflex and quadriceps.*
a. model of one cycle of the movement. The stimulation timing vector τ *is the input, the movement parameter vector* $\mathbf{p}$ *is the output. The dynamic model consists of neural, muscle and leg dynamics (double pendulum).*
b. neural dynamics (delays and first order dynamics) and muscle dynamics (three factor model with activation dynamics, angle and angular velocity dependance).

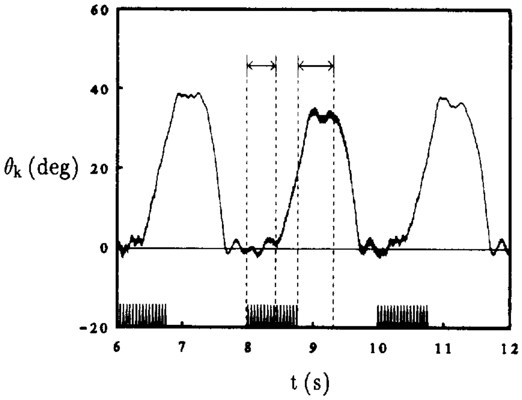

Figure 3. *Illustration of one of the preliminary experimental identifications of model parameters: Assessment of the delay times* D_1 *and* D_2 *of the flexion withdrawal reflex. The paraplegic subject was lying on a bench, with her heel on a smooth surface. The reflex stimulation resulted in hip and knee flexion (stimulation amplitude = 70 mA, stimulation pulse time = 300 μs). Estimated onset delay* $D_1 = 0.2$ *s; offset delay* $D_2 = 0.3$ *s (taking into account the dynamics of the musculo–skeletal system).*

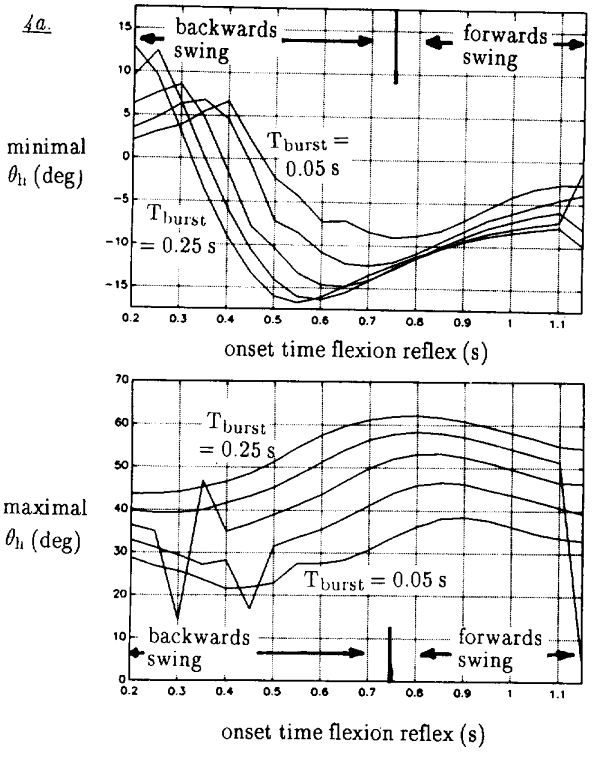

Figure 4. *Simulations of minimal (Figure a) and maximal (Figure b) hip angles at varying onset timing and burst duration of the flexion withdrawal reflex stimulation. Each curve shows the minimal or maximal hip angles as a function of onset time. Between curves the burst duration* T_{burst} *is varied between 0.05 s to 0.25 s (in steps of 0.05 s). The values were determined after 5 simulated cycles, which resulted in most cases in almost steady state movement.*

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