

Identification of Electrically Stimulated Quadriceps - Lower Leg Dynamics - The use of Accelerometers for Estimating Knee Joint Acceleration and Quadriceps Torque

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Abstract - Knee joint acceleration and quadriceps torque can be estimated from the signals of two tangentially placed accelerometers. This enables the identification of quadriceps dynamics, loaded with a freely swinging lower leg, during electrical stimulation.

I. INTRODUCTION

In the control of Functional Electrical Stimulation a dynamic model of the muscle-skeleton system is required.

The model should describe the dynamics in the same working range and under the same loading conditions as during actual restoration of the desired motor function. Therefore, the model structure and parameters should be determined under the same conditions. This might lead to a simple model structure and relatively accurate model.

As an example, we consider the problem of controlling a freely swinging lower leg by electrical stimulation of the quadriceps [1].

II. METHODS

A. Experimental Setup

Experiments were performed on one complete T5-T6 spinal cord injured patient, enrolled in the FES-training program of the *Roessingh Rehabilitation Centre*.

The subject was seated on a chair (Fig. 1), the lower leg was swinging freely. The quadriceps were stimulated using two adhesive electrodes on the skin (Pals, Axelgaard Co.).

The stimulation was controlled by a IBM-PC compatible computer. Stimulation was performed supramaximally using monophasic stimulation pulses (Pulse Width = 300 μ s; Pulse Amplitude = 100 mA).

B. Estimation of Knee Joint Angular Velocity from Accelerometer Data

Knee Joint angular acceleration $\ddot{\phi}$ was estimated using two tangentially placed accelerometers at two distances from the knee joint (r_1 and r_2). The knee joint angular acceleration can be estimated from the measured equivalent acceleration α_1 and α_2 , eliminating the measured equivalent acceleration because of gravity [2]:

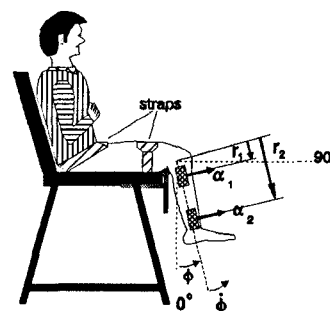


Fig. 1. Experimental setup. The subject is sitting on a chair. The lower leg can swing freely. Two tangential accelerometers are positioned at different distances from the knee joint.

$$\ddot{\phi} = \frac{\alpha_1 - \alpha_2}{r_1 - r_2} \quad (1)$$

The knee joint acceleration thus estimated is proportional to the total knee joint torque M . The inertia I of the lower leg is the proportionality factor. M can be conceived to consist of 4 components: the active muscle torque M_m , the torque M_p from passive elasticities, the damping torque M_d and the gravity torque M_g . M_d was assumed to be proportional to $\dot{\phi}$ (factor D'), M_g was assumed to be proportional to $\sin \phi$ (factor K'):

$$\ddot{\phi} = \frac{M}{I} = \frac{M_m + M_p + M_d + M_g}{I} = \frac{M_m + M_p}{I} + D\dot{\phi} + K\sin\phi \quad (2)$$

$D = D'/I$ and $K = K'/I$ were estimated from the knee joint acceleration data by a Least Square estimation procedure. $(M_m + M_p)/I$ was estimated by subtracting the damping and gravity contributions.

C. Generation of Pseudo Random Stimulation Sequences

A stimulation sequence of supramaximal stimulation pulses was composed on the basis of a Pseudo-Random InterPulse Interval (IPI) sequence. The IPI-sequence had a two-part uniform probability distribution (Fig. 2). In the experiment $P_1 = 0.2$ and $P_2 = 0.8$ was chosen. This sequence resulted in a good excitation of the muscle dynamics as well as the lower leg dynamics (resonance frequency around 1 Hz).

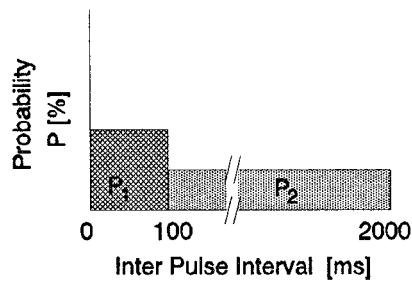


Fig. 2. The IPI sequence was composed to have a two-part uniform probability density function.

III. RESULTS

A typical result of $(M_m + M_p)/I$ estimation is shown in Figure 3. Figure 4 shows the lower leg pendulum states in which the quadriceps has been stimulated. They coincide with the working range of a passive lower leg response.

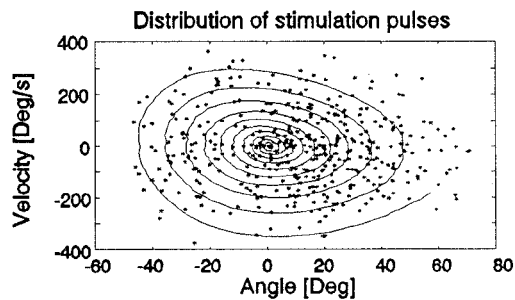


Fig. 4. The lower leg pendulum states in which the muscle was stimulated, because of the pseudo random IPI sequence. A passive swing response of the lower leg is included in the figure.

IV. DISCUSSION

Ladin and Wu [3] also proposed to use accelerometers for estimating joint torque.

The measurement procedure will enable the identification of the quadriceps - lower leg dynamics in the desired working space and under desired loading conditions.

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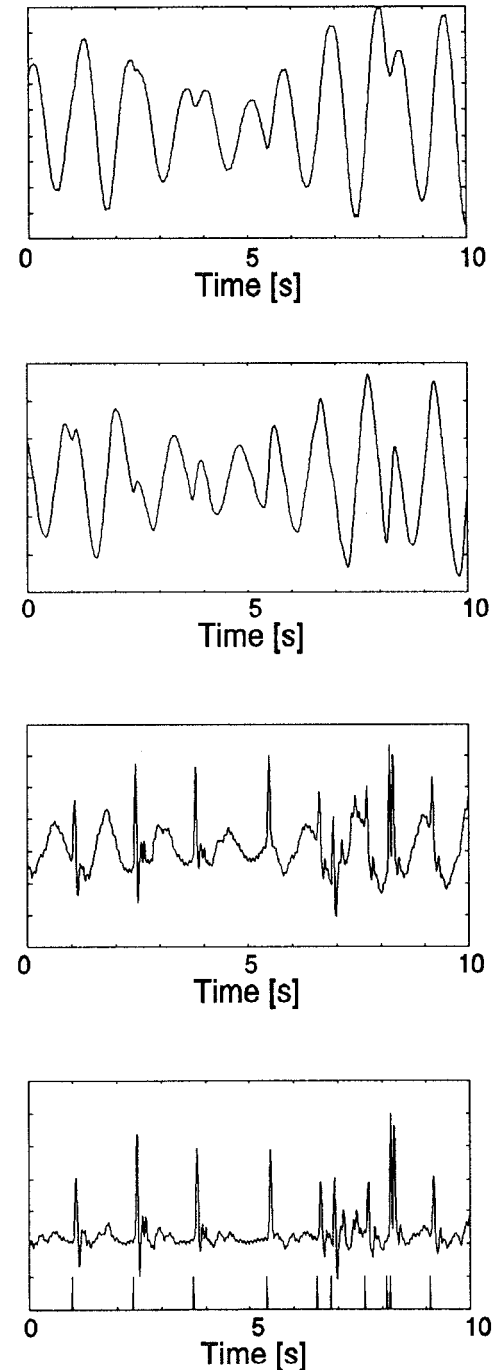


Fig. 3. Typical responses of the pseudo random stimulation sequence: a. Knee joint angle (measured by goniometer); b. Knee joint angular velocity (estimated from goniometer signal); c. Knee joint acceleration; d. $(M_m + M_p)/I$ estimate and stimulation sequence (bottom of graph).