COMPUTER SYSTEM FOR ANKLE JOINT MUSCLE IDENTIFICATION

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Abstract – *The poster gives an overview of a complex system designed for functional electrical stimulation (FES) assisted standing experiments. The overall system comprises a personal computer (PC), Optotrak system for non-contact position measuring, two force plates, force-sensor shoe insoles, computer controlled electrical stimulator and mechanical rotating frame (MRF). The software core is based on universal simulation environment Matlab Simulink. When stimulating, the sample times of individual sensor device blocks are synchronized with the stimulation pulses. The system functioning was verified in on-line ankle joint muscle identification trials with intact subject and proved to be accurate and reliable.*

Keywords: functional electrical stimulation, biomechanics, Matlab Simulink, automatic control.

1. Introduction

This presentation adresses digital control of neuroprostheses in which muscle is stimulated electrically. Important role in the analysis of motor control and the design of motor system neuromuscular prostheses play the muscle models. Modeling a neural prosthesis system including the neuromuscular stimulator, and the electrically stimulated muscle can be used to test stimulation patterns as well as feedback control strategies. The model output is assumed to be the muscle generated force, while the model input consist from rectangular pulse trains characterized by pulse amplitude (*A*), pulse width (*PW*), and pulse frequency (*f*). The input-output relation can be described with physiologically based models of muscle activation where individual model parameters present anthropometric properties [1]. An alternative approach is black-box parametric modeling as a common identification method [2], [3], [4], [5], [6]. The greater part of these models was derived *in vitro* in animal studies by dissecting muscle tendons and attaching them to the force transducers. *In vitro* experiments are advantageous for the general understanding of dynamic properties of skeletal muscles, but can not include realistic aspects of spasticity and aspects of remaining neuromuscular control of the intact upper body.

The entry point for *in vivo* digital control (e.g. with paraplegic subjects) could be the FES of muscle passing ankle joint. Appropriate activity of ankle joint extensors (plantarflexors) and flexors (dorsiflexors) can provide some body stabilization of paraplegic subject and is thus convenient object of closed-loop FES [2], [7]. There are several advantages in working with the ankle joints: when standing, they are not at extreme position of their range of motion, and the ankle extensor muscles (plantarflexors) are easily accessible for surface stimulation [8].

In closed-loop muscle modeling applications is required accurate sensory information about human body position, reaction forces and reaction moments to surrounding environment. Considering the necessity for experiments, where standing subject is electrically stimulated, we decided to develop a laboratory setup with PC controlled electrical stimulator, commercially available sensor devices and MRF. Here are presented the development and application of the setup. Electrically stimulated isometric muscle was identified with recursive discrete-time model in Hammerstein form.

2. Laboratory setup

The overall system comprises a PC, Optotrak system for non-contact position measuring, two force plates, force-sensor shoe insoles, computer controlled electrical stimulator and MRF (Fig. 1). The essential task was to construct computer interfaces for each measuring device and for electrical stimulator in order to describe and run the system. The selected software platform is Matlab Simulink® simulation computation environment in the Microsoft Windows based graphical user interface (GUI). The communication algorithms for running sensory devices and stimulator are written in programming language C. Algorithms were included into Simulink models by using S-function blocks, one of the Simulink choices which allow custom sampling time and other parameter setting (Fig. 2). In the following points are described the experimental environment components:

a.) Optotrak system

The Optotrak system[1] is a non-contact, high speed, high accuracy, three dimensional motion measurement and analysis system which provides 3D data in real time and sampling rates of sensor data up to 400 Hz. The Optotrak uses three 1D sensors (Fig. 1, 1), each of which employs a 2048 element linear CCD array and a cylindrical lens.

1 Northern Digital Inc., Canada.

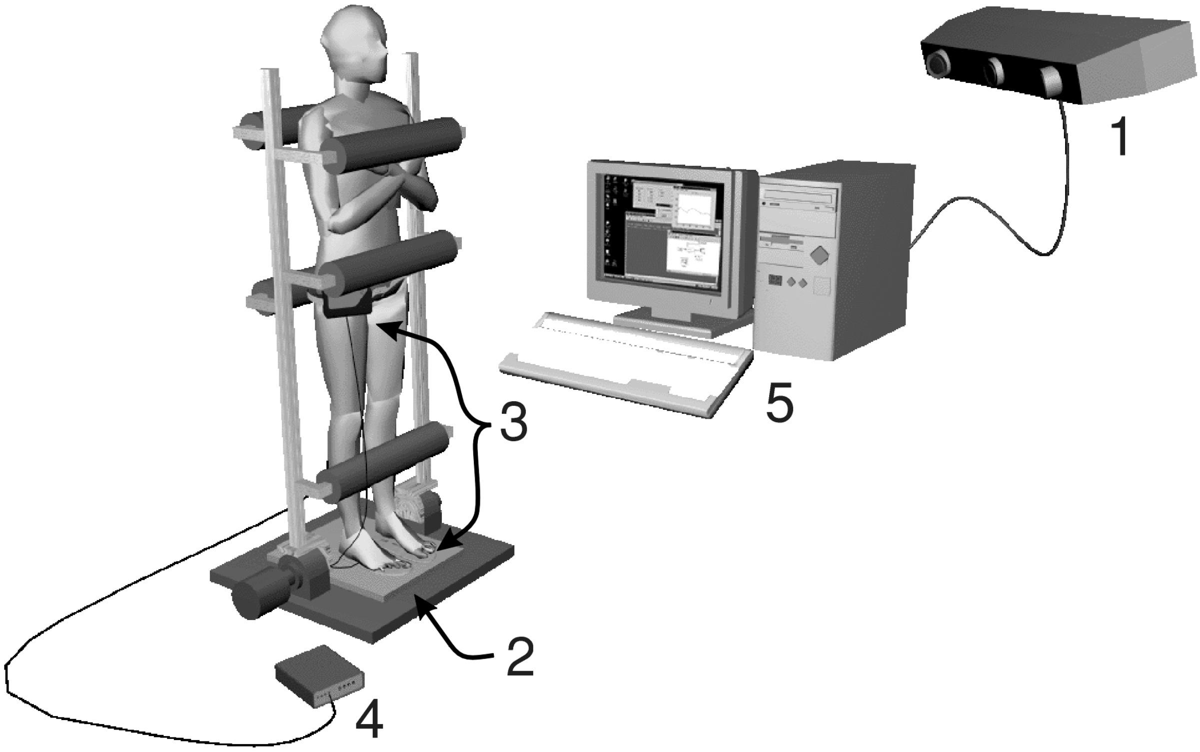

Fig. 1: Experimental environment with subject standing in MRF. 1 - Optotrak system, 2 - Force plate, 3 – Force sensor shoe insoles, 4 – Electrical stimulator, 5 – PC with Matlab Simulink.

Sensors track target points defined by up to 256 miniature infrared emitting diodes – markers that can be sticked on the measured subject. Optotrak system connects to a standard PC platform via ISA card. The number of our custom created Simulink block outputs (Fig. 2, block 1) can be changed to desired number of markers. Sampling frequency can be likewise set up previous to the measurement trial.

b.) Force plates

Two AMTI[2] platforms simultaneously deliver three force components along and three moment components around the X,Y,Z axes. Analog acquisition is synchronized with Optotrak 3D motion measurement using the Optotrak hardware clock. In the initialization of force plate Simulink block (Fig 2., block 2) are defined sampling frequency and number of analog channels.

c.) Force sensor shoe insoles

Parotec[3] force-sensor shoe insoles as depicted here represent an alternative to force-plates (Fig. 2, block 3). Force plates are frequently impractical in gait investigations due to their limited surface size, which bounds examinations to the plate surface. Force-sensor shoe insoles enable load pressure readings separately for the left and the right foot. There are 24 capacity sensors disposed on each insole and 48 pressure values are sampled at 10 Hz or 50 Hz frequency. Transfer speed to PC via RS232 connection can be set in a Simulink block (figure) up to 57600 bit/s.

d.) Electrical stimulator

FES system with 4 stimulation channels and direct PC control via RS-232 line was utilized. The PC to stimulator communication protocol enables Simulink to drive the parameters of electrical stimulation. The timing for each pulse starts only after the complete command string was downloaded from a PC. Stimulation frequency is, for ensuring synchronized real time execution, defined my Simulink and was in our experiments set constantly to 20 Hz.

e.) Mechanical rotating frame (MRF)

MRF was built in laboratory to study human body stability and properties in sagittal plane. The frame braces knee, hip and lumbosacral joints in extended positions and both ankle joints are constrained in middle neutral position. In this way are enabled investigations of control strategies with ankle muscles as actuators in both intact and paraplegic subjects.

2 Advanced Mechanical Technology, Inc., MA, USA.
3 Paromed Medizintechnik GmbH, Germany.

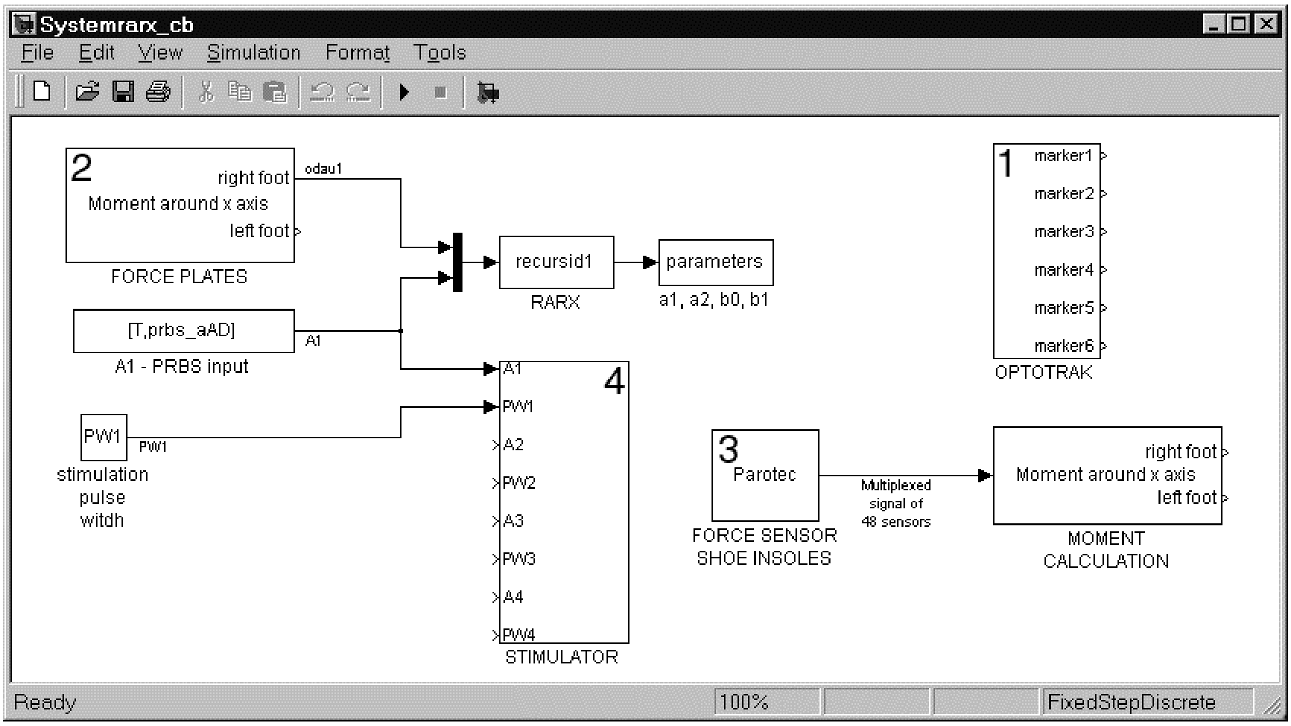

Fig. 2: Matlab Simulink model with blocks for sensory devices and electrical stimulator: 1 - Optotrak system, 2 - Force plate, 3 – Force sensor shoe insoles, 4 – Electrical stimulator.

3. Muscle model identification

The subject stood in the MRF, which was for isometrical conditions fixed in upright position with four strings in forward and backward direction. Each foot acted directly on one of two force plates. In the casual shoes were placed force sensor shoe insoles. In this particular experiment subject cannot move in the frame, meaning that Optotrak use is not necessary. We still collected Optotrak data for verification purposes. The self-adhesive 50 mm x 90 mm Axelgaard[4] electrodes were placed on the midlines of the soleus and the gastrocnemius muscles of the subject.

The plantarflexor muscle identification test consisted of two parts. In the first half was defined the isometric recruitment curve. The isometric nonlinear curve of muscle can be defined as the static gain relation between stimulus activation level and output force when the muscle is held at fixed length. The recruitment level – activation (0 mAct – 1000 mAct) is interpreted as the fraction of muscle activated by each stimulus pulse and was defined in twitch response procedure with variation of pulse amplitudes [9]. Second half of model following the recruitment nonlinearity, the linear transfer function of the Hammerstein structure (Fig. 3), was determined in parametric identification procedure. The transfer function has been chosen as second order discrete-time form that was justified by other authors [2], [3]. Transfer function test inputs in this study were trains of pulses, amplitude modulated with pseudo-random binary sequences (PRBS). At each stimulus instant, the pulse amplitude took one of two choices. The pulse width was set constant at 400 μs. 10 s test random sequences were computer generated. The muscle activation range was divided into three subranges for identifying three local models as follows:

a.) 375 mAct ± 125 mAct
b.) 625 mAct ± 125 mAct
c.) 875 mAct ± 125 mAct

Parameters of transfer function can be estimated on-line with recursive ARX (RARX) algorithm [10]. For implementation of RARX algorithm, was written special Matlab script in Simulink S-function.

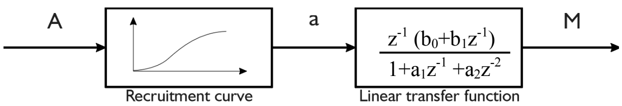

Fig. 3: Muscle model in Hammerstein form. A – stimulation amplitude, a – muscle activation, M – generated moment.

4. Results

The course of sample muscle response to 20 Hz stimulation with PRBS activation is shown with solid line in Fig. 5. Muscle moment was measured with force-plate. Dotted line represents the predicted muscle moment as the output of RARX identified model. The initial parameters of linear transfer function a_1, a_2, b_0, b_1 (Fig. 3, block 2) were set to 0. The parameter adaptation at the beginning of identification causes anomalous deviations for time points before 1 s time and afterwards the model output improves the following of the measured value. Parameters after the 10

4 Axelgard Manufacturing Company, Fallbrok, CA, USA.

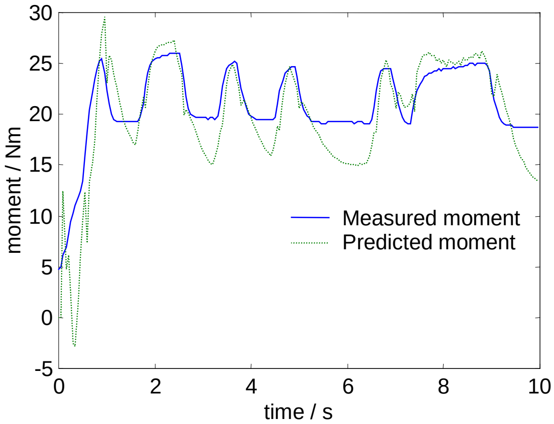

Fig. 4: Measured muscle generated moment and moment predicted by recursive model. Model with coincidental parameters constantly improves its prediction capabilities.

s adaptation sequence indicate pole values at –1.81 Hz and –1.07 Hz.

5. Discussion

Complex system for biomechanical and FES experiments, which is supervised by universal simulation environment Matlab Simulink was built and tested in muscle model identification procedure. System for non-contact position measurement Optotrak operated efficiently at 100 Hz and 20 Hz sampling frequencies in connection with computer controlled electrical stimulator, which delivered pulses at 20 Hz. Electrically stimulated plantarflexors of an intact subject generated joint moments that were measured with force plates. The force plate measurements can be compared to the measurements from force sensor shoe insoles (Fig. 5). Spikes in the moment course calculated from insole measurements are originating from relatively large digitalization errors in shoe insole controller device equal to 1 N. This is first disadvantage of existing shoe insoles compared to force plates. Second disadvantage is a necessity of extra calculation time for recalculating data acquired by shoe insoles. With force plates the moments are measured directly from strain gauges, voltages and calibration matrices. With shoe insoles the moment is calculated indirectly by using values from each single force sensor. The algorithm is computationally more time

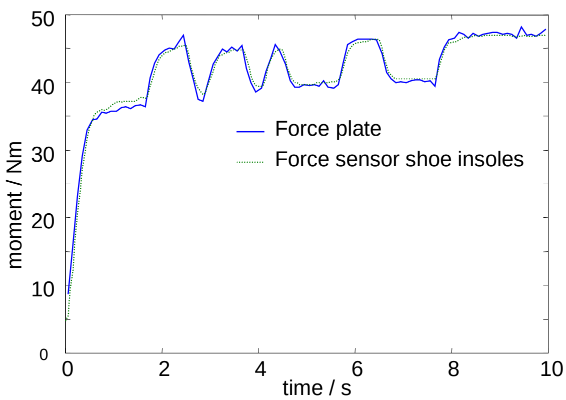

Fig. 5: Moment around ankle axis measured with force plate and force sensor shoe insoles.

demanding. On the other hand have the force sensor shoe insoles a capability of avoiding the limitation of force plates where the subject needs to stand on relatively small plate surface.

For identifying electrically stimulated muscle was used an equivalent discrete time muscle model preceeded by a static nonlinear recruitment curve. This common identification approach was applied earlier in model identification by several authors [2], [6]. The position of poles of second order transfer function dictates the dynamic properties of the complete model that are similar to findings of other authors.

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