EXPERIMENT DESIGN FOR PARAMETER ESTIMATION OF A MULTI-SCALE ARM MODEL*

Cs. Fazekas[1,2], K. M. Hangos[2]

[1]Department of Information Systems, University of Veszprém, Veszprém, Hungary
[2]Systems and Control Laboratory, Computer and Automation Research Institute, Budapest, Hungary

Abstract: The design of the experiments for parameter estimation of a multi-scale arm model is described in this paper. The aim of the estimation is to obtain low level (molecular and structural) parameters of an arm model from high level, easier measurable (movement pattern and electromyogram) signals. The parameters to be estimated as well as the movement patterns to be used in the experiments are determined by using sensitivity analysis.

Keywords: Nonlinear parameter estimation, Experimental design, Sensitivity analysis, Arm model.

1. INTRODUCTION

There is an increasing importance of applying the methods of modern systems and control theory in bio-mechanical systems for developing passive (i.e. non-intervening) methods for diagnosing musculoskeletal diseases and to construct human-like prosthesis. The dynamic modelling and simulation of the human musculoskeletal systems can help us understand how musculotendon actuators produce force (Hill, 1938; Huxley, 1957), how the actuators and their excitation coordinate the movements (Hatze, 1976; Cheng, *et al*, 2000; Laczko, *et al*, 2004).

The estimation of musculoskeletal parameter values from series of experimental observations in vivo represents a considerable problem in physiology and biomechanics. “It thus becomes imperative to devise methods which make it possible to estimate, for each of the muscles involved, the values of the parameters which characterize the behavior of that muscle” (Hatze,1981).

The internal structure and the properties of the building blocks in a muscle can be described by suitable models (Zajac, 1989; Raikova and Aladjov, 2005; Linden, *et al*, 1998). Then, by measuring the macroscopic properties of the biological limb such as EMG signals, muscle forces and movement patterns, both the functional and anatomical parameters of the limb's elements can be estimated, (Delp, 1990). Anatomical parameters, such as segment mass, length, attachment points, muscle volume, pinnate angle etc. are generally estimated from investigation of cadavers. The results of such investigations are reported in (Veeger, *et al*, 1991; Veeger *et al*, 1997; Murray, *et al*, 2000).

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However, the estimation of dynamic parameters, such as maximum isometric force as a function of muscle length, optimal muscle length, tendon slack length or maximum tendon extension, moment arm as a function of joint angles etc. is much more difficult. Murray, *et al*, (2000) estimated the moment arm, optimal length, tendon slack length, etc. of elbow muscles as a function of joint angle investigating cadavers; Raikova and Aladjov (2005) investigated the effect of muscle structure to the exerted force and movement; Hatze (1981) estimated the maximum isometric force, maximum isometric tendon extension and optimal muscle length from the measured isometric torque-angle relation; Garner and Pandy (2003) estimated peak isometric force, optimal muscle-fiber length and tendon slack-length from the measured isometric torque-angle relation. Lloyd and Besier (2003) estimated the muscle force, tendon slack length, activation parameters from different movement tasks and measured EMG, joint angle and moment signals.

The aim of this study is to develop and apply a general method for estimating physiological and structural parameters and properties of human, multi-scale musculoskeletal systems in vivo from measured EMG signals of muscles and the time-variation of joint angles by using dynamic modelling and model analysis.

2. THE ESTIMATED PARAMETERS

2.1 Multi-Scale Arm Model

To model processes on different length and time scales a multi-scale arm model is applied. The model describes the movement of an arm by modelling the contraction and force generation mechanism of the muscles containing fibers, tendon and aponeurosis while takes the molecular events, muscle structure, muscle activation and external loads into account and handles different space and time scales. The model is built in a multi-scale framework (Fazekas, *et al*, 2005) that consists of four levels (see fig.1.), corresponding to important anatomical and/or physiological parts of a limb. These four levels are: (1) level of sarcomere, (2) level of fiber, (3) level of muscle, (4) level of limb. The level of sarcomere models the basic force exerting mechanism with corresponding molecular processes. The level of fiber integrates the force of serially and parallel connected sarcomere belonging to the same fiber and modifies this net force with the properties of the fiber and motor unit. The level of muscle consists of three sub-levels: (1) sub-level of muscle, (2) sub-level of tendon and (3) sub-level of aponeurosis. The sub-level of muscle is responsible for integrating the fiber's force and modifying it with the properties of muscle and computing the muscle torques. The sub-level of aponeurosis computes the behavior of aponeurosis based on muscle states and models the pinnate effect, while the sub-level of tendon is responsible for simulating the tendon behavior. The level of limb computes the joint torques and solves the nonlinear dynamic equation of the limb. The inputs of the multi-scale model are the activation signal of muscles vs. time and outputs are the movement pattern, i.e. the time behavior of a set of joint angles.

The applied arm model, based on (Laczko, *et al*, 2004), integrates different sub-models known from the literature (Cheng, *et al*., 2000; Derényi and Vicsek, 2000; Zajac, 1989). As Fig. 2. shows, it contains three segments (tribe, upper arm and forearm+wrist complex) and seven muscles (triceps brachii long head, triceps brachii lateral+medial heads, biceps brachii (short and long heads), brachialis, brachioradialis, deltoideus anterior, deltoideus posterior). For the sake of simplicity, our arm model can describe movements in the sagittal plane only, and we assumed that the moment arm is constant. Anatomical data of muscles, such as attachment points, optimal length, tendon slack length, moment arms, etc. are taken from the literature (Murray, *et al*, 2000; Veeger, *et al*, 1991; Veeger, *et al*, 1997).

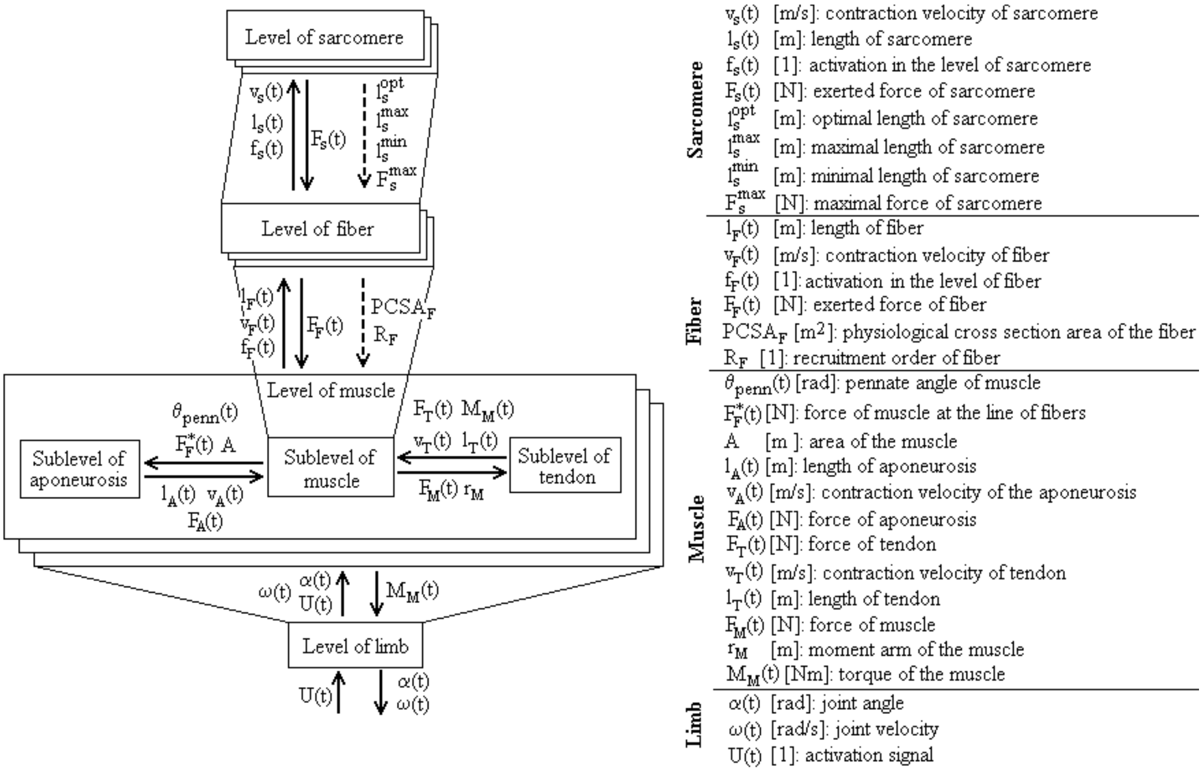

Fig. 1. Multiscale framework.

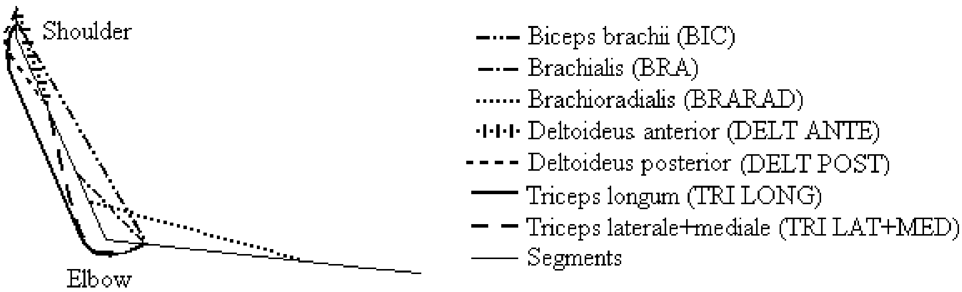

Fig. 2. Applied arm model with three segments and seven muscles

2.2 Sensitivity Analysis

Sensitivity analysis is performed to determine which parameters influence significantly the output of the model. For the purpose of the analysis we changed the value of a parameter with *±10%* from its reference value and the deviation of the movement pattern from its corresponding reference pattern was calculated in terms of a simple dimensionless sensitivity coefficient

$$\varphi = \frac{\sum_{i=1}^{N} \left| \alpha(t_i) - \alpha^{orig}(t_i) \right|}{N} \tag{1}$$

where N is the number of simulation time steps, α [rad] is the joint angle of the limb during the movement of system with modified parameter, α^{orig} [rad] is the joint angle of the limb during the movement of the original system and t_i is the i^{th} discrete time instance.

Sensitivity analysis (Fazekas, *et al*, 2005) showed that the model output is highly sensitive to the molecular parameters (molecular concentration, association and dissociation rates), parameters of muscle structure and geometry, parameters of force-length-velocity relation (active force generation) and less sensitive to the parameters of tendon and aponeurosis.

The model parameters to be estimated are selected based on the above sensitivity results: the most influental parameters have been estimated and the value of the rest are taken from the literature. In this way two parameters of each muscle are chosen to be estimated: the number of parallel connected sarcomeres (structural parameter) and the steady state probability of the strongly bound state (molecular parameter). Since there are seven muscles, 14 parameters should be estimated from dynamic measurements.

Parameter Estimation Algorithm: Because the estimated parameters enter into the model in a non-linear way, the non-linear, sequential Nelder-Mead simplex algorithm (Nelder and Mead, 1965) is applied for parameter estimation that requires a proper initial value for each of the estimated parameters (Lagarias, *et al*, 1998). Proper initial values are given from the literature.

3. DESIGN OF THE EXPERIMENTS

The aim of the experiment design was to decouple the parameter estimation task by using experiments with movement patterns that are influenced by only a few dynamic parameters. For this purpose we investigated what kind of movement was influenced the most by the chosen parameters of a given muscle using sensitivity analysis. We simulated elbow flexion-extension and shoulder anteversion-retroversion from different initial conditions. *Characteristic movement patterns* have been determined from these investigations.

*Static measurement*s: From static measurements the height and mass of the measured subjects will be determined. From these data the mass, inertia, length and location of center of mass of the segment can be computed applying the regression equation and data of (Zatsiorsky, 2002).

Dynamical measurements: The parameter estimation uses dynamical measurements when the surface EMG signal of seven muscles and the joint angles (elbow and shoulder) are measured. The dynamical measurements will consist of characteristic movement patterns to be done by the measured subject that have been determined based on the sensitivity analysis such, that each characteristic movement is suitable for estimating one or two parameters of one of the muscles therefrom. The applied characteristic movements are shown in fig. 3. They contain elbow flexion-extension and shoulder anteversion-retroversion separately in the sagittal plane. Either the elbow or the shoulder is fixed (black points) while the other joint is moved (light points). Fig. 3 shows the initial position of the moving segment(s) (broken lines), a position of segments during the movement (solid line), the movement direction (thick arrows) and the muscle that influences the characteristic movement the most.

Measurement process: The measured subjects will be young (25-30 years old), healthy and average man that volunteer to take part in the experiments and will be informed about its goals.

First the static measurements will be completed. Then the movements defined for the dynamic measurements will be completed in the same order as their order number in fig. 3. Each characteristic movement will be repeated 5 times, in between two characteristic movements the subject will have a 1 minute rest. During dynamic measurements the back of the subject will be fixed to the chair in order to his back cannot move. While doing the movements, the subject will have to move his joint as fast as possible. The fixation of his shoulders on both the right and left arms will be achieved by a table which angle is set and fixed. A rigid rod that will be fixed to the upper arm and forearm of the subject is used to the fixation of his elbow.

The movement of the right arm of the subject will be measured, while the left arm will be used to set the initial joint angles by fixing its joints accordingly. When starting a movement, the subject will be catching a rigid, light and horizontal rod into his left palm that is long enough to reach the right palm. Before starting the measurement, the subject will have to place his right palm to the rod to set the initial position of his right arm.

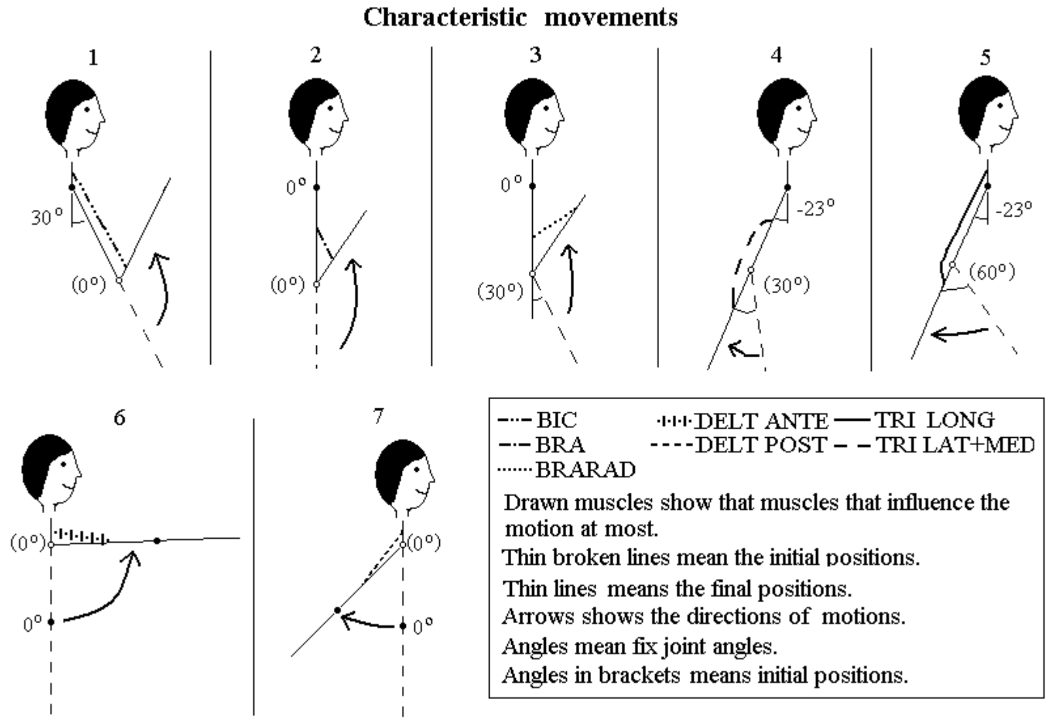

Fig. 3. Characteristic movement patterns.

Measurement Systems: To measure the movement pattern the PAM system (Jobbagy, *et al*, 2005) developed in the Bioengineering Laboratory, Department of Measurement and Information Systems, University of Technology and Economic of Budapest, Budapest, Hungary will be used. Passive markers will be attached to anatomical landmark point and trajectories of markers will be determined with a camera.

The camera will watch the sagittal plane of the subject. While he does the exercises with his right arm the distance between the camera and the subject's right arm will be *3 m* and the middle line of the tribe has to be in the middle line of the image. The height of the camera lens will be at the middle point of the hanging upper arm.

Surface EMG will be recorded with the BioSemi ActiveTwo system with active Ag/AgCl, circle shape, diameter *10 mm* electrodes situated at the Department of Bioengineering, Research Institute for Technical Physics and Materials Science. The distance between the two center of the two electrodes is *20 mm*. Sampling frequency is *1000 Hz*. During the electrode placement we take into account the recommendation of SENIAM (Freriks and Hermens, 1999) and De Luca (1997). The electrodes will be located on the middle line of the muscle belly.

3. CONCLUSION

In this paper the design of an experimental procedure for biomechanical parameter estimation is described. Using sensitivity analysis the estimated parameters and the characteristic movement patterns have been defined. The Nelder-Mead simplex algorithm will be used for estimation. The measurements are scheduled for the next year.

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