Identification and Validation of FES Physiological Musculoskeletal Model in Paraplegic Subjects

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Abstract— The knowledge and prediction of the behavior of electrically activated muscles are important requisites for the movement restoration by FES in spinal cord injured subjects. The whole parameter's identification of a physiological musculoskeletal model for FES is investigated in this work. The model represents the knee and its associated quadriceps muscle. The identification protocol is noninvasive and based on the in-vivo experiments on paraplegic subjects. The isometric and nonisometric data was obtained by stimulating the quadriceps muscles of 3 paraplegic subjects through surface electrodes.

A cross validation has been carried out using nonisometric data set. The normalized RMS errors between the identified model and the measured knee response are presented for each subject.

I. INTRODUCTION

Functional Electrical Stimulation (FES) is commonly used to produce an artificial contractions in order to control the paralyzed muscle-limb system in subject with spinal cord injury. However, the restoration of human paralyzed muscle-limb involves a complicated control problem due to the high complexity, nonlinearity and the time variation of the fatigued stimulated muscle. An accurate numerical model of the muscle-limb dynamics is needed for the model-based control technique. Hill [1] described the macroscopic mechanical characteristics of muscle while Huxley [2] detailed its microscopic concepts. An adaptation of these models to FES control was done in [3],[4]. The accuracy of the model implies to identify several parameters using the FES signal as an excitation input. Identification of the FES-induced quadriceps-shank dynamics in nonisometric condition was investigated in several works, online [5],[6] or off-line, [7]. An identification in isometric and isotonic conditions was achieved in [8] based on a black-box nonlinear model.

The aim of this work is the parameter's identification of the physiological-based model of the quadriceps-shank including both isometric and nonsometric conditions. Thus, an isometric and nonisometric identification procedures are combined and the measured kinematic data set in dynamical condition is used for a cross validation. This identified model allows to predict the behavior of the quadriceps-shank system which is very useful for the synthesis of the optimal stimulation patterns in the movement restoration context [9].

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In the next section, the experimental setup and subjects characteristics are introduced; the quadriceps-shank physiological model is presented in section III. In section IV, the parameter's identification protocol is described. In section V, we present and discuss the results. Section VI presents the conclusion and the perspectives.

II. EXPERIMENTAL SET-UP

Experiments were conducted on three male subjects, who have complete paralysis of lower extremity due to spinal cord injury. An authorization from the ethical review board and an agreement from each subject were obtained. The general information about the subjects is summarized at Table I.

TABLE I
PATIENTS CHARACTERISTICS

Subject	Age (years)	Body weight (Kg)	Body height (m)	Injury level	post injury (years)
LT (S1)	37	72	1.75	T6	12
BD (S2)	46	94	1.88	T10	14
AL (S3)	38	65	1.8	T6	12

The paraplegic patients were seated on a chair with their hip flexed at approximately $90°$ and their thigh held against the seat. Two types of experiments were performed according to isometric or nonisometric conditions:

1) in isometric condition, The joint torques were recorded with $2KHz$ sampling frequency through a dynamometer of *BIODEX* system. The experimental setup is described at Fig.1 - part (a).

2) in nonisometric condition, the same stimulator was used while the leg is free. The flexion/extension of the knee joint angle was measured with $100Hz$ sampling frequency, using a mounted electrogoniometer as presented at Fig.1 - part (b).

The applied stimulation signal and the EMG ($4KHz$ sampling frequency) were recorded through *BIOPAC MP100* acquisition system. The quadriceps muscle group was stimulated, through surface electrodes, for the knee extension while the other muscles are considered to have a passive effect. In these experiments the right and left leg were tested, however the results of only the left leg are presented in this paper. The frequency of stimulation was fixed at $20Hz$ for all subjects and experiments, and the specific fixed amplitude I was chosen previously for each subject. During the experiments, as described in this paper, only the pulse width PW was modulated to make a FES control.
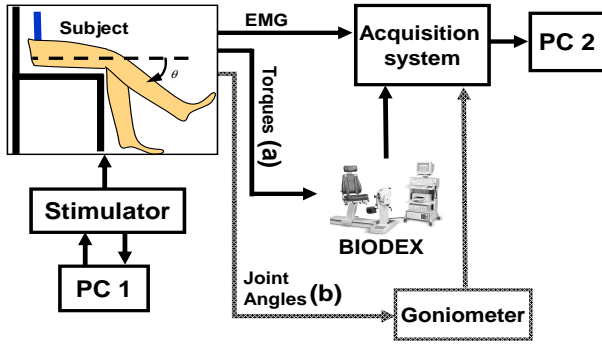
Fig. 1. The experimental setup in isometric and nonisometric conditions. In isometric case, the torques are measured (part **a**) through the Biodex system. In nonisometric case, the joint angles (part **b**) are recorded through an electrogoniometer.

III. MODELING

A. Knee joint model

We consider a 2D model in the sagittal plane with one degree of freedom characterizing the knee joint and controlled by the quadriceps torque through a constant moment arm r_q. The rest position is at $\frac{\pi}{2}$ and the full knee extension is at 0. The geometrical formulation of quadriceps muscle length is as follows:

$$L_q(\theta) = L_{q_{ext}} + r_q\theta \quad (1)$$

Where θ is the knee joint angle and $L_{q_{ext}}$ the quadriceps length at the maximal extension (*i.e.* $\theta = 0°$).

The dynamic behavior of the joint around the rest position is given by the following second order nonlinear equation [10]:

$$T_q = J\ddot{\gamma} + F_v\dot{\gamma} + T_g + T_e \quad (2)$$

where, $\gamma = \frac{\pi}{2} - \theta$ is the knee angles from the vertical in counter-clockwise direction. $T_q = F_q.r_q$ is the active quadriceps torque, $T_g = m.g.L_{og}.sin(\gamma)$ is the gravitational torque and T_e is the nonlinear elastic torque. F_v and J are respectively the viscosity coefficients and the shank inertia around the center of rotation O.

B. Muscle model under FES

The muscle model used in this work is a physiological model with macroscopic and microscopic muscle properties [4]. Fig.2 describes the model controlled by a stimulation input. It is composed of two parts:

- The activation model: It describes the fiber recruitment function which represents the relation between the electrical charge applied on the muscle and the ratio of the activated fiber. This part includes also the description of the calcium dynamics.
- The mechanical muscle model which is based on the Hill-Maxwell structure. It includes the contractile element, the serial element and the parallel element which effect was considered in the knee joint as a part of passive effect (in elastic torque T_e of Eq.2).

The dynamic equations, describing the contractile element behavior under FES, are detailed in our previous works [11].
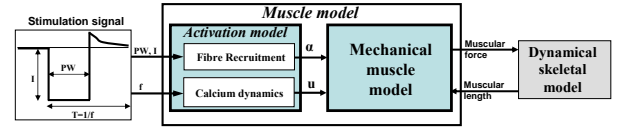

Fig. 2. Complete muscle model [4]. The muscle applies a force on the skeletal system while the joint position has effect back on the muscle length.

IV. IDENTIFICATION PROTOCOL

Our identification protocol includes five successive parts:

A. The geometrical parameters

Linear least square method provides the value of $L_{q_{ext}}$ and r_q in Eq.1 using the quadriceps length at different samples of knee angle. Quadriceps length estimation was obtained from the Hawkins equation [12] combined with the anthropometrical estimations of the limbs length [13].

B. The joint dynamics parameters

From Eq.2 and based on the linearization technique used in [10], the equivalent torque $T_K = T_g + T_e$ becomes linear such as $T_K = K\gamma$. The data were collected without any muscle activation ($T_q = 0$). Two steps are required to identify the parameters of Eq.2:

- The first test was done in static condition ($\dot{\gamma} = 0$, $\ddot{\gamma} = 0$). We used the BIODEX system (Fig.1-part (a)) to measure the passive torque (*i.e.* gravity + passive elasticity) at several knee joint positions. A linear least square identification allows to obtain the parameter K.
- In the second part, the passive pendulum test was used. The knee joint angles were recorded using the electrogoniometer (Fig.1-part(b)) and filtered using a Butterworth low-pass filtering at $30Hz$. Knowing K from the first step, an analytical identification procedure was used to identify the parameters J and F_v.

C. Muscle force-length relationship

To identify the force-length relationship, isometric knee torques were measured at different knee angles ($\theta = 90°, 75°, 60°, 50°, 40°, 30°$) during quadriceps stimulation with the same pulse width ($PW = 300\mu s$). The measurements were repeated with 2 times and the measured torques were filtered and averaged. The muscle lengths L_q were estimated from the geometrical equation (Eq. 1). The linear least square method was applied to identify the shape parameter b and the optimal length of muscle L_{opt} of the gaussian curve:

$$F_l(\varepsilon_q) = \exp\left\{-\left(\frac{\varepsilon_q}{b}\right)^2\right\} \quad (3)$$

Where F_l is the normalized force-length relationship and $\varepsilon_q = \frac{L_q - L_{opt}}{L_{opt}}$ the relative muscular length.

D. Recruitment function

The recruitment curve is generally described by a sigmoid function (Eq.4) [14]. It relates the stimulation pulse width PW to the recruitment rate α. Isometric knee torques at

optimal knee position were measured at different *PW* (between $0 - 420\mu s$). The recruitment rate was obtain from the normalized measured torques. Nonlinear least square method was applied to identify the parameters c_1, c_2 and c_3 of the following recruitment function:

$$\alpha(PW) = \frac{c_1}{1 + \exp\{c_2(c_3 - PW)\}} \quad (4)$$

From the identified recruitment function, the maximal muscular force F_m which corresponds to $F(PW_{max} = 420\mu s)$ was obtained.

E. Mechanical parameters of muscle

The mechanical parameters of the muscle are the passive stiffness of the serial element k_s and the the maximal active stiffness of the contractile element K_m. The quadriceps was stimulated and the knee angles were measured (Fig.1-part(b)) in nonisometric conditions. From the identified model in isometric test, a nonlinear programming (NLP) method was used to identify the parameter k_s minimizing the knee angular errors between the subject measurements and the model output. Then, the parameter K_m was taken proportional to the maximal isometric forces and minimizing the dynamical oscillations (Fig.4). In the stimulation patterns used here, the pulse widths *PW* were modulated in order to make a sensitivity of the model to the mechanical parameters.

V. RESULTS AND DISCUSSION

The identified parameters for each subject are summarized in Table II. The performance of each identification step and cross validation was quantitatively estimated using RMS error, calculated between predicted and measured data. The RMS error was normalized to the RMS value of the measured data (NRMSE) as shown in Table II. The presented graphs correspond to the identification results of the left quadriceps-shank of the first subject. The geometrical parameters of r_q

TABLE II

PARAMETER IDENTIFICATION RESULTS AND CROSS VALIDATION.
NRMSE IS A NORMALIZED RMS ERROR OF IDENTIFICATION (%).

Identification step	Parameters	Value			NRMSE [%]		
		S1	S2	S3	S1	S2	S3
Geometrical	r_q [cm]	4.8	5.2	4.9			
	$L_{q_{ext}}$ [cm]	41.2	44.3	42.4			
Joint dynamics	K [Nm/rad]	9.41	11.4	9.28	10.2	8.92	5.1
	J [Kgm²]	0.25	0.28	0.26	16	15.2	18.3
	F_v [Nms/rad]	0.16	0.23	0.18			
Force-length	b [10^{-2}]	7.64	9.38	9.33	2.2	6.11	3.89
	L_{opt} [cm]	46.4	49.7	46.9			
Recruitment	c_1	1.37	0.99	0.88	5.15	6.68	8.85
	c_2	3.98	11.4	34.8			
	c_3	0.74	0.65	0.51			
	F_m [N]	438	400	239			
Mechanical of muscle	K_m [N/mm]	400	375	250	2.85	3.13	3.09
	k_s [N/mm]	10	10	2.4			
Cross Validation					3.52	6.74	8.28

and $L_{q_{ext}}$ seem realistic according to the femur lengths which were measured directly on the subjects.
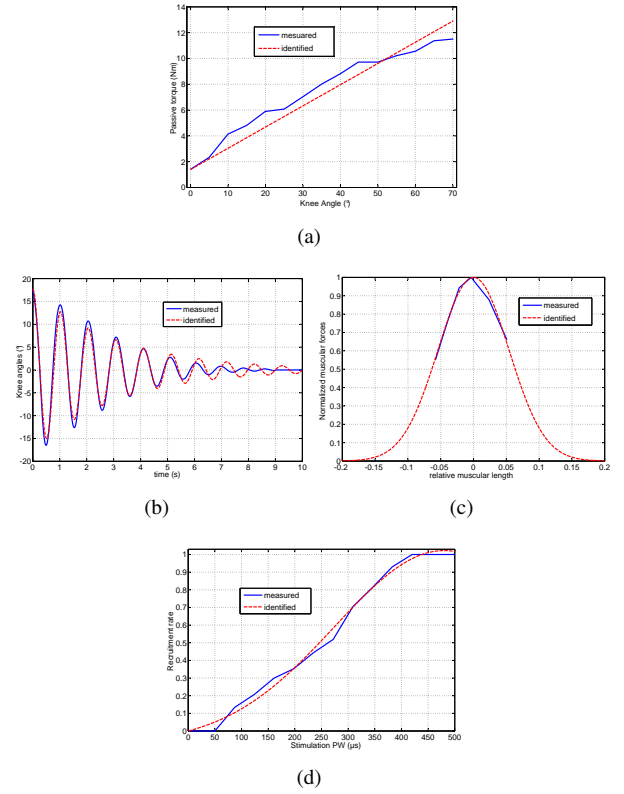

(a)

(b)

(c)

(d)

Fig. 3. Identification results: (a) Static passive torque. (b) Passive pendulum test. (c) Force-Length relationship. (d) Recruitment function.

The total joint stiffness K was identified. A linear approximation and the measured static passive torques are presented in Fig.3(a). The identified parameter K in Table II highlights the strong correlation with the body weight for all the subjects (see Table I) although it includes the passive elasticity of muscle around the knee joint. Indeed, this nonlinear elasticity is small compared to the gravity effect in our range of motion [10]. The parameters J and F_v were identified from the passive pendulum behavior, it was fitted well as presented in Fig.3(b). However, the model continues to oscillate after the limb comes around the rest position. The parameter J has correlation to the body height as shown in Table I and Table II. The measured and identified force-length relationship curves are presented in Fig.3(c). The parameters b of the force-length relationship in subjects are close however their muscular force are very different depending on the strength of each subject's muscle. The recruitment function obtained from measured forces is presented in Fig.3(d). The recruitment function parameters presented in Table II show a small intersubject variability except the parameter c_2 which represents the slope of the sigmoid recruitment function. The isometric identification was not enough to predict the dynamical behavior of the quadriceps-shank system as we can see in Fig.4 (dashdot line). In fact, some parameters of the muscle model are not significant in isometric conditions as k_s and K_m and their identification requires a nonisometric behavior of the muscle. The identification of these parameters from the leg motion
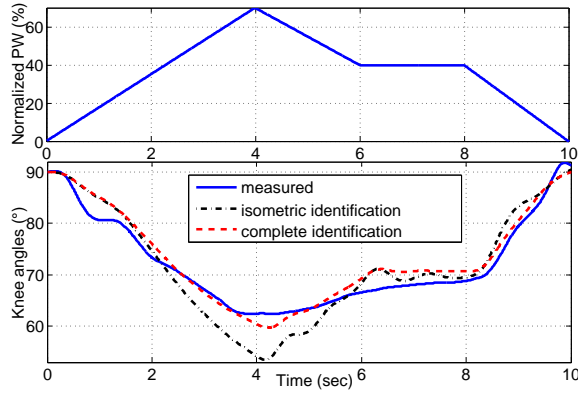
Fig. 4. Pulse Width of stimulation input and the mechanical parameters identification results (The complete model). The isometric model (dashdot line) is the model before the identification of the mechanical parameters of muscle k_s and K_m.
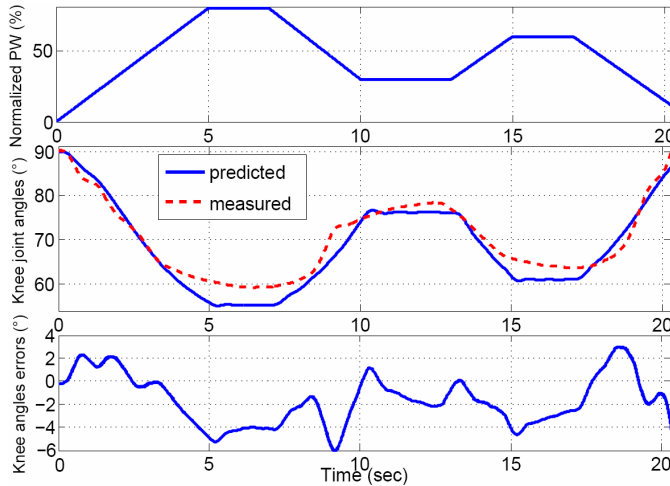

Fig. 5. The cross validation of the complete identified model. (a) Pulse Width (*PW*) of stimulation input. (b) The measured (dashed line) and predicted knee joint angles (solid line). (c) The knee angle errors.

improves the prediction as shown in Fig.4 (dashed line). The cross validation was performed using a set of data that has not been used for the identification. Its results are presented in Fig.5 and highlight a good prediction of the leg motion (see NRMSE of Table II). However, some errors still remain because of the time-varying responses of muscle due to the fatigue and the use of the surface electrodes.

The intersubject variability of joint dynamics, force-length and k_s are less than the intersubject variability of maximal force F_m, maximal stiffness K_m and the slope of recruitment function c_2. Then, the variability of some parameters are clearly related to the variability of the subjects characteristics (Table I). K is related to the body weight and J is related to the body height. These variabilities give an idea about which parameters are more subject-specific.

The aim of this study is to establish a subject-specific model for a feedforward open-loop strategies. A critical aspect of this control strategy is its inability to compensate for any unknown internal or external disturbances. Thus, a closed-loop strategy is required for FES control. However, The approach only with closed-loop increases significantly the time lag of trajectory tracking. It is known that the time lag can be reduced by the combination of feedforward and feedback control [15]. Thus, it is significant to realize the identification of the subject-specific model to make an optimized feedforward.

VI. CONCLUSIONS AND PERSPECTIVES

In this work, the quadriceps-shanks parameters under FES were identified for 3 paraplegics subjects and the cross validation was performed successfully with the identified model. The measurements were conducted in isometric and nonisometric conditions. The time-varying responses under the same stimulation raised a problem for some cases due to the fatigue and the surface myostimulation.

The on-line identification and closed-loop control would be required as future work in order to compensate these time-varying responses and unknown internal and external disturbances.

VII. ACKNOWLEDGMENTS

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