Modelling Neuromusculoskeletal Response to Functional Electrical Stimulation

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***Abstract*—A model for functional electrical stimulation with hysteretic muscle recruitment is used to reproduce experimental tibialis anterior stimulation to control ankle dorsiflexion. The subject-specific parameters of the muscle recruitment model where identified from experimental data by solving a nonlinear least-squares problem.**

I. Introduction

Functional electrical stimulation (FES) is a technique to generate controlled functional joint movement by inducing muscle contraction through electrical assistance [1].

Movement control through FES application can be challenging because subjects react differently to electrical stimuli. Thus, accurate computational predictions of FES-assisted movement require subject specific models. Here, we propose a model of FES with hysteretic muscle recruitment for neuromusculoskeletal model simulation, where subject-specific model parameters were identified using experimental data.

II. Methods

Electric current in FES is commonly delivered by transcutaneous electrodes that stimulate muscle nerves. The current can be delivered as pulse waves, which are characterized by the pulse amplitude u, width w, and frequency f. However, muscle response to electrical stimulation is nonlinear, time-dependent due to muscle fatigue, and exhibits hysteresis [2].

Muscle recruitment represents the level of neural excitation e for a given electrical stimulation, which can be expressed as $e = s_u s_f$, where s_u and s_f are functions of the pulse amplitude u and frequency f, respectively [3]. Here, we represent s_u as a piece-wise linear function, which is 0 below current threshold u_{thr} and 1 above the saturation current u_{sat}. In addition, a hysteresis current u_{hys} was added to account for the difference in muscle recruitment when the current increases or decreases.

Ankle joint control was achieved by stimulating the tibialis anterior of the right leg of a healthy male subject The pulse amplitude u was increased by increments of $\Delta u = 2\,\text{mA}$ until the maximum comfortable value ($u_{\text{max}} = 60\,\text{mA}$, in that case), and decreased back to zero. Pulse frequency f and width w were kept constant in our experiments, and the joint angle was measured with an electronic goniometer.

To determine the model parameters from the experimental data, a set of simulations with a neuromusculoskeletal model of the leg were carried out (see Fig. 1, left). The simulations reproduced the experimental setup using different parameter combinations. Then, the parameter values were determined from experimental data by solving a nonlinear least-squares problem with the Gauss–Newton algorithm.

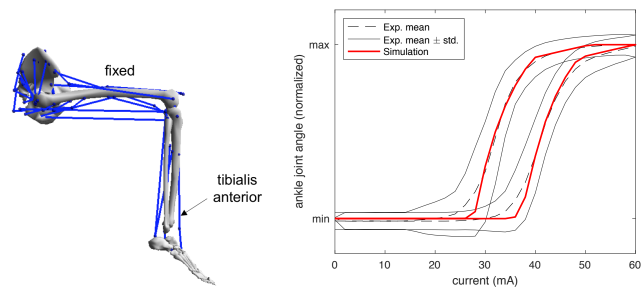

Fig. 1. Neuromusculoskeletal model of the lower limb (left), and ankle joint angle response to functional electrical stimulation (right).

III. Results and Discussion

Simulation results with the identified FES model parameters fits the experimental data and exhibits the characteristic hysteresis of the joint angle (see Fig. 1, right), where the normalized root-mean-square (RMS) error of the angle joint angle is 2.87%. These results show that a piece-wise linear recruitment model with hysteresis is capable of representing the muscle excitation in a subject-specific neuromusculoskeletal model of the lower limb with FES.

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References

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