Computer-aided generation of stimulation data and model identification for functional electrical stimulation (FES) control of lower extremities

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Abstract—Standard stimulation data for unassisted standing up of paraplegic patients was generated by dynamic optimization linked with model simulation, to overcome the difficulties in the present electromyogram (EMG)-based method. The generated stimulation data were roughly in agreement with the normal subjects’ EMG. From these, it is suggested that the ‘model-based’ method is useful as an alternative of the ‘EMG-based method’. The same technique can be applied to generation of patient-specific stimulation data once the musculoskeletal system of a patient is properly identified. The musculoskeletal system must be identified from data taken from simple and non-invasive experiments for the identification method to be practically acceptable. We developed a musculoskeletal model and systematic identification protocols for this purpose. They were validated for the vastus lateralis muscle at the knee joint. The identification was successful and the predicted joint angle trajectories closely matched the experimental data. This implies that the model-based generation of patient-specific stimulation data is possible.

Key words: FES; stimulation data; dynamic optimization; model identification; lumped model; identification protocols.

1. INTRODUCTION

Functional electrical stimulation (FES) is an effective method for restoring motor functions to limbs paralyzed by spinal cord injury or cerebral apoplexy. Desired motion could be restored by applying proper artificial electrical pulse trains to

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the muscles or nerves instead of the neural control signal from the brain. It has been demonstrated that FES can induce essential functions of the hand and arm in tetraplegics [1], and rudimentary standing and walking in paraplegics [2]. However, despite more than three decades of research, many problems still remain to be solved for FES to come into wide use. Among these is the problem of generating proper stimulation data, which is defined, in this paper, as the predetermined data for stimulation (typically, envelopes of stimulation intensity) to restore the desired motion. Its importance is highlighted in that all clinically oriented FES systems have employed open-loop control schemes. Closed-loop control has not been used in clinic because it has problems including the lack of proper sensors for automatic feedback control [3], rapidly induced muscle fatigues [4], spinal reflexes and spasticity [5], time varying and unstable characteristics of the muscle [6], and difficulty in identifying the musculoskeletal system [7, 8].

Concerning the generation of stimulation data, Sendai FES Research Project has used the ‘electromyogram (EMG)-based method’ where the standard stimulation data is generated based on the EMG of normal subjects [9]. The generated standard stimulation data set was adjusted to each patient in a trial-and-error manner. The EMG-based method proved to be useful because it can generate multi-channel stimulation data reflecting the coordination of multiple muscles at once. However, it imposes burdens on normal subjects when measuring EMG with intramuscular electrodes, on those who analyze EMG data, and also on patients and medical staff when modifying the standard stimulation data for each patient [10]. Therefore, as the final goal, this study aims at the automatic generation of patient-specific stimulation data with a practical musculoskeletal model which is easily applied in clinical sites. Automatic generation of ‘standard stimulation data’ was selected as a first step to the final goal, because it will still resolve a lot of problems related to EMG measurement and analysis in the EMG-based method, and application to other movements will be possible. In this context, in Section 2, we show that the stimulation data generation by the dynamic optimization method linked to the simplified model is useful as an alternative to the EMG-based method for generation of standard stimulation data. We set the standing-up motion of a paraplegic patient unassisted by the upper extremities as the first example problem, because it is thought to be the starting point of motor function restoration of paraplegics. In Section 3, we suggest the same technique of stimulation data generation can be applied to the generation of patient-specific stimulation data when the musculoskeletal system of a patient is properly identified. As an example problem of identification, the vastus lateralis muscle and the knee joint are identified and evaluated.

2. GENERATION OF STANDARD STIMULATION DATA

A model simulation system and the automatic iterative modification routine are required for the generation of stimulation data. Details of the developed model