Performance improvement of walker-assisted FES-supported paraplegic walking

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Abstract

In this paper we present a method to generate optimal stimulation pattern for walker-assisted paraplegic walking using FES systems. To determine the stimulation patterns, a musculoskeletal model of walker-assisted FES-supported paraplegic walking is introduced. The optimal stimulation patterns are determined through minimizing the trajectory tracking error of the lower body and mechanical energy of the upper body with penalty functions on the activation of the muscles and handle reaction force. Experimental results on two thoracic-level complete spinal cord injury subjects show that the walking performance is improved compared to the conventional FES walking in terms of the handle reaction force and walking speed.

***Keywords**: Functional electrical stimulation, paraplegia, walking, biomechanical model.*

Introduction

For over three decades, many researchers have demonstrated that limited crutch- or walker-assisted walking can be restored in paraplegic subjects by functional electrical stimulation (FES) systems [1]. However, two fundamental limitations are associated with the development of the current walking motor neuro-prostheses. The first is the high metabolic rate and the high upper body effort [2], which limits the achievable duration of FES-assisted walker-supported walking. The more fundamental second limitation directly related to the determining the stimulation pattern. A conventional method for determining the walking stimulation patterns is a time-consuming process through trial and error. To overcome this problem, Popović et al. [3] used a musculoskeletal model of *human normal walking* and solved an optimal problem to generate the stimulation patterns. A cost function was selected as the sum of the squares of the tracking errors from the desired trajectories, and the weighted sum of the squares of agonist and antagonist activations of the muscle groups acting around the hip and knee joints. However, the proposed model does not consist of walker and it can not explain the whole dynamic of walker-assisted walking.

A major problem related to walker-assisted standing and walking is the high upper body effort [2]. This motivates us to develop a model to characterize the contribution of each muscle to the handle reaction forces (HRF) during walker-assisted walking using FES. In this paper, we introduce a musculoskeletal model of *walker-assisted* FES-supported walking to find the optimal stimulation patterns.

Methods

The Musculoskeletal Model

The skeletal system with two crutches is modelled as a 13-segment, 11 DOF rigid linkage in sagittal plane. The model consists of feet, shanks, thighs, trunk, arms, forearms and two crutches. Each joint is modelled as a hinge joint. The head and trunk are lumped into a single rigid body. Interactions of the feet with the ground were modelled using ten viscoelastic elements distributed under the sole of each foot. Each unit applies forces in the vertical direction. The ground reaction force (GRF) acting on the feet and the HRF acting on the wrist are outputs of the model.

For each lower body joint, a pair of equivalent flexor and extensor muscles is considered. The net torque acting at each joint comprises active torques generated by the equivalent muscles and resistive torque resulting from elastic tissues crossing the joint. Flexor and extensor muscles of the upper body are not considered in the model.

Optimal Control

Two concurrent controllers are acting in parallel, the central nervous system (CNS) which controls the upper body, and the artificial support system which controls the paralyzed lower extremities via FES. Artificial CNS generates joint torques of the upper body by minimizing the mechanical energy of the upper body with the penalty function on the HRF. Stimulation patterns of the lower body muscles are produced by solving a dynamic optimization problem that minimized the sum of the squares of tracking errors from desired trajectories with the penalty function on the sum of the muscle stimulations squared and the HRF per distance travelled.

Outputs of the CNS are torques acting on the trunk, arms, forearms, and wrists while outputs of the artificial support system are activation patterns of the six equivalent muscles acting at the hip, knee, and ankle joints for every leg to track the recorded trajectories of the healthy subject during walker-assisted walking.

A modified particle swarm optimization (PSO) method [4] is used to solve the optimal problems for both optimal controllers. The algorithms are implemented in Matlab Simulink (The Mathworks, R2007b).

Experimental Procedure

A front-wheeled walker was used to allow the walker to be moved without lifting. The subject was asked to force the walker light and not forceful as much as possible especially in the vertical direction. The joint angles were measured by motion tracker system MTx (Xsens Technologies, Netherlands). The HRF was measured by a 3-component piezoelectric force sensor (9602, Kistler, Switzerland) mounted underneath the walker handle. The GRF were measured by the pedar-x system (Novel, Germany). The data were recorded at 100 Hz.

The experiments of FES-supported walking (Fig. 1) were conducted on two thoracic-level complete spinal cord injury subjects with injury at T7 (RR, 39 years old, H = 165 and M = 75 kg) and T12 (MS, 27 years old, H = 183 and M = 70 kg).

Fig. 1: A paraplegic subject with injury at T12 level using ParaWalk for walking.

The paraplegic subjects are active participants in a rehabilitation research program involving daily electrically stimulated exercise of their lower limbs using ParaWalk neuroprosthesis [5]. Pulsewidth modulation (from 0 to 700 μsec) with balanced bipolar stimulation pulses, at a constant frequency (25 Hz) and constant amplitude was used to stimulate the muscles. The experiment sessions of subjects were managed once a week and each session consisted of six trials with inter-trial resting interval at least 5 min.

The walking performance was assessed by the maximum of walking speed, maximum and average of the vertical HRF, and a questionnaire. Table 1 summarizes the results of walking performance by using conventional stimulation sequences [2] and simulation pattern generated by the model.

Results

The results of simulation studies (i.e., simulation-generated joint angles and muscle stimulation pattern, HRF, and GRF) for paraplegic subject MS are shown in Fig. 2. The reference trajectories (i.e., the hip, knee, and ankle joint angles) were recorded from an able-body human walker-assisted waking (27 years old; H = 176 cm; M = 65 kg). The generated stimulation patterns were programmed into a portable programmable electrical stimulator (i.e., Parawalk) for FES-supported paraplegic walking.

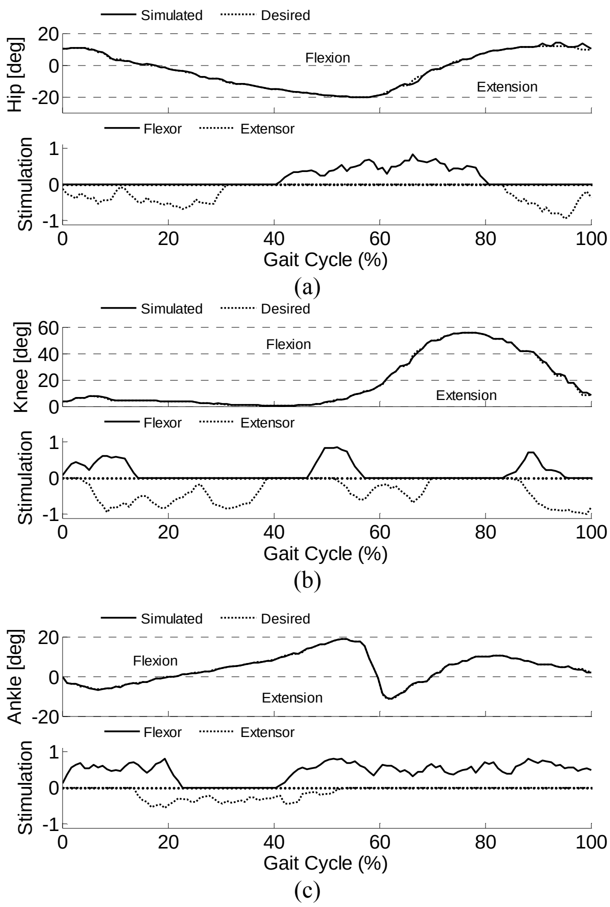

Fig. 2: Simulation-generated joint angles and muscle stimulation patterns for paraplegic T12. (a) Hip joint. (b) Knee joint. (c) Hip joint.

Table 1. Average of the HRF (% of body weight) during walker-assisted FES supported walking for two paraplegics using model-based generated stimulation sequences (M) and stimulation sequences used by the 6-channel Parastep-I (C).

Days / Subject		1st		2nd		3rd		4th		Average	
		HRF	Speed	HRF	Speed	HRF	Speed	HRF	Speed	HRF	Speed
MS	C	24±12	0.23±0.03	25±11	0.25±0.02	25±12	0.24±0.02	25±12	0.23±0.03	25±12	0.24±0.02
	M	18±10	0.51±0.02	17±11	0.53±0.02	16±10	0.53±0.03	16±10	0.51±0.02	17±10	0.52±0.02
RR	C	21±9	0.21±0.02	22±10	0.22±0.03	23±9	0.20±0.04	22±9	0.19±0.04	22±9	0.20±0.03
	M	14±11	0.47±0.03	14±10	0.48±0.03	13±10	0.49±0.02	15±9	0.49±0.02	14±10	0.48±0.02

Typical results of paraplegic walking by using the stimulation sequences generated by the model for subject MS are shown in Fig 3. It observed that a good agreement between the measured joint angle trajectories and the desired trajectories was achieved. However, it is observed that during pre swing, the ankle did not extend and remained to extend. The reason is that we used peroneal nerve stimulation to flex the knee and hip during initial swing. Stimulation of peroneal nerve cases withdrawal reflex which induces simultaneous activation of hip and knee flexors, and ankle dorsiflexors.

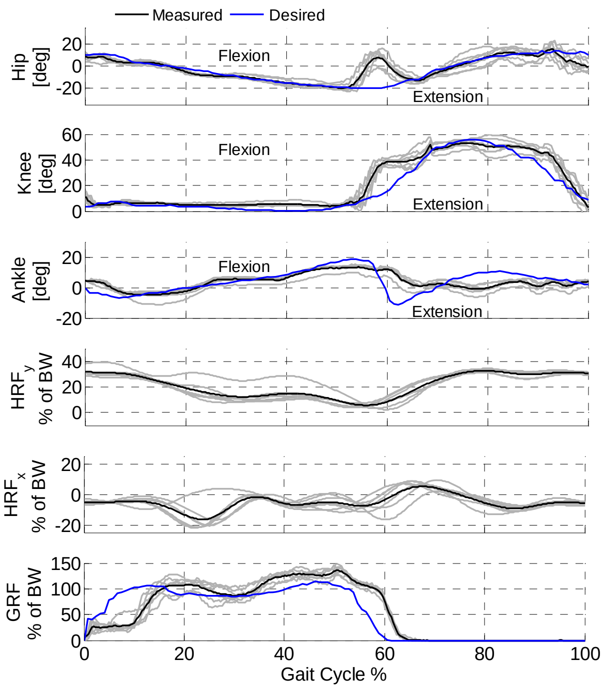

Fig. 3: Typical results of paraplegic walking by using the stimulation sequences generated by the model for subject MS.

Table 1 summarizes the results of walking performance using model-based generated stimulation sequences. The results indicate that the average values of maximum walking speed are 0.52±0.02 m/s and 0.48±0.02 m/s for subjects MS and RR, respectively. The average values of HRF are 17±10 % of BW and 14±10 % of BW for subjects MS and RR, respectively.

The results of walker-assisted FES-supported walking using stimulation sequences used by the 6-channel Parastep-I [2] are also summarized in Table 1 for the same two subjects. Comparing the results obtained by using two different stimulation sequences, it is observed that, on average, the walking speed was increased by 128% and HRF was decreased by 34% when the model-based generated stimulation sequences was used.

Conclusions and Discussion

In this paper, a musculoskeletal model was presented for paraplegic walker-assisted FES-supported walking to find the optimal stimulation patterns. The simulation of walking was generated by solving a dynamic optimization problem. The optimization criterion was to minimize the sum of the squares of tracking errors from desired trajectories with the penalty functions on the total muscle efforts and the HRF acting on the hand. The results of experiments of two paraplegic subjects show the proposed method leads to faster walking and causes to reduce HRF during walker-assisted walking. The questionnaire shows that subjects preferred the new FES-walking.

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