Optimal walking trajectories estimation using wavelet neural network for FES-assisted arm-supported paraplegic walking

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Abstract

One major limitation of arm-supported walking using functional electrical stimulation in paraplegic subjects is the high energy expenditure and the high upper body effort. One major factor that affects the energy expenditure and the high upper body effort during arm-supported FES-assisted walking is the gait pattern. To obtain a gait pattern that lead to minimum handle reaction force (HRF), a method is proposed to find the optimal gait patterns that lead to minimum HRF. For this purpose, a neural network model of the human walking is presented to relate the joint angles to the HRF. Using the neural model, an optimal walking trajectory is determined to minimize the HRF. The experiments were conducted on two paraplegic subjects. The results show that the HRF obtained for optimal gait pattern is less than the measured HRF.

***Keywords**: Wavelet neural network, gait, paraplegic, functional electrical stimulation.*

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]-[2]. Major problem that limits the success of the current motor neuro-prostheses for standing and walking is the high metabolic rate and the high upper body effort observed in paraplegic subjects during the task [3]-[5].

Low-strength of electrically-stimulated muscle and difficulty of controlling multi-link multi-actuator neuromusculoskeletal can be considered as the major factors for high upper body activities and high energy consumption during FES-assisted arm-supported walking.

One major factor that can affect the energy expenditure and the upper body effort is the reference trajectory of walking. In this paper, we present a method to find an optimal trajectory for FES-assisted paraplegic walking and demonstrate that handle reaction force (HRF) can be reduced by defining a suitable walking trajectory.

To find an optimal reference trajectory, a neural model is proposed to relate the joint angles (i.e., ankle, knee, and hip joint angles) with hand reaction forces. The model is identified using a local linear wavelet neural network (LLWNN) [6]. Based on the identified model, an optimal walking trajectory is estimated to obtain the minimum hand reaction force.

Methods

The LLWNN

Local linear wavelet neural network (Fig. 1) is a feed-forward network which is used for approximation, classification, and prediction [6]. The output of a LLWNN is given by

$$y = \sum_{j=1}^{n} v_j Z_j(x) \tag{1}$$

$$v_j = w_{j1}x_1 + w_{j2}x_2 + \ldots + w_{jn}x_n \tag{2}$$

where $x = [x_1, x_2, ..., x_n]$ is the input vector, w_{ji} is *i*th weight of the *j*th node and

$$Z_j(x) = a_j^{-1/2}\Psi\left(\frac{x-b_j}{a_j}\right) \tag{3}$$

that $\Psi(x)$ is a mother wavelet which is localized in both the time space and the frequency space and $a_i = [a_{i1}, a_{i2}, ..., a_{in}]$ and $b_i = [b_{i1}, b_{i2}, ..., b_{in}]$ are the scale and transition parameters, respectively.

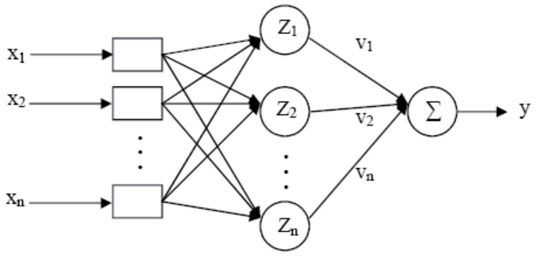


Fig. 1: Schematic of the LLWNN.

Neural Modelling of the Skeletal System

To model the relation between the joint angles of the lower extremities and the HRF, a LLWNN with 6 inputs, 1 output and 12 hidden nodes is used. The input vector is defined as

$$x(t) = [\theta_a(t-1), \theta_a(t), \theta_k(t-1), \theta_k(t), \theta_h(t-1), \theta_h(t)]$$

where θ_a, θ_a and θ_a are the joint angles of the right ankle, right knee and right hip, respectively. The output is the HRF of the right hand at time *t*. The particle swarm optimization (PSO) algorithm [7] is employed to train LLWNN by using the data measured during arm-supported FES-assisted walking of two paraplegic subjects using neuroprosthesis ParaWalk [8].

Optimal Trajectory of Walking

Optimal trajectory of the paraplegic walking $\boldsymbol{\theta}^*(t) = \left[\theta_a^*(t),\ \theta_k^*(t), \theta_h^*(t)\right]^T$ is determined as:

$$\boldsymbol{\theta}^*(t) = \arg\min_{\theta_a,\ \theta_k,\theta_h}\left[\int_{t=0}^{T} f\big(\theta_a(t), \theta_k(t), \theta_h(t)\big)\right] \tag{5}$$

where $f\big(\theta_a(t),\ \theta_k(t), \theta_h(t)\big)$ is a nonlinear function relating the HRF and joint angles (i.e., the ankle, knee and hip joint angles). The HRF-joint angles relationship f is unknown but can be approximated by using LLWNN. To determine the optimal trajectory $\boldsymbol{\theta}^*$ with minimum hand reaction force, the function f should be minimized (5). In this work, the PSO algorithm is used for optimization process.

Results

Experimental Procedure

The experiments were conducted on two thoracic-level complete spinal cord injury with injury at T7 (Fig. 2) and T11 levels. The paraplegic subjects were active participants in a rehabilitation research program involving daily electrically stimulated exercise of their lower limbs (either seated or during standing and walking) using ParaWalk neuroprosthesis [8]. The hip, knee, and ankle joint angles were measured by using the motion tracker system MTx (Xsens Technologies, B.V.) which is a small and accurate 3-DOF Orientation Tracker. The hand reaction force was measured by a 3-component piezoelectric force sensor (9602, Kistler, Switzerland) mounted underneath the walker handle. Two pairs of electrodes (1 left, 1 right) over the quadriceps muscle, two pairs over the common personal nerve, and two pairs over the gluteus maximus/minimus muscle. Pulsewidth modulation (from 0 to 700 μsec) with balanced bipolar stimulation pulses, at a constant frequency (25 Hz) and constant amplitude is used to stimulate the muscles.

Fig. 2: A paraplegic subject with injury at T7 level uses ParaWalk to stand and walk.

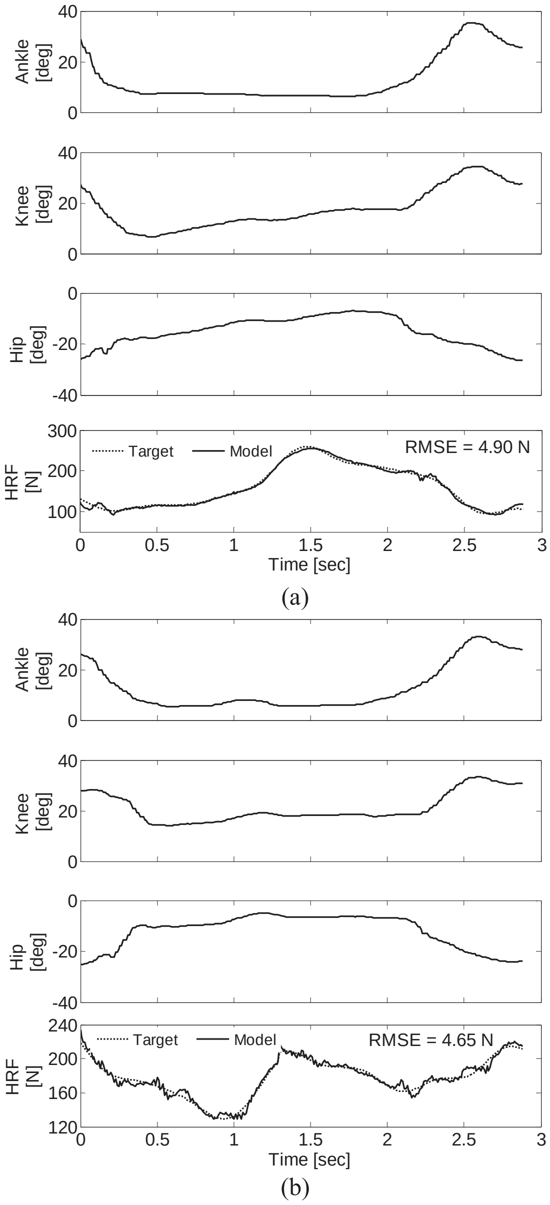


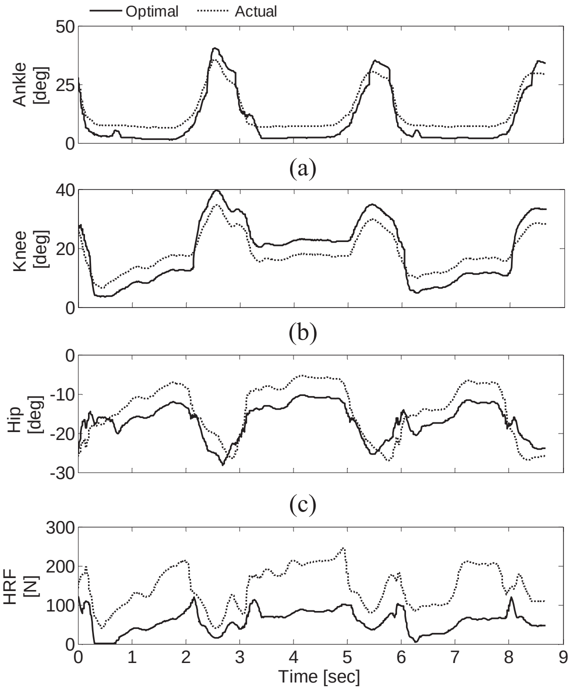
Fig. 3: The joint angles, measured and predicted HRF using the LLWNN for two paraplegic subjects RR (a) and MS (b).

Neural Network Model of Skeletal System

The neural network is trained using the data obtained from one strike of FES-assisted arm-supported walking during the first day of experiment. Then the trained network is used to predict the hand reaction force during subsequent sessions of experiment. Fig. 3 shows the results of the HRF prediction using the LLWNN for both subjects. The root-mean-square (RMS) prediction error for a typical strike are 4.90 N (2.99%) and 4.65 N (4.43%) for subjects RR and MS, respectively.

Optimal Walking Trajectory

The trained LLWNN was used to determine the optimal walking trajectory using the PSO algorithm. Fig. 4 shows the obtained optimal walking trajectory for the subject RR. It can be clearly seen that the HRF for optimal trajectory is less than the measured HRF. The same results was obtained for the subject MS. The average of the optimal HRF is 57.76 N (36.8 N) while the average of the measured HRF is 145.12 N (113.0 N) for the subject RR (MS). The peak of the optimal and measured HRF are 140.48 N (206.0 N) and 244.88 N (285.0 N) respectively, in subject RR (MS).



(a)

(b)

(c)

(d)

Fig. 4: Result of the walking trajectory optimization for subject RR, (a) ankle joint, (b) knee joint, (c) hip joint, (d) the HRF.

Conclusions and Discussion

In this work, a model was presented for relating the lower extremities joint angles to the hand reaction force using neural network during FES-assisted arm-supported walking in paraplegic subjects. Neural network is a black box model identification technique without requiring information about the physical parameters of the system.

The most important result obtained is that the proposed model is bale to estimate accurately the HRF using only joint angles. The developed model was used to determine the optimal walking trajectory. It was observed that the HRF for optimal trajectory is less than the measured HRF. The results indicate that the HRF was reduced 60.9% and 67.4%, in subjects RR and MS, respectively, during walking with optimal trajectory.

The closed-loop control of walking using the estimated optimal trajectories constitutes the key issue of our current research.

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