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Sliding-Mode Control of Walking Using Functional Electrical Stimulation: A Simulation Study

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1. Introduction

The lower extremities of human walking are a highly nonlinear, highly time-varying, multi-actuator, multi-segment with highly inter-segment coupling, and inherently unstable system. Moreover, there always exits uncertainties in system model. A useful and powerful control scheme to deal with the uncertainties, nonlinearities, and bounded external disturbances is the sliding mode control (SMC) [1]. In this paper we use a sliding-mode control for control of walking in paraplegic subjects.

2. Aims

The aim of this paper is to present a robust control system for online controlling of paraplegic walking.

3. Methods

A planar model of bipedal locomotion [2] is considered here as a virtual patient. The equation motion of the musculoskeletal system can be described as:

$$\ddot{\mathbf{x}} = \mathbf{F}(\mathbf{x}) + \mathbf{G}(\mathbf{x}) \cdot \mathbf{u} \tag{1}$$

where

$$\mathbf{u} = \hat{\mathbf{G}}^T(\mathbf{x},\boldsymbol{\theta}_g)[\varepsilon_0 \mathbf{I}_m + \hat{\mathbf{G}}(\mathbf{x},\boldsymbol{\theta}_g)\hat{\mathbf{G}}^T(\mathbf{x},\boldsymbol{\theta}_g)]^{-1} \left(-\hat{\mathbf{F}}(\mathbf{x},\boldsymbol{\theta}_f) + \mathbf{v} + \mathbf{K}_1 \operatorname{sgn}(\mathbf{s})\right) \tag{2}$$

$\hat{\mathbf{F}}(\mathbf{x},\boldsymbol{\theta}_f)$ and $\hat{\mathbf{G}}(\mathbf{x},\boldsymbol{\theta}_f)$ are estimates of $\mathbf{F}(\mathbf{x})$ and $\mathbf{G}(\mathbf{x})$ functions, respectively. $\mathbf{s}$ is a vector of sliding surface for every state space. ε_0 is a small positive constant and $\mathbf{I}_m$ is $m \times m$ identity matrix. $\mathbf{K}_1 = diag(k_{11},\ldots,k_{1m}) > 0$. In this work, we use fuzzy systems to estimate the nonlinear functions $\mathbf{F}(\mathbf{x})$ and $\mathbf{G}(\mathbf{x})$. The identified system is used to design the sliding control law.

4. Results

The results indicate that the sliding mode control strategy provides accurate tracking control with fast convergence during different conditions of operation, and could generate control signals to compensate the effects of muscle fatigue and external disturbances. Interesting observation is that the controller generates muscle activations and net joint moments that accurately mimic those observed during normal walking. Figure 1 shows the results of the fuzzy-based sliding mode control of walking in the virtual subject. It is observed that a good tracking performance can be achieved by using proposed control strategy. Interesting observation is the fast convergence of the proposed control strategy.

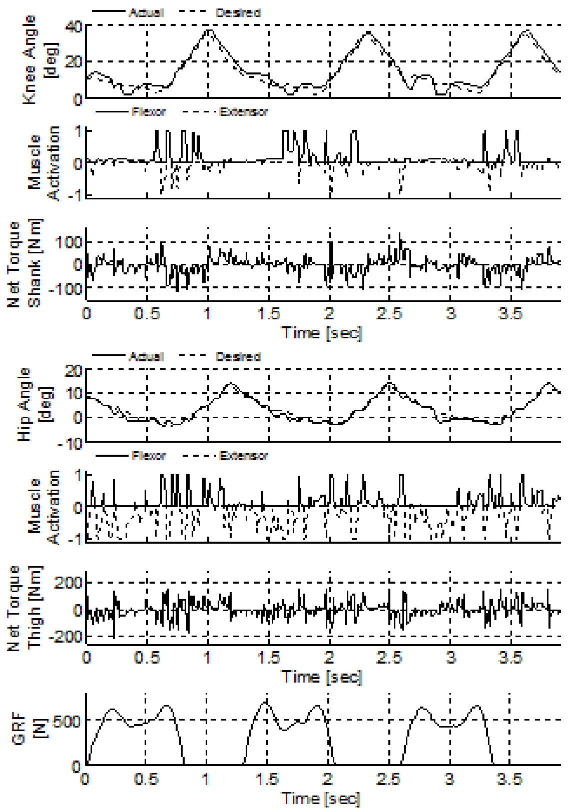

Figure 1: Walking control results over three gait cycles: Measured (desired) and actual joint angle of knee and hip, activation of flexor and extensor muscle groups, active torque acting at the joint, the net torque acting at the shank and thigh, and ground reaction force.

5. Discussion and Conclusions

The results of this work indicate that SMC is a promising approach to online control of walking.

References

1. Slotine JE et al. *Applied Nonlinear Control*. Prentice Hall, 1991.
2. Popović DB et al., *Optimal control of walking with functional electrical stimulation: A computer simulation study.* IEEE Trans Rehab Eng. 1999. 7: 69-79.