Reduced order analysis of human gait kinematics based on spatiotemporal mode decomposition

Xin Wang[1], Yunzhe Zhang[2], Xi Zhang[2], Boyang Zhang[2], Jianqiao Guo[1],
[1]MOE Key Laboratory of Dynamics and Control of Flight Vehicle, School of Aerospace Engineering, Beijing Institute of Technology, Beijing, 100081, China
[2] National Engineering Research Center of Neuromodulation, School of Aerospace Engineering, Tsinghua University, Beijing,100084, China

Email: guojianqiao@bit.edu.cn

Summary

Complex human motion can be regarded as a combination of simple motion patterns. This study establishes a reduced-order analysis framework to obtain nonlinear motion patterns in the spatiotemporal domain. The principal synergy modes for the lower limb joints are extracted by principal component analysis (PCA). In temporal domains, the main intrinsic mode functions (IMFs) are determined by the Hilbert-Huang transform (HHT). Results show a more sophisticated pattern for paraplegic patients with functional electrical stimulation than that in healthy subjects, indicating that the patients need more training for motion coordination.

Introduction

Time-frequency analysis of the human gait kinematics is necessary to understand its motion complexities. HHT [1] decomposes motion primitives to extract characteristics in the instantaneous frequency domain, but it overlooks synergy patterns of the lower limb. The motion coordination patterns can be extracted by PCA [2]. This study aims to combine PCA and HHT to understand the complexities of the gait patterns of paraplegic patients.

Methods

A healthy subject and two paraplegic patients are recruited. The three-dimensional kinematics of lower limbs $\boldsymbol{K}(t)$ is measured by seven inertial measurement units (IMUs). Each subject performs three repetitive trials with self-selected gait velocity, and ten cycles are selected for further investigations. Principal components, chosen using cumulative contribution rate exceeding 85%, are determined by eigenvalues and eigenvectors $\boldsymbol{\Phi}_i$ of covariance matrix. PCA extracts motion coordination patterns $\boldsymbol{\Phi}(t)$ to achieve spatial dimensionality reduction.

$$\boldsymbol{K}(t) \approx \boldsymbol{\Phi}(t) = \sum_{i=1}^{n} w_i \boldsymbol{\Phi}_i$$

The recruitment coefficient of synergy w_i is a nonlinear and non-stationary signal. The time-dependent frequency component of w_i can be extracted by HHT. Its main idea is to decompose the original signal into IMFs using empirical mode decomposition (EMD). By this means, w_i can be expressed by the set of IMFs $w_{i,j}(t)$, and a residual $r_i(t)$.

$$w_i = \sum_{j=1}^{m} w_{i,j}(t) + r_i(t)$$

The instantaneous amplitude and frequency of the IMFs are obtained by the Hilbert transform (HT), i.e.:

$$w_{i,j}(t) = A_{i,j}(t)\cos\left[\omega_{i,j}(t)\cdot t\right]$$

In consequence, the measured joint angles can be decomposed by a combination of PCA and HHT.

$$\boldsymbol{K}(t) \approx \boldsymbol{\Phi}(t) = \sum_{i=1}^{n}\left[\sum_{j=1}^{p<m} A_{i,j}(t)\cos\left[\omega_{i,j}(t)\cdot t\right]\right]\boldsymbol{\Phi}_i$$

Results and Discussion

The number of decomposed PCA and IMF modes in patients is higher than that in healthy subjects, indicating the complexity of patients' motion. The kinematic data and the extracted movement patterns by PCA are used as separate inputs to calculate the joint moments, and their correlation is reflected by correlation coefficient R^2. As shown in Fig. 1, the obtained movement patterns are sufficient to reflect the kinetic characteristics of the patient's gait.

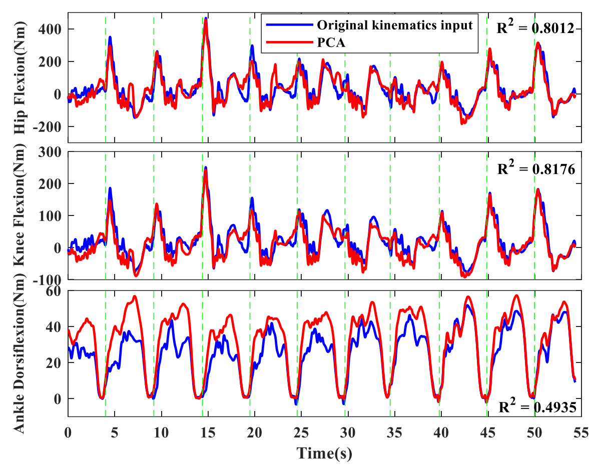

Figure 1: Joint moment of paraplegic patient.

Conclusions

A reduced-order analysis using PCA and HHT successfully captures the abnormal motion patterns of paraplegic patients in the spatiotemporal domain. Results show patients have more principal components and IMFs than healthy subjects. Few correlative motion patterns extracted by PCA are sufficient to reflect patients' gait characteristics.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (12472037).

References

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