Mode Analyses on the Kinematical Structure of Basic Movements and Residual Patterns in Human Locomotion using Motion Capture Data

Nanase Takata, Sadahiro Senda, Kazutaka Nakai and Katsuyoshi Tsujita
Department of Biomedical Engineering, Osaka Institute of Technology, Osaka, Japan
(Tel : +81-6-6954-4243; E-mail: m1m11h15@st.oit.ac.jp)

Abstract: This article treats mode analysis of kinematic structure of human locomotion. We investigated human locomotion using singular value decomposition. From motion-captured data of human locomotion, we extracted common basic movements and residual modes, and analyzed kinematical structures. The results show that there are basic movements commonly observed for all participants in usual walk. On the other hand, higher modes in knee-constrained walk represent different control strategies depending on the physical property of the legs. These residual modes involve personal peculiarities or symptoms of motor dysfunction in locomotion.

Keywords: Human locomotion, Mode analysis, Motion patterns

1. INTRODUCTION

Human locomotion control is typical of a multi-body system control that may be specific for periodic and stable motion patterns of locomotion[1]-[4]. During rhythmic and steady motion such as straight walking, many joints and muscles are organized into a collective unit that is controlled as though it has fewer degrees of freedom (DOFs), even though it still needs to retain the necessary flexibility for adapting to changes in the environment[5]. In this study, we investigated human locomotion by mode analyses using singular value decomposition[6]-[8]. From motion-captured data of human locomotion, we extracted common basic movements and residual modes, and analyzed kinematical structures. The results show that there are basic movements whose proportion of variance is significant, and those are common to all the test participants. The residual modes involve personal peculiarities or symptoms of motor dysfunction in locomotion. We can note that by utilizing the results, we may expect to identify personal traits and run diagnostic check systems for applications.

2. METHOD

Human locomotion on a treadmill is measured with an optical motion capture system. The motion capture system in this study is composed of six cameras with a frame rate at 100[Hz] and 34 markers attached to the human body. Nine healthy participants (4 men and 5 women, 1.47-1.77 m) volunteered for the experiments. Two types locomotion conditions are given for all participants: One is usual walk; the other is constrained walk that the knee on the left side is physically constrained (Figure 1). Measured data on participants' motions are transformed to joint angle vectors of the 18 DOF skeleton models (Figure 2). The motion pattern matrix consists of the obtained time series of joint angle vectors as follows:

$$A = \begin{bmatrix} \theta_1(t_1) & \theta_2(t_1) & \cdots & \cdots \\ \theta_1(t_2) & \theta_2(t_2) & \cdots & \cdots \\ \vdots & \vdots & \ddots & \\ \vdots & \vdots & & \theta_N(t_M) \end{bmatrix} \quad (1)$$

The motion pattern matrix is decomposed to motion components with the SVD (Singular Value Decomposition) method as follows:

$$A = U \Sigma V^* \quad (2)$$

where Σ consists of singular values. U and V^* are composed of temporal basis vectors relating time-dependent motion patterns and spatial basis vectors relating inter-joint coordination, respectively. We first defined correlation coefficient S in equation (3). We evaluated the correlation between mode basis vectors for all participants, and extracted commonly observed modes between participants. The modes are named common basic modes, in this study.

$$S = \frac{\left|Trace(A_A^T A_B)\right|}{\left|\sqrt{Trace(A_A^T A_A)}\right| \left|\sqrt{Trace(A_B^T A_B)}\right|} \quad \begin{matrix} A_A = u_A \\ A_B = u_B \end{matrix} \ \text{or} \ \begin{matrix} A_A = v_A \\ A_B = v_B \end{matrix} \quad (3)$$

From the decomposed motion components, we investigated the kinematical structure and discrepancy of the basic movements and the residual motion patterns in human locomotion.

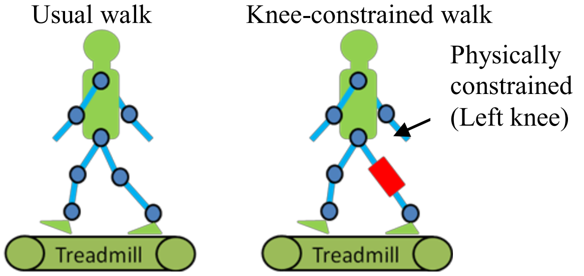


Fig. 1 Experimental conditions

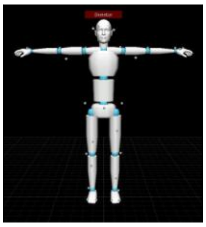
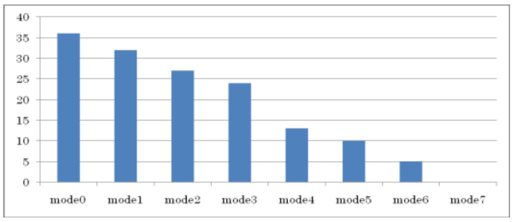


Fig. 2 Human skeleton model with 18 joints and 34 markers

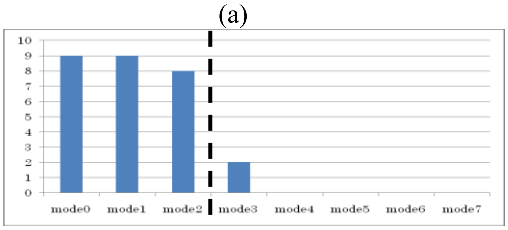
3. RESULTS AND DISCUSSION

The results show that there are three modes whose numbers of high correlation (S>0.75). (Figure 3). These modes are common to all the participants in experiments. On the other hand, we investigated the locomotion of participants whose knees on the left side were physically constrained with knee supporters. In those cases, the two significant higher modes (modes 3 and 4) also observed. Correlation coefficients between the spatial modes for different participants in knee-constrained walk are around 0.79-0.95. In mode 3, knee's motion on the opposite side became larger. The motion pattern is considered as compensation of posture balance due to the left-knee constraints (Figure 4). In mode 4, on the other hand, situations are completely different from mode 3. There are two types of spatial vectors in mode 4 in knee-constrained walk. One is the activation of the opposite side of ankle; this motion pattern is standing on tiptoe. The other is activation of the same side of ankle; this motion pattern is posture swaying. And interestingly, these two types of inter-joint coordination does not depend on gender, age, and so on, but on physical structure of legs, such as X legs, bandy legs, and so on.

We can note that the results show the common basic modes are essential movements in human locomotion. As well, higher-order modes, in this study, modes 3 and 4 whose correlation coefficients are high between the participants in knee-constrained walk are the residual modes that involve personal peculiarities or symptoms of motor dysfunction in locomotion. It is expected that by utilizing the results, we will be able to identify personal traits and run diagnostic check systems for applications.



(a)



(b)

Fig. 3 (a) Histogram of mode numbers with high correlation (>0.75) (a) in usual walk: Primary 4 modes are commonly observed between participants (b) between usual walk and constrained walk: Primary 3 modes are commonly observed. But mode 3 has a difference between usual walk and knee-constrained walk.

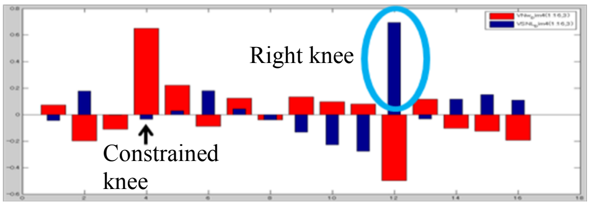
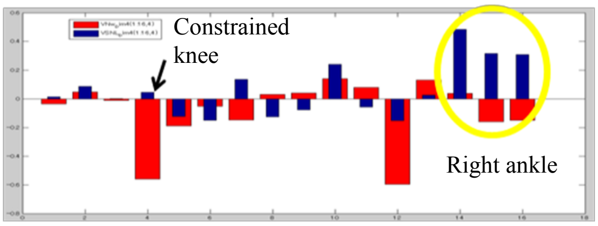
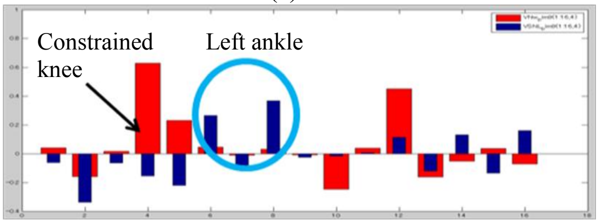


Fig. 4 Spatial basis vector in mode 3
(Red bar: usual walk, Blue bar: knee-constrained walk)



(a)



(b)

Fig. 5 Spatial basis vector in mode 4 in usual walk and in knee-constrained walk (Red bar: usual walk, Blue bar: knee-constrained walk) There are two types of control strategies: (a) Standing on tiptoe (b) Posture swaying

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