SPATIOTEMPORAL DECOMPOSITION OF GAIT DATA TO ESTABLISH THE MAIN GAIT MODES THAT FORM THE FINAL WALKING KINEMATICS

Luciano Santos Constantin Raptopoulos
Mechanical Engineering Program – PEM/COPPE/UFRJ
e-mail: luciano@mecanica.coppe.ufrj.br

Max Suell Dutra
Mechanical Engineering Program – PEM/COPPE/UFRJ
e-mail: max@mecanica.coppe.ufrj.br

Fernando Augusto de Noronha Castro Pinto
Mechanical Engineering Program – PEM/COPPE/UFRJ
e-mail: fcpinto@mecanica.coppe.ufrj.br

Armando Carlos de Pina Filho
Mechanical Engineering Program – PEM/COPPE/UFRJ
e-mail: pina-filho@bol.com.br

Abstract: *The human walking is a very complex and coupled system, where the movement of one joint influences and is influenced by the dynamics of the other joints. In this work a new technique based in the Karhunem-Loève transform (KL) to decompose the kinematics data in modes of walking, or gait modes is presented. The KL is a statistical pattern analysis technique for finding dominant structures in an ensemble of distributed data. This technique can be used to decompose a spatiotemporal signal into time-independent, orthogonal, spatial components and time-dependent amplitudes. The mathematical formulation of KL for the sagittal, frontal and transverse kinematics results is presented. This study was undertaken to demonstrate the existence of common gait modes through the analysis of 33 young, healthy Brazilian female subjects.*

Keywords: *Gait Modes, Gait analysis, Human Locomotion, KL Decomposition.*

1. Introduction

The human locomotion is rhythmic and composed of synchronized motions that involve a very large number of degrees of freedom, an adequate physical structure and a complex controlling system (Pina Filho *et al*., 2005). This pattern of walking can be interpreted as a linear combination of basic or primitive patterns of gait. These patterns are classified in this paper as gait modes and represent the diverse functions that when combined compose the final form of walking.

The Karhunem-Loève transform (KL) has been studied as a potentially efficient means of analyzing spatiotemporal data. This technique is also known as the Proper Orthogonal Decomposition, Method of Empirical Eigenfunctions or Principal Component Analysis. This procedure determines an optimal orthogonal basis that can be used for the representation and investigation of the data.

During the past years, some researchers have been using the KL in the study of spatiotemporal systems. Deluzio *et al*. (1997) analyzed 29 asymptomatic elderly subjects and 13 patients to describe knee joint kinematics and kinetics as measurement by the three principal components (PCs) of the bone-on-bone forces, net reaction moments and relative knee angles. The patients were submitted to pre-operative and one-year post-operative gait analysis, and received unicompartmental arthroplasties. Through these PCs, Deluzio could detect which gait measurements were abnormal as well as the interpretation of the gait cycle responsible for the differences. Shutte *et al.* (2000) applied the KL technique to derive a set of 16 independent parameters from selected kinematics gait data and interpreted the sum of the square of these 16 independent variables as the deviation of subject’s gait from normal. In this study, 24 normal subjects were used to define the normal pattern and 71 patients with a diagnosis of cerebral palsy were analyzed. Sadeghi *et al.* (2000) demonstrated how the KL analysis can be applied to detect the main functional structure of actions taken by hip extensors and flexors of able-bodied subjects, and to determine whether or not symmetrical behavior between right and left hip muscle power activity exists. Sadeghi analyzed 20 young, healthy male subjects and applied the KL as a classification and curve structure detection method to hip sagittal muscle power calculated for the right and left lower limbs. Over 70% of the information was captured by the first four principal components and the existence of functional asymmetry in gait was detected.

The KL transform approach for the approximation of time varying joint angular displacement is presented in this work, as well as the mathematical formulation of KL for the sagittal, frontal and transverse kinematics results.

2. Method

2.1. KL decomposition

The gait data obtained can be represented as a set of time functions of some chosen parameters or coordinates. This can be assembled in a matrix M , with dimension mxn, where the element M_{ij} represents the measured amplitude for the parameter j (one of the joint angles) at the instant i. The KL is able to decompose this spatiotemporal data set into time-independent spatial structures and corresponding time-dependent scalar amplitudes. At the same time this method indicates the relative importance of each spatial structure in retaining the original information contained in the data set. In order to perform the KL, the mean values $\bar{M}_j$ of each of the original data columns corresponding to the mean value of each joint angle must be subtracted from the elements M_{ij}, giving:

$$W_{ij} = M_{ij} - \bar{M}_j \tag{1}$$

The n eigenvectors q_i of the correlation matrix R of ankle, knee and hip kinematics variables, obtained by the standard eigenvalue problem (2)

$$R.q_i = \lambda_i.q_i \tag{2}$$

represent a different way of expressing the spatial relationships among the various joint angles. The original data set can be reconstructed (3) from the eigenvectors q_i using scalar associated time functions a_i obtained by the projection of W_{ij} into the corresponding eigenvector q_i. If the space of eigenvectors is extended to include $q_0 = \bar{M}_j$, and the time function $a_0 = 1$ for every time instant, the original data set M can be obtained as:

$$M = \sum_{i=0}^{n} a_i.q_i \tag{3}$$

It is possible to approximate the original data using fewer eigenvectors than n restricting the summation over i in (3). Assuming that the eigenvalues are ordered from the greatest to the smallest, truncating the series after *l* terms (4), the result is

$$\hat{M} = \sum_{i=0}^{l} a_i.q_i \quad , \qquad l \le n \tag{4}$$

an approximation $\hat{M}$ of the original data M. The eigenvectors of the correlation matrix R define vectors q_i, which represent the extreme values of the variance of the data M. The KL decomposition is an effective technique for reduction of the dimensionality of the data discarding the linear combinations of the joint angles that have small variances. The eigenvectors q_i can be understood as *gait patterns or gait modes* with specific time varying amplitudes. The relative importance of each *gait mode* representing the whole motion is defined by the eigenvalues λ_i.

2.2. Data analysis

The KL analysis as a modal decomposition method was applied to the ankle, knee and hip relative joint angles in the sagittal, frontal and transverse planes of 33 healthy young female subjects. This technique was used to identify the main structure of the data and decompose it in *gait modes*, according to the description of the previous section. The assembly of a data matrix M_v for a specific volunteer v has 101 rows (5), corresponding to the time duration (0-100%) of the gait cycle, and 9 columns that are related to the kinematics variables observed (sagittal, frontal and transverse angles of ankle, knee and hip joints, respectively).

$$M_v = \begin{bmatrix} & | & & | & \\ ankle & | & knee & | & hip \\ (101x3) & | & (101x3) & | & (101x3) \\ & | & & | & \end{bmatrix}_{101x9} \tag{5}$$

According to (2) the eigenvalues λ_{iv}, the eigenvectors q_{iv} and the time functions a_{iv} for each volunteer v are calculated. Finally, the mean eigenvector was obtained from a group of 24 volunteers. The eigenvalues λ_{iv} identify the variance of the kinematics variables $M_v(1..101,i)$ and the eigenvectors q_{iv} identify how the joints angular displacements influence the final walking pattern. So, through these eigenvalues the number of gait modes l $(l < n)$ is determined and the approximate curve obtained (6).

$$\hat{M}_v = \sum_{i=0}^{l} a_{iv}.q_{iv} \quad , \qquad l \leq n \tag{6}$$

It is important to observe that each *gait mode* is a combination of the influences of all joints motion.

2.3. Experimental protocol

The motion analysis by using a computer-aided video motion analysis system with three infrared cameras (VICON 140) synchronized to two Bertec Co. force plates was performed. The signal was filtered by a fourth-order Butterworth low pass filter with video cut-off frequency of 6 Hz and force plate cut-off frequency of 30 Hz. The force plates were used to determine the initial contact and final support instants. The position of the markers was used in the inverse kinematics approach (Raptopoulos, 2003) to calculate the relative angle joint angles in the sagittal, frontal and transverse planes. The hip joint center was estimated through regression equations (Bell *et al*., 1989; Seidel *et al*., 1995; Leardini *et al*., 1999).

Thirty-three female subjects, students at the Federal University of Rio de Janeiro - Brazil, formed the group of volunteers for this research. They had no previous history of surgery or musculoskeletal problems that could affect their walking pattern. They were asked to walk at their normal cadence. The group presented an average and standard deviation age of 21.91 ± 1.51 years and cadence of 104.10 ± 7.25 steps/min, respectively. This cadence agrees with healthy values for the Brazilian population (Raptopoulos, 2003).

3. Results and Discussion

The relative importance of each eigenvalue is presented (Fig.1). The five greatest eigenvalues summed covered 99.6 % of the total variance (information) of the original data. The other four eigenvalues can thus be neglected in order to approximate the measured gait cycles. The five most important eigenvalues are used to choose the eigenvectors for the angular displacement approximation. The angular displacements and spatiotemporal parameters are in agreement with those presented in the literature for young subjects (Winter, 1991; Raptopoulos, 2003).

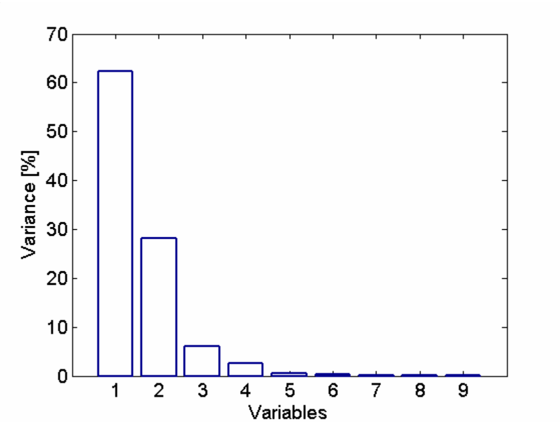

Figure 1. Variances obtained by the kinematics data of the control group.

The set of five eigenvectors are presented in the following graphics (Fig. 2). These eigenvectors show how the combination of the joint angles could build the kinematics pattern of each joint. The corresponding time-dependent amplitudes are also presented in the same figure for each volunteer.

It can be observed that the projection of an individual walking into the gait modes leads to similar time dependent amplitudes (right column of graphics in the Fig. 2), which have the same shape of the dominant variables. The first amplitude function is more influenced by the knee sagittal angle (variable 4), while the second and third amplitude functions were more influenced by the hip (variable 7) and ankle (variable 1) sagittal angles, respectively.

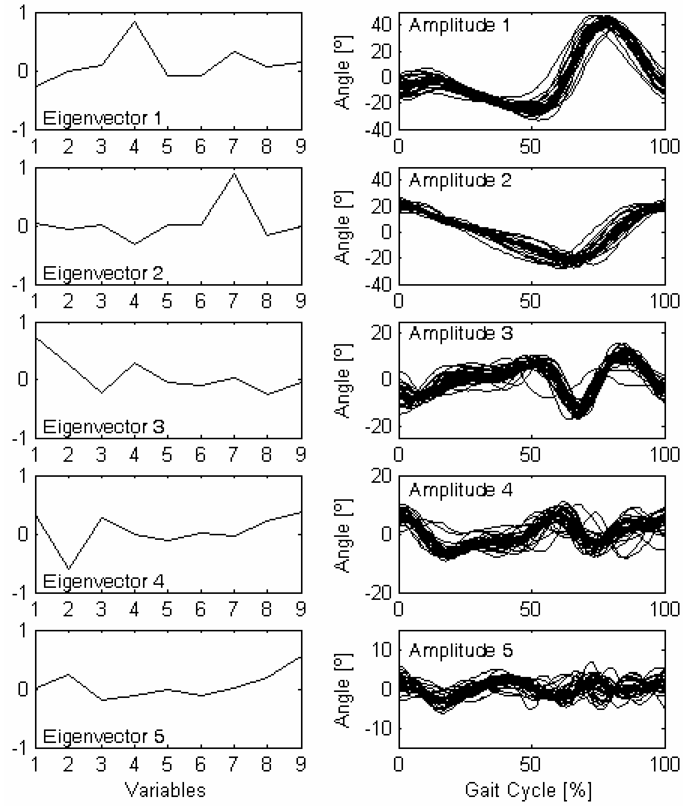

Figure 2. Mean gait modes and individual amplitude functions of a female group of control.

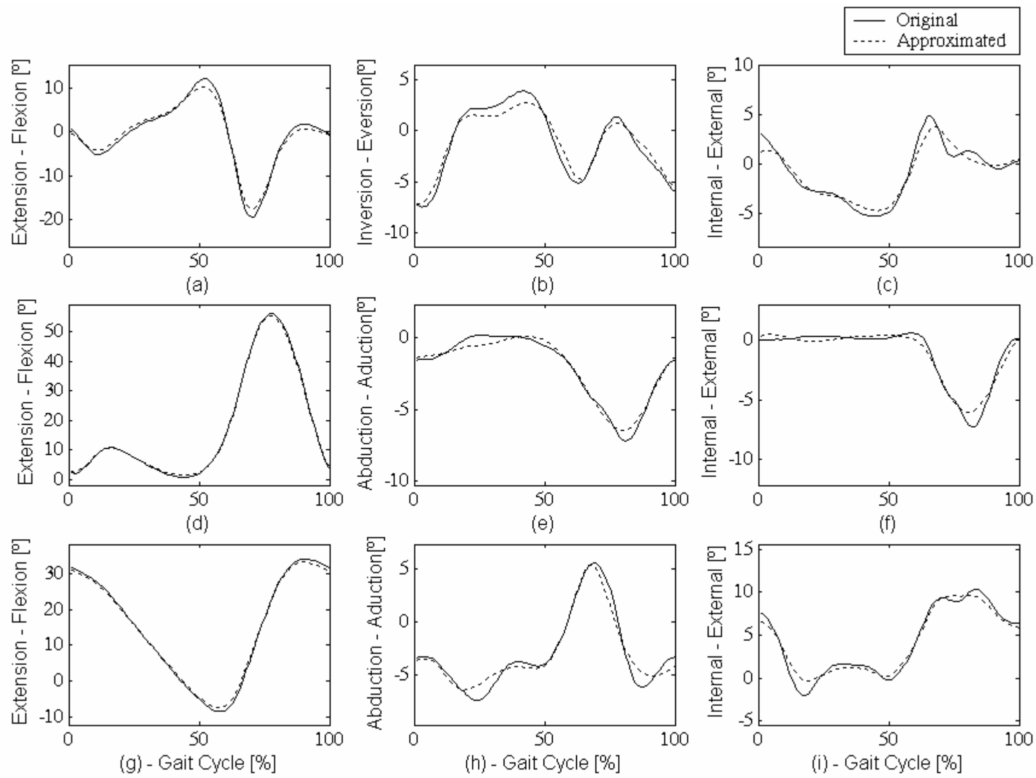

Figure 3. Original and approximated kinematics data of the control group: ankle (a – sagittal, b – frontal, c – transverse), knee (d – sagittal, e –frontal, f – transverse) and hip (g – sagittal, h – frontal, i – transverse) angular displacements.

The first and second modes, being responsible for more than 85% of the motion data that was captured, show less deviation in the time functions. As expected, the analysis of the first gait mode indicates the predominance of the sagittal knee angle, while in the second and third modes the predominance of the sagittal hip and ankle angles can be observed. Finally, the frontal and transverse ankle and hip angles are more influenced by the fourth and fifth gait modes.

The sagittal, frontal and transverse angular displacements and the approximation functions of the ankle, knee and hip joints are shown in the next figure (Fig. 3). These approximations were built through the main five gait modes and compared to the mean of the original data. The similarities between the original and approximated curves confirm the efficiency of the method and the existence of a common way of walking, i.e. dividing the gait cycle in common and particular modes.

4. Conclusion

The aim of this work was to demonstrate the use of KL in the study of the gait cycle. It was possible to use this technique to decompose the locomotion kinematics in gait modes and amplitude functions. For this, a new space of variables composed by the angular displacements of each joint was defined, and a description and implementation of the method to calculate the mean gait modes of 33 volunteers using the KL was presented.

The results obtained for the sagittal, frontal and transverse kinematics of the ankle, knee and hip joints, respectively, confirm the existence of the gait modes proposed in this work. The main gait mode was used with success to approximate the kinematics pattern of joint motion.

Based on the results presented here, further works can investigate how to apply this technique in clinical gait analysis, comparing pathological and normal gait modes; and determining the differences between male and female gait cycles, for example.

5. Acknowledgements

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