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Principal Component Analysis of Vertical Ground Reaction Force: A Powerful Method to Discriminate Normal and Abnormal Gait and Assess Treatment

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Abstract **This study aims at testing the application of principal component analysis (PCA) in the ground reaction force (GRF) in discriminating the gait pattern between normal and abnormal subjects, and assessing the rehabilitation treatment. The sample was composed by 31 subjects, organized into two groups: a control group (CG) of 25 normal and a group (FG) of six patients with lower limb fractures, which was considered before (FGB) and after (FGA) a treadmill physiotherapeutic treatment. The vertical component of GRF data was collected with an instrumentized treadmill. PCA method was applied and the first two coefficients (PCC) were obtained for the three groups. The region of CG values was separated in the PCC plane with the elliptical area of displacement and with a linear threshold between CG and FGB obtained by stepwise logistic regression. Results show that all values of FGA moved towards CG region from the corresponding FGB position, indicating the potential power of PCA in discriminating between normal and abnormal gait and objectively evaluating the effects of rehabilitation treatment.**

Keywords – **Ground Reaction Force, Principal Component Analysis, Rehabilitation, Gait analysis.**

I. Introduction

Gait analysis provides an effective tool for evaluating and quantifying the effects of a given therapy or surgical intervention on patient's gait. It is widely recognized as a central element in the quantitative evaluation of gait and in planning of treatments for subjects with movement disorders [1]. In clinical research and routine gait analysis, ground reaction forces (GRF) are commonly recorded by force platforms and its morphology is used to better understand the mechanisms of pathological gait [2]. According to Giakas and Baltzopoulos [3], the GRF can be applied to discriminate normal and pathological gait, as well as pre- and post-treatment conditions.

Discrete parameters from the GRF have been investigated in numerous studies [4]-[6]. Usually, three heuristic parameters (local peaks and minimum values) are used to compare normal and pathological gait. This approach often provides limited additional insight into gait data beyond that observable from bivariate plots. Thus, there is a lack of effective and robust techniques to reduce gait data and to extract useful information from highly correlated time-dependent gait variables [7]. According to Sadeghi et al. [8], although the description of the gait pattern promotes a characterization of the lower member behavior, the absence of adequate statistical analysis makes the interpretation difficult and confusing.

During the last two decades, the interpretation of gait data was improved by different methods of multivariate analysis, based on variance estimates [8]-[14]. Principal Component Analysis (PCA) is a classical technique employed for reducing the number of variables to a subset of orthonormal factors or principal components, which maximize the representation of variance of the original data [7]-[8],[11]-12]. PCA takes into account the complete gait curve, satisfying the objectives of the gait analysis: detection and interpretation [11].

To accurately evaluate the extent of gait deviations form normal pattern or to assess the changes in a gait resulting from a specific treatment, it is important to consider not only how each feature of the gait pattern has changed but also how the relationship between the feature changed. To evaluate whether a specific gait variable is normal, abnormal, or improved following treatment, the natural correlation that exists between gait variables must be determined. For this reason, multivariate statistical techniques are used to develop a measure of how closely an individual gait pattern approaches normal [13].

The measurements of the gait cycle represent large amount of information, hitherto it is not clear so far what are the more suitable measures or analysis, with a lack of methodological standardization.

The present study aims at testing the application of principal component analysis in the ground reaction force to discriminate the gait pattern between normal subjects and patients with lower limb fractures, as well as to evaluate the evolution of a rehabilitation treatment.

II. Methods

The ensemble for this study comprehend 31 subjects, organized into two groups: a control group (CG) of 25 normal subjects (13 men and 12 women), without physical lesions, neurological or muscle skeletic disorders, with age 22,82 ± 2,93 (mean ± standard deviation) years and body mass 67,29 ± 13,59 kg, and a group (FG) of six patients

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with lower limb fractures (5 men an 1 woman), with age 26,67 ± 7,99 years and body mass 65,37 ± 9,86 kg. The FG group was considered before (FGB) and after (FGA) a treadmill physiotherapeutic treatment. Experimental protocol was previously approved by a local ethics committee and all subjects signed a free informed consent.

The vertical component of the Ground Reaction Force (GRF) data was collected with an instrumentized treadmill Gaitway® model 9819S1 (Kistler Winterthur, Swiss). After adapting subjects to the experimental environment (10 min walking), subjects weight were measured for data normalization. Data from the three groups CG, FGB and FGA was collected with sampling frequency 300 Hz and walking velocity 4 km/h during 10 s. This epoch corresponds to approximately 10 strides, from those it was obtained the average GRF.

The rehabilitation protocol, applied three times a week with an hour in average, consisted on stretching, gait practice on treadmill, strenthning and balance practice, as well as proprioceptive and gait practice in ground. The treatment duration varied for each case, being maintained until the patient reached comfortable walking for 20 min at 6 km/h with 6% inclination.

After normalized by the subject's body weight, the GRF data was decimated and resampled with 300 samples corresponding to 100% of stance phase. A 2^{nd} order Butterworth low-pass filter, cut-off frequency of 30 Hz was applied to both right and left feet GRF, in direct and reverse directions to avoid phase distortion and to reduce noise (as proposed by [8]). Thus the average GRF pattern (GRF_m) was obtained for a complete stride (right and left side in NG and affected and unaffected limb in FG).

Principal Component Analysis (PCA) method, as described in [15] was applied to the covariance matrix of GRF_m from 31 subjects (Groups CG and FGB). The first two coefficients were thus obtained for the three groups.

The area of displacement for the coefficients from each group was calculated using the method proposed by [16], so as to include 97% of the samples along each axis.

Stepwise logistic regression was applied to define a linear threshold between NG and FGB [17], as follows:

$$p(Y=1)=\frac{1}{1+\exp\left[-\left(\beta_o+\sum_{j=1}^{2}\beta_j X_j\right)\right]} \qquad [1]$$

where β_j (j = 1, 2) represent the adjustment coefficients, and the logistic variable Y separates the pattern space into two classes, one for E[Y] > 0.5 (FG) and the other for E[Y] < 0.5 (CG), as a function of the two principal component coefficients (PCC) X_1 and X_2 [1].

All signal processing procedures were implemented with the software Matlab 6.5 (The Mathworks, USA).

III. RESULTS

The splitting of the plane generated by the first 2 PCC with logistic regression (Fig. 1) shows a reazonable separation between CG and FGB, with two subjects from FGB in the CG side. The arrows in Fig. 2 shows the effect of treatment, where points from all subjects from FGB moved toward the normal side, with only one subject from FGA remainning in the abnormal side.

When delimiting each group by the corresponding elliptical area with 97% confidence interval (Fig. 2), it becomes clear the reduced dispersion of the PCC values from FGB to FGA, with values again moving toward the CG ellipse.

The shape of GRF from each group allows a qualitative evaluation of the pathological chances of gait pattern (Fig. 3). The morphology of GRFm from CG showed the typical bimodal pattern with reduced dispersion around the first and second peak of force, with good symmetry between sides (Figs. 3a and 3b). In the FGB, however, marked asymmetry is observable between the affected (AL – Fig. 3c) and unaffected (UL – Fig. 3d) lower limbs, with greater variability around the peaks in UL. After treatment (Figs. 3e and 3f), the GRFm shapes recovers symmetry and becomes more similar to the normal shapes.

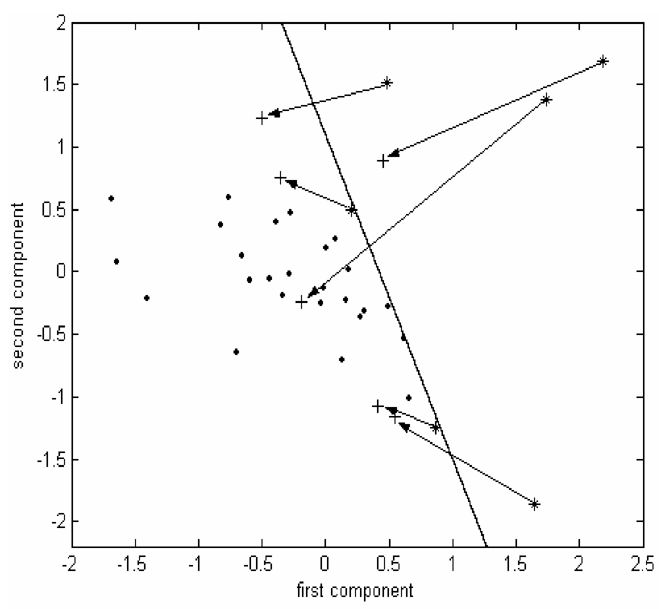

Fig. 1. Scatter plot of the first two PCC of subjects from CG (●), FGB (*) and FGA (+), with the linear separator given by logistic regression. The arrows are connecting each patient data before treatment with the corresponding after treatment values.

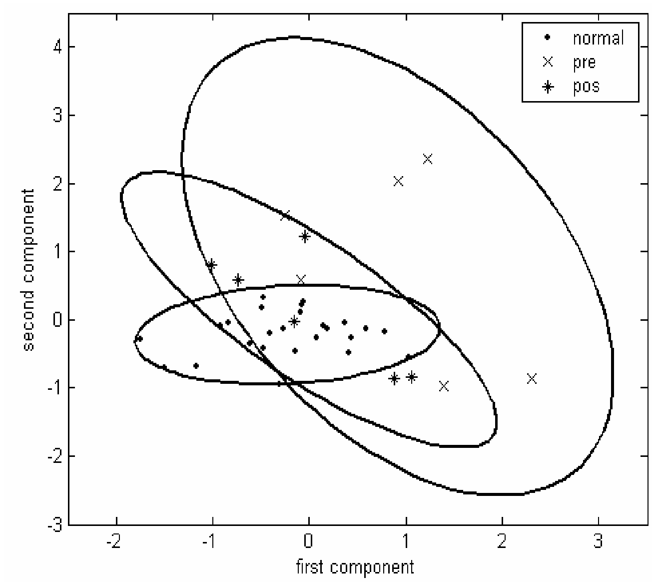

Fig. 2. The same data of Figure 1, with the corresponding elliptical area for 97% confidence interval. The greater ellipse corresponds to FGB, the medium to FGA and the smaller to CG.

DISCUSSION

The main advantage of PCA over classical approaches is that principal components reflect the variance of the complete GRF curve, instead of focusing only in the two GRF peaks and local minimum [4]-[6]. The qualitative differences between CG and FGB are evidenced in the GRF_m shapes, but such descriptive approach represents only the first step in gait analysis [9]. The scatter diagram of PCC allows, additionally, an objective assessment of each patient, as well as the effect of treatment over such patient.

The use of a reduced number of coefficients allows to easily describe the individual characteristics of each patient gait [7], by considering the value of the PCC and the shape of the corresponding eigenvector [10]-[11],[18]. For example, the subject from FGB whose PCC values were located inside the normal side of the scatter plot presented reduced damage due to lesion, and showed a GRF curve quite similar to the normal shape. By the other side, the subject who does not reached the normal side after treatment suffered exposed fracture of tibia and partial loss of the anterior tibial muscle during an accident. After treatment, such patient maintained ankle joint limitation, being incapable to make dorsiflexion. Since the normal

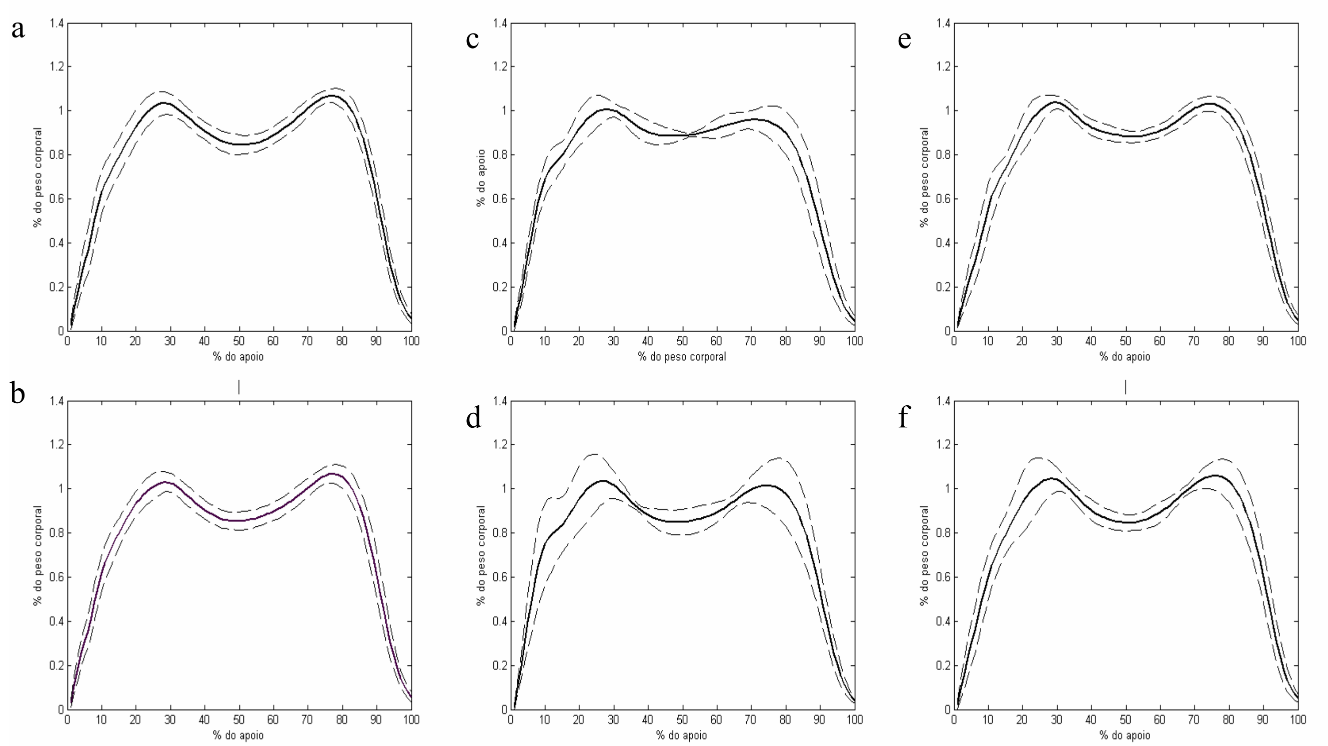

Fig. 3. Average vertical Ground Reaction Force (continuous) and ± 1 standard deviation (dotted): a) Right and b) Left lower limb from CG; c) Affected and d) Unaffected limb from FGB; e) Affected and f) Unaffected limb from FGA.

foot function during gait requires 10^o of dorsiflexion [19], the complete normalization of gait becomes difficult. However, this patient present notable gait progress, as observable by the length of the arrow towards the normal side in Fig. 2.

The present results agrees with [11],[14],[18], that found PCA modeling useful for quantifying differences between normal and osteoarthritic aged patients, also showing progress after treatment. The differences between FGB and FGA shows evidence that PCA is a powerful method to distinguish different degrees of injury, which reinforces the founds of [1],[13], who showed that a single index derived from PCA was robust enough to categorize pathology, ranging from mild disorders to quadriplegia.

The use of elliptical areas is useful to demonstrate that PCC coefficients present increased variance for abnormal gait, in accordance with [1], which seems to be related to the difficulty of subjects in presenting a uniform locomotor pattern after lower limb fracture.

The scope of this paper was limited to explore the potentiality of principal component analysis in objectively discriminating between normal and abnormal gait. These preliminary results does not allows to access the power of PCA in classifying groups, since the first two PC explained only 48.9% of CG and FGB data variance, and only a linear separator was considered over the same data set used for the logistic regression. For classification purposes, a larger sample becomes necessary for performance assessment with independent data, as well as an increased number of PCC could be considered together with nonlinear separators.

As a conclusion, the present results pointed out the potential power of principal component analysis in discriminating between normal and abnormal gait and objectively evaluating the progress and effectiveness of rehabilitation treatments.

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