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Principal Component Analysis of gait in Parkinson's disease: Relevance of gait velocity

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ABSTRACT

Principal Component Analysis (PCA) is a method to estimate the relation between data points. We used PCA to analyse movements of the upper and lower extremities during treadmill walking in healthy subjects and two groups of Parkinsonian patients.

Healthy subjects ($n = 35$) showed a typical pattern with high values of PC1 and low values in a descending order of PC2–PC4. Increase of speed resulted in a significant increase of PC1 and a significant decrease of the following PC's. In more severely affected patients ($n = 19$, UPDRS > 20), PC1 was significantly decreased and PC2–PC4 were significantly increased compared to healthy subjects. Speed could be increased only within a small range without corresponding changes of the PC's. In less severely affected patients ($n = 17$), significant differences of the PC's were only found with fast pace. Separate analysis of arms and legs revealed that these changes are only due to altered movements of the arm.

Analysis of the pattern of PC's in response to changes of gait velocities reveal alterations even in less severely affected Parkinsonian patients. The changes of the PC's with higher gait velocities in healthy subjects are suggestive of an increase of intersegmental coordination. This is impaired even in less severely affected Parkinsonian patients.

1. Introduction

Disturbances of gait are typically associated with Parkinson's disease. Patients show a reduced gait velocity, a shortened step length, a forward bent posture, and diminished extension–flexion-movements within the joints of the upper and lower extremities. For clinicians, this pattern is easily recognized, but the quantification of these alterations would be desirable for diagnostic and therapeutic purposes.

Many mathematical attempts to characterize normal and pathological gait have been used, such as Fourier analysis, wavelet transform or support vector machines [1,2]. These methods are not appropriate to analyse pattern of data points. However, in many diseases there are typical pattern of alterations. For example, in Parkinson's disease, one side of the body is primarily affected. In frontal gait disorders, the lower extremities are more severely affected than the upper extremities. Thus, a method to estimate relations between several data points is required. Principal Component Analysis (PCA) is a suitable method for this purpose as it has been shown by the analysis of the pattern of EMG during locomotion [3,4]. The method has also been used to evaluate gait pattern [5,6] and especially the intersegmental coordination in position space during locomotion in healthy subjects [3,7–9].

The value of PCA to discriminate different gait-patterns has been shown in healthy children [10] and adults [6,11,12], as well as in patients with different kinds of diseases resulting in gait abnormalities such as stroke [13,14], or Parkinson's disease. The latter studies focused on parameters of gait such as the vertical ground reaction forces [15] spatial–temporal image of plantar pressure [16], and movements of joints of the lower extremities [17–19].

In Parkinson's disease, the asymmetry in symptomatology of the upper and the lower extremities is characteristic. We therefore used PCA to analyse synchronously the movements of both arms and legs with special attention to factors probably responsible for the alterations found in these patients. A main factor is the gait-velocity which is well known to be clearly reduced in Parkinsonian

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patients [20]. Since PCA analysis of gait parameters in stroke patients [14] clearly demonstrated the relevance of this factor, we studied systematically the impact of the gait velocity on the principal components in healthy subjects and Parkinsonian patients. Gait-velocity itself depends strongly on the severity of the disease [21]. Therefore, we focused on the significance of this parameter, too.

2. Patients and methods

We studied 35 healthy subjects and 36 patients with Parkinson's disease (PD). All subjects gave their written informed consent and the study was approved by the local ethics committee. The healthy group consisted of 15 female and 20 male subjects, the mean age was 60.8 years (SD: 4.7; range 52–70 years). In the patients group, there were 12 female and 24 male subjects with a mean age of 63.1 years (SD: 9.2, range 40–76 years). All patients had an akinetic-rigid type of the disease, patients showing a resting or postural tremor were not studied. All patients were stable under medication without fluctuations or freezing. The motor function impairment was classified at the time of gait analysis using the motor-part (III) of the UPDRS. It ranged from 7 to 47 points (mean 22.3, SD 10.4). In order to analyse the relevance of the severity of the disease, we divided the patients into two groups: 17 patients were classified $\leq$2 on the Hoehn & Yahr (HY) staging scale and had an UPDRS III below 20 points (mean age 61.8 years, SD: 9.8; 6 female, 11 male). Patients of this group (PD_L) were classified as less severely affected patients. 19 patients (mean age 64.3 years, SD: 8.8; 6 female, 13 male) had an HY stage $>$2 and $\leq$4 and had an UPDRS higher than 20 points and were classified as more severely affected PD patients (PD_S).

Gait was analysed during walking on a treadmill. All subjects were given enough time to adapt to the experimental procedure to avoid a protective gait pattern. All subjects were secured by safety belts. We tested three gait paradigms: at first, convenient pace was measured according to the individual normal gait velocity (V_n). Afterwards, the individual slowest (V_{lo}) and the fastest (V_{fa}) gait velocities were determined. Care was given to avoid running. The slowest gait velocity adjusted by decision of the subjects or patients, corresponded to the velocity which just allowed a rhythmical movement pattern. The range of gait velocities was calculated by the difference between V_{fa} and V_{lo}. At each level of velocity, a recording lasted at least 5 min to assure artefact-free recordings. We analysed a period of 20 s which has been shown to be sufficient to recognize the typical gait pattern [22]. This corresponded to at least 12 steps regardless the gait velocity. Between the recordings, a rest period of 10 min was given to prevent fatigue.

We used a 3D real-time movement analysis system (CMS-HS, Zebris medical GmbH) which enables us to measure movements of the upper and lower extremities on both sides simultaneously. Movement analysis works on basis of the travel-time measurement of ultrasound pulses using measuring markers placed on the upper and lower extremities. The sampling rate was 30 Hz.

12 positions at the body were used for analysis: shoulder, elbow, hand, hip, knee and ankle, right and left in each case. Each position is defined by the 3 Cartesian coordinates (x, y, z). Thus a posture is defined by 36 parameters. Analysis of 20 s recorded with 30 Hz results in 600 postures according to 600 data points within a coordinate system with 36 dimensions. These large multidimensional data sets were analysed using PCA which is, from a mathematical point of view, defined as an orthogonal linear transformation of the data to a new coordinate system. The new coordinate system has its origin in the mean of the data set. The first coordinate axis of the new system points to the direction of largest variance. It represents in a mathematical sense a vector, and is called the first Principal Component (PC1). The next coordinate axis points to the direction of the second largest variance, called the second Principal Component (PC2), and so on. Thus, the new coordinate system with 36 dimensions results in 36 coordinate axes that are the 36 PC's. Thereby, the dimension of such a Principal Component or vector is 36, which is not expressed by a simple value. The terms "value of PC" or "PC" which we will use below refer not to a value of the PC itself in the mathematical sense but to the percentage of the PC's at the overall variance of the data along this vector. For details see Daffertshofer [23] and Chau [1]. The sums of the variances of all 36 PC's result in the total variance of 100%. It depends on the structure of the data sets, how many PC's are required to achieve a sufficiently high percentage of the total variance.

The comparison of groups was done using the Kruskal–Wallis-Test with the Mann–Whitney-U-post hoc Test and Bonferrroni-correction respective the Mann–Whitney-U-Test for the comparison of 2 groups (Table 3). To analyze quantitative variables such as velocity or the PC-values within a group the Friedman-Test with the Wilcoxon post hoc test and Bonferroni-correction were applied. Significant differences were assumed with $p < 0.05$.

Correlations were determined using the Spearman-rho-correlation coefficient; p-values below 0.05 were regarded as statistically significant. Statistical analysis was done with PASW Statistics 19.

3. Results

We asked patients and healthy subjects to walk with 3 different velocities and the resulting low, convenient, and fast pace differed significantly within the control-group as well as within the two patient groups (p always < 0.001). PD_L patients walk faster than PD_S patients when slow walk was requested. With fast gait velocities, no differences of the velocities could be found between both patient groups. In comparison to healthy subjects, PD_L patients walk as fast as healthy subjects when slow walk was requested, but with fast gait velocities, they walk significantly slower than healthy subjects. Thus, only fast pace disclosed differences of the gait velocities between healthy controls and less severely affected patients. In more severely affected patients, all gait-velocities and the range of gait-velocities are always clearly reduced (Table 1) in comparison to healthy subjects.

The cadences (Table 1) with low, convenient and fast pace were equal in all groups but this did not apply when equal velocities independent of the intended pace were compared (see below).

The first 4 PC's sum up to at least 94% (Fig. 1) in healthy subjects and patients. All other 32 PC's share the remaining 6%. Furthermore, the SD of PC4 which has the lowest values, range between 30% and 50% (Table 2). According to Jollife [24], we therefore decided to analyse only the first four PC's. The typical gait in healthy subjects and patients can be reconstructed by the data characterized by first 4 PC's (demonstrated at http://www.num.uni-sb.de/iam/index.php/en/).

With low gait-velocities, the sum of the 4 PC's (Fig. 1) are similar in all groups. With normal and fast gait-velocities, significant differences of the sums of the PC's were found only between healthy subjects and the PD_S group ($p < 0.002$). In healthy subjects, we found a significant increase the sum of the 4 PC's as the gait velocity increases. This significant increase could not be found in both patient groups.

Looking to the respective PC's in healthy subjects, PC1 had clearly the highest values, followed in descending order by PC2, PC3 and PC4. In patients, this typical pattern is significantly altered (Fig. 1, Table 2): PC1 is lower and PC's 2–4 are higher than in healthy subjects. This applied to all gait velocities. The analysis