Quantification of fractal properties of postural sway patterns as a step toward fall prevention

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ABSTRACT

In a first step to preventing falls in the elderly, postural sway was examined by use of fractal dimension analysis to gain understanding into the different balance patterns associated with age and disease. It was thought that the complex fractal-like patterns of center of pressure displacement breakdown and change with natural aging and disease, with this breakdown associated to fall risk. To test this hypothesis, center of pressure displacement and associated data were collected from 10 healthy young individuals, 10 healthy elderly individuals, and 10 individuals with Parkinson's disease. Detrended fluctuation analysis was performed to determine the fractal dimension of each individual's data in both the anterior-posterior and medial-lateral sway directions, with both eyes open and eyes closed. The fractal dimension revealed the pattern of sway with respect to the equilibrium position. It was found that for both short-term (less than one second) and longer-term time intervals, significant statistical differences in the fractal dimensions allowed some group differentiation. Most significantly, in the medial-lateral direction the long-term fractal dimension allowed differentiating of the Parkinson's group from both healthy groups with eyes open, and from the healthy elderly group with eyes closed. This study led to a better understanding of the effects of Parkinson's disease on balance. It was found that, on average, individuals with Parkinson's disease experience more variability, resulting in a less consistent sway pattern, in the medial-lateral direction than the healthy groups. This may be to make up for a restricted limit-of-stability in the anterior-posterior direction due to rigidity associated with the disease. As individuals with Parkinson's disease are at higher risk of falling than age-matched peers, the differences in sway pattern found in this study may be responsible for the prevalence of falling in this population.

INTRODUCTION

Falls have been recognized as a serious and frequent problem, particularly in those over the age of 65. As many as one-third of the elderly living in the community and 60% of those in nursing homes will experience a fall during the year. (Brauer et al. 2000, Perell et al. 2001) The consequences of these falls can be serious, including hospitalization, fracture, significant psychological impact, and death. (Perell et al., Fletcher and Hirdes, 2002) These serious fall-related consequences have become a major implication for health care costs, with the estimate costs in the billions of dollars. (Perell et al., Bell et al. 2000)

Identifying those people at risk of falling is the first step at understanding and preventing falls and the consequences associated with them. For those at risk, intervention programs including structured exercise and balance training may prove to be beneficial in reducing this risk. However, the immense cost associated with prevention and rehabilitation treatment, and the time required by healthcare to administer such treatment, makes it even more important to target those at highest risk of falling such that the benefits be maximized.

One of the most common fall risk factors is poor balance. The postural instability that is characteristic of poor balance is caused by the inability to control the normal sway of the body that is present even when standing still. (Rogers et al. 2001) It has been found that recurrent fallers have been shown to experience more postural sway than those of the same age that have not fallen, further suggesting balance as a significant risk factor. (Blaszczyk and Klonowski 2001) Monitoring the center of pressure (COP) displacement is a quick non-invasive means of examining human balance.

The COP plots for upright quiet-standing generally appear as highly erratic and chaotic. Recently, however, researchers have begun to notice trends in the irregularity of the plots. The COP plots exhibit interesting properties in terms of smoothness and correlation. (Morales and Kolaczyk 2002) They have also been found to have long-range dependence, scaling behavior, and other fractal-like properties. It is these fractal-like trends, which allow for the development of the hypothesis of this work that COP displacement may be used to quantitatively differentiate the sway patterns of healthy individuals from those that have compromised balance due to age or disease.

Fractals are those spatial objects and temporal series, which exhibit some degree of self-similarity in their composition. Mandelbrot, who coined the term in 1975, gives the defintion as, “A fractal is a shape made of parts similar to the whole in some way.” (Feder 1988) To quantify the degree of self-similarity exhibited by a fractal, the fractal dimension was developed. This numeric quantification enables a greater understanding of the underlying structure of objects that were initially thought to be irregular.

It has been found that both age and disease cause a breakdown of fractal-like properties in many physiological systems. Within recent years much work has been done applying fractal analysis to human balance, with the findings suggesting that the breakdown of fractal-properties and loss of complexity, both indicated by a change in the fractal dimension, are able to indicate differences between age, health, and experimental condition. The most recent research in this area also suggests that the use of fractal dimension as a means to analyze the data is at least as accurate, and a seemingly more informative measure of balance, than traditional measures commonly used. (Doyle et al. 2004)

This study's evaluation of the ability to discriminate between healthy young individuals, healthy older individuals, and individuals with Parkinson's disease, based on fractal dimension, may therefore serve to merit further work in this field, and suggest more accurate and informative methods of reporting balance scores than those currently used. This will serve as a basis for a deeper understanding of human balance and changes that occur with advanced aging or disease. The results of this study will enable progress towards preventing falls in the elderly.

METHODS

Subjects

Ten healthy young subjects served as controls for this study. These were compared to a group of 10 healthy elderly individuals, and 10 individuals with Parkinson's disease. All 20 healthy subjects were verbally administered a short overview-of-health survey, and gave responses consistent with the inclusion criteria of the study. This meant participants serving as healthy subjects all reported having: no existing balance, neurological, or orthopedic disorders; no history of seizures, dizziness, or falls; no surgeries or injuries to their legs that affect balance; and did not take any medication that had side effects of drowsiness or dizziness, affecting balance. Additionally, none of the subjects in the healthy group were diabetic or had suffered a stroke. The 10 individuals with Parkinson's were assessed by physical therapist or physician as having moderate disability, with some degree of postural instability. The healthy young group was made up of 6 females and 4 males with a mean age of 22.6 ± 2.4 years. Mean height was 171.5 ± 9.8 cm, and mean weight was 66.9 ± 14.5 kg. Nine of the 10 reported regularly exercising. The healthy elderly group was also made up of 6 females and 4 males. The mean age was 73.2 ± 5.3 years, mean height 162.9 ± 10.9 cm, and 69.3 kg. Nine of the 10 reported regularly exercising. The Parkinson's disease group was made up of 2 females and 8 males. The mean age was 75.8 ± 6.6 years, mean height 172.9 ± 8.2 cm, and mean weight 83.0 ± 24.0 kg. The Institutional Review Board of The Ohio State University approved this study, and all subjects gave written consent.

Experimental Protocol

Postural sway data was collected while subjects stood quietly on a Model BP5050 balance plate (Bertec Corporation, Columbus, OH). Four trials of 90 seconds each were taken per subject; 2 with eyes open (EO) and 2 with eyes closed (EC). All data was collected at 1000 Hz. Subjects stood with arms to the side, avoiding any unnecessary movements during the trial. The experimental set-up is shown in Figure 1.

Figure 1: Set-up of Experimental Procedure

Data Analysis

COP-related moment data corresponding to anterior-posterior (A/P) and medial-lateral (M/L) sway direction of each trial were analyzed using Detrended fluctuation analysis to obtain a fractal dimension. Detrended fluctuation analysis was first introduced by C.-K Peng as an improved technique to that of R/S Hurst analysis, power spectral density, and fourier transform methods. (Peng et al. 1995, Goldberger et al. 2000) It is a way of integrating and detrending the data series that allows for a scaling exponent to be calculated. This scaling exponent can then be related back to the fractal dimension. The general idea of detrended fluctuation analysis is to compare the root mean square fluctuations of best-fit curves fit to different ranges of data that are known to be fractal-like. Most commonly a linear relationship exists such that the smaller the amount of data being looked at, the smaller the fluctuations. The slope of this linear relationship is known as the α-scaling-exponent. The fractal dimension, FD, is then calculated as
$FD = 2 - \alpha$.

Values of the fractal dimension range from 0.5 to 2. A value close to 2 corresponds to a strong anti-persistent trend. In the case of balance, the body tries to recover from movements made away from equilibrium by returning to a relative equilibrium position. A fractal dimension close to 1.5 indicates that all movement is random. A value close to 1 indicates a persistent long-memory trend, with positive correlations. In terms of balance, this means that the person's center of pressure moves away from its relative equilibrium and continues to drift away, without recovering back. Any value less than one suggests that though correlations may exist, they are no longer easily described.

Three different linear regions stood out on all detrended fluctuation plots of the data. Two of these corresponded closely to the regions Collins and DeLuca had previously acknowledged, having identified positive correlations at time intervals less than one second, and negative correlations at time intervals of one second or more. (1994) This study also observed an additional region from 0 to 0.1 seconds. To be consistent with previous literature, this region was not examined further for this study. A short-term α-scaling exponent was determined for the linear region existing for a time intervals 0.1 to approximately 1 second. A long-term α-scaling for time intervals longer than 1 second. A custom-written Matlab script (The MathWorks, Natick, MA) was used to determine the crossover-point of one linear region to the other.

Statistical Analysis

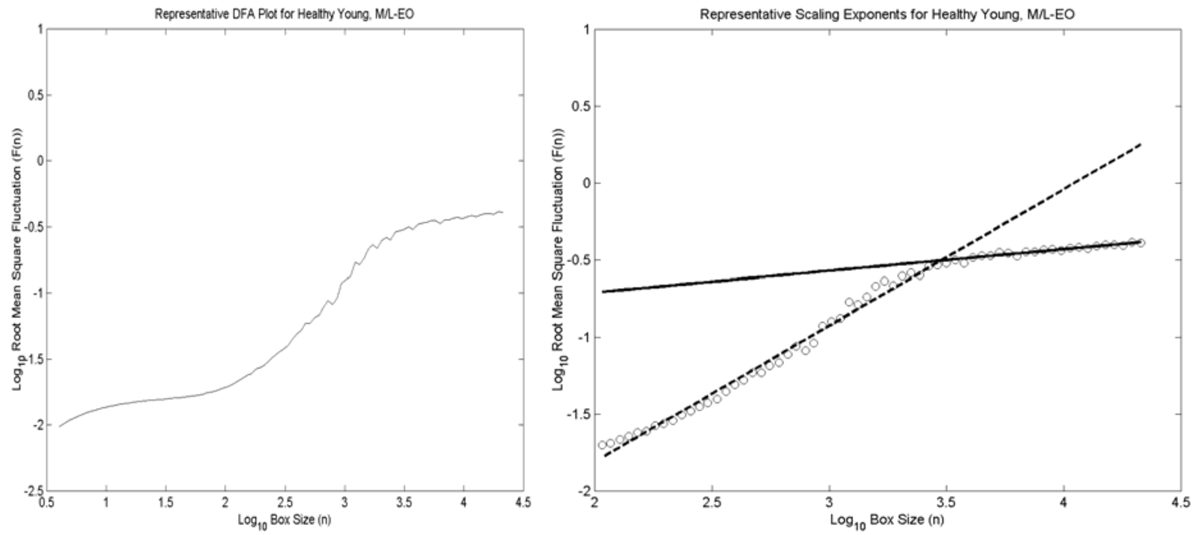
Minitab statistical software (Minitab Inc., State College, PA) was used to perform one-way analysis of variance (ANOVA) tests on the means of the data. A series of null hypotheses were formed relating different groups, sway directions, and visual conditions. Only long-term fractal dimensions were examined in differentiating sway directions, and visual conditions. All null hypotheses were rejected when $p < 0.05$. In cases where the ANOVA test showed statistically significant differences between the means of the three subject test-groups, Tukey's Honestly Significant Difference test was used to determine between which groups the significance difference existed.

RESULTS

Between Group Differentiation

To determine whether discrimination between groups was possible, the group means for short-term fractal dimension, long-term fractal dimension, and crossover point were compared for both the anterior-posterior and medial-lateral sway directions and eyes open and eyes closed conditioned. Results of crossover point are not reported in this paper.

Representative detrended fluctuation analysis plots are shown in Figure 2. Figure 2.a shows the entire data region. Figure 2.b shows the two linear regions of interest for this analysis, the short-term region and the long-term region.



a. b.

Figure 2: Detrended fluctuation analysis plots for obtaining fractal dimension

Short-term and long-term fractal dimensions are listed below in Tables 1 and 2 for both sway directions (A/P and M/L) and visual conditions (EO and EC). All statistically significant findings ($p<0.05$) are noted. Differences between groups are noted with * representing the group of interest, and ~ representing the group(s) with which it significantly differs.

Table 1: Short-term fractal dimensions for both A/P and M/L sway directions and both visual conditions.

	SHORT-TERM FRACTAL DIMENSION			
	A/P-EO	**A/P-EC**	**M/L-EO**	**M/L-EC**
Healthy Young	$1.080 \pm 0.245^{*}$	0.969 ± 0.164	$1.006 \pm 0.097^{*}$	0.958 ± 0.108
Healthy Elderly	$0.862 \pm 0.182^{\sim}$	0.804 ± 0.183	0.894 ± 0.134	0.901 ± 0.138
Parkinson's Disease	$0.817 \pm 0.155^{\sim}$	0.837 ± 0.183	$0.822 \pm 0.224^{\sim}$	0.833 ± 0.210

Table 2: Long-term fractal dimensions for both A/P and M/L sway directions and both visual conditions

	LONG-TERM FRACTAL DIMENSION			
	A/P-EO	**A/P-EC**	**M/L-EO**	**M/L-EC**
Healthy Young	1.702 ± 1.245	1.735 ± 0.087	$1.864 \pm 0.064^{\sim}$	1.861 ± 0.079
Healthy Elderly	1.698 ± 0.100	1.711 ± 0.102	$1.854 \pm 0.089^{\sim}$	$1.867 \pm 0.082^{\sim}$
Parkinson's Disease	1.705 ± 0.117	1.745 ± 0.097	$1.711 \pm 0.111^{*}$	$1.768 \pm 0.125^{*}$

Differentiation was particularly notable between group with Parkinson's disease and the healthy groups in the long-term fractal dimension in the medial-lateral direction. Figure 3 shows the 95% confidence intervals of the mean for the eyes open condition to further show this differentiation.

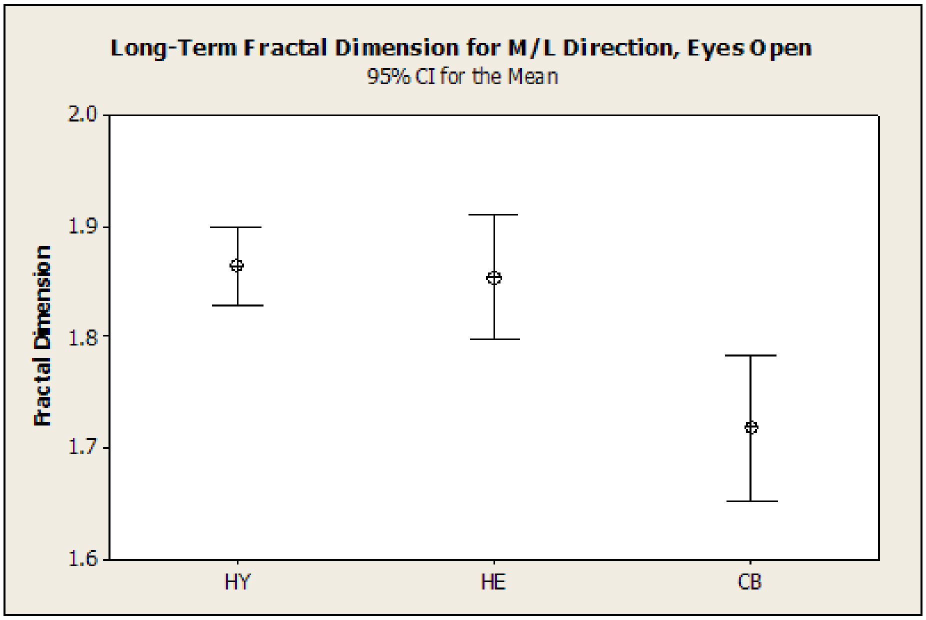


Figure 3: Statistically significant long-term fractal dimension findings differentiating the group with compromised balance due to Parkinson's disease (CB) from both healthy elderly (HE) and healthy young (HY) in the M/L direction with eyes open

Differentiation Between Visual Conditions

No statistically significant difference between eyes open and eyes closed could be found for the long-term fractal dimension in either anterior-posterior or medial-lateral direction.

Differentiation Between Sway Directions

The long-term fractal dimension in the anterior-posterior direction was differentiable from the medial-lateral with both eyes open and eyes closed, in both healthy groups. No statistically significant difference existed between sway direction in the group with Parkinson's disease. Table 2 lists these fractal dimensions.

CONCLUSIONS

This study examined whether quantifying COP-related data with a fractal dimension could allow for differentiation between young healthy individuals, elderly healthy individuals, and individuals with compromised balance due to Parkinson's disease. Various statistically significant differences between the groups were found, suggesting that differentiation is possible under certain conditions.

Ability to Discriminate Between Groups

The most notable findings of this study occur in the long-term region for the M/L sway direction. In both visual conditions, the Parkinson's group was found to have a lower average fractal dimension than either of the healthy groups. The fractal dimension of the Parkinson's group is closer to 1.5 than the healthy groups, suggesting that the balance patterns associated with this disease have higher variability. These findings of increased variability in sway are in support of recent research examining postural stability of individuals with Parkinson's disease (Mitchell et al. 1995, Van Wegen et al. 2001) and have special merit as a potential diagnostic tool.

One of the characteristics inherent to Parkinson's disease is rigidity, which is often responsible for reduced amplitude of sway in the A/P direction. The results of this study suggest that though sway may be decreased compared to healthy individuals, the pattern of sway oscillation about equilibrium is the same. Previous research has suggested that it is these limitations in the A/P direction that lead to changes in M/L sway, such as the increased variability observed in this study. (Mitchell et al.) Research has also shown M/L sway in Parkinson's patients to be more complex. (Mitchell et al., Van Wegen et al. 2001, Romero and Stelmach 2003) The findings of our study support these previous works.

The high variability observed in the M/L direction may be directly related to the prevalence of falls in Parkinson's individuals, particularly lateral falls. Van Wegen *et al.* found increased variability in Parkinson's patients to be associated with greater side-to-side instability than healthy elderly individuals. Findings by Mitchell *et al.* showed medial-lateral sway parameters to be more indicative of falls than other sway parameters.

The results of this study serve to suggest that it is not desirable to have high degree of variability in sway pattern. This study supports it most advantageous to have a fractal dimension somewhere between 1.5 and 2. The ideal range appears dependent on sway direction, as significant differences exist in the M/L and A/P directions.

Ability to Discriminate Between Visual Conditions

No statistically significant differences were found in fractal dimension with eyes closed versus eyes open in either the A/P or M/L directions. Doyle *et al.* also found no significant differences between the visual conditions of healthy young individuals. Blaszczyk and Klonowski and Doyle *et al.* both found that discrimination between eyes open and eyes closed was possible in the A/P direction for healthy elderly subjects. Both of these findings support increased oscillation about equilibrium, as noted by a higher fractal dimension, with eyes closed. Though not statistically significant, similar results were found in the present study. One reason that a statistical difference between may not have been found in this study was due to the level of health and activeness maintained by the healthy elderly subjects. Many participated in regular exercise, and this may have helped slow the age-related changes that other studies found.

Ability to Discriminate Between Sway Directions

In both healthy groups the long-term fractal dimension in the M/L direction was significantly higher than in the A/P direction. These results support the findings of Doyle *et al.*, who compared the fractal dimension of a healthy young group to a healthy elderly group and found the fractal dimension of center of pressure displacement to be higher in the medial-lateral direction. The results of the current study suggest that it is more advantageous to have a greater degree of variability in the A/P direction than the M/L direction.

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