Detrended Fluctuation Analysis of Temporal Variation of the Center of Pressure (COP) during Quiet Standing in Parkinsonian Patients

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Abstract. [Purpose] Parkinson’s disease (PD) leads to stance instability in the late stage of the disease. Conventional studies of the center of pressure (COP) have difficulties characterizing postural instability in the early stage of PD. The present study analyzed stabilograms of PD patients using a recently developed method, detrended fluctuation analysis (DFA). [Subjects] The subjects were 7 PD patients in stages I–III of Hoehn and Yahr, and 10 age-matched healthy elderly (HE) persons. [Method] COP signals were measured during quiet standing, and subjected to DFA and conventional analysis. DFA parameters (scaling exponents) relating COP fluctuation to time interval showed similar behaviors both in PD and HE subjects. Both in the anterior-posterior (AP) and medio-lateral (ML) directions, three exponents, $\alpha_1$, $\alpha_2$, and $\alpha$ were obtained for short- and long-term fluctuations, and the whole range, respectively. [Results] Magnitudes $\alpha_1$, $\alpha_2$, and $\alpha$ were almost the same: $\alpha_1 \approx 1.5$, $\alpha_2 \approx 1.0$, and $\alpha \approx 1.3$. The crossover points dividing the short- and long-term fluctuations in the AP direction, however, differed between PD and HE subjects. The former was about 0.6 times shorter than the latter. [Conclusion] PD patients may control upright posture with the similar postural strategies to HE subjects, but the switching times between the short- and long-term strategies may be different.

Key words: Upright stance, Postural instability, Parkinson’s disease

INTRODUCTION

In Parkinson’s disease (PD), midbrain dopaminergic neurons projecting to the neostriatum progressively degenerate, and dysfunction of the basal ganglia gradually manifests itself in motor deficits such as tremor, bradykinesia, rigidity, and postural abnormality. While quantitative evaluation of such deficits may be important for diagnosis as well as treatment, it is rather difficult in the early stage of the disease. The stabilogram, continuous measurements of displacement of the center of pressure (COP) during quiet standing on a force plate, might be an appropriate method for the purpose. However, conventional analyses of COP, such as excursion area and total length of trajectory, and power spectra of the temporal fluctuation have shown rather conflicting results. Some studies have reported that PD patients exhibit larger postural sway than age-matched healthy elderly (HE) subjects, but others have shown the inverse. Studies of power spectra suggest higher frequency distribution of the power in PD patients, but they are not conclusive, because
of filtration of brief abrupt changes of COP that often appear in PD patients\(^9\). Thus, data analysis and interpretation of stabilograms of PD need further investigation.

Complex trajectories of COP may occur in the complicated task of bipedal standing and due to the high degree of freedom of movement of the human body. During standing COP has to be localized just under the center of the body mass (COM), which is kept in a high vertical position, against gravity, which is forcing it to the ground. For standing, the COP is also required to stay within a support area delineated by the two feet. The brain has to control the high degree of freedom of movement of the body to satisfy these requirements, and there may be no unique solution, rather various ways are assumed. For brain control, the dominant limiting conditions and primary regulation of joints could vary case by case even for the same person. Thus, to characterize COP fluctuation with conventional parameters based on a simple stochastic analysis might be too simple. The COP fluctuation should be investigated by other methods, such as analysis considering temporal characteristics with random variables, including chaos analysis\(^9\), random walk analysis\(^10\), and detrended fluctuation analysis (DFA)\(^11,12\). Among these, DFA is known to provide scaling exponents, which characterize short- and long-term correlations in time-varying signals, which presumably are important properties of temporal characteristics of COP fluctuation. The scaling exponents, \(\alpha\), obtained with DFA are reported to have diagnostic and prognostic values for patients with various types of cardiac diseases. The present study applied DFA to COP data from PD and HE subjects, and compared the results with those of conventional analysis.

### SUBJECTS AND METHODS

Subjects comprised 7 patients who had a clinical diagnosis of PD, stage I-III of Hoehn and Yahr, and were aged 67 +/- 10 years old. They showed no sign of dementia, since their Minimal Mental State Examination (MMSE) scores exceeded 20. Ten age-matched, HE subjects, 66 +/- 6 years old were supplemented for comparison. Informed consent was obtained from each subject. The study was approved by the institutional review board of Yamagata Prefectural University of Health Sciences.

Participants were asked to stand quietly on a force plate (SAKAI Medical Co., Ltd, Active Balancer, Japan) with their eyes open. There was a target for subjects to look at 2 m to the front. For each measure, subjects stood on the force plate with their bare feet positioned freely. Movements of the center of pressure (COP) were recorded in the anterior-posterior (AP) and medio-lateral directions (ML), and stored on a computer for off-line analysis, at a sampling rate of 20 Hz. Each person performed 3 trials with rests between trials of about 1 min. One trial had a 30 sec length, which provided 600 data points. For each subject, 3 sets of experimental parameters (see below) were calculated, and averaged.

DFA is a modified form of root-mean square analysis of random walk\(^11\). It gives a scaling exponent, \(\alpha\), of the power law relating mean squares of fluctuation to time intervals. The calculation of \(\alpha\) was as follows:

1. First, the COP time series \(X(i)\) was integrated to create a new time series, \(y(k)\)

\[
y(k) = \sum_{i=1}^{k} [X(i) - M]
\]

where, \(M\) is the average of the series \(X(i)\).

2. To calculate root-mean square of \(y(k)\) against time interval \((n)\), the time series of \(y(k)\) was divided into boxes of equal length, \(n\) (i.e., a time interval of \(n\)). Then, the trend of \(y(k)\) within each box was determined by the best-fitting line segment. The linkage of the line segments, which is denoted by \(y_n(k)\) is the total trend for the division of \(n\). Finally, root-mean squares of detrended fluctuation \((y(k) - y_n(k))\) were calculated for each \(n\) value.

\[
F(n) = \left( \frac{1}{N} \sum_{k=1}^{N} (y(k) - y_n(k))^2 \right)^{1/2}
\]

For a time interval of 2, the line segments for the boxes are equivalent to \(y(k)\); thus, \(F(2) = 0\). The maximal \(n\) is limited by the number of data points, 600. Thus, we calculated \(F(n)\) for the range of \(4 \leq n \leq 150\).

3. The plot of \(F(n)\) vs. \(n\) with log-log scale provided a straight line with a positive slope; the slope is the scaling exponent of the power relation between the detrended fluctuation and the time interval. A DFA plot often consists of two distinct regions characterized by two straight lines with different slopes, which intersect at a crossover point (CP). In such instances, there exist both a short-term
scaling exponent, \( \alpha_1 \), and a long-term exponent, \( \alpha_2 \). The former reflects power related to the short-term fluctuations and the latter reflects the long-term fluctuations. Numerical values of \( \alpha_1 \), \( \alpha_2 \) and \( \mathrm{CP} \) were obtained by a least squares method. According to Peng et al.\textsuperscript{12}) is a self-affinity parameter representing the long-term correlation properties of the signal. If \( \alpha < 0.5 \), the correlation in the signal may be anti-persistent; if \( \alpha > 0.5 \), the correlation is persistent. In the case of no correlations, \( \alpha = 0.5 \).

To further clarify the temporal character of the COP fluctuation, scaling exponents were also obtained from surrogate data\textsuperscript{14}), which were calculated from original COP time series by randomization both in the time and frequency domains. Because time-randomized surrogate data completely lose temporal correlations, the scaling exponent must be close to 0.5 of white noise. Phase-randomized surrogate data retain the power spectral characteristics of the original data.

Conventional parameters of COP displacements were also recorded and calculated, including total length of COP trajectory (LNG), mean velocity along the trajectory (LNG/TIME), excursion area (Ex area), and mean density of the trajectory (LNG/ENV area), root-mean-square area (RMS area), and mean COP displacements in anterior-posterior (Mean-AP) and medio-lateral (Mean-ML) directions. Mean-AP and Mean-ML were measured against a reference point on the force plate, the center of the plate.

To determine the significance of group differences in parameters obtained from DFA and conventional analysis between PD and HE subjects the unpaired t-test was used. The significance of differences between original and surrogate data was also examined in the same way. To investigate the correlation between DFA and conventional analysis, we produced a correlation matrix for each subject group (PD and HE). The elements of the matrix were correlation coefficients, which were calculated for all pairs of the 9 parameters (LNG, LNG/TIME, Ex area, LNG/ENV area, RMS area, Mean-AP, Mean-ML, \( \alpha_1 \)-AP, \( \alpha_2 \)-ML) obtained in DFA and conventional analysis.

**RESULTS**

Conventional stabilometric parameters of COP displacements in the AP and ML directions measured and calculated for PD and age-matched HE subjects are shown in Table 1. LNG, LNG/TIME, and RMS area were significantly larger in PD than in HE subjects. In other parameters there were no clear differences between the two groups.

DFA plots of COP displacement in the AP and ML directions for PD and HE subjects provided two scaling exponents, one for the short-term fluctuation, denoted by \( \alpha_1 \), and the other for the long-term fluctuation, denoted by \( \alpha_2 \). As shown in the first column of Table 2, averages of \( \alpha_1 \) in the AP direction were 1.42 ± 0.11 and 1.46 ± 0.08, and those of \( \alpha_2 \) were 0.98 ± 0.15 and 0.98 ± 0.17 for PD and HE subjects, respectively. In the ML direction, \( \alpha_1 \) were 1.51 ± 0.10 and 1.50 ± 0.07, and \( \alpha_2 \) were 0.94 ± 0.26 and 1.02 ± 0.19 for PD and HE subjects, respectively. The whole time interval domain provided a scaling exponent, \( \alpha \), which had intermediate values between \( \alpha_1 \) and \( \alpha_2 \).

In the AP direction, \( \alpha \) were 1.25 ± 0.11 and 1.29 ± 0.08, and in the ML direction, \( \alpha \) were 1.33 ± 0.15 and 1.32 ± 0.09 for PD and HE subjects, respectively. For \( \alpha_1 \), \( \alpha_2 \) and \( \alpha \), these were no significant differences between PD and HE subjects.

The CP that divides the time interval into shorter and longer interval ranges was significantly different between PD and HE subjects. In the AP direction, they were 2.27 ± 1.35 sec and 3.89 ± 1.47 sec for PD and HE subjects, respectively, and
in the ML direction, the respective values were 4.05 +/− 2.98 and 3.70 +/− 2.42. The CP of PD patients was significantly shorter than that of HE subjects (p < 0.01).

The phase-randomized surrogate data (Surrogate (P-R)) showed similar time-varying aspects of displacement to the original data, because the former has the same power spectrum as the latter. On the other hand, the time-randomized data (Surrogate (T-R)) loses the original temporal structure and the original spectral profile.

Table 2, results of surrogate analyses are compared with those of the original data. In every case (AP and ML for PD and HE) the time-randomized surrogate data provided α values of about 0.5, which is expected for time series without any temporal character. In contrast, the phase-randomized surrogate data showed α values similar to those of the original data, especially for ML of both PD and HE subjects. There were significant differences in α2 of AP direction of both PD and HE subjects: α2 values were increased by phase-randomization from 0.98 to 1.31 for PD patients and to 1.36 for HE subjects.

Correlation coefficients between the nine parameters measured and calculated for conventional analysis and DFA parameters were calculated for PD and HE subjects, and are illustrated in Table 3. There were significant correlations within conventional parameters, as shown by asterisks in the two tables. However, the scaling exponents did not exhibit any significant correlation with those parameters.

DISCUSSION

To characterize COP displacement of PD patients during upright standing, the present study analyzed their stabilograms, and those of age-matched HE subjects using two different methods, conventional analysis, and DFA. In the former analysis, PD patients exhibited statistically significant larger
fluctuations in most parameters than HE subjects, suggesting a significantly unstable COP displacement for PD patients in comparison with HE subjects. However, in DFA, PD and HE subjects showed quite similar characteristics, producing similar DFA parameters, scaling exponents ($\alpha_1$, $\alpha_2$, and $\alpha$). Thus, the scaling exponents of DFA represent aspects of COP displacement which are completely different from those obtained by the conventional method.

It is known that in temporal fluctuations, such as COP, one-dimensional Brownian motion generates a scaling exponent of 1.5, while white noise, or “random walk” motion gives a value of 0.5\(^{15}\). The former is obtained by integration of the latter. In fact, low-pass filtering (integration) of the time-randomized data of the present study changed the short-term scaling exponent from 0.5 to 1.5 (unpublished data). In the present study, the scaling exponents in the short-term fluctuation ($\alpha_1$) were very close to 1.5 regardless of direction both in PD and HE subjects, suggesting that common dynamics like Brownian motion regulate COP displacement in short-term fluctuation in both directions for both PD and HE subjects.

On the other hand, the scaling exponents of the long-term fluctuation ($\alpha_2$) exhibited about 1.0 in each case. The numerical value of 1.0 corresponds to “pink” noise, suggesting some deterministic dynamics\(^{15}\) underlying the regulation of COP displacement common to both PD and HE subjects. The dynamics representing long-term scaling exponents of 1.0 may be completely different from Brownian motion.

Collins and De Luca\(^{10}\), who developed diffusion analysis of COP displacement suggest that temporal correlation of COP displacement in the short-term fluctuation might reflect open-loop dynamics controlling upright standing, while that in the long-term fluctuation range might reflect closed-loop

Table 3. Correlation coefficients among conventional parameters and scaling exponents for PD (n=7) patients and HE (n=10) subjects

(PD)

<table>
<thead>
<tr>
<th></th>
<th>LNG</th>
<th>LNG/TIME</th>
<th>LNG/ENV area</th>
<th>Ex area</th>
<th>RMS area</th>
<th>Mean -AP area</th>
<th>Mean -ML area</th>
<th>$\alpha$ - AP</th>
<th>$\alpha$ - ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG</td>
<td>1.00</td>
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<tr>
<td>LNG/TIME</td>
<td>-0.57</td>
<td>1.00</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNG/ENV area</td>
<td>-0.47</td>
<td>0.17</td>
<td>1.00</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ex area</td>
<td>0.55</td>
<td>-0.42</td>
<td>-0.80**</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>RMS area</td>
<td>0.41</td>
<td>-0.34</td>
<td>-0.80**</td>
<td>0.98**</td>
<td>1.00</td>
<td></td>
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<tr>
<td>Mean -AP</td>
<td>0.78**</td>
<td>-0.75**</td>
<td>-0.48</td>
<td>0.63*</td>
<td>0.55</td>
<td>1.00</td>
<td></td>
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<tr>
<td>Mean -ML</td>
<td>0.15</td>
<td>0.15</td>
<td>0.06</td>
<td>-0.31</td>
<td>-0.33</td>
<td>-0.11</td>
<td>1.00</td>
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</tr>
<tr>
<td>$\alpha$ - AP</td>
<td>-0.07</td>
<td>-0.14</td>
<td>-0.19</td>
<td>0.23</td>
<td>0.24</td>
<td>-0.05</td>
<td>-0.21</td>
<td>1.00</td>
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</tr>
<tr>
<td>$\alpha$ - ML</td>
<td>0.28</td>
<td>-0.03</td>
<td>0.15</td>
<td>-0.02</td>
<td>-0.13</td>
<td>0.04</td>
<td>0.13</td>
<td>0.20</td>
<td>1.00</td>
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</tbody>
</table>

Note that scaling exponents, $\alpha$ did not show any significant correlation with conventional parameters, LNG to Mean-ML.

(HE)

<table>
<thead>
<tr>
<th></th>
<th>LNG</th>
<th>LNG/TIME</th>
<th>LNG/ENV area</th>
<th>Ex area</th>
<th>RMS area</th>
<th>Mean -AP area</th>
<th>Mean -ML area</th>
<th>$\alpha$ - AP</th>
<th>$\alpha$ - ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG</td>
<td>1.00</td>
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<tr>
<td>LNG/TIME</td>
<td>0.49</td>
<td>1.00</td>
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<td></td>
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<tr>
<td>LNG/ENV area</td>
<td>-0.29</td>
<td>-0.55</td>
<td>1.00</td>
<td></td>
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<td></td>
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<tr>
<td>Ex area</td>
<td>0.85**</td>
<td>0.60**</td>
<td>-0.62**</td>
<td>1.00</td>
<td></td>
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<tr>
<td>RMS area</td>
<td>0.59*</td>
<td>0.75**</td>
<td>-0.79**</td>
<td>0.85**</td>
<td>1.00</td>
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<tr>
<td>Mean -AP</td>
<td>0.03</td>
<td>-0.18</td>
<td>-0.12</td>
<td>0.13</td>
<td>0.07</td>
<td>1.00</td>
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<tr>
<td>Mean -ML</td>
<td>-0.27</td>
<td>0.29</td>
<td>-0.09</td>
<td>-0.07</td>
<td>0.07</td>
<td>-0.18</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$ - AP</td>
<td>-0.05</td>
<td>0.16</td>
<td>-0.29</td>
<td>-0.03</td>
<td>0.03</td>
<td>-0.38</td>
<td>-0.37</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ - ML</td>
<td>-0.29</td>
<td>0.15</td>
<td>-0.13</td>
<td>-0.17</td>
<td>-0.05</td>
<td>-0.35</td>
<td>-0.05</td>
<td>0.75**</td>
<td>1.00</td>
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</table>
dynamics. If this is the case, the results of the present study imply that both for PD and HE subjects, similar open- and closed-loop controls may be at work, even though the amplitudes of fluctuation vary in extent between the two groups as shown by the conventional analysis.

DFA produced different results for PD and HE subjects, with respect to CP dividing short- and long-term fluctuations in displacement in the AP direction. For PD patients, CP occurred at a shorter time interval than for HE subjects. There could be several interpretations of the shorter time interval of CP of in PD patients. First, if the short- and long-term fluctuations are separately controlled by open- and closed-loop mechanisms, the switching between the two controls may occur at a shorter time in PD patients than in HE subjects. Second, the CP may be the minimal loop time for the closed-loop control. If this were true, it implies that the loop time of the closed-loop control in PD patients is reduced. It is also possible that the time interval of CP shorter of PD patients might reflect some changes in the dynamics of COP displacement, such as chaotic nonlinear ones. These possibilities may not be exclusive of each other, and further studies are required to explore them.

In conclusion, the present study explored COP displacement of PD patients using DFA. The DFA plots provided similar scaling exponents for PD and HE subjects, but they showed a significant difference in the CP dividing the short- and long-term fluctuations. There are difficulties in interpretation of stabilograms not only of patients with neurological diseases but also of HE subjects. The DFA method may be appropriate for analyzing these cases.

REFERENCES