Relationship between Fractal Property of Gait Cycle and Severity of Parkinson's Disease

Leo Ota, Hirotaka Uchitomi, Kazuki Suzuki, Michael J. Hove, Satoshi Orimo and Yoshihiro Miyake

Abstract— **Parkinson's disease (PD) is a neurodegenerative disorder characterized by degeneration of dopaminergic neurons, affecting motor controls by basal ganglia. Serious movement disorders such as tremor or gait disturbance are often observed, but early diagnosis of PD is difficult. From such a background, Detrended Fluctuation Analysis (DFA) attracts attention as one of the methods for analyzing the fluctuation of the gait cycle in recent years. Therefore, the aim of this study is to clarify the relationship between the fractal exponent of DFA and disease severity of the PD patients. We performed the DFA analysis of gait cycle in 200 meters' walk of 17 PD patients and 12 healthy young people. Particularly, we divided PD patients based on the Hoehn and Yahr (HY) scale into an HY2 group (n=9) and an HY3 group (n=8) in order to examine the relation to disease severity. Results indicate that fractal exponent was significantly lower in both PD groups (HY2, HY3) compared to the young healthy person. Fractal exponent also tended to be lower for the HY3 group compared to the HY2 group, although this tendency for fractal exponent decreasing with the disease severity was not significant here. From these results, the randomness of gait fluctuation seems to related to the severity of PD, suggesting a possibility for diagnosis of PD using fluctuation analysis of gait.**

I. INTRODUCTION

Parkinson's disease (PD) is a neurodegenerative disorder characterized by degeneration of dopaminergic neurons. Due to strong depression of motor control and dysfunction of rhythm generation in basal ganglia, movement disorders such as tremor, akinesia, rigidity, and impairment of postural reflex are typical symptom of PD. For example, gait disturbances (festinating gait and freezing gait) are widely observed. Fluctuation of such gait becomes bigger than healthy people and their dynamic stability becomes lower [1], [2], [3].

On the other hand, the initial symptoms of PD are often overlooked by the patient. Therefore biomarkers for early detection of the disease have been studied, such as medical diagnostic imaging system, test of cerebrospinal fluid, and so on [4]. However, a problem that the procedure for such early detection system becomes large-scale was remaining. From this background, the establishment of the early detection method of PD through simple measurement procedure is strongly needed.

L. Ota, H. Uchitomi, K. Suzuki, Y. Miyake are with the Department of Computational Intelligence and Systems Science, Tokyo Institute of Technology, Midori, Yokohama 226-8502, Japan. ohta@myk.dis.titech.ac.jp, uchitomi@myk.dis.titech.ac.jp, max.zukin@gmail.com, miyake@dis.titech.ac.jp

M. J. Hove is with Max Planck Institute for Human Cognitive and Brain Sciences, 04103 Leipzig, Germany. michaeljhove@gmail.com

S. Orimo is with the Department of Neurology, Kanto Central Hospital, Setagaya, Tokyo 158-8531, Japan. orimo@kanto-ctr-hsp.com

In recent years, fluctuation analysis of time series data is attracting attention and Detrended Fluctuation Analysis (DFA) is an example [5]. By this method, we can analyze the fractal properties of non-stationary time series data. For application, long-term correlation and fractal property of the fluctuation of the cardiac cycle are reported and the fractal property becomes lower by a specific disease [6]. Similarly, the fluctuation of the gait cycle analyzed with DFA differs between healthy young people and aging or specific disease (Parkinson's disease and Huntington's disease) [3].

Based on these background, the aim of this study is to investigate relationship between the disease severity of the PD patient and the fluctuation of gait cycle as the first step. Particularly, Hoehn and Yahr (HY) scale is widely used in the clinical field as an index of the severity of the PD [7]. In addition, a fractal exponent is used for an index of the fluctuation for gait cycle by the DFA analysis [3]. Therefore, in this study, we examined the relationship between the fractal exponent of the DFA and HY scale. The possibility of diagnosing PD by analyzing gait cycle fluctuation was considered.

II. MATERIAL AND METHOD

A. Participants

Seventeen patients (11 women, 6 men) with idiopathic Parkinson's Disease participated in the experiment. We recruited the patients whose HY stage is 2 or 3, and they did not exhibit freezing or festinating gait. HY stage 2 (HY2) is defined as bilateral disorder without balance impairment, and HY stage 3 (HY3) is defined as bilateral disorder with balance impairment, but physically independent [7]. These participants were divided into two groups. One group HY2 consisted of 9 patients whose HY stage was 2 (mean age = 65.3 years; s.d. = 6.1 years; see Table II) and the other group HY3 consisted of the patients whose HY stage was 3 (mean age = 70.9 years; s.d. = 8.0 years; see Table III). Mean duration of disease of HY2 was 3.8 years (s.d. = 3.1 years) and that of HY3 was 4.1 years (s.d.=4.5years). All were tested while on dopaminergic medication. Twelve healthy controls (11 men, 1 woman) also participated (mean age = 25.0 years; s.d. = 3.2 years; see Table I). Informed consent was provided and participants were paid for participating. Experimental procedures were approved by the Kanto Central Hospital Ethics Committee.

B. Task and Experimental setup

Participants were instructed to walk at a natural and comfortable pace around a long corridor. The length of the

978-1-4577-1524-2/11/$26.00 ©2011 IEEE

(a) ***A scene of walking experiment***

(b) ***Foot switches for detecting heel contact***

Fig. 1. Experimental scene and experimental setup

course was 200m. On average, each trial lasted about 3 minutes and contained approximately 320 footsteps. Foot step timing was collected via foot switches (OT-21BP-G, Ojiden, Japan) attached to participants' shoes, was relayed to a laptop (CF-W5, Panasonic, Japan) via radio frequency every 10 ms, and was processed in real time. Two transceivers (S-1019M1F, Smart Sensor Technology, Japan) and a receiver (WM-1019M1F, Smart Sensor Technology, Japan) were used. Fig. 1 shows a scene of the walking experiments and foot switches. The computer algorithm controlling the above experimental system was run on the laptop.

C. Data Analysis

The stride interval time series were analyzed. The time series data are represented by $u(i)$ in the following (1),

$$u(i) = T(i+1) - T(i), \tag{1}$$

where $u(i)$ is the i-th stride interval, and $T(i)$ represents the i-th step timing (i.e. the time to get the right foot on the ground).

Fluctuation amplitude is evaluated by CV (Coefficient of variation). This is standard deviation (s.d.) normalized by the mean value, as in (2).

$$CV = \frac{u_{s.d.}}{u_{ave}} \times 100 \qquad [\%], \tag{2}$$

where u_{ave} is average of stride interval and $u_{s.d.}$ is standard deviation of stride interval.

We quantified the long-range correlations using Detrended Fluctuation Analysis (DFA). This technique offers certain advantages over other methods (e.g., spectral or Hurst analyses) when dealing with non-stationary time series, for it "avoids spurious detection of apparent long-range correlations that are an artifact of non-stationarity" [5].

First the human's stride interval time series $u(i)$ is integrated as in (3),

$$y(k) = \sum_{i=1}^{k} (u(i) - u_{ave}), \tag{3}$$

where u_{ave} is the average of stride interval time series. Then, this integrated time series $y(k)$ is divided into equal boxes of length, n. In each box of length n, a least-squares line is fit to the data, which represents the trend in each box. The fluctuation $F(n)$ for each box is then calculated as the root-mean-square deviation between the integrated time-series and its local trend $y_n(k)$ as in (4).

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} [y(k) - y_n(k)]^2} \tag{4}$$

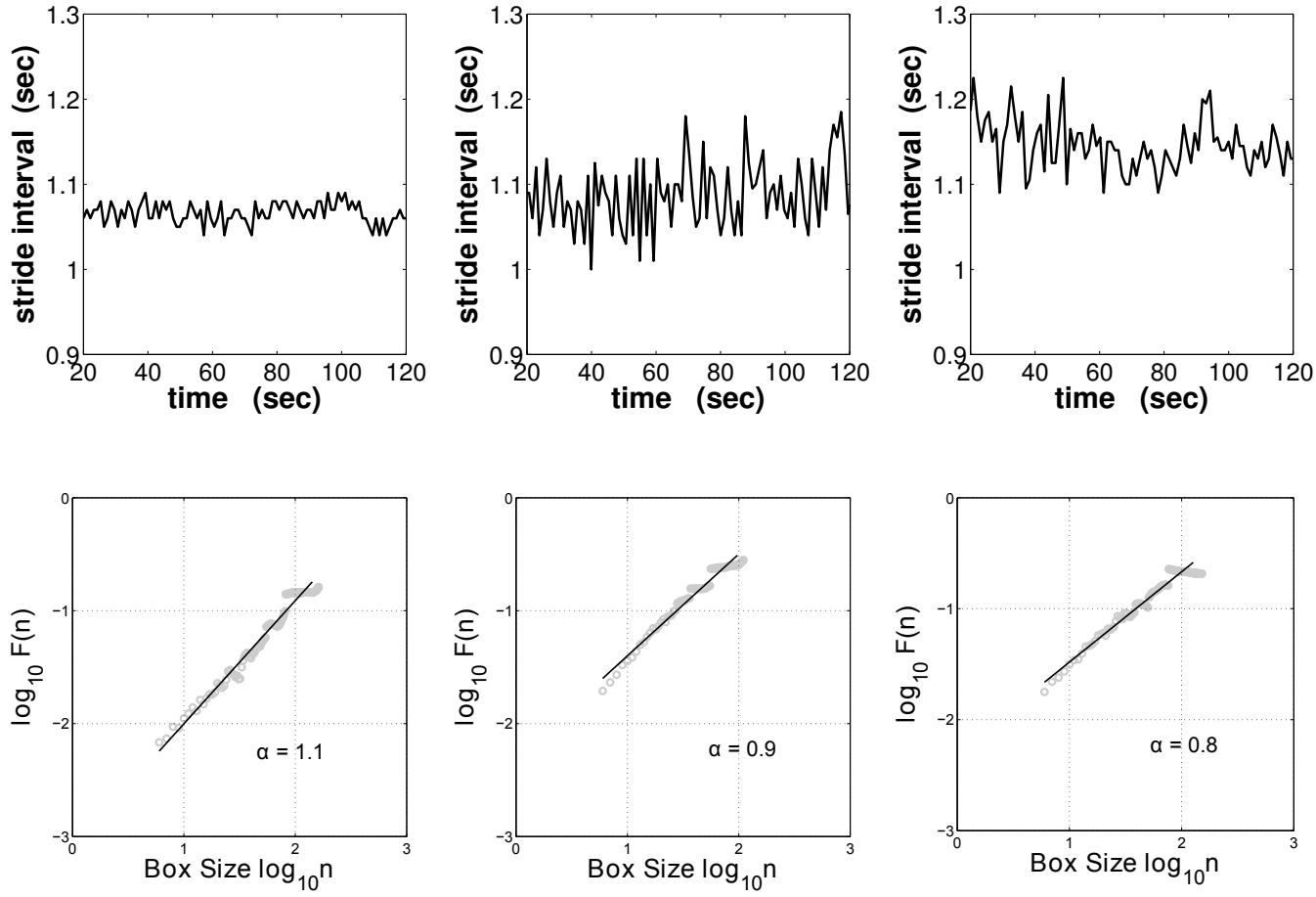
This calculation is repeated for all possible time scales (box sizes) to provide a relationship between $F(n)$, the average fluctuation as a function of box size, and the box size n (i.e. the number of stride interval in a box which is the size of the window of observation).

Typically, the fluctuation, $F(n)$, will increase with larger box sizes. A linear relationship between n and $F(n)$ on a log-log plot indicates self-similar scaling property, in that fluctuations in the smaller boxes are related to the fluctuations in the larger boxes in a power-law relation. The slope of the line $\log_{10} F(n)$ over $\log_{10} n$ is the fractal exponent α, and gives a measure of the "randomness" of the original stride interval time series. Using DFA, a fractal scaling exponent $\alpha = 0.5$ corresponds to rough and unpredictable white noise; $\alpha = 1.0$ corresponds to 1/f-like noise and long-range correlations [5], [6]. Because no significant difference were observed between fractal exponent of stride interval of right and left, analyses were performed on the stride interval of the right leg.

III. Result and Discussion

Fig. 2 shows examples of the time series data of stride interval (upper panels) and the DFA plot (lower panels). Fig. 2(a), 2(b) and 2(c) correspond to healthy young, HY2 and HY3 group, respectively. Comparing these three groups, the temporal variation of stride interval of healthy young group was shown to be smaller than that of HY2 or HY3. The fractal property of these time series data suggests that the fractal exponent becomes lower in bigger HY stage. Furthermore, all DFA fractal exponents are shown in Table I, II and III. The mean values of each fractal exponent were in the order of disease severity. Therefore, the fractal exponent becomes lower in bigger HY stage, suggesting that the higher disease severity means more unpredictable gait.

Fig. 3 is a box and whisker plot of CV. Using Kruskal-Wallis test, the significant difference among healthy, HY2 and HY3 group was shown ($\chi^2(2) = 8.79$, $p = 0.012$). Furthermore, CV of HY3 ($Mean = 2.88\%$) was significantly higher than that of healthy participants ($Mean = 2.02\%$), using Holm's method ($p = .018$). Similarly, CV of HY2 ($Mean = 2.73\%$) was also significantly higher than that of



(a) ***Healthy young participant*** **(b)** ***Patient of HY2*** **(c)** ***Patient of HY3***

Fig. 2. Examples of time series data of stride interval (figures above) and DFA fractal exponents (figures below)

healthy young ($Mean = 2.02\%$) ($p = .032$). These results suggest that fluctuation amplitude of PD patients' stride interval is higher than that of healthy participants. Here, the result that CV of PD patients was significantly higher than that of healthy participants is consistent with previous studies [1], [2], [8]. On the other hand, the significant difference of CV between HY2 and HY3 was not observed (using Holm method, $p = .64$). Mean of CV of HY3 ($Mean = 2.88\%$) was similar to that of HY2 ($Mean = 2.73\%$), but median of CV of HY3 ($Median = 2.72\%$) was likely to lower than that of HY2($Median = 3.28\%$). Median of CV of healthy participants ($Median = 1.94\%$) was the lowest.

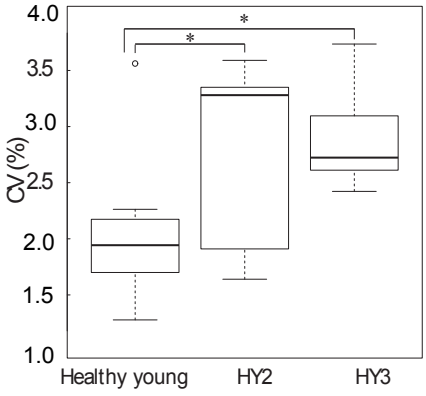


Fig. 3. Comparison of CV of stride interval among healthy young, HY2 and HY3 group (*: $p < .05$)

Fig. 4 is a box and whisker plot of DFA fractal exponents. Using Kruskal-Wallis test, the significant difference among healthy, HY2 and HY3 group was shown ($\chi^2(2) = 7.67, p = 0.02$). Furthermore, the fractal exponent of HY3 ($Mean = .84$) was significantly lower than that of healthy participants ($Mean = 1.04$), using Holm's method ($p = .006$). Similarly, the fractal exponent of HY2 ($Mean = .90$) was also lower than that of healthy young ($Mean = 1.04$) ($p = .03$). These results suggest that randomness of PD patients' stride interval is higher than that of healthy participants. The significant difference of fractal exponent between HY2 and HY3 was not observed (using Holm method, $p = .35$), but mean of fractal exponent of HY3 ($Mean = .84$) is likely to be lower than that of HY2 ($Mean = .90$). Here, similar tendency

TABLE I

DFA FRACTAL EXPONENTS OF HEALTHY YOUNG PARTICIPANTS (M:*Male*, F:*Female*)

Participants	Sex	Age (years)	Stride interval mean (sec)	CV (%)	fractal exponent
1	M	34	1.07	1.28	1.12
2	M	23	1.23	2.71	1.29
3	M	24	1.21	2.18	0.98
4	M	24	1.08	1.49	0.85
5	M	26	1.06	1.84	0.90
6	F	25	1.07	2.02	1.21
7	M	26	1.14	2.12	0.88
8	M	22	1.09	1.70	1.29
9	M	22	1.19	2.26	1.01
10	M	24	1.07	1.86	0.94
11	M	27	1.18	1.70	0.96
12	M	23	1.22	3.56	1.04
mean	-	25.00	1.13	2.02	1.04
s.d.	-	3.25	0.07	0.57	0.15

TABLE II

DFA FRACTAL EXPONENTS OF HY2 PATIENTS (M:*Male*, F:*Female*)

Patients (HY2)	Sex	Age (years)	Disease duration (years)	Stride interval mean (sec)	CV (%)	fractal exponent
1	F	59	0.6	1.01	3.60	0.93
2	F	57	0.5	0.91	1.92	0.91
3	F	76	6	1.01	1.74	0.80
4	F	71	5	0.99	2.22	1.14
5	M	66	0.25	1.00	3.51	0.79
6	F	63	8	1.21	3.35	0.88
7	F	66	2	1.14	3.28	0.99
8	F	61	4	0.95	1.64	0.82
9	F	69	8	1.05	3.35	0.83
mean	-	65.33	3.82	1.03	2.73	0.90
s.d.	-	6.06	3.13	0.09	0.83	0.11

TABLE III

DFA FRACTAL EXPONENTS OF HY3 PATIENTS (M:*Male*, F:*Female*)

Patients (HY2)	Sex	Age (years)	Disease duration (years)	Stride interval mean (sec)	CV (%)	fractal exponent
1	M	69	14	0.97	2.72	0.85
2	F	74	6	1.05	2.54	0.76
3	M	78	4	0.99	2.42	0.90
4	M	53	4	0.99	2.73	1.02
5	F	69	1	1.07	3.29	0.80
6	M	76	0.25	1.15	2.69	0.77
7	F	77	3.00	1.14	3.74	0.72
8	M	71	0.25	0.95	2.90	0.89
mean	-	70.88	4.06	1.04	2.88	0.84
s.d.	-	8.03	4.51	0.08	0.43	0.10

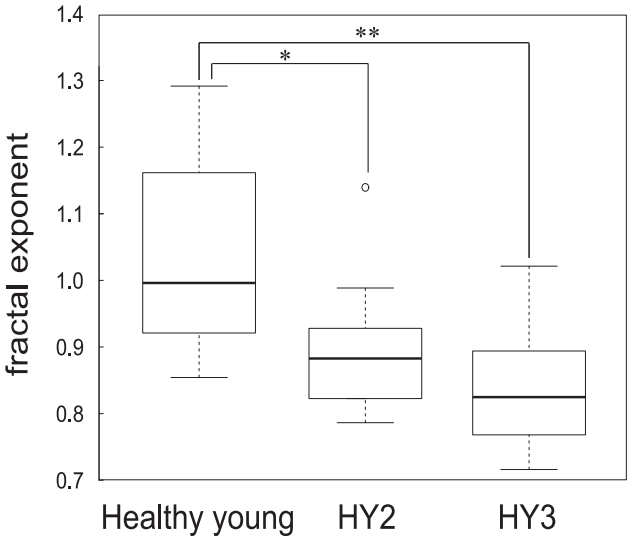


Fig. 4. Comparison of DFA fractal exponents of stride interval among healthy young, HY2 and HY3 group (**: $p < .01$, *: $p < .05$)

were confirmed in previous studies [3], [9]. Moreover, the median of fractal exponent of HY2 ($Median = .88$) was higher than that of HY3 ($Median = .82$). Median of fractal exponent of healthy participants ($Median = .99$) was the highest, and the magnitude relation in median was consistent to the magnitude relation in mean.

From these results, DFA fractal exponent of gait cycle seems to be associated with HY scale compared with CV of gait cycle. These results suggest that the dynamics of gait cycle fluctuation have potential to diagnose the PD disease severity, by only measuring some gait cycle information. To support them, further researches for healthy elderly people and PD of HY stage 1 are needed.

IV. ACKNOWLEDGMENTS

The authors express to participants our deepest gratitude. The authors gratefully acknowledge the contribution of Kanto Central Hospital.

REFERENCES

[1] J. M. Hausdorff, Merit E. Cudkowicz, R. Firtion, J. Y. Wei and A. L. Goldberger, "Gait variability and basal ganglia disorders: stride-to-stride variations of gait cycle timing in Parkinson's disease and Huntingon's disease", *Movement Disorders*, vol. 13, No. 3, 1998, pp. 428-437.

[2] J. M. Hausdorff, "Gait variability: method, modeling and meaning", *Journal of NeuroEngineering and Rehabilitation*, vol. 2:19, 2005.

[3] J. M. Hausdorff, "Gait dynamics in Parkinson's disease : Common and distinct behavior among stride length, gait variability, and fractal-like scaling", *CHAOS*, vol. 19, 026113, 2009, pp. 1-14.

[4] A. W. Michell, S. J. G. Lewis, T. Foltynie and R. A. Barker, "Biomarkers and Parkinson's disease", *Brain*, vol. 127, No. 8, 2004, pp. 1693-1705.

[5] C. -K. Peng, S. Halvin, H. E. Stanley and A. L. Goldberger, "Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series", *CHAOS*, vol. 5-1, 1995, pp. 82-87.

[6] A. L. Goldberger, L. A. N. Amaral, J. M. Hausdorff, P. Ch. Ivanov, C. -K. Peng, "Fractal dynamics in physiology: Alterations with disease and aging", *PNAS*, vol. 99, suppl. 1, 2002, pp. 2466-2472.

[7] C. G. Goetz, W. Poewe, O. Rascol, C. Sampaio, G. T Stebbins, C. Counsell, N. Giladi, R. G. Holloway, C. G. Moor, G. K. Wenneng, M. D. Yahr and L. Seidl, "Movement Disorder Society Task Force Report on the Hoehn and Yahr Staging Scale: Status and recommendations", *Movement Disorder*, vol. 19, No. 9, 2004, pp. 1020-1028.

[8] R. Baltadjieva, N. Giladi, L. Gruendlinger, C. Peretz and J. M. Hausdorff, "Marked alterations in the gait timing and rhythmicity of patients with *de novo* Parkinson's disease", *European Journal of Neuroscience*, vol. 24, 2006, pp. 1815-1820.

[9] R. Bartsch, M. Plotnik, J. W. Kantelhardt, S. Havlin, N. Giladi and J. M. Hausdorff, "Fluctuation and synchronization of gait intervals and gait force profiles distinguish stage of Parkinson's disease", *Physica A*, 383, 2007, pp. 455-465.