Spectral Analysis of Gait Variability of Stride Interval Time Series: Comparison of Young, Elderly and Parkinson’s Disease Patients

Abstract. [Purpose] The purpose of this study was to verify a method of spectral analysis of stride-to-stride variability, and to apply this method to the analysis of the gait pattern of patients with Parkinson’s disease. [Subjects] Ten healthy young individuals, ten community-dwelling elderly individuals and nine individuals with Parkinson’s disease were recruited. [Methods] To quantitatively evaluate stride-to-stride variability, we used fast Fourier transform, calculated the power spectrum, and separated it into three frequency ranges. We plotted a double-log graph for the power spectrum and calculated the slope of the line using least-squares regression. For each of the participants we measured 10-meter walking speed, stride-to-stride variability, and disease severity (only Parkinson’s disease). [Results] Each of three ranges of the power spectrum was four times larger for Parkinson’s disease patients than for the healthy groups (p < 0.05). The severity of Parkinson’s disease correlated significantly with the very low frequency range (0.01–0.05 Hz) of the power spectrum (r = 0.767, p = 0.0159) and the scaling factor β of the power spectrum (r = 0.850, p = 0.0037). [Conclusion] This method of spectral analysis of stride-to-stride variability may be useful for gait analysis of patients with Parkinson’s. [Key words: Gait, Spectral analysis, Parkinson’s disease]

INTRODUCTION

Spectral analysis provides basic information on how power (variance) distributes as a function of frequency. Spectral analysis has been applied to analyze biological signals, such as heart rate, breathing, brain waves, electromyography, and human gait. For example, spectral analysis of heart rate variability has been used as a noninvasive technique to study cardiac autonomic control. This technique provides quantification of the low-frequency and high-frequency oscillations of R-R intervals and reflects the autonomic modulation of the sinoatrial node.

Many patients with Parkinson’s disease walk slowly, with short, shuffling steps and stooped posture. Several studies have used gait speed, step width, and cadence to quantify these disturbances. Housdorff et al. have reported gait fluctuation focusing on stride intervals. They reported that when healthy subjects walked at their normal pace, the fractal
index of the stride interval indicates the presence of long-range self-similar correlation\(^{19}\). The scaling exponent was significantly lower in elderly subjects compared with young subjects\(^{15}\), and the fractal index was significantly different between “fallers” and “non-fallers”\(^{20}\).

Spectral analysis is often used for data mixed with multiple fluctuating factors. Many fluctuations in nature have been evaluated by a scaling factor \(\beta\), for example, signals in the human body, heart rate\(^{21,22}\), respiration\(^{22,23}\), brain waves\(^{22,24}\) and human gait\(^{14,18,19,22,23}\). The scaling factor \(\beta\) is defined as the parameter obtained when the power spectrum is approximated by \(A f^{-\beta}\). Representative fluctuation of time series is roughly classified into three types: \(\beta = 0\) for white noise; \(\beta = 1\) for \(1/f\) noise; and \(\beta = 2\) for brown noise. White (uncorrelated) noise contains even degrees of all frequency ranges. The \(1/f\) noise has many examples in nature, such as fluctuation of heart rate variability in healthy individuals.

There have been numerous reports of gait variability\(^{13–18}\), but few researchers have reported the relationship between the power spectrum of stride-to-stride variability with Parkinson’s disease patients and the disease severity. We hypothesized that the features of the power spectrum of stride-to-stride variability with Parkinson’s disease patients would differ from those of healthy individuals, and that the disease severity would correlate with the features of the power spectrum. The purpose of this study was to verify a new method to analyze the power spectrum of stride-to-stride variability and to apply this method to a comparison of healthy young and elderly subjects and Parkinson’s disease patients.

### SUBJECTS AND METHODS

#### Subjects

Twenty-nine individuals participated in this study: (i) ten healthy young individuals (five males and five females), (ii) ten healthy elderly individuals (five males and five females), and (iii) nine individuals diagnosed with idiopathic Parkinson’s disease (PD; four males, five females). The mean ages of the healthy young and elderly subjects, and the PD subjects were 23 years old (range, 22–32), 70 years old (range, 65–81), and 66 years old (range, 54–77), respectively. The mean heights of the healthy young and elderly subjects, and the PD subjects were 168 cm (range, 153–177), 154 cm (range, 140–163), and 157 cm (range, 141–173), respectively. The healthy young and elderly subjects were enrolled to verify measurement accuracy, and the PD subjects (Table 1) were enrolled to obtain pilot data on the efficacy of spectrum analysis. All participants provided their informed written consent. Subjects who had severe bone joint disease, dementia (Mini-Mental State Examination < 25), or “off” periods in which their medicine suddenly becomes ineffective were excluded.

Participant characteristics (sex, age, height and weight), medical history, physical condition, and the timing and kinds of medication were obtained from all participants. The elderly group and PD patients were examined for dementia by the use of mini-mental state examination. We measured the severity of PD by means of the Webster scale (a gross clinical rating for 10 listed items, each of which was assigned a value of 0–3; total score is 30)\(^{25}\).

<table>
<thead>
<tr>
<th>No.</th>
<th>Sex</th>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>BMI</th>
<th>MMSE</th>
<th>WS</th>
<th>Morbidity</th>
<th>WT</th>
<th>Cane</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>59</td>
<td>1.48</td>
<td>45</td>
<td>20.54</td>
<td>30</td>
<td>1</td>
<td>70</td>
<td>20'00&quot;</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>70</td>
<td>1.41</td>
<td>49</td>
<td>24.65</td>
<td>27</td>
<td>2</td>
<td>3y</td>
<td>20'00&quot;</td>
<td>Right</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>61</td>
<td>1.65</td>
<td>54</td>
<td>19.83</td>
<td>30</td>
<td>3</td>
<td>7y</td>
<td>20'00&quot;</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>77</td>
<td>1.46</td>
<td>35</td>
<td>16.42</td>
<td>25</td>
<td>4</td>
<td>3y6m</td>
<td>10'40&quot;</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>74</td>
<td>1.52</td>
<td>50</td>
<td>21.64</td>
<td>26</td>
<td>6</td>
<td>13y</td>
<td>20'00&quot;</td>
<td>None</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>62</td>
<td>1.62</td>
<td>60</td>
<td>22.86</td>
<td>25</td>
<td>8</td>
<td>12y</td>
<td>10'00&quot;</td>
<td>None</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>67</td>
<td>1.61</td>
<td>57</td>
<td>21.99</td>
<td>29</td>
<td>10</td>
<td>18y</td>
<td>20'00&quot;</td>
<td>None</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>54</td>
<td>1.62</td>
<td>54</td>
<td>20.58</td>
<td>29</td>
<td>11</td>
<td>10y</td>
<td>20'00&quot;</td>
<td>None</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>71</td>
<td>1.73</td>
<td>60</td>
<td>20.05</td>
<td>29</td>
<td>13</td>
<td>4y5m</td>
<td>20'00&quot;</td>
<td>Right</td>
</tr>
</tbody>
</table>

BMI is the body mass index, MMSE is the mini-mental state examination, WS is the Webster scale, and WT is the walk time.
Methods

First, the number of steps and the time to walk 10 meters at each subject’s normal pace were measured twice for each participant. Gait speed was measured using a stopwatch over the distance covered. To identify the heel contact points, a single-axis accelerometer (Acceleration transducer TA-512G /NIHON KODEN, JAPAN) was placed on the participant’s left heel. In advance, we confirmed the heel contact points on the accelerometer using a force platform (AMTI SGA6-4, Advanced Mechanical Technology Inc, USA). The participants were instructed to walk around a 40 meter circular walkway continuously for 20 minutes at their normal pace after walking the circle walkway once to warm up. For PD patients, when the subjects used a cane in daily life, he/she was permitted to use it in the experiment. If a subject stopped walking before finishing the 20-minute walking trial, the trial was stopped.

A telemeter system (Multi-telemeter system WEB-5000/NIHON KODEN, JAPAN) was used to send the data obtained by the accelerometer data to a receiver. The data were recorded on a data recorder (PCM Data Recorder PC208A/SONY, JAPAN), and subsequently processed offline using computer software (PC scan MK2 PCIF250EP/NI/SONY, JAPAN).

The stride interval data recorded by the single-axis accelerometer were stored on the data recorder at a sampling rate of 24,000 Hz. After applying a low-pass filter at 500 Hz, the data were then resampled at 1,000 Hz. Subsequently, each stride interval was determined using data analysis software (MATLAB Version 7.4, Math Works, USA). The coefficient of variation (CV = 100 × standard deviation / mean) and power spectrum were used as indices of walking variability.

Power spectral analysis is commonly used in the frequency analysis of R-R intervals of electrocardiograms. Because the power spectrum of stride to stride variability has many properties in common with the power spectrum of an electrocardiogram, we used an approach that is very similar to the spectral analysis of heart rate variability\(^1\). Consequently, we used the same frequency ranges as those used in the frequency analysis of R-R intervals of electrocardiograms: very low frequency range (VLF; 0.01–0.05 Hz), low frequency range (LF; 0.05–0.15 Hz), high frequency range (HF; 0.15–0.5 Hz), and total frequency range (TF; 0.01–0.5 Hz) as the summation of these three ranges. We also calculated the areas under the power spectrum in the VLF, LF, and the HF ranges.

To investigate the complexity of power spectrum obtained from the stride time data, we calculated the scaling factor \(\beta\), which is an index used when approximating the power spectral density \(P(f)\) by

\[P(f) \approx f^{-\beta},\]

where \(f\) is the frequency, and \(\beta\) is the index (generally, \(0 \leq \beta \leq 2\)) that quantifies self-similarity of biological signals\(^2\).

The coefficient of variation (CV), the areas under the power spectrum in VLF, LF, and HF frequency ranges, and the \(\beta\) values were compared among the three groups of participants. In addition, the relationships between these indices and disease severity were investigated in individuals with PD.

Statistical analysis was performed with SAS software release 9.1.3 and JMP 6 (SAS Institute Japan, Japan). Group results are shown as the mean ± standard deviation. For continuous data, the Tukey-Kramer honestly significant difference test for multiple comparisons was used to test for a statistical difference among the three groups with a significance level of \(p < 0.05\). Spearman’s correlation coefficient was used to evaluate the relationships between these indices and disease severity in individuals with PD.

RESULTS

Figure 1 illustrates the representative walking time series of the young group, the elderly group, and the PD group. For the PD subjects, the walking time series suddenly changed by about 0.2 seconds at about nine minutes. This big change was not seen in the healthy young or elderly groups. Table 2 shows a comparison of the parameters characterizing gait fluctuation in the three groups. The mean values of the stride time series in the three groups were about one second. The mean stride time CV of subjects with PD was almost twice that observed for healthy young and elderly subjects (Table 2).

Figure 2 illustrates the power spectra of the stride time series for all subjects. Table 2 shows the mean values of the areas under the VLF, LF, and HF curves of the three groups. In the PD group, the area...
for each frequency range (VLF, LF and HF) was about four times larger than the respective values for the healthy young and elderly groups, and the differences were significant ($p < 0.05$) (Table 2). The ratios of VLF/TF, LF/TF and HF/TF were compared among the three groups but there were no significant differences.

The scaling factor $\beta$ was compared among the three groups (Table 2). The value of $\beta$ was lowest in the elderly adults, intermediate in PD patients, and highest in young adults. The value of $\beta$ was significantly lower in the elderly adults compared to the young adults ($p < 0.05$), but comparisons of PD patients versus young adults or PD patients versus elderly adults showed no significant differences.

Higher values of CV in PD patients were associated with higher scores of the Webster scale, but there was no statistical significance ($r = 0.467, p = 0.2054$).

As for the relation between the score of the Webster scale and the frequency ranges of the power spectrum, the power located in the VLF range correlated significantly with the score of the Webster scale ($r = 0.767, p = 0.0159$) (Fig. 3), whereas those of LF ($r = 0.45, p = 0.2242$) and HF ($r = 0.283, p = 0.4500$) did not. The VLF range ($0.01 – 0.05$ Hz) involves fluctuations that take place over 20–100 seconds of cycle length. Thus, it
109

is the power located in this range that correlated to disease severity and not the power located within cycle lengths of less than 2–20 seconds.

We found that the higher the score of the Webster scale, the larger the values of the scaling factor $\beta$ in the PD patients. There was also a statistical significance ($r = 0.850, p = 0.0037$) for the correlation between the score of the Webster scale and the scaling factor $\beta$ (Fig. 4).

### DISCUSSION

Using spectral analysis, we evaluated stride-to-stride temporal variations of gait in a twenty-minute walk performed by healthy young and elderly subjects and patients with PD. We found that for patients with PD, the walking time series had a tendency to change suddenly, and this was not apparent in healthy young or elderly subjects. To confirm the long-term fluctuation of gait variability of Parkinson’s disease patients, several researchers have reported gait fluctuations in two- to five-minutes walk$^{13, 26, 27}$. Hausdorff et al.$^{13}$ reported gait variability of PD in a five-minute walk, but they reported no such sudden change as was seen in the present study. Our results indicate that researchers should measure the stride interval time for a longer time, as in the present study, if they wish to focus on such changes.

The mean value of CV for the PD group was almost twice that of those for the healthy groups (young and elderly) for this study. A previous study by Hausdorff et al.$^{13}$ showed that the CV of the stride time for PD patients in a five-minute walk was almost twice as much as that in the control group$^{13}$, and our results for a twenty-minute walk are consistent with their findings.

Three spectral ratios, VLF/TF, LF/TF and HF/TF, were compared among the groups but no significant differences were found. These results indicate that

| Table 2. Comparison of the parameters characterizing gait fluctuation for the three groups |
|----------------------------------|----------|--------|--------|-----------------|---------|---------|
|                                  | Young    | Elderly| PD     | Young vs Elderly| Young vs PD| Elderly vs PD |
| Mean stride time (sec)           | 1.07 ± 0.05 | 0.98 ± 0.06 | 1.04 ± 0.08 | *               | NS      | NS      |
| Mean stride time CV              | 1.25 ± 0.20 | 1.39 ± 0.14 | 2.38 ± 0.53 | NS              | *       | *       |
| VLF ($10^{-4}$) (sec$^2$)        | 0.43 ± 0.16 | 0.36 ± 0.17 | 1.52 ± 0.95 | NS              | *       | *       |
| LF ($10^{-4}$) (sec$^2$)         | 0.34 ± 0.12 | 0.32 ± 0.07 | 1.32 ± 0.56 | NS              | *       | *       |
| HF ($10^{-4}$) (sec$^2$)         | 0.52 ± 0.17 | 0.64 ± 0.18 | 2.25 ± 0.81 | NS              | *       | *       |
| $\beta$                          | 0.88 ± 0.09 | 0.68 ± 0.17 | 0.77 ± 0.20 | *               | NS      | NS      |

Group results are shown as mean ± standard deviation. The Tukey-Kramer honestly significant difference test was used to test for statistically significant differences among the three groups with a significance level of 0.05 (* $p < 0.05$) and NS indicates that the difference was not significant.

![Fig. 3.](image) The relationship between the disease severity of individuals with Parkinson’s disease and the power of very low frequency range. A significant positive correlation was recognized between the disease severity of the PD patients and the VLF ($r = 0.767, p = 0.0159$).

![Fig. 4.](image) The relationship between the disease severity of individuals with Parkinson’s disease and the scaling factor $\beta$. A significant positive correlation was recognized between the disease severity of the PD patients and the scaling factor $\beta$ ($r = 0.850, p = 0.0037$).
power in all frequency ranges in PD patients increased and the ratios, VLF / TF, LF / TF and HF / TF of stride interval time series were not modified substantially by the disease.

It was previously reported that the severity of PD correlated significantly with the CV of stride time variability of PD patients\(^{13}\). In that study, using the Hoehn and Yahr scale, the severity correlated positively with the CV of stride time variability (r = 0.63, p < 0.01). We did not find such trends were significant in our study using the Webster scale.

We found that the power distributed in the VLF range correlated significantly with the score of the Webster scale. The VLF range (0.01–0.05 Hz) represents fluctuations that take place over 20-100 seconds of cycle length. Thus, this result newly reveals a periodicity in stride time of 20–100 seconds that is related to disease severity in individuals with PD. Yulmetyev et al.\(^{27}\) reported that the most trustworthy information can be obtained only from low power frequencies of gait in Parkinson’s disease, but they did not report the relationship between the disease severity and the power spectrum.

In stride-to-stride variability of gait rhythm in humans, it was reported that \( \beta \) has a value of about one in healthy young adults walking at their normal pace\(^{19}\). Hausdorff et al. reported that for healthy elderly adults, stride interval fluctuation tends to be close to random noise (\( \beta = 0 \))\(^{15}\). The results of the twenty-minute walk indicate that the mean of \( \beta \) in the elderly group was significantly lower than that of the young group, and decreased from one to a value of zero, which is in agreement with other reports\(^{15}\).

The results of the twenty-minute walking trial indicate that the scaling factor \( \beta \) calculated from the power spectrum correlated significantly with disease severity in individuals with PD; i.e., the scaling factor \( \beta \) increased with disease severity in PD. It can be interpreted that the power of the VLF range increased with the disease severity causing an increase of scaling factor \( \beta \), because the scaling factor \( \beta \) is the slope of the power spectrum. We speculate that these spectral changes with the disease severity are caused by lesions of the basal ganglia, which could play an important role in initiating and regulating the motor programs involved in balance, gait, and fluidity and sequencing of movement\(^{13,28}\).

ACKNOWLEDGMENT

The authors thank the individuals who participated in this study, the staff at Kitasato East Hospital, and associate professor James Goddard and junior associate professor Leon Bax at Kitasato University.

REFERENCES


