Detecting Freezing-of-Gait Symptom in Parkinson's Disease by Analyzing Vertical Motion from Force Plate

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Abstract. Introduction: Freezing of Gait (FoG) is a common symptom in Parkinson's Disease (PD), which has impact on the gait pattern and relevant to risk of falls. Data-driven approach to FoG detection would allow systematic assessment of patient's condition and objective evaluation of the clinical effects on treatments. Many researchers recently studied FoG in PD by analyzing patient's center of pressure dynamics in term of various features such as path-length. **Objective**: In this research, we attempt to automatically separate two groups of PD patients that with and without FoG by considering standing balance ability during cognitive loading tasks. **Methods**: The dataset consists of sixty PD patients (Hoehn and Yahr stages 1-3) were collected from Thammasat University Hospital, Thailand. The participants were categorized either to be FoG or non-FoG according to the Freezing of Gait-Questionnaire (FoG-Q) scores. Their postural balance ability was measured with Nintendo Balance board which produces a time-series of center of pressure along with the value of changing weight. We turn to a new kind of feature named "FVA" which informs us the acceleration due to the body's up-down motion, and employ Wilcoxon signed-rank statistic to compare the changing of postural control between one with the cognitive loading state (Reading or Counting Backward) and the other in the rest state (Before I or Before II). We also use Student's t-test statistic to analyze the difference of the changing of postural control between two groups, FoG and non-FoG. **Results**: Significant increases of FVA were observed for all cases (for all data, for each group) with cognitive loading ($p<0.001$). The FVA also increases between the rest state and the other rest state after a cognitive loading ($p<0.001$). The changing of FVA between Reading (RE) and Counting Backward (CB) is significant for all data ($p<0.001$) and it is more sensitive in FoG group than in non-FoG group (p 0.03 and 0.21 respectively). To compare two groups, the increase of FVA from the rest state to other with cognitive loading is larger in FoG than in non-FoG ($p<0.01$). The significance is for most cases greater than or equal to features extracted from trajectory of center

of pressure (such as path-length). **Conclusions**: The new feature FVA seems to well reflex postural control in people with PD. It informs us the postural instability in PD, which is more informative than other indices when the subject are under cognitive loading. It is also monotonous with level of complexity of cognitive loading, and is sensitive with FoG group.

Keywords: Parkinson's disease, Postural control, Cognitive loading, Freezing of gait

1 Introduction

Freezing-of-gait (FoG) is a common clinical symptom in Parkinson's disease[2] (PD), observed as inability to start doing a motion and shaking/shuffling gait in a motion [13, 9]. FoG is usually found in PD patients in the advanced stages, but recently FoG has been reported in the early stages as well. Approximately 44–53% of PD patients have the symptom of FoG [6, 12] and the percentage increases up to 80% of PD patients in the advanced stages [17, 10]. PD patients with FoG often have significant changes in their gait progression, decreased foot length, and tremors in FoG attacks [13]. Due to these changes, a basic risk for PD patients with FoG is falling over [15, 1, 14] and so PD patients with FoG are exposed to high risk of fatal accidents, such as fractures or immobility [3]. Therefore, early detection of FoG symptom among PD patients is helpful to prevent them from such accidents, as well as to improve their quality of life.

The mechanism of FoG is yet not entirely understood up to now. Currently, with or without FoG is classified by clinical assessment but often detected after accidents. Recent researches have attempted to elucidate procedures of FoG assessments by incorporating recent findings on the relationship between FoG and other factors. In bio-mechanical approach, Pelykh et al. [16] and Buated et al. [4] characterized the postural control ability of PD patients during cognitive loading tasks by analyzing their center-of-pressure time series. Both studies showed reduced postural control during cognitive loading tasks in both FoG and non-FoG groups; however, no significant difference between groups was reported. In clinical approach, Duncan et al. [8] invented the sub-clinical screening test, called the BESTest, to examine some difference between FoG and non-FoG and obtained high reliability ($p < 0.001$). However, a shortcoming of this test is taking longer than 30 minutes, and expert factors will be cause of limitations in clinical application to a large number of patients.

In this study, our objective is to defect the freezing-of-gait (FoG) symptom in Parkinson's disease (PD) patients based on physical or bio-mechanical data. For this objective, we develop a new feature statistic (or factor) for automatically detecting the FoG symptom of PD patients, easily applicable in clinical assessments. To test our proposed feature, including the standard path length, we analyzed the center-of-pressure time series under cognitive loading tasks.

2 Methodology

2.1 Participants

We briefly describe our data, originally collected by our colleagues [4]. See Buated et al. [4] for details.

60 patients (24 males and 36 females) with Parkinson's disease (PD) were recruited and their center-of-pressure time series were collected in Thammasat Hospital, Thailand. Their clinical stages of Parkinson's disease were classified according to the modified Hoehn & Yahr scale [11]. Patients who can stand alone for 3 minutes were included to this study. Patients with other problems (e.g., atypical parkinsonism, unable to stand without support, partial or complete blindness, etc.) were excluded. All participants with Parkinson's disease were examined during the on-time medication without presenting excessive rigidity, bradykinesia, or tremor.

2.2 Apparatus and Procedures

Center-of-pressure (CoP) time series were recorded using a force place, called Nintendo Wii Balance Board [5], which is a platform for measuring distribution of weight bearing of the subject on it. A recorded data consists of the relative positions of the center-of-pressure (CoP) along the medial-lateral (x) and anterior-posterior (y) dimensions, on the two dimensional surface of the Wii Balance Board. Plus, as a force plate, this Wii Balance Board can record the additional dimension, we call it, 'weight' acting on the balance board surface, due to the motion of the subject. This 'weight' is measured in units of kilogram [kg], unlike the units in physics [kg $\times$ g] with gravitational acceleration $g = 9.8(m/s^2)$.

Each patient was instructed first to stand upright on the balance board, looking horizontally to a marker on the wall at 3 meter apart, and then to follow the four instructions: (1) Before I: Keep standing for 30 seconds; (2) Reading (RE): Keep standing with reading a material for 30 seconds; (3) Before II: Keep standing for 30 seconds; and (4) Counting Backward (CB): Keep standing with counting numbers backward for 30 seconds.

3 Features for Postural Instability

In this section, we described the newly proposed feature statistic, called Fluctuation of Vertical Acceleration (FVA), as well as the clinical standard, known as path length.

3.1 Path Length

Path length is simply the total length of a CoP path. Given time series of CoP $(x(t), y(t))$ at time frame t, it was calculated by summing up the distances be-

tween consecutive data points [7], i.e.,

$$\text{PathLength} := \sum_t \sqrt{[x(t+1) - x(t)]^2 + [y(t+1) - y(t)]^2} \tag{1}$$

3.2 Fluctuation of Vertical Acceleration (FVA)

We derive a new feature statistic, we name it, Fluctuation of Vertical Acceleration (FVA). As we have described, the Wii Balance Board can record the 'weight', divided by $9.8(m/s^2)$ (unit equivalent to kg) of the subject for each time. This 'weight' has not been incorporated for characterizing the balance dynamics of PD patients. You may think that it is strange if the 'weight' of the subject changes over time. Then, we have to clarify the difference of 'weight' and 'mass' in physics terminology. In physics, 'weight' is simply the mass × 9.8, in units of kg × 9.8, where 9.8 is the gravitational acceleration on Earth. If the subject has exactly no motion on the balance board (or force place), then the 'mass' of the subject and 'weight' divided by 9.8 can take the same or close value. However, if the subject has in motion on it, then the force (or kinetic acceleration) acted on the surface of the balance board can be detected and included in part of the 'weight' measured by the balance board. And so, the 'weight' of the subject measured can vary over time. In other words, the 3rd dimension of recorded data, 'weight' divided by 9.8, contains information due to vertical acceleration. In this paper, we proposed to incorporate this feature, vertical acceleration, to characterize the postural stability of subjects.

According to the Newton's second law, the weight $\bar{w}$ on Earth at the rest state is the body mass m times gravitational constant g: $\bar{w} = mg$. In addition to this, the weight $w(t)$ measured by the balance board at time t can include the additional factor due to the acceleration (or force) approximately along the vertical $a_z(t)$: $w(t) = mg + ma_z(t)$. Then, from recorded time series $w(t)$, we can extract the vertical acceleration at time t by

$$a_z(t) = \frac{w(t) - \bar{w}}{m} \quad . \tag{2}$$

Taking the ratio gives a quantity independent of the body mass m as

$$\frac{a_z(t)}{g} = \frac{w(t)}{\bar{w}} - 1 \quad . \tag{3}$$

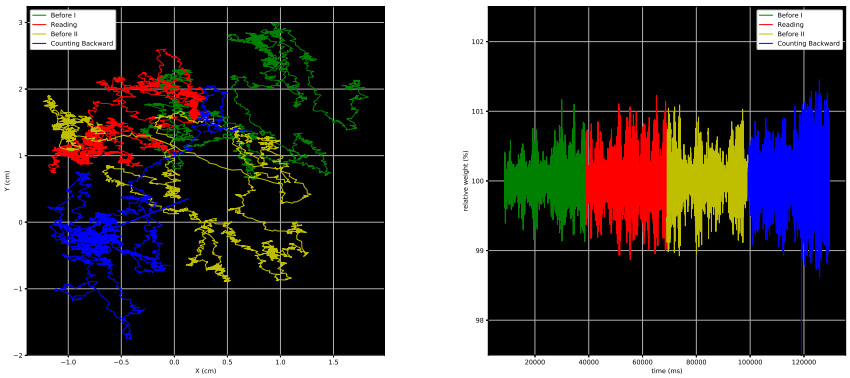
which is in units of percent [%]. The value of $\bar{w}$, the weight at no motion, can be measured by a weight scale at home or estimated by the average over time $\bar{w} = (1/T)\sum_t w(t)$. Finally, our new feature, Fluctuation of Vertical Acceleration (FVA), is defined as its deviation from the mean

$$\text{FVA} = \text{std}\left(\frac{a_z(t)}{g}\right) \times 100 \quad , \tag{4}$$

where the std(·) operator calculates the standard deviation.

3.3 Visualization of Features

Figure 1(a) visualized a CoP path of a patient. Four colors, green, red, yellow, and blue, were used for the four conditions, i.e., Before I, Reading, Before II, Counting Backward, respectively. In Figure 1(b), we showed the time series of Vertical Acceleration (VA), calculated by using Equation (3). Our new feature, Fluctuation of Vertical Acceleration (FVA), Equation (4), characterizes the variation of Vertical Acceleration in Figure 1(b).



(a) Center-of-Pressure path (b) Vertical Acceleration (VA)

Fig. 1: (a) A visualization of a patient's center-of-pressure data. The green, red, yellow, and blue colors corresponds to the four conditions: Before I, Reading, Before II, Counting Backward. (b) Part of the new feature, Vertical Acceleration, in Equation (3).

4 Results

4.1 Data Processing

In our data analyses, for each PD patient's CoP path, we calculated two feature statistics, Path Length (PL) and Fluctuation of Vertical Acceleration (FVA), for four data segments corresponding to the four conditions of our data recording: i.e., Before I, Reading, Before II, and Counting Backward. In some analyses, we also used two combined features, difference in the values of each feature (FVA or PL) between Before I and Reading and between Before II and Counting Backward. Resulting, we obtained $4 \times 2 = 8$ features, or $4 \times 2 + 4$ features for each PD patients.

PD patients were classified into two groups, FoG and non-FoG, based on FoG-Q scores, FoG-Q ≥ 6 for FoG (n = 39) and the rest for non-FoG (n = 21).

Table 1 is the summary of two kinds of feature statistics for all combinations of the four conditions times three subsets of data. Each cell of Table 1 contains $\mu \pm \sigma$ as the mean μ and the standard deviation σ. In most cases, the mean values increase from non-FoG to FoG and from Before I, Before II, RE, to CB, orderly.

Feature	FVA			Path length		
Task	All data	FoG	non-FoG	All data	FoG	non-FoG
Before I	0.23 ± 0.18	0.25 ± 0.21	0.19 ± 0.08	81 ± 33	85 ± 39	73 ± 14
RE	0.32 ± 0.32	0.36 ± 0.39	0.23 ± 0.07	93 ± 58	100 ± 70	79 ± 16
Before II	0.27 ± 0.28	0.32 ± 0.34	0.20 ± 0.06	89 ± 47	95 ± 56	77 ± 17
CB	0.41 ± 0.54	0.48 ± 0.65	0.28 ± 0.12	109 ± 82	121 ± 98	87 ± 24

Table 1: The average and standard deviation of FVA and path length in the dataset. RE = Reading; CB = Counting Backward; FVA: unit in percent; Path length: unit in centimeter

4.2 Goals and Procedures of Statistical Analysis

In this study, we set two goals for analysis. Firstly, we analyze the effects of the cognitive loading tasks (Reading and Counting Backward) on postural control by comparing them from the preceding rest conditions (Before I and Before II), within the groups. Secondly, to demonstrate the power of the new feature for detection of FoG in PD patients, we compared the effects on postural control between the groups, the FoG and non-FoG group. To evaluate the influence of cognitive loading to postural control within the groups, we used the Wilcoxon signed-rank test with the null hypothesis of no difference between the tasks. To evaluate differences between the groups, we used the Student's t-test with the null hypothesis of no difference between the groups.

4.3 Impact of Cognitive Loading on Postural Control

The results of empirical data analysis showed in Table 2. Each cell contains the p-values of Wilcoxon signed-rank statistics in comparison between the conditions. We observed that both FVA and PL produced the significant influence (mostly $p \leq 0.01$) of cognitive loading on posture control. Generally, using FVA tends to be more significant. The results suggest that both features, FVA and PL, can work for defecting FoG in comparing the CoP paths within the groups or between the conditions.

We observed the influence of the cognitive loading tasks, within the groups, also in Figure 2. Figure 2 shows the FVA's of all patients, their ID $= 0, 1, 2, \ldots, 59$,

separately, along the horizontal axis of each figure. The bottom figure includes all four conditions, i.e., Before I (green), Reading (red), Before II (yellow), and Counting Backward (blue). The top-left includes only Before I (green) and Reading (red) and the top-right includes only Before II (yellow) and Counting Backward (blue). We also observed the increases in FVA's clearly from Before I (green) to Reading (red), and from Before II (yellow) to Counting Backward (blue).

Task		FVA			Path Length		
A	B	All data	FoG	non-FoG	All data	FoG	non-FoG
Before I	RE	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Before II	CB	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Before II	RE	< 0.001	0.002	< 0.001	0.010	0.044	0.120
RE	CB	< 0.001	0.035	0.021	0.002	0.008	0.010
Before I	Before II	< 0.001	0.001	0.01	0.003	0.01	0.006

Table 2: Results (p-values) of Wilcoxon signed-rank test between the experimental conditions. RE = Reading, CB = Counting Backward

4.4 Comparison between the FoG and non-FoG group

Next, we examined differences between the FoG and non-FoG group. In this analysis, we used the combined features, described in the section of data processing, denoted by Δ(Before I, RE) for the difference in a feature between the Before I and Reading condition, and Δ(Before II, CB) between the Before II and Counting Backward condition. The results showed in Table 3 with p-values of the Student's t-test. We observed the significant difference between the non-FoG and FoG group, in using both features, FVA and PL. In some cases, using FVA tends to be more significant.

We can also confirm visually the results of statistical tests in Figure 3. Figure 3, the left two figures compare the impacts of the Reading task and the right two figures compare the impacts of the Counting Backward task. The bottom two figures contain the FVA's of PD patients with non-FoG and the top two figures contain the FVA's of PD patients with FoG. From these figures, we observed that the patients with FoG tend to show larger individual variation in FVA, in both the cognitive loading tasks.

5 Discussion

In this paper, we tried to defect the freezing-of-gait (FoG) symptom in Parkinson's disease (PD) patients based on physical or bio-mechanical data. In our data analysis, in addition to the standard Path Length (PL), we evaluated our newly proposed feature, called Fluctuation of Vertical Acceleration (FVA). Our results

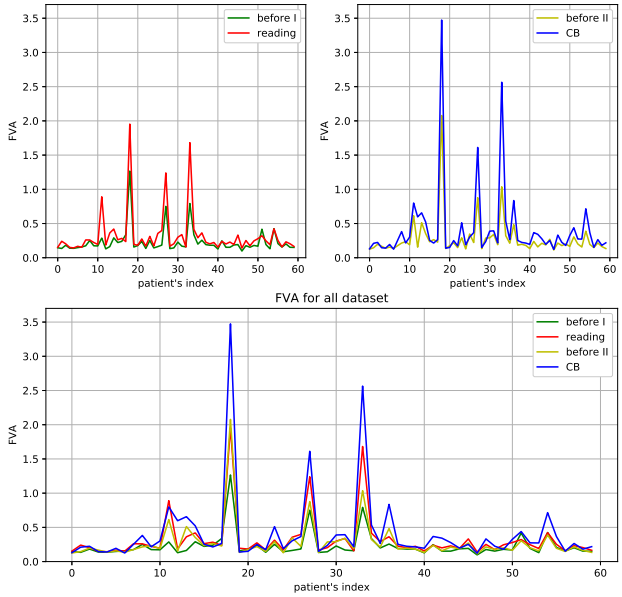


Fig. 2: Comparison of FVA between the experimental conditions. Before I (green), Reading (red), Before II (yellow), and Counting Backward (blue).

Task	FVA	Path length
Before I	0.073	0.054
RE	0.018	0.035
Before II	0.017	0.042
CB	0.034	0.023
Δ(Before I, RE)	0.010	0.040
Δ(Before II, CB)	0.085	0.022

Table 3: Results (p-values) of Student's t-test between the FoG and non-FoG group. RE = Reading and CB = Counting Backward. Δ(Before I, RE) = change from Before I to Reading. Δ(Before II, CB) = change from Before II to Counting Backward.

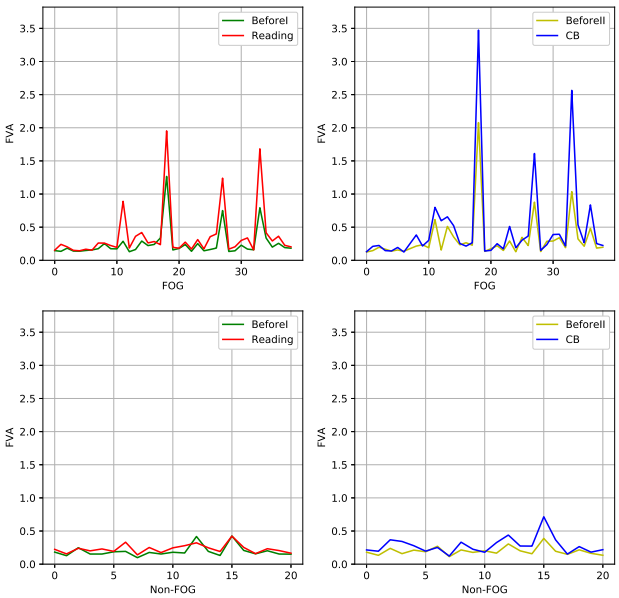


Fig. 3: Comparison of FVA between the FoG and non-FoG group. Before I (green), Reading (red), Before II (yellow), and Counting Backward (blue).

suggest that both PL and FVA can work for defecting the FoG symptom. Thus, our new feature, FVA, can be as good as the clinical standard, PL. In our results, we observed that, in some experimental conditions, our new feature, FVA, can be better than PL. This suggest that we can develop some experimental schemes suitable for FVA, which can be helpful for earlier defection of the FoG symptom. One of our future works is to develop such experimental schemes, toward data-driven clinical assessments, to help people with the freezing-of-gait symptom in Parkinson's disease patients.

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