Exploring precursors of Parkinson's disease by characterizing dynamic postural balance in center-of-pressure time series

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Abstract— Postural balance is our basic motor ability that recently measured for clinical assessment of Parkinson's disease. Based on our hypothesis that a loss of dopamine-secreting neurons causes delay in reaction time, we explored to characterize postural balance ability by applying auto-regressive models with time delay to the center-of-pressure time series. The binary classification between Parkinson's disease patients and healthy people achieved about 70% of accuracy, by adding features from auto-regressive models.

***Keywords*— Postural balance, Center of pressure, Parkinson's disease, Time-series analysis**

1. Postural balance and Parkinson's disease

Postural balance is one of the basic motor abilities to maintain our body's center of gravity within our body's base of support. The center of gravity outside the base of support raises a risk of falling over, which can be caused even by simple daily motions, such as walking and pushing/pulling. Thus, difficulty in keeping postural balance may significantly increase difficulty in our daily tasks and so in our life.

Difficulty in postural control is often reported as one of the symptoms of Parkinson's disease. Parkinson's disease is known as a neurological degenerative disorder, specifically developed due to a loss of dopamine-secreting neurons in the substantia nigra [1]. It affects mainly the motor system of the patient's brain. The observed motor symptoms of Parkinson's disease include shaking of limbs, freezing of gait, and difficulty in postural balance [2,4]. Parkinson's disease is typically slowly-progressive, and several medicinal treatments (e.g., levodopa injection) can be effective especially for patients in early stage. Earlier detection of Parkinson's disease is desirable.

The Hoehn-Yahr scale [2] is a clinical system commonly used for assessing the progression of Parkinson's disease based on observed symptoms. Based on the current knowledge on Parkinson's disease symptoms, namely difficulty in postural balance, the handy biomechanical device called "force plate" has been adopted to evaluate each patient's ability of maintaining postural balance. Force plates are a measurement device on the floor to record the center of pressure (CoP) of the user, who mounted on it, instead of hardly-accessible the center of gravity of the user. The merits of using force plates are non-invasive, inexpensive, and easy-to-use. Previously, the length of a CoP path or trace (called "path length") for a fixed time range [3] has been known to be a better predictor of the progression stage of Parkinson's disease [4] in the sense of the Hoehn-Yahr scale. In this paper, we explore the use of a dynamic model-based characteristics to discriminate patients with Parkinson's disease from healthy people, based on their CoP paths, toward early detection of postural balance difficulty, or Parkinson's disease.

2. Method

2.1. Data collection

The data was collected by [4] at Thammasat University in Thailand. We describe briefly here; see [4] for details. Sixty-two patients of Parkinson's disease (in short, PD patients) and 53 healthy people were recruited. We call them simply participants.

The center-of-pressure of each participant was recorded by a force plate, the Wii Balance Board from Nintendo. It contains four pressure sensors at the corners of the bottom and the four sensors are used to calculate the location (x, y) of the user's center of pressure over time. Each sensor measures in unit of about 10 gram. The sampling rate is about 100 Hz. The side-to-side dimension (x) is 511mm and the front-to-back dimension (y) is 316mm.

For the data we used here, the participants were instructed to keep standing naturally on the force plate while looking at a marker on the wall in about 3m distant from them. The participants were just standing for the first and last 30 seconds with open eyes and were asked to close their eyes for 30 seconds in the middle of measurement. The raw time series for all 90 seconds were analyzed here.

2.2. Hypothesis and statistical modeling

Making an indicator of inability of postural balance has been attempted in clinical practice, for example, by the total length of a CoP path, called "path length", for a fixed time range [3]. Path length can be convenient from a clinical point-of-view. But, the time series of CoP paths would enclose more to detect the latent presence of Parkinson's disease than a scalar-valued quantity (path length). This motivated us to incorporate time-series models for characterizing the underlying dynamics behind CoP paths.

Based on the current neurological findings that Parkinson's disease correlates with a loss of dopamine-secreting neurons and the symptoms include difficulty in postural balance, we hypothesized that there might be a time delay unusual in their sensor feedback and motor activation cycle (sensor-motor loop), so in their reaction time, hopefully due to the weakness of secreting dopamine. We suspect that accumulated effects of instantaneous delayed reactions cause instability of postural balance to (probably not all but some types of) Parkinson's disease patients, and their delays in reaction time could be extracted from their CoP paths. For this hypothesis, the underlying dynamics behind a CoP path observed is

modelled by an auto-regressive process with time delay, which can exhibit mean-reverting behaviors given some parameters. Indeed, observed CoP paths usually are apparently moving around some point, often the middle between their feet; otherwise, the participants fall over or get outside the force plate (we observed no such case).

An auto-regressive model AR(p) we adopted here is

$$y_{t+1} = c + \sum_{i=1}^{p} a_i y_{t+1-i} + \varepsilon_t$$

where y_t is observed variable at time $t = 1, \dots, T$, $a_1, \dots, a_p$ is auto-regression coefficients, $\varepsilon_t \sim N(0, \sigma)$ is Gaussian noise, and c is constant. AR(p) models predict future observation y_{t+1} from its own past observations $y_t, \dots, y_{t+1-p}$. The coefficients $a_1, \dots, a_p$ characterize linear dependence on past values of the process itself. The smaller $|a_1|$, the AR(1) is the more like the white noise, moving around near the mean. Given $a_1 = 1$, the AR(1) is well-known the random walk, which can go away from the mean. The variance σ^2 of noise can be interpreted as a velocity of the AR(p) process. The larger σ^2, the AR(p) will move the more at an instant.

To incorporate the effects of reaction time delays in AR(p) models, we replace y_{t+1-i} by $y_{t+1-i\delta}$ given step size δ. We refer to $\delta > 0$ as time delay parameter. Let us denote this by $\mathrm{AR}_\delta(p)$.

We set the task here to a two-class classification between patients with Parkinson's disease and healthy people, based only on their CoP paths. That is, the task is identifying the latent medical/physical condition of a participant (PD patient or healthy person) from the force place data. We applied a logistic regression analysis for the feature vector consists of (c, a_1, σ) estimated by $\mathrm{AR}_\delta(p)$ models for $\delta = 1, \dots, 20$. For each $\mathrm{AR}_\delta(p)$, the best lag p was chosen so as to minimize AIC. The feature vector for each participant has length 3×20.

Based on this $\mathrm{AR}_\delta(p)$ model, we expect that the CoP paths of PD patients tend to show larger coefficients a_i and/or larger variance σ^2, since combining both yields wider spreading, more fluctuated path within a fixed time range; it is considered to be instable in postural balance. Oppositely, we expect that the CoP paths of healthy people will show smaller a_i and σ^2, resulted in narrower spreading path is considered to be stable in balance.

3. Results

In our logistic regression analysis, $N_P = 62$ of Parkinson's disease patients and $N_H = 53$ of healthy people were involved. A half from each class were randomly taken for a training set and the other half from each class for a testing set. Totally, 200 different training sets and testing sets were used to obtain the classification accuracy.

The average accuracy of this binary classification was about 66.6% with auto-regressive features, while path length, one of the clinical standard measurements for clinical assessment, could achieve only near 50% change level in classification accuracy. Thus, our auto-regressive features might successfully extract more clues related to Parkinson's disease from their CoP time series.

We have also considered two other features, such as $\max\{a_i\}$ and/or $\sum_{i=1}^{a_i>0} a_i$ to characterize largest positive correlation and/or total positive correlation on their history (in our analysis, the first $a_1 > 0$ for all participants). Adding those into the feature vectors increased the classification accuracy to about 70.1%.

4. Discussion

To know how the classification accuracy increased, we checked the weights (i.e., logistic regression coefficients; not a_i) of the logistic regression analysis. The 1st auto-regression coefficient a_1 of time delay $\delta = 3$ had the largest contribution to the accuracy, and those of $\delta = 4, 5$ showed similarly but less. It has been known that the human reaction time for limb reflexes is about 25~35ms [5,6]. In our study, from the frame rate of the Wii Balance Board which is 100 Hz, the time delay $\delta = 3$ corresponds to 30ms. Thus, this result might suggest that there are informative difference even in such small time fragments to discriminate participants' medical/physical conditions relating their ability of postural balance.

At this time delay $\delta = 3$, we found that the coefficients a_1 of healthy people tended to take smaller values than those of Parkinson's disease patients ($t(113) = 3.84, p = 0.00$) and the variances σ^2 also showed similar tendency ($t(113) = 1.86, p = 0.06$). These results were roughly saying consistent with our expectation (the last paragraph of Section 2) based on $\mathrm{AR}_\delta(p)$ models. Thus, our results suggest that our dynamic model-based characterization of participants' CoP paths may capture some nature of the unknown underlying postural control systems, of human participants, which might be informative for early detection of difficulty in postural balance control. Hopefully, our findings promote early detection of some trends for Parkinson's disease.

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