31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Analyzing 180° Turns Using an Inertial System Reveals Early Signs of Progression of Parkinson's Disease

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Abstract— **Changes in turning are one of the early motor deficiencies in Parkinson's Disease (PD). We have proposed a system based on wearable, inertial sensors and a novel automatic analysis algorithm that can assess 180° turns. Twelve patients in early stages of PD and 14 age-matched healthy subjects were enrolled in this study. Inertial sensors were attached on shanks and sternum. Measurement protocol included walking on a straight pathway, turning 180° and returning back. Subjects were measured 4 times, once every 6 months during an 18 months period. At the baseline, 9 subjects from each group repeated the test twice to assess test-retest reliability. Patients with mild PD had a very low Postural Instability Gait Difficulty (PIGD subscore of UPDRS III) score (average 0.67, min 0, max 3). The analysis showed that the patients had a significantly longer turning duration (2.18±0.43 vs. 1.79±0.27 seconds, $p<0.02$) and longer delay in their last step before initiating a turn (0.56±0.04 vs. 0.52±0.04 seconds, $p<0.03$). Estimated turning duration and other metrics had a high test-retest reliability ($\rho>0.85$). Turning duration also showed a significant *Group*Time* interaction ($p<0.03$) during the longitudinal study highlighting early signs of the progression of the disease.**

I. INTRODUCTION

Turning difficulties are common in patients with Parkinson's Disease (PD). These difficulties, especially in advanced PD, are related to freezing of gait (FOG) and increased risk of falling [1]. Unfortunately the motor section of the Unified Parkinson's Disease Rating Scale (UPDRS), which is the most widely used assessment method in clinical practice, does not directly assess turning in PD. Recent studies have shown that the duration of turns and number of steps during turns are effective metrics to assess turns in PD [2], [3].

Recently, there has been a lot of progress in developing objective methods to characterize these complex activities in clinical environments using wearable, inertial sensors [4]. Researchers have used gyroscopes and accelerometers to assess different movement disorders associated with PD including tremor [5], [6], bradykinesia [6], [7], gait [8], [9] and dyskinesia [10]. As a part of *Timed Up and Go* test, recent studies have also used inertial sensors to quantify turning [11], [12].

An interesting problem in turning analysis is defining the onset and offset of turns [12], [13]. Reference [11] used angular velocity in the yaw-axis and a fixed threshold to define onset and offset of turning. While [12] did not clearly define turning duration, it is assumed a similar approach was used. A problem with this approach is sensitivity to noise especially during slow turns where rotations of trunk during gait might have a noticeable amplitude compared to the turn velocity.

In this study, we use a mathematical model to detect and analyze 180° turns. Combined with our previously published method of gait analysis [9], our turning analysis algorithm not only estimates duration of turns, but also provides other useful metrics. We demonstrate sensitivity of these metrics by comparing performance of a group of early, untreated PD patients with a group of age matched healthy controls. We also investigate the test-retest reliability of these metrics as well as their responsiveness by looking at early signs of the progress of PD in this group of patients.

II. METHODS

A. Patients

Twelve subjects with idiopathic Parkinson's disease (60.2 ± 8.9 years old, 7 males) and 14 age-matched control subjects (61.1 ± 7.9 years old, 3 males) participated in this study. Healthy control subjects were either spouses of the patients or recruited from the community. Subjects were in early-to-moderate stage of disease (H&Y score between 1 and 2.5, UPDRS motor score 20.3 ± 9.8) and had never taken anti-Parkinsonian medications. Subjects did not have any neurological disorders other than PD, or any orthopedic disorders or other impairments that could potentially interfere with gait. All participants provided informed consent approved by the Oregon Health & Science University Institutional Review Board. Since UPDRS does not have a turning subscore, we used its Postural Instability Gait Difficulty (PIGD) subscore as the clinical measure of mobility and balance of the subjects. PIGD has a range between 0 and 16 where 0 is unaffected and 16 is the most affected.

This work was supported by the Kinetics Foundation, a pilot grant from Oregon Center for Aging and Technology (AG024978), and the National Institutes on Aging (AG006457). *Asterisk indicates corresponding author.*

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978-1-4244-3296-7/09/$25.00 ©2009 IEEE

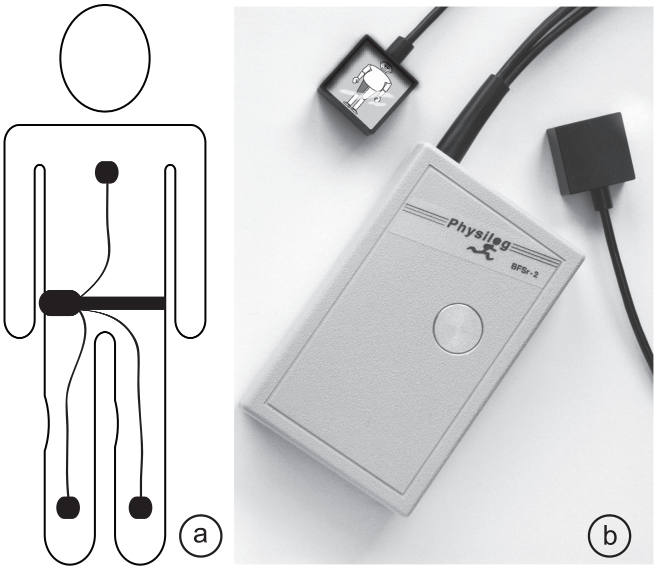

Fig. 1. a) System consisted of 3 sensors connected to a portable data-logger. b) The Physilog inertial recording system.

B. Measurement Protocol

Subjects were measured during a period of 18 months at 6 months intervals. In each visit, they completed three turning trials. They walked on a straight, seven meters long, clearly marked pathway. These markings were shown to the subjects before the test. The end line was 3 meters away from the wall. Subjects were instructed to walk at their normal speed, turn around right after passing the tape at the end of the pathway and return back. All sessions were recorded on video to verify performance.

To assess test-retest reliability of the measured parameters, nine subjects in each group repeated the protocol at the baseline a second time. After finishing the three initial tests, sensors were removed. After one hour, the sensors were replaced, and the protocol was repeated. The same researcher placed the sensors and conducted the tests. We assumed that the subjects' performance remained the same within this time period.

C. Measurement System

Subjects carried a small data-logger, Physilog (BioAGM, CH) [14], in a waist-worn pack with three inertial sensors attached on the shanks and sternum (see Fig. 1). The sensor on sternum was fixed with double stick tape and had a gyroscope in yaw axis (range ±400 °/s). Sensors on the shanks had a gyroscope in pitch axis (range ±600 °/s) [9] and were fixed with Velcro straps. Sampling rate was 200 Hz. The data were recorded on a 128MB SD flash card.

D. Analysis of Turning

The most important problem in analyzing turns is identifying the onset and offset of the turns. Unlike initial and terminal contacts in gait analysis, onset and offset of turns are not time events marked by sudden, distinct movements of the body or impacts with the floor, but are rather a slow transition from one form of activity (straight walk) to another (turn). In [11] the onset and offset of turns were defined by setting a fixed threshold on the trunk angular velocity in the yaw axis. However, gait and transitions may produce noticeable noise in the trunk sensor. As a result threshold-based methods may be sensitive to noise especially in slower gait and turning speeds.

The signal from the yaw gyroscope on the sternum was used to detect 180°turns ($\omega_{yaw}(t)$, Fig. 2.a). The signal showed large variations associated with shoulder girdle rotation during walking. Although it is relatively easy to identify when turns occurred in this signal, due to marked peaks in yaw velocity amplitude, it is difficult to see exactly where turns begin and end. By integrating $\omega_{yaw}(t)$, the relative trunk angle in the horizontal plane, $\theta_{yaw}(t)$, was obtained. An initial value of zero was used for the integration. Thus, $\theta_{yaw}(t)$ showed how much the trunk was turned to the left or right relative to the beginning of the test. As seen in Fig. 2, walking components appear in $\theta_{yaw}(t)$ as low amplitude rhythmic oscillations round a flat line. The turning component appears as a positive or negative ramp, depending on the direction of the turn. Since the sensor attached on the trunk could have a small inclination relative to the horizontal plane due to anatomy of this part of the body, differences in $\theta_{yaw}(t)$ before and after turns could be smaller than 180°. A continuous mathematical model was used to describe $\theta_{yaw}(t)$:

$$M(t) = aE(\frac{t-b}{c}) + Ct \qquad (1)$$

$$E(t) = \begin{cases} -\frac{1}{2} & \text{if} \quad t \leq \frac{1}{2} \\ \frac{1}{2}\sin(\pi t) & \text{if} \quad -\frac{1}{2} < t < \frac{1}{2} \\ \frac{1}{2} & \text{if} \quad t \geq \frac{1}{2} \end{cases} \qquad (2)$$

where $E(t)$ is a continuous piecewise function changing smoothly between two levels and $M(t)$ is the turning model. Drift and offset of the gyroscopes were assumed to be constant during the short period of the turns and were described as a constant slope C. Duration of turns were defined as $[b - c/2, b + c/2]$. A subspace trust-region based, non-linear,

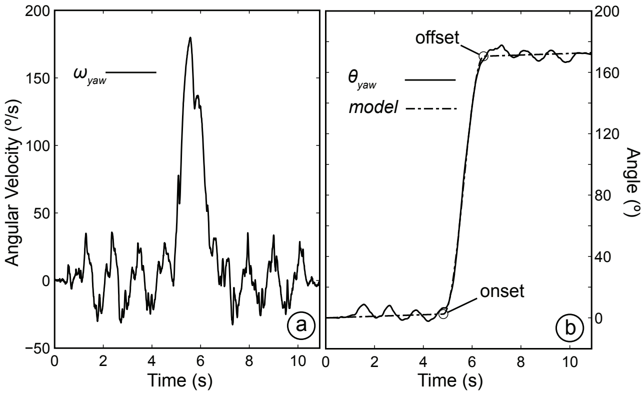

Fig. 2. a) Raw signal of the yaw gyroscope on sternum during a 180° turn. b) Relative angle of trunk in horizontal plane and the fitted turning model.

TABLE I

TEST-RETEST RELIABILITY AS WELL AS COMPARISON OF THE TURNING METRICS BETWEEN THE TWO GROUPS.

	PD		Control		rank-sum	ICC	95% CI bounds of ICC	
Parameter	Mean	S.D.	Mean	S.D.	p-value	**ρ**	Lower	Upper
Peak Angular Velocity (°/s)	162.3	30.85	172.44	30.13	0.7950	0.86	0.67	0.95
Duration (s)	**2.18**	**0.43**	**1.79**	**0.27**	**0.0226**	**0.89**	**0.74**	**0.96**
Steps	4.08	1.00	3.50	0.52	0.1422	0.75	0.45	0.90
Average Step Time (s)	0.57	0.07	0.56	0.07	0.7508	0.61	0.21	0.84
Max Step Time (s)	0.71	0.15	0.69	0.12	0.7507	0.50	0.05	0.78
Step Before Turn (s)	**0.56**	**0.04**	**0.52**	**0.04**	**0.0302**	**0.85**	**0.64**	**0.94**
# of Double Steps	**0.33**	**0.49**	**0.00**	**0.00**	**0.0357**	**0.22**	**-0.27**	**0.62**

least squares optimization method [15] was use to fit $M(t)$ on $\theta_{yaw}(t)$ to find $\langle a, b, c\rangle$. Coefficient of determination (R^2) was used to evaluate the quality of the model fit to data.

E. Turning metrics

The following outcomes were calculated for each turn: Duration of turns (in seconds), peak angular velocity of the trunk in the horizontal plane (in degrees per seconds), number of steps, average step duration (from heel-strike to heel-strike, in seconds), duration of the longest step (in seconds), duration of the last step right before a turn (in seconds) and number of double steps, i.e. successive steps with the same foot. Steps and gait events were detected using the gyroscopes attached on the shanks [9].

F. Data Analysis

To compare differences between the mild PD and control groups, Wilcoxon's non-parametric test (rank-sum) was used. Since the tests for the metrics were pre-planned, the p-values were not adjusted for multiple-comparisons. To evaluate test-retest reliability, Intra-Class Correlation (ICC) was used [16]. Since the same subjects and same device was used for reliability, an ICC(1,1) was used. ρ and 95% confidence intervals were reported.

To analyze the longitudinal data, a marginal linear model (3) was used [17]. $\mathbf{X}_i$ were the matrices of fixed factors in the model that consisted of *Group*, *Time* and their interaction. The i index indicated individual subjects. An *AR(1)* covariance structure was used for matrix $\mathbf{V}_i^*$.

$$\mathbf{Y}_i = \beta_0 + \mathbf{X}_i\boldsymbol{\beta} + \epsilon_i^*, \;\; \epsilon_i^* \sim N(\mathbf{0}, \mathbf{V}_i^*) \qquad (3)$$

All analysis algorithms, as well as statistical evaluation of outcomes were performed in MATLAB.

III. RESULTS

The analysis algorithm automatically detected all turns. The mathematical model of turning, M(t), was a very good fit on the raw data (average R^2=0.9989, min 0.9973 , max 0.9997).

The PIGD scores of all control subjects were zero. PIGD scores of seven patients were 0, three had 1, one subject had 2 and one subject had 3. There were significant differences between the early PD and healthy controls groups in duration of turns, number of double-steps and duration of last step before turn (see Table I). Patients were slower and had more double-steps. Test-retest reliability of duration of turns, peak angular velocity of trunk and the duration of the last step before turn was very good (ρ>0.85, see Table I). The number of double-steps, however, had a poor test-retest reliability.

In longitudinal analysis, duration of turns showed a trend toward getting worse in the early PD group but was very stable across 18 months in the healthy control group (see Fig. 3). Analysis of the marginal linear model of turning duration (3) also showed a significant *Group*Time* interaction ($F_{1,95.02} = 4.835$, $p \leq 0.030$) as well as a significant *Group* effect ($F_{1,46.47} = 5.042$, $p \leq 0.030$). None of the other metrics had a significant *Group*Time* effect.

IV. CONCLUSIONS AND FUTURE WORKS

The results show that our novel mathematical turning model fits the data very well and produces sensitive and reliable outcomes. It is based on modeling the whole dataset, unlike previous methods [11], [12], it is not sensitive to local

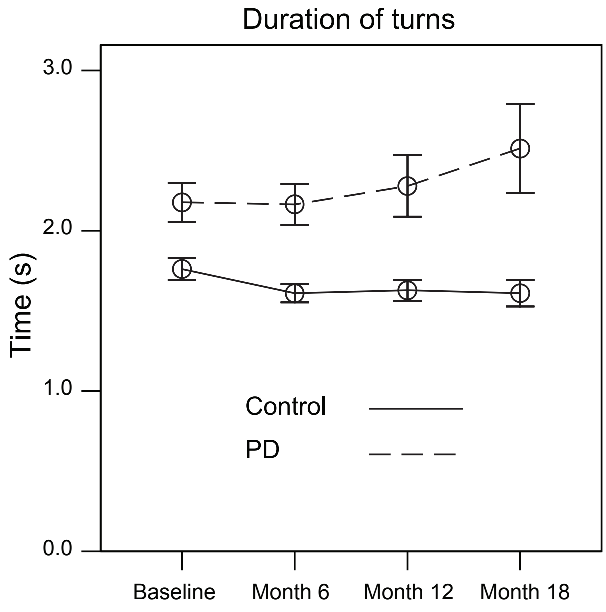

Fig. 3. Duration of turns in PD and Control groups over period of 18 months. Error bars show standard error of mean (SEM).

noise and artifacts near the moment of onset and offset of turns. The reason is that the model fits over the angle of trunk rotation in the yaw axis rather than over the angular velocity. During slow turns angular velocity in horizontal axis can be very low and comparable to the trunk rotation during the walking period. The angle signal, however, does not have this problem (see Fig 2.a) since the ranges of rotations during walking are much smaller than 180° turns. Finally our model is not population-dependent, unlike the threshold based methods, where the optimal threshold might be different across different populations.

Although PIGD score of the early PD patient was very low (average score was 0.67 out of max 16) and 7 out of 12 subject were in normal range (their scores were 0), some of our turning metrics showed significant differences between groups which could suggest the method is very sensitive. Duration of the turns was the most sensitive measure. It had the highest test-retest reliability and was the only metric that showed early progress of the disease during the 18 month period. The least reliable measure related to turning was the number of double steps. The relatively mild PD subjects rarely took double steps and did not need to use double steps consistently in all trials. Healthy subjects never took double steps.

Sensitive and reliable analysis of turning might be useful in larger clinical studies related to the progression of the PD or evaluation of new therapies as well as monitoring patients in early stages in daily clinical practice. However, the proposed turning analysis model should not be limited to PD as it can be used in objective assessment of turns in any group with balance or gait deficiency. It is not limited to 180° turns either. In fact, due to alignment of the sensor on the body, turns were not exactly 180° thus as part of the fitting process, the model measures the turning angle. We hypothesize that this approach can be used to analyze turns under various other conditions, including unplanned, free turns during continuous measurement of spontaneous activity. The turning model might also be used in a more complex setup to analyze *Timed Up and Go* (TUG) [18], [19] or other clinical paradigms.

In conclusion, we have proposed an objective, sensitive and reliable way to analyze turning using low-cost, wearable technology.

V. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of Kinetics foundation and Oregon Center for Aging and Technology. We thank Caroline Paquette and Triana Nagel-Nelson for assistance with data collection. We also thank Pascal Morel and Jean Gramiger for designing and development of the Physilog system. Dr. Horak was a consultant for the Kinetics Foundation. This potential conflict of interest has been reviewed and managed by OHSU.

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