CONTINUOUS MONITORING OF MOVEMENT IN PATIENTS WITH PARKINSON'S DISEASE USING INERTIAL SENSORS

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Gait impairment is a hallmark of Parkinson's disease (PD). The assessment of gait and balance in the clinic may not adequately reflect mobility in daily life. It is often reported that patients with PD walk better when they are examined in an outpatient clinic or in a research laboratory than at home. Continuous monitoring of mobility during spontaneous daily activities may provide clinicians and patients with objective measures of the quality of their mobility. We show that continuous monitoring of spontaneous gait with wearable inertial sensors during daily activities is feasible for patients with PD. We tested 13 patients with PD and 8 healthy controls to evaluate the feasibility of using wearable inertial sensors at home for one week. The inertial system successfully detects walking bouts and provides sixteen objective measures that can characterize gait changes in patients with PD.

KEY WORDS: Parkinson's disease, movement disability, continuous monitoring, inertial sensors.

INTRODUCTION: PD is a chronic disorder of the nervous system that leads to progressive loss of motor function including gait. Estimates suggest that PD affects more than four million people worldwide with the highest prevalence in North America and Europe (Huse et al., 2005). Gait impairment is a hallmark of PD and is characterized by reduced speed, decreased step length, small shuffling steps, altered cadence, unsteadiness on turning, and increased gait variability. Gait impairment increases with disease progression, resulting in increased disability and risk for falls (Morris, Huxham, McGinley, & Iansek, 2000; Hausdorff, 2009; Song, Sigward, Fisher, & Salem, 2012).

Clinical examinations to assess gait and balance are brief and primarily rely on subjective clinical impression and patient reports, which are known to be unreliable (Brown, MacCarthy, Jahanshahi, & Marsden, 1989). Referrals to motion analysis laboratories are expensive, time consuming, and unavailable to most people. Although systems, such as the GAITRite gait analysis system, can be used to provide objective measures of gait, the measures reliability in people with high gait variability may be limited (Brown et al., 1989). In addition, a single, sparsely spaced measure of mobility does not adequately reflect mobility function during daily life, cannot assess diurnal (within-a-day) fluctuations, or day-to-day motor fluctuations. Furthermore, it is often reported that patients with PD walk better when they are examined in an outpatient clinic or in a research laboratory than at home. This is known as the “white coat effect.” For example, our group previously showed that patients with PD walk a prescribed Get Up and Go task significantly slower at home than in the laboratory (Zampieri et al., 2010).

Clinicians would benefit from a system they can easily use to measure daily mobility and effects of treatment and exercise on functional mobility. Earlier studies to measure movement for long periods of time utilized activity monitors such as ActiGraph. They monitor activity cycles and provide a measure of step count averages and variability. Unfortunately, these activity monitors provide no information on the type or quality of movement. Although activity monitors can measure the overall physical activity and step counts, human gait has many measurable characteristics that are important to identify fall risk and for diagnosis. Several research groups have recently utilized new technologies, such as the Microsoft Kinect system, to examine gait in the home. However, these systems are constrained to tracking movement within its line of sight, and the surrounding environment may significantly affect accuracy.

The need to characterize human movement has led to an upsurge in research on the use of wearable inertial sensors (Horak & Mancini, 2013). Sensors, including accelerometers and gyroscopes, have widely been used in wearable systems to quantify balance and characterize gait in clinical or laboratory settings]. In a previous study, we have shown that PD and elderly subjects can easily use wearable sensors to quantify their movement in the their home environment for seven days (El-Gohary et al., 2013). Our system successfully characterized subjects' turning mobility and quantified daily and weekly variability of turning metrics including turn duration, angle, and velocity.
In this study, we use inertial sensors to characterize straight ahead walking in patients with PD in their home environment for seven days. We developed novel gait-tracking algorithms to calculate several spatiotemporal gait metrics that are especially important to study gait impairments in PD. These metrics include step and stride length and duration, cadence, foot clearance, pitch angles at heel strike and toe off, as well as stance and swing ratio of the gait cycle. These metrics provide significant insight into the nature of gait and mobility beyond just the simple movement speed or step count. Moreover, each of these gait features has been related to other movement disorders or to health issues for older adults. To the best of our knowledge, our study is the first to use inertial sensors on the feet to characterize spontaneous walking in the home for one week to provide objective measures of gait in PD.

METHODS: We enrolled 13 PD subjects with idiopathic PD (65±6 years, UPDRS) version III 24.5±7.5) and 8 age-matched, control (CT) subjects (67±9 years) in the home for seven days. On the morning of the first day, a study coordinator met the subjects to show them how to wear the sensors and how to charge them at the end of each day. Three Opal inertial sensors (APDM, OR, USA) were worn: one on the pelvis at the lumbar level and one on each foot. The pelvis sensor was used to quantify turning and trunk motion. The Opal sensor includes triaxial accelerometers, gyroscopes and magnetometers and records signal data at 128 Hz. The Opal's on-board data storage can hold 720 h worth of data, and have sufficient battery life to continuously record data over 16 h throughout the day. Participants wore the Opal sensors all day for the rest of the seven days, recharging them each night. The Opals use patented, wireless synchronization technology to ensure multiple units collect data with a precision of better than ±1 ms.

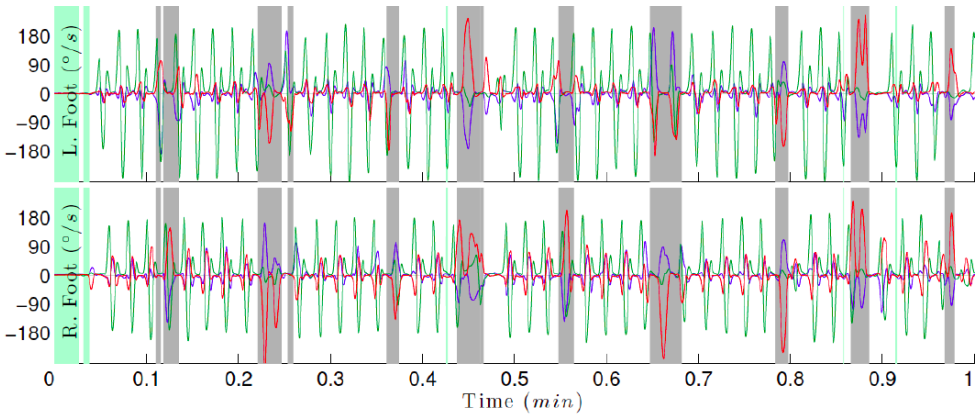

Figure 1: Rotational rate of the sensors attached to the left foot (top) and right foot (bottom). Blue, green and red traces are the x, y and z-axes of the gyroscope. Gray and white areas represent periods of turning and walking, respectively.

We analysed the data to characterize walking and turning events during spontaneous activities. Turning results from this study have been previously published in (El-Gohary et al., 2013). Figure 1 shows how gyroscope data can be used to automatically identify periods of turning,

walking and standing. The figure shows one minute of the rotational rate of the gyroscope sensors attached to the left and right foot. Blue, green and red traces are the x-, y- and z-axes of the gyroscope in degrees per second. Green areas represent periods in which the subject is not walking; gray represents periods of turning, and white areas represent periods of walking.
Periods of walking (bouts) were detected from the Opals attached to the feet. The algorithm detects steps independently for each foot. The acceleration and angular velocity for each foot sensor are used. The vector magnitude is calculated at each time, for each sensor, and these magnitudes are low pass filtered with a cut-off frequency of 4 Hz. Then steps are detected when a period of sufficient movement is found between two stationary periods. Steps are then matched in a left-right alternating pattern, and bouts are identified as sequences of steps that are at least 10 s long, where no pair of steps is more than 60 s from the following pair.
The number and duration of each step during detected walking bouts and turns were calculated using the rotational rate data. For each step, peak of the pitch angular velocity was used to detect the mid-swing event. Initial and terminal contact of the foot with the ground, marked by the zero crossing of the pitch angular rate around the mid-swing, was used to detect each step and its duration. The algorithm identifies the walking bouts and calculates more than 80 gait metrics using the rotational rate and acceleration. In this study, we report results on select metrics that are thought to be of a particular interest to clinician studying PD.

RESULTS: All PD and CT subjects complied with wearing the inertial sensors and charging them at night, for an average of ten hours per day for a week. The ait parameters of interest are presented in Table 1 with averages (μ), standard deviation (σ), and coefficient of variation (CoV). The CoV summarizes the amount of variation as the ratio of the standard deviation to the mean. The table summarizes the metrics averaged across the week for the PD and CT groups. The table also shows the difference in gait metric averages, and the p-value for a *t*-test at a 5% level of significance to determine if PD and CT gait measures significantly differ from each other.
Results show that the PD group walked significantly slower with shorter strides than the CT group ($p<0.001$). Although percentage of each gait cycle spent in total stance was not significantly different between groups, subjects in the PD group had an increased double-support period. Similarly, subjects with PD spent less time in the initial, mid-swing phase of the gait cycle, compared to the CT group. In addition, subjects with PD exhibited a larger foot clearance and smaller lateral swing ($p<0.001$) compared to the CT subjects.

Table 1
Descriptive statistics for select gait metrics averaged throughout the week for the PD and CT groups. The p-value is for a *t*-test at a 5% level of significance

Metric	PD			CT			PD-CT	
	μ	σ	CoV	μ	σ	CoV	μ	p
Gait Speed (m/s)	1.075	0.320	0.298	1.207	0.241	0.200	-0.131	< 0.001
Stride Length (m)	1.093	2.142	1.961	1.277	0.560	0.439	-0.184	< 0.001
Cadence (Steps/m)	109.798	13.100	0.119	109.276	10.054	0.092	0.522	< 0.001
Gait Cycle Duration (s)	1.118	0.214	0.191	1.112	0.150	0.135	0.006	< 0.001
Step Duration (s)	0.560	0.117	0.209	0.556	0.080	0.145	0.004	< 0.001
Stance (%)	60.231	4.801	0.080	60.241	3.125	0.052	-0.010	0.674
Initial Double Support (%)	10.319	4.890	0.474	10.267	3.075	0.300	0.052	0.032
Single Limb Support (%)	39.618	5.003	0.126	39.706	3.050	0.077	-0.088	< 0.001
Terminal Double Support (%)	10.294	4.773	0.464	10.268	3.098	0.302	0.026	0.273
Swing (%)	39.769	4.801	0.121	39.759	3.125	0.079	0.010	0.674
Initial Mid Swing (%)	28.160	5.227	0.186	29.391	4.817	0.164	-1.231	< 0.001
Terminal Swing (%)	11.609	4.728	0.407	10.368	4.396	0.424	1.241	< 0.001
Foot Clearance (cm)	4.351	4.824	1.109	3.360	4.426	1.317	0.990	< 0.001
Lateral Swing Max (cm)	4.193	8.067	1.924	4.890	4.009	0.820	-0.696	< 0.001
Pitch at Toe Off (°)	27.028	10.040	0.371	26.904	10.579	0.393	0.124	0.035
Pitch at Initial Contact (°)	-18.305	15.785	0.862	-29.097	14.728	0.506	10.792	< 0.001

Subjects with PD exhibited greater variability of gait performance throughout the day and week, compared to subjects in the CT group. Figure 2 shows box plots for an example comparison of the daily average of stride length through the week for a representative control (left) and PD (right) subject. The figure shows significant variation not only from one day to another, but also greater variability through the day for the subject with PD. This increased variability of performance is consistent for the majority of the PD subjects in all gait metrics listed in Table 1.

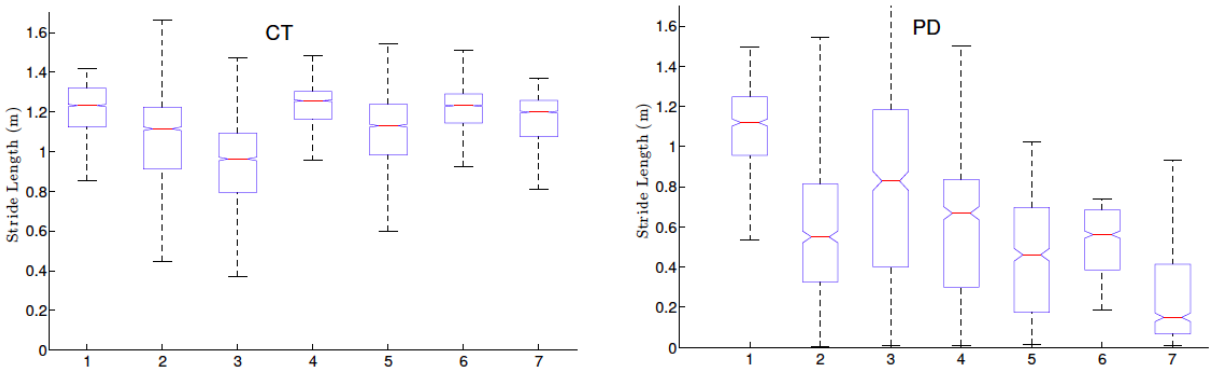

Figure 2: Daily distribution of the stride length of a control (CT) subject (left) and a PD subject (right).

CONCLUSIONS: In this study, we demonstrated that we could use inertial sensors to measure locomotor activities and to characterize gait and turns in the home throughout the day and week using wearable inertial sensors on the feet. The algorithm successfully characterizes spontaneous walking with sixteen gait metrics. Results show significant differences between gait characteristics of PD and control subjects. Continuous monitoring of mobility during spontaneous daily activities may provide more realistic measures of gait performance. Precise measures of spontaneous gait and turning mobility will improve intervention for gait and balance disorders and fall prevention in the elderly and in patients with neurological diseases.

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