On-Shoe Wearable Sensors for Gait and Turning Assessment of Patients With Parkinson's Disease

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***Abstract*—Assessment of locomotion through simple tests such as timed up and go (TUG) or walking trials can provide valuable information for the evaluation of treatment and the early diagnosis of people with Parkinson's disease (PD). Common methods used in clinics are either based on complex motion laboratory settings or simple timing outcomes using stop watches. The goal of this paper is to present an innovative technology based on wearable sensors on-shoe and processing algorithm, which provides outcome measures characterizing PD motor symptoms during TUG and gait tests. Our results on ten PD patients and ten age-matched elderly subjects indicate an accuracy ± precision of 2.8 ± 2.4 cm/s and 1.3 ± 3.0 cm for stride velocity and stride length estimation compared to optical motion capture, with the advantage of being practical to use in home or clinics without any discomfort for the subject. In addition, the use of novel spatio-temporal parameters, including turning, swing width, path length, and their intercycle variability, was also validated and showed interesting tendencies for discriminating patients in ON and OFF states and control subjects.**

***Index Terms*—Gait analysis, inertial sensors, Parkinson, spatio-temporal parameters, timed up and go.**

I. Introduction

PARKINSON'S disease (PD) is a neurodegenerative disorder that can cause multiple impairments, notably in motor function due to tremor, rigidity, bradykinesia, and postural instability. Nowadays, prevalence varies from 10 to 800 people over 100 000 in different countries, concerning more than 6 million people worldwide. Pharmacological treatments for PD include L-dopa. During the ON state, the medication is active and motor performance is improved while in OFF state the effects of the medication wear off. Outcome evaluation and ON–OFF monitoring in PD is mainly based on clinical score such as Unified Parkinson's Disease Rating Scale (UPDRS) [1] and common techniques including posturography [2], gait analysis [3], and timed up and go test (TUG) [4].

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Gait is a motor task which is particularly sensitive to ON–OFF changes in PD. When OFF, PD patients walk slowly with short shuffling steps affecting the trajectory of foot, reduced stride length, and less regular cycle, as shown by the increase of interstride variability [5]. The TUG is also a powerful test to assess some motor symptoms in PD because it includes walking and turning, which are both affected by PD, especially when performed as sequence. Gait analysis is usually performed in laboratory based on optical motion capture. While this technique allows an accurate measurement, it is too complex to be used in clinical setting. Moreover, laboratory condition does not replicate natural conditions for the subject and cannot measure long-term variability of gait. TUG is a simple and practical test, but its outcome is limited to the time measured by a stop watch.

Recently, using motion sensors, effort has been done toward the instrumentation of TUG [6], [7] and gait [8], [9]. For instance, trunk sensor allowed to characterize different phases of TUG, and showed that the turning phase was particularly relevant in PD analysis [7]. Regarding gait analysis, wearable sensor technology has been so far limited to the 2-D assessment of walking with limited outcome measures [9], whereas 3-D aspects have shown to be important in PD analysis [10]. In addition, the accuracy and precision of the system should be adequate to measure clinical differences. For instance, differences exceeding 5-cm/s threshold in gait velocity can be considered as clinically meaningful [3].

The goal of this paper is to present and validate the use of on-shoe wearable sensors and dedicated algorithm, which can assess both TUG and long-distance walking with enough accuracy and precision to distinguish control and PD subjects. Comparison of TUG and longer distances walking test is also provided to find which test is more adapted to assess gait performance. Our method provides outcome measures which quantify objectively 3-D gait parameters and allow detecting gait initiation, steady state, turning, and termination. The potential of the method is illustrated by comparing PD patients in ON and OFF states and control subjects.

II. Method

A. Wearable Measurement System

A stand-alone Physilog module [BioAGM, CH], integrating microcontroller, memory, three-axis accelerometer and gyroscope, and battery, was designed. Physilog module is small (50 mm × 40 mm × 16 mm), lightweight (36 g), low power (71 mA in recording), and conveniently fixed on upper shoe using elastic strap (see Fig. 1) with shape memory foam to guaranty a stable position and easy manipulations. Signals were

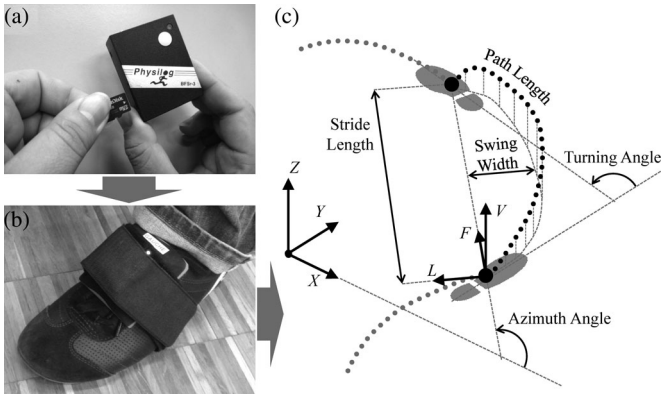

Fig. 1. (a) Physilog inertial sensing module. (b) On-shoe fixation. (c) Spatio-temporal parameters with fixed (*XYZ*) and walking frame (*FLV*).

low-pass filtered at 17 Hz, sampled at 200 Hz on 16 bits, converted to physical units (g or °/s), and recorded on micro-SD cards before transferring to the PC. Signals from two modules are synchronized wirelessly.

B. Spatio-Temporal Analysis of Gait

For each gait cycle, Midswing was first detected by the positive peak of pitch angular velocity. Initial and terminal contacts were then detected by the zero-crossings of pitch angular velocity around Midswing. This way of detecting gait cycles was robust to PD gait pattern. A method for assessing 3-D foot kinematics with automatic alignment and periodic drift correction at each foot flat ff was previously described and validated on elderly subjects [11]. It was used to obtain at each time frame *t:* 3-D orientation *M(t),* velocity *V(t)*, and position *P(t*), expressed in fixed frame *XYZ* (see Fig. 1). Spatio-temporal parameters were extracted at each cycle n between successive foot flats ff_n, ff_n+1. Stride Velocity was obtained by the average of *V(t)* projection in *XY* plane:

$$\text{Stride Velocity}_n = \sqrt{\sum_{t=\mathrm{ff}_n}^{\mathrm{ff}_{n+1}} V_X^2(t) + V_Y^2(t)}. \quad (1)$$

Since subject's locomotion was unconstrained in *XY* plane, walking direction was expressed at each cycle n by azimuth angle AA_n, the projection of linear displacement on X-axis:

$$\mathrm{AA}_n = [1,0,0] \bullet \frac{(P_{XYZ}(\mathrm{ff}_{n+1}) - P_{XYZ}(\mathrm{ff}_n))}{\|(P_{XYZ}(\mathrm{ff}_{n+1}) - P_{XYZ}(\mathrm{ff}_n))\|}. \quad (2)$$

For t between ff_n and ff_n+1, position in frontal–lateral–vertical (FLV) walking frame can be expressed by the rotation of position in *XYZ* frame around Z-axis with a value of AA_n:

$$P_{\mathrm{FLV}}(t) = P_{XYZ}(t). \begin{bmatrix} \cos(\mathrm{AA}_n) & -\sin(\mathrm{AA}_n) & 0 \\ \sin(\mathrm{AA}_n) & \cos(\mathrm{AA}_n) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (3)$$

Stride length was, thus, defined as the relative linear distance between two successive foot-flat positions in frontal axis:

$$\text{Stride Length}_n = \sqrt{(P_F(\mathrm{ff}_{n+1}) - P_F(\mathrm{ff}_n))^2}. \quad (4)$$

In order to assess the amount of circumduction of lower limb, swing width was defined as the maximum of lateral deviation of foot trajectory during swing:

$$\text{Swing Width}_n = \max_{t \in \{\mathrm{ff}_n : \mathrm{ff}_{n+1}\}} (P_L(t)). \quad (5)$$

The rectification of the 3-D curve *P(t)* was normalized to stride length, and defined as normalized path length:

$$\text{Path Length}_n = \sqrt{\sum_{t=\mathrm{ff}_n}^{\mathrm{ff}_{n+1}} P_F^2(t) + P_L^2(t) + P_V^2(t)} / \text{Stride Length}_n \quad (6)$$

Finally, turning angle, the change of azimuth between two successive foot flats, was computed by the Euler axis/angle:

$$\text{Turning Angle}_n = \arccos((tr(R_n) - 1)/2) \quad (7)$$

with tr(R_n) being the trace of the rotation matrix between $M(\mathrm{ff}_n)$ and $M(\mathrm{ff}_n+1)$.

Parameters extracted using (1) to (7) are illustrated in Fig. 1.

C. Gait Initiation, Termination, Turning, and Steady Phases

Gait cycles were automatically classified into transition, steady, and turning phases, by using specific spatio-temporal parameters. Transition cycles were defined by analogy to system response time as the gait cycles with a stride length below 63% of steady-state value, estimated by the median over all cycles. The first and the last Transition cycles were classified as gait initiation and termination. Turning cycles were defined by turning angle over a threshold of 20° [11]. Finally, after discarding turning, initiation and termination, the remaining cycles were classified as steady gait. For each phase, the number of cycles were detected and total duration was computed by the sum of gait cycles time.

D. Experimental Setup and Validation

This study included ten PD patients with mild to moderate disease (UPDRS = 15.7±7.6, mean age 64±7 years) and ten age-matched control subjects (UPDRS = 1.2±1.3, mean age 66±7 years) who were asked to perform a standard 3-m TUG and gait tests with Physilog inertial units attached on both feet (see Fig. 1). Gait was performed at self-selected speed in hospital through a long and wide corridor on moderate (2 × 20 m) and long (4 × 50 m) distance, including 180° turns between straight walking periods. The protocol was approved by local ethical comity. All the patients were evaluated in ON state under their current medication, and four of them also consented to perform trials in OFF state (at least 8-h off medication).

During TUG tests, four reflective markers were attached to the shoe and tracked by the reference optical motion capture system (Mocap) with submillimeter accuracy, including seven cameras (Vicon, U.K.). Spatio-temporal parameters were also estimated from Mocap trajectories using (1) to (7), and constituted reference data. TUG tests were done first on self-selected turning side and second by asking the subject to turn on the opposite side. It was repeated twice by removing and fixing again shoe sensors to assess test–retest repeatability.

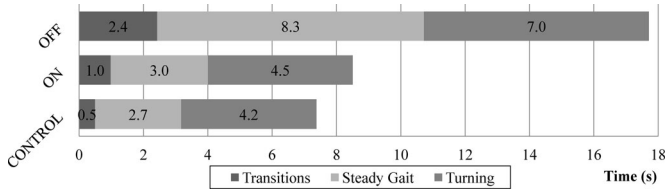

Fig. 2. TUG phase's duration estimated from on-shoe wearable sensors.

III. Results

A. Comparison With Reference System and Validation

Accuracy and precision of extracted spatio-temporal parameters were estimated by the mean and standard deviation (STD) of the set of difference between proposed and reference systems, among 1243 recorded cycles in control and PD subjects. Overall, compared to reference system, stride velocity and stride length showed an accuracy±precision of 2.8±2.4 cm/s and 1.3±3.0 cm. For normalized path length, swing width, and turning angle, accuracy±precision was 4.5±3.6%, 0.15±2.13 cm, and 0.12±3.59°. Same performances were obtained in control, ON, and OFF groups.

Test/retest repeatability of spatio-temporal parameters obtained by the wearable system during each TUG phase was evaluated using intraclass correlation coefficients ICC(1,1) [7] and interpreted using established benchmarks [12]. Overall PD patients and control subjects, TUG total duration, step count, mean stride velocity and stride length during steady gait, and number of steps during turning phase, obtained excellent repeatability (ICC(1,1) > 0.75). The other parameters during steady gait and turning phases all showed fair to good repeatability (ICC(1,1) > 0.4), whereas parameters during Transition phases were least repeatable (ICC(1,1) < 0.4).

B. Analysis of Timed Up and Go Test

Wilcoxon rank-sum test was used as a robust nonparametric statistical test for pair wise comparison because of small number of participants and unsteady distribution of gait cycles. Stride length and path length were not significantly affected by turning side neither in control ($p = 0.09$ and $p = 0.55$) nor in ON ($p = 0.26$ and $p = 0.14$) nor in OFF ($p = 0.06$ and $p = 0.32$) group. Only swing width was significantly affected by turning side in ON group ($p = 0.00$), as well as stride velocity in control subjects ($p = 0.02$).

TUG phases were detected in the three groups of subjects (see Fig. 2). All TUG phases duration were significantly increased in ON and OFF PD patients compared to control subjects ($p < 0.05$), except between ON and controls during steady state and turning phases. Turning was the longer phase during TUG in control and ON group, but not in OFF group. TUG durations obtained were similar in OFF group and slightly smaller in ON group compare to the literature [13].

C. Short, Moderate, and Long-Distance Gait Analysis

Turning and transition cycles were discarded during TUG, 2×20 m and 4×50 m gait tests, to obtain parameters representing short, moderate, and long distance gait, respectively. Mean and variability of those parameters were computed for the different subject's groups (see Fig. 3), and statistically compared with nonparametric test. As in previous studies [5], interstride variability was estimated by the coefficient of variation (CV = Mean/STD in%). STD was used for swing width, due to its small mean and high fluctuations from 2.6 to 5 cm.

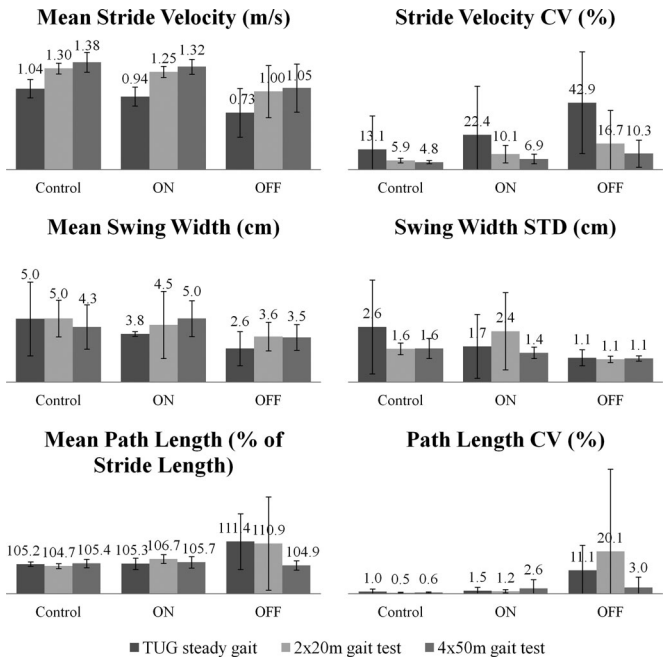

Fig. 3. Mean ± STD of mean and variability of gait parameters obtained from shoe-sensors versus walking distance and subjects groups.

In all groups, mean stride velocity was significantly increased with walking distance ($p < 0.01$), whereas its CV was decreased. CV changes were not significant between 2×20 m and 4×50 m though ($p = 0.1$). For all tests, mean stride velocity was comparable between control and ON groups ($p > 0.23$), but significantly lower in OFF group ($p < 0.02$). Stride velocity CV tended to be higher in ON and OFF groups compared to control group, without significance though. Same tendencies were observed for stride length (not reported in Fig. 3). Both mean and STD of swing width tended to be smaller in OFF group compared to control and ON groups, significantly for swing width STD in 2×20 m and 4×50 m tests ($p < 0.01$). Both mean and CV of normalized path length tended to be higher in OFF group, though such changes were not significant.

IV. Discussion

In this study, on-shoe wearable sensors were used to instrument commonly used motor function tests for PD. TUG and Gait were assessed through standard spatio-temporal parameters such as stride velocity and stride length beside new parameters, i.e., turning angle, path length, and swing width. These parameters were validated during TUG against a gold standard Mocap system and results indicate their technical validity. Particularly, for stride velocity and stride length, our results showed better accuracy (2.8 cm/s and 1.3 cm) and precision (2.4 cm/s and 3.0 cm)

than previously reported system based on inertial sensors, which reported an accuracy±precision of 3 cm/s ± 7.6 cm/s for stride velocity and 3.5 cm ± 8.5 cm for stride length [9]. The system is simple to attach on shoe, and allows automatic estimation of 3-D parameters independently of sensor positioning on shoe. It offers therefore a practical tool to assess objectively TUG and Gait in people with movement disorder such as PD at home or clinics. It can be hypothesized that tests such as TUG are inadequate to measure gait variability. However, our results suggest that 40-m gait shows comparable variability than 200-m gait, with the advantage of being shorter for patients.

The proposed method confirmed the pertinence of the turning analysis and novel parameters quantifying 3-D foot trajectory during swing phase for discriminating PD and control subjects. Interestingly, whereas stride length changes were strongly associated with stride velocity changes, it was not the case for swing width and path length. In particular, the lower swing width obtained in OFF group could be interpreted as a consequence of axial rigidity. We believe those novel parameters bring a new insight into PD motor signs quantification during gait. This study offers new perspectives with regard to the feasibility of home monitoring of patient with movement disorder using wearable devices [14]. Nevertheless, further clinical research and statistical analysis using bigger sample sizes are needed to confirm the significance of the novel gait parameters.

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REFERENCES

[1] S. Fahn, R. L. Elton, U. D. Committee *et al.*, "Unified Parkinson's disease rating scale," *Recent Dev. Parkinson's Dis.*, vol. 2, pp. 153–163, 1987.

[2] L. Rocchi, L. Chiari, and F. B. Horak, "Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease," *J. Neurol. Neurosurgery Psychiatr.*, vol. 73, no. 3, pp. 267–274, Sep. 2002.

[3] S. Perera, S. H. Mody, R. C. Woodman, and S. A. Studenski, "Meaningful change and responsiveness in common physical performance measures in older adults," *J. Amer. Geriatrics Soc.*, vol. 54, pp. 743–749, 2006.

[4] A. D. Macleod and C. E. Counsell, "Timed tests of motor function in Parkinson's disease," *Parkinsonism Related Disorders*, vol. 16, no. 7, pp. 442–446, Aug. 2010.

[5] J. M. Hausdorff, M. E. Cudkowicz, R. Firtion, J. Y. Wei, and A. L. Goldberger, "Gait variability and basal ganglia disorders: stride-to-stride variations of gait cycle timing in Parkinson's disease and Huntington's disease," *Movement Disorders: Off. J. Movement Disorder Soc.*, vol. 13, no. 3, pp. 428–437, May 1998.

[6] A. Weiss *et al.*, "Can an accelerometer enhance the utility of the timed up & go test when evaluating patients with Parkinson's disease?" *Med. Eng. Phys.*, vol. 32, no. 2, pp. 119–125, Mar. 2010.

[7] A. Salarian, F. B. Horak, C. Zampieri, P. Carlson-Kuhta, J. G. Nutt, and K. Aminian, "iTUG, a sensitive and reliable measure of mobility," *IEEE Trans. Neural Syst. Rehabil. Eng.: Publ. IEEE Eng. Med. Biol. Soc.*, vol. 18, no. 3, pp. 303–310, Jun. 2010.

[8] I. Tien, S. D. Glaser, and M. J. Aminoff, "Characterization of gait abnormalities in Parkinson's disease using a wireless inertial sensor system," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, pp. 3353–3356.

[9] A. Salarian *et al.*, "Gait assessment in Parkinson's disease: Toward an ambulatory system for long-term monitoring," *IEEE Trans. Bio-med. Eng.*, vol. 51, no. 8, pp. 1434–1443, Aug. 2004.

[10] M. Morris, R. Iansek, J. McGinley, T. Matyas, and F. Huxham, "Three-dimensional gait biomechanics in Parkinson's disease: Evidence for a centrally mediated amplitude regulation disorder," *Movement Disorders: Off. J. Movement Disorder Soc.*, vol. 20, no. 1, pp. 40–50, Jan. 2005.

[11] B. Mariani, C. Hoskovec, S. Rochat, C. Büla, J. Penders, and K. Aminian, "3D gait assessment in young and elderly subjects using foot-worn inertial sensors," *J. Biomech.*, vol. 43, no. 15, pp. 2999–3006, Nov. 2010.

[12] P. E. Shrout and J. L. Fleiss, "Intraclass correlations: Uses in assessing rater reliability," *Psychol. Bull.*, vol. 86, no. 2, pp. 420–428, Mar. 1979.

[13] S. Morris, M. Morris, and R. Iansek, "Reliability of measurements obtained with the timed get up & go test in people with Parkinson disease," *Phys. Ther.*, vol. 81, no. 2, pp. 810–818, 2001.

[14] S. Patel *et al.*, "Home monitoring of patients with Parkinson's disease via wearable technology and a web-based application," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2010, vol. 2139, pp. 4411–4414.