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Quantitative and qualitative gait assessments in Parkinson's disease patients

Kvantitativna i kvalitativna procena obrasca hoda kod bolesnika sa Parkinsonovom bolešću

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Abstract

Background/Aim. Postural impairments and gait disorders in Parkinson's disease (PD) affect limits of stability, impaire postural adjustment, and evoke poor responses to perturbation. In the later stage of the disease, some patients can suffer from episodic features such as freezing of gait (FOG). Objective gait assessment and monitoring progress of the disease can give clinicians and therapist important information about changes in gait pattern and potential gait deviations, in order to prevent concomitant falls. The aim of this study was to propose a method for identification of freezing episodes and gait disturbances in patients with PD. A wireless inertial sensor system can be used to provide follow-up of the treatment effects or progress of the disease. **Methods.** The system is simple for mounting a subject, comfortable, simple for installing and recording, reliable and provides high-quality sensor data. A total of 12 patients were recorded and tested. Software calculates various gait parameters that could be estimated. User friendly visual tool provides information about changes in gait characteristics, either in a form of spectrogram or by observing spatiotemporal parameters. Based on these parameters, the algorithm performs classification of strides and identification of FOG types. **Results.** The described stride classification was merged with an algorithm for stride reconstruction resulting in a useful graphical tool that allows clinicians to inspect and analyze subject's movements. **Conclusion.** The described gait assessment system can be used for detection and categorization of gait disturbances by applying rule-based classification based on stride length, stride time, and frequency of the shank segment movements. The method provides an valuable graphical interface which is easy to interpret and provides clinicians and therapists with valuable information regarding the temporal changes in gait.

Key words:
parkinson disease; gait, disorders, neurologic; disease progression; biomedical engineering.

Apstrakt

Uvod/Cilj. Poremećaji hoda i ravnoteže kod bolesnika sa Parkinsonovom bolešću (PD) uključuju i poremećaje stabilnosti, održavanja ravnoteže prilikom hoda i nemogućnost adekvatne reakcije na iznenadne perturbacije. U kasnijim fazama bolesti neki bolesnici razvijaju i epizode motornog bloka, odnosno „frizing" tokom hoda. Objektivno praćenje i merenje karakteristika hoda i promena obrasca hoda tokom progresije bolesti mogu pomoći kliničarima jer ukazuju na promene koje bi dovele do padova i ugrozile bolesnika. Cilj rada bio je razvoj metode koja bi identifikovala ovakve epizode kod bolesnika sa Parkinsonovom bolesti. Razvijeni bežični sistem sa senzorima mogao bi se koristiti za posmatranje efekata terapije ili progresije bolesti. **Metode.** U radu je prikazan sistem za objektivnu procenu obrasca hoda. Korišćenjem bežičnog senzorskog sistema koji koristi akcelerometre, žiroskope i senzore sile, moguće je dobiti procenu parametara hoda, ali i identifikovati „frizing" epizode karakteristične za PD. Uz pomoć ovog sistema snimljeno je 12 bolesnika, te je na osnovu snimljenih signala razvijen novi softverski alat koji omogućava praćenje parametara hoda. **Rezultati.** Na osnovu dužine koraka, trajanja koraka i frekvencije pokreta, razvijen je algoritam za klasifikaciju tipova koraka i uočavanje promena frekvencija pokreta tokom hoda. Prikaz rezultata ovog sistema je dat kroz primer jednog bolesnika. **Zaključak.** Opisani sistem za procenu hoda može biti korišćen za kategorizaciju poremećaja hoda kroz posmatranje promena u dužini i trajanju koraka, kao i frekvencija segmenata noge. Razvijeni metod omogućava iliustrativni prikaz i grafički interfejs koji je jednostavan za interpretaciju i omogućava dobijanje informacija koje kliničarima mogu ukazati na trenutne promene u obrascu hoda.

Ključne reči:
parkinsonova bolest; hod, poremećaji, neurološki; bolest, progresija; biomedicinsko inženjerstvo.

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Introduction

Postural and gait disorders are the most disabling cardinal motor signs found in people with Parkinson's disease (PD). Patients with PD have been reported to have postural impairments including reduction of limits of stability, impaired postural adjustment and poor responses to perturbation [1–3]. Gait disturbances include slow gait speed, shorter step and stride length, and increased variability of stride time (i.e., cycle time) as well as of stride length. In the later stage of disease progression, some patients can suffer from episodic features such as freezing of gait (FOG) [4, 5]. Gait and balance deficits predispose people with PD to falls. In a 20-year follow-up study, it has been reported that 87% of individuals with PD experienced one or more falls and 35% sustained injuries resulting from falls during walking [6]. Falls can lead to physical injuries and psychological traumas such as fear of falling. This results in functional mobility restriction, loss of independence, social isolation, decreased quality of life with increased risk of institutionalization and consequently increased mortality rate. Therefore, the objective gait assessment and monitoring progress of the disease can give clinicians and physical therapist important information about changes in the gait pattern and potential gait deviations, as well as supply data regarding disturbed gait pattern, especially for patients who exhibit FOG episodes and concomitant falls.

We have developed a wireless sensor system for assessment and evaluation of gait patterns for patients with various gait disturbances [7, 8]. The system uses inertial sensors (3D accelerometers and gyroscopes) which record body kinematics and estimation of gait parameters in any environment and for unlimited number of steps during a subject's walk.

This paper presents a new method for identification and classification of freezing episodes for patients with PD. This method, merged with the analysis of standardized temporospatial gait parameters and 3D trajectory reconstruction provides an illustrative clinical tool providing quantitative and qualitative information about a patient's gait pattern and its changes. This assessment was performed in a more detailed and more objective manner than it can be obtained by visual observation or any of existing clinical rating scales.

This system can also be used to provide follow-up of the treatment effects or progress of the disease. In some cases, given medications can stabilize gait by increasing the stride length and/or decreasing stride-to-stride variability [9–11]. The benefit of this treatment can be in monitoring the stride characteristic, length, and timing, before and after treatment application. Therefore, the presented method is an illustrative clinical tool to monitor gait pattern and gait pattern changes.

Methods

Instrumentation – Wireless sensor system for gait analysis

The proposed system, named SENSY was designed and developed within collaboration between the Faculty of Electrical Engineering, University of Belgrade, Serbia and Tecnalia Research Center, San Sebastian, Spain [12]. SENSY hardware comprises six peripheral inertial measurement units (IMUs), one per each leg segment of both legs, and a central PC communication unit connected to a USB port of a remote computer, where signals are monitored and stored (Figure 1). Foot IMUs include connectors for force sensors, which can be attached to the system, either incorporated in shoe insoles or as independent force sensors. Force sensors used in this study were integrated in shoe insoles, with active areas under heel, metatarsals, and toes (Figure 1, left). Each IMU comprises a 3-D analog accelerometer and a 3-D analog gyro sensor. The IMUs are powered by rechargeable batteries.

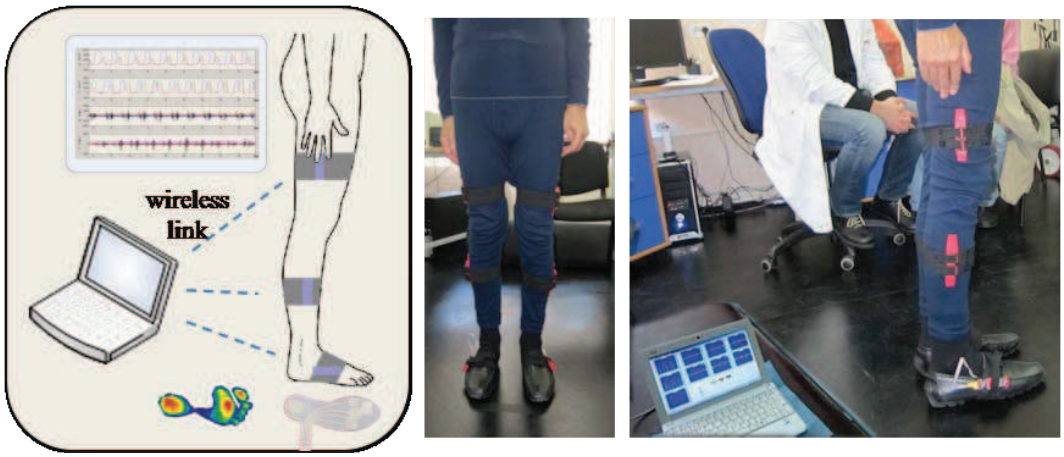

Fig. 1 – Sensor system mounted on a subject. Left: mounting scheme with inertial sensors placed on leg segments and shoe insole with integrated force sensors; Middle and right: photos of the mounted system, front view and profile.

The developed system is light and compact (30 g per unit), simple for mounting on a subject, comfortable to wear, simple for installing and recording, and presents a reliable system which provides high-quality sensor data. Custom-made acquisition software was developed in LabWindows CVI program (National Instruments, USA) enables real-time monitoring and automated storage of recorded data. Further

signal processing of recorded data is performed in Matlab (MathWorks Inc, USA).

Subjects

A total of 12 patients with idiopathic PD (age of 60 ± 9 years, range 41–71 years) participated in this study. The demographic and clinical data on the study group are shown in Table 1. The recordings were performed at the Clinic for Neurology, Clinical Centre of Serbia, Belgrade, Serbia. The study was performed in accordance to the ethical standards of the Declaration of Helsinki. All the participants gave informed written consent prior to the participation in the study.

Table 1

Patients' demographics, motor and clinical data

Patient	Age (years)	Onset (years)	HY	UPDRS III	NFOG-Q	FOG UPDRS item
#1	59	5	2	45	27	3
#2	57	13	3	65	28	3
#3	64	8	2	35	11	2
#4	66	5	2	43	/	2
#5	70	20	2	42	/	2
#6	57	27	3.5	56	26	2
#7	69	7	3	34	22	2
#8	61	18	2.5	40	17	2
#9	50	5	2.5	24	27	2
#10	41	12	/	/	11	2
#11	71	2	4	56	25	3
#12	60	8	3	/	/	/
Mean ± SD	60.4 ± 8.7	10.8 ± 7.4	2.7 ± 0.68	44 ± 12.16	21.5 ± 6.85	2.27 ± 0.47

HY – Hoehn and Yahr scale, UPDRS – Unified Parkinson's Disease Rating Scale, NFOG-Q – New Freezing of Gait Questionnaire, FOG – Freezing of gait.

The patients were recorded and tested during "off" periods of the disease. At the study entry, the stage of the disease was scored using the Hoehn and Yahr (HY) stage score (this scale is widely used for overall Parkinson's disease severity assessment [13]), the patient disability and motor evaluation of condition by using the Unified Parkinson's Disease Rating Scale (UPDRS) [14], and the global cognitive function using the Mini-Mental State Examination (MMSE) [15]. The inclusion criteria for appropriate data collection were the following: a Hoehn and Yahr disease stage score from 2 to 4, a stable and optimized antiparkinsonian treatment during 4 weeks prior to study entry, and appropriate cognitive functions - MMSE score more than 25.

The patients were assessed by neurologists with Hoehn and Yahr scale, Unified Parkinson's Disease Rating Scale, New Questionnaire (scale for quantitative and qualitative FOG assessment and its influence to activities of daily living [16] (NFOG-Q) and timed "up-and-go" test (TUG) with obstacles [17]. See Table 1 for test details. Based on observation and clinical tests the patients were classified as freezers (PD+FOG).

Experiment setup and recording protocol

The sensor system was mounted on the patients' limbs, as shown in Figure 1. IMUs were placed laterally on leg segments (thigh, shank, and foot of both legs). Shoe insoles with integrated force sensitive resistors (FSR) were used as shown in Figure 1, left panel. The patients were asked to walk along a complex pathway, as illustrated in Figure 2. The pathway was created to provoke freezing episodes in patients. It included start/stop, turns, U-turns, and passing through doorways with different widths. Each trial started from the chair where the patient was sitting. Upon a voice command, the patient had to stand up and start walking straight towards the door 1 to pass the doorway, turn left towards (very narrow) door 2, to make a U-turn, return through door 2, then to go straight along the corridor, where he/she would pass (wide) door 3, several strides later make another U-turn around the obstacle, pass through door 3 again, turn left, pass through door 1, return to the chair, and sit down. This session was repeated four times per subject, with 5-minute breaks between trials. Directions of the U-turn rotations were chosen by the patient. All experiments were recorded with a video camera. Clinicians used videos to identify gait disturbances and FOG episodes (type and duration), and these data were further used for validation of our method.

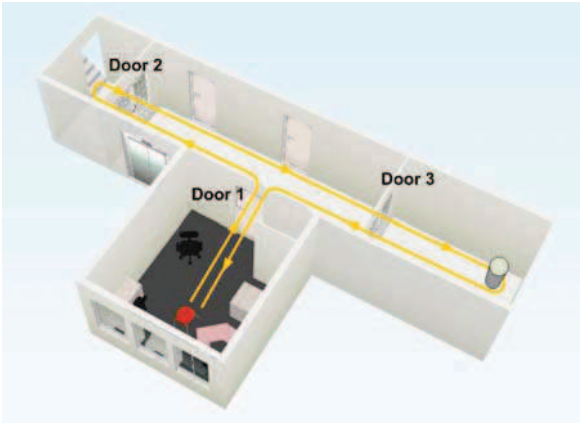

Fig. 2 – Floor plan with the pathway along which the patients were walking (starting from the Lab room, through the doors and hallways, and back).

Data processing

1. Spatiotemporal gait parameters

In order to estimate gait parameters, reliable and accurate estimations of the particular gait events are needed. Heel contact and toe-off delimit swing and stance phases of the gait cycle, so that identification of these events can be used for estimation of various temporal gait parameters. One of the most reliable and easiest methods is by applying thresholds to heel switch or FSR data [18]. The detection of gait events from force sensors is a simple and reliable technique, especially for applications to patients with pathological gait, where it is difficult to adapt rules or thresholds for detection methods for gait events based on IMUs [19]. The estimation of temporal gait parameters is provided by the ground reaction force obtained from force sensors placed under the heel, metatarsal, and toe area of the foot.

FSRs were used to detect gait phases by summing signals from one leg, normalizing to the maximum of the sum, and applying a threshold (THfsr) at 5% of the normalized sum. Intervals where the signal is beyond THfsr are considered to belong to the stance phase, while the other intervals (the normalized sum is below THfsr) are considered to be the swing phase.

Spatial gait parameters (e.g. stride and step length) require the data recorded from accelerometers. Double numerical integration of linear accelerations (recorded by accelerometers) provides information about spatial displacement. For estimation of the stride length, we performed double integration of acceleration signals recorded from foot segments and transformed to the global coordinate system. However, due to the integration drift typical for this type of sensors, a drift-elimination procedure needs to be performed. One successful method for drift elimination is based on a polynomial drift approximation. In this way, we obtained estimation of stride length with only a 4% error [20].

By applying the definitions of gait phases and temporal gait parameters to the detected gait events, SENSY software calculates various gait parameters for each stride within recorded sequence. A list of gait parameters that could be estimated by this system include: stride time, cadence, velocity, stride length, swing time, stance time, swing/stance ratio, single support time, double support time, symmetry etc. A stride parameter that cannot be estimated by this system is the stride width, since that would require information from additional sensors.

2. Reconstruction of gait trajectory

In order to provide 3-D gait analysis and trajectory reconstruction, the software employs transformation matrices and combines human locomotion and biomechanical constraints in order to fuse accelerometer and gyroscope data. Polynomial fitting eliminates the drift [12].

3. Frequency analysis based on spectrogram

PD patients may exhibit changes in movement frequencies of limb segments during gait. Normal walking is typically characterized with frequencies from 0.5 Hz to 3 Hz (vertical shank acceleration), while FOG in patients with alternate leg trembling is typically manifested with a tremor in the range from 3 Hz to 8 Hz. FOG patients can also experience motor blocks without performing movement at all [21–23]. Therefore, it is very practical to display spectrum as a function of time, so that a clinician can follow changes of patient's stride frequency, correlate these alterations to existing obstacles along the path, and estimate duration and intensity of these disorders.

A very intuitive and "user friendly" visual tool for frequency follow-up is a spectrogram, calculated from the temporal signal by using the short-time Fourier transform preformed for each stride independently. The spectrogram used in this application is a graph with the horizontal axis showing time or number of strides, while the vertical axis corresponds to the frequency. A third dimension indicates the amplitude of a particular frequency at a particular time instant, which is coded by the intensity or color of each pixel of the image. We selected the Jet color map in Matlab software, where low amplitudes are represented by cold color tones (starting from navy blue for the lowest amplitude), heading towards warmer colors with amplitude increase, finishing with dark red color for the highest amplitude, as shown in Figure 3 example.

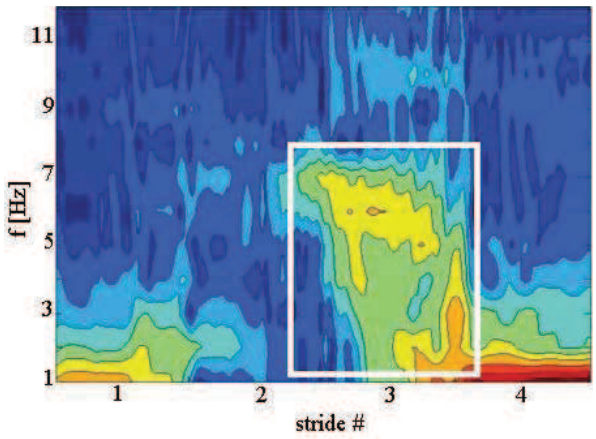

Fig. 3 – Example of spectrogram: FOG episode begins as a motor block (stride #2) and is followed by FOG with tremor episode of the frequencies 5–7 Hz (stride #3), as depicted by the frame.

4. Stride classification and identification of freezing of gait episodes

We illustrated the method with examples of stride-to-stride variability and FOG appearances, both described by the stride length (SL), stride duration (SD), and power spectrum. If we classify each stride based on these three parameters, we can assign each stride to a certain class type according to: normal, short, shuffling, FOG with tremor or FOG with complete motor block. Thresholds for stride length and duration can be calculated from straight-line gait sequence (suggested length not less than 5 m). The thresholds are then defined from mean ± SD of the two observed parameters (Figure 4), while for shuffling strides (typical for FOG) the threshold for stride length is set to 20 cm. If the patient's gait

pattern is severely disturbed even for the straight-line gait sequence, the clinician can apply thresholds obtained from the available data or can manually adjust the threshold according to his/her assessment.

Figure 4 shows an example of the threshold setup.

Classification of strides and FOG types were made accordingly to the rules presented in Tables 2 and 3.

Results

The described stride classification was merged with an algorithm for stride reconstruction [12], resulting in a useful graphical tool that allows clinicians to inspect and analyze a subject's movement. Along the reconstructed trajectory gait disturbances are highlighted for detailed gait analysis.

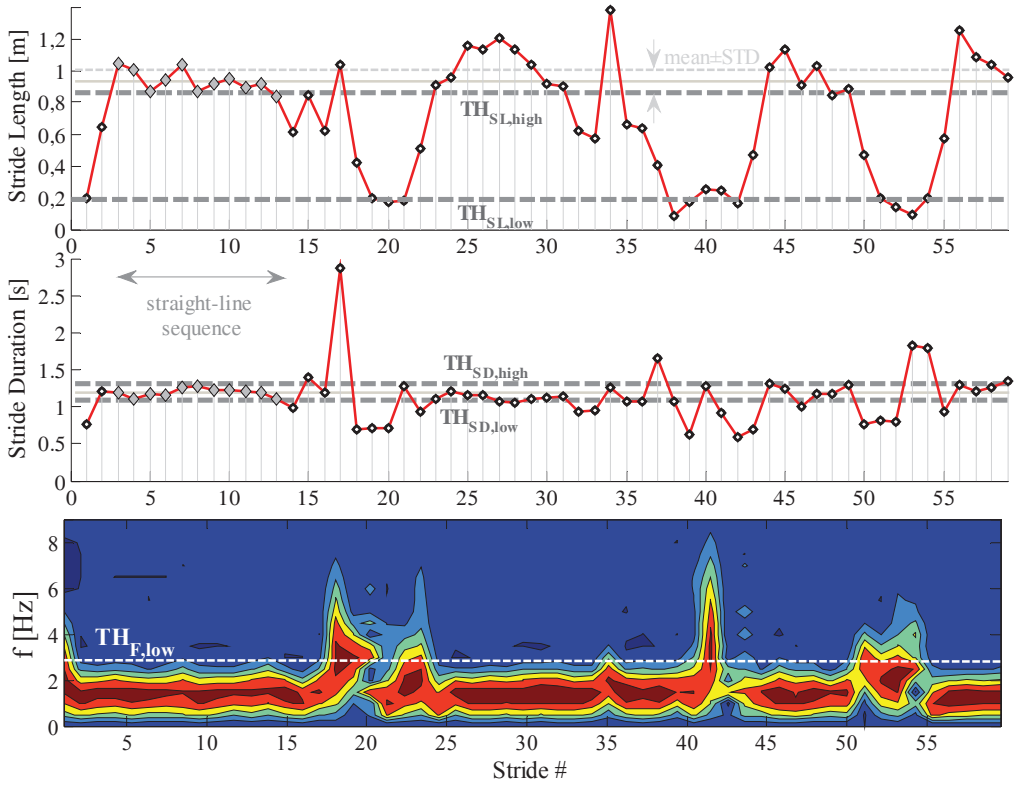

Fig. 4 – An example of stride-to-stride variability of a Parkinson's disease (PD) patient's gait shown by the stride length (top), stride duration (middle), and spectrogram (bottom). Thresholds are shown with thick dashed horizontal lines ($TH_{SL,high}$, $TH_{SL,low}$, $TH_{SD,high}$, $TH_{SD,low}$, $TH_{F,low}$). Mean values and standard deviations of stride length and duration are calculated from initial strides while the patient was walking along a straight path (grey markers). Spectral analysis is shown as a spectrogram, with the white dashed line (threshold value) separating frequencies during "normal" gait and gait with trembling/tremor.

Table 2

Typical values for gait parameters with lower and higher thresholds (TH) applied for classification

Gait parameter	Normal (typical)	TH_{low}	TH_{high}
Stride length (SL) [m]	0.7–1.3	0.2	0.5
Stride duration (SD) [s]	0.8–1.2	0.5	2
Dominant frequency band (F_1 –F_2) [Hz]	0.5–3	3	8

Table 3

Rule-based stride classification and identification of freezing of gait (FOG) episodes.

Stride or FOG type	Rule (Condition)
Normal	Default
Short stride	$TH_{SL,low} < SL < TH_{SL,high}$
Shuffling stride	$SL < TH_{SL,low}$
FOG motor block	$Freq < TH_{F,high}$ & $ST > TH_{ST,high}$
FOG & trembling	$Freq > TH_{F,low}$ & $ST > TH_{ST,high}$

TH – threshold; SL – stride length; ST – stride time.

This graphical tool plots the trajectory in 3D as a stick diagram (Figure 5), where one "leg" represents each stride, and the gait disturbances are color coded according to the following scheme: black = normal, blue = short, green = shuffling, red = FOG with trembling, and pink = FOG with motor block. The algorithm identifies and marks freezing episodes by different colors and indicates gait sequences which should be observed and analyzed more carefully.

As an example of recorded gait shown in Figure 4, such generated plot is presented in Figure 5. The following is a

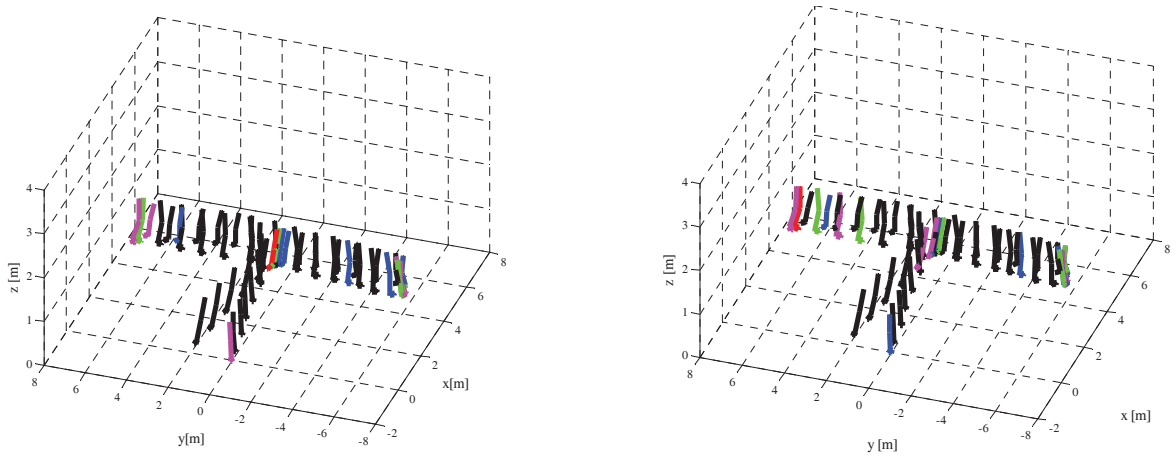

Fig. 5 – Illustration of 3D gait trajectory for the left and the right leg (left and right panel) with identified and classified freezing of gate (FOG) episodes shown by color coding. Stride types are color coded according to following: black – normal, blue – short, green – shuffling, red – FOG with tremor, pink – FOG with motor block. Left leg and right leg comparison shows asymmetry of the existing gait disturbances.

detailed description of Figure 5: the changes in the gait pattern were present at the beginning of the sequence (start hesitation), which is shown at (0, 0, 0) coordinate in Figure 5. The patient had the hesitation start at the first step. Further on, he experienced gait disturbances with FOG after passing through door 2 and during turning. He had a complete motor block on the left leg while he was trying to initiate/continue walking with the right leg (manifested by FOG with tremor and shuffling). Thereafter, he successfully proceeded through the hallway towards door 3 and through door 3, but once again he experienced problems during the U-turn. While turning around the obstacle, he had short shuffling strides combined with a complete motor block. Further, he started walking towards door 1, which manifested as a regular gait until he reached the door, where he dramatically decreased the stride length and eventually exhibited FOG with leg trembling. After this episode, he passed through door 1, walked forward and returned to the chair with his natural gait pattern.

This method for identification and classification of FOG episodes has been evaluated by experienced clinicians who compared the system/method outputs with video recordings of the same episodes. Comparison showed an excellent matching between visual observations and sensor detection of FOG episodes (both sensitivity and specificity test showed more than 95% success). Furthermore, sensors were able to quantify particular episodes and provide more detailed information also about the strides which preceded them.

Estimated gait parameters for gait sequence presented in Figures 4 and 5 are shown in Table 4. The parameters are shown in terms of their mean values, standard deviations and coefficient of variations (calculated according to $CV = \frac{STD}{mean} \cdot 100\ \%$), for the left and right leg separately.

Table 4

Gait parameters for the observed gait sequence

Gait parameters	mean L	SD L	mean R	SD R	CV L [%]	CV R [%]
Step count	107.00	/	/	/	/	/
Ambulation time [s]	68.12	/	/	/	/	/
Cadence [steps/min]	94.25	/	/	/	/	/
Stride counts	51.00	/	57.00	/	/	/
Distance [m]	37.79	/	36.21	/	/	/
Velocity [m/s]	0.65	0.31	0.66	0.32	47.55	49.46
Stride time [s]	1.31	0.98	1.20	0.50	74.57	42.07
Swing time [s]	0.34	0.13	0.33	0.14	37.41	42.56
Stance time [s]	0.97	0.98	0.86	0.54	100.94	62.69
Cycle time Dif [s]	-0.12	1.10	0.00	0.00	0.00	0.00
Single supp time [s]	0.36	0.13	0.31	0.16	36.88	49.82
Double supp time [s]	0.61	0.95	0.55	0.61	156.54	110.56
Swing cycle [%]	28.85	10.26	29.33	10.98	35.58	37.45
Stance cycle [%]	71.15	10.26	70.67	10.98	14.43	15.54
Single supp cycle [%]	30.54	10.29	27.27	11.92	33.70	43.70
Double supp cycle [%]	40.61	18.84	43.40	21.75	46.39	50.11
Stride length [m]	0.74	0.34	0.72	0.33	45.52	46.28

L/R – left or right leg; SD – standard deviation; CV – coefficient of variation.

Discussion

The described gait assessment system can be used to detect and categorize gait disturbances by applying the rule-based classification according to stride length, stride time,

and frequency of the shank segment movements. The spectrogram used in this application is easy to interpret and provides clinicians and therapists with valuable information regarding the temporal changes in the frequencies of lower limb's movement. This method discriminates among normal walking, appearance of FOG with leg trembling, and appearance of motor blocks during walking. This could point towards valuable information about walking unsteadiness and possible falls.

The SENSY system with the proposed method provides full information about FOG episodes in PD patients, as well as changes in gait patterns which could precede these episodes. However, the decisions about the proper and accurate classification of gait disturbances (such as short strides *vs* normal strides, or short strides *vs* shuffling) are sensitive to the established threshold values. Therefore, the visual tool (shown in Figure 5) should be considered in combination with the stride-to-stride variability data (Figure 4) with shown thresholds. These thresholds can be also adapted and changed manually by a referred clinician, if needed.

Unlike the clinical rating scales commonly used for FOG assessment (presented in the last two columns of Table 1), this assessment provides information about the types of stride or FOG episodes, its duration and intensity. Another advantage of the system, compared to clinical scales is that there are no issues with subjectivity which is based on the observer's experience and individual bias, or subjectivity of the patient responding the questionnaire.

Compared to other ambulatory systems for FOG detection [8, 21, 23], the described system provides more detailed information combining data from all three leg segments of both legs, and classify strides according to five previously defined states (normal or abnormal), while other systems typically classify gait patterns according to normal *vs* FOG, where some differentiate FOG to FOG with motor block or FOG with trembling.

When it comes to patients with gait disturbances that are present in PD, the gait analysis performed in a clinical environment frequently does not actually capture patient's real state of locomotion, i.e., the gait pattern which is prevalent. Being aware that their gait is being observed and recorded, patients often (consciously or subconsciously) change their gait pattern, trying to walk "better", faster, or the opposite, to emphasize their movement disorders and problems they have. Therefore, having a gait assessment system which could be used in home environment, as a holter monitor, would provide clear and objective image about patient's state in a quiet environment, as well as frequency and duration of experienced gait disturbances and episodes. This could be arranged by simple hardware adaptation, allowing the sensor units to store data internally, instead of sending the data to a remote PC.

Conclusion

For patients with PD, the objective spatiotemporal measure of gait disturbances provides a very important tool not only to follow the progress of the disease, but also to investigate how the patients respond to treatment (medication) and to monitor effects of prescribed therapies on gait characteristics. Also, since the proposed system could be used as a holter monitor, the required time for patients to stay in hospital could be significantly shortened. A patient can be examined during the day, sensor system attached to their limbs and returned home with a standalone holter unit to record gait while at home environment. In this way, clinicians can get real picture about patient's gait disturbances (types and timings) while at home, during their usual activities without being at the hospital. Furthermore, having illustrative graphic clinical tool to monitor gait pattern and gait pattern changes enables even inexperienced clinicians to note the changes in gait pattern, and signal the concomitant walking problems in monitored patients to clinicians or to patient's caregivers.

Acknowledgments

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REFERENCES

1. *Carpinella I, Crenna P, Calabrese E, Rabuffetti M, Mazzoleni P, Nemni R*, et al. Locomotor function in the early stage of Parkinson's disease. IEEE Trans Neural Syst Rehabil Eng 2007; 15(4): 543−51.
2. *Alves G, Forsaa EB, Pedersen KF, Dreetz GM, Larsen JP*. Epidemiology of Parkinson's disease. J Neurol 2008; 255(Suppl 5): 18−32.
3. *Wolters EC*. Variability in the clinical expression of Parkinson's disease. J Neurol Sci 2008; 266(1−2): 197−203.
4. *Giladi N, Treves TA, Simon ES, Shabtai H, Orlov Y, Kandinov B*, et al. Freezing of gait in patients with advanced Parkinson's disease. J Neural Transm 2001; 108(1): 53−61.
5. *Nutt JG, Bloem BR, Giladi N, Hallett M, Horak FB, Nieuwboer A*. Freezing of gait: moving forward on a mysterious clinical phenomenon. Lancet Neurol 2011; 10(8): 734−44.
6. *Hely MA, Reid WG, Adena MA, Halliday GM, Morris JG*. The Sydney multicenter study of Parkinson's disease: the inevitability of dementia at 20 years. Mov Disord 2008; 23(6): 837−44.
7. *Jovicic NS, Saranovac LV, Popovic DB*. Wireless distributed functional electrical stimulation system. J Neuroeng Rehabil 2012; 54(9): 1−10.
8. *Popovic MB, Djuric-Jovicic M, Radovanovic S, Petrovic I, Kostic V*. A simple method to assess freezing of gait in Parkinson's disease patients. Braz J Med Biol Res 2010; 43(9): 883−9.
9. *Morris M, Iansek R, Matyas T, Summers J*. Abnormalities in the stride length-cadence relation in parkinsonian gait. Mov Disord 1998; 13(1): 61−9.
10. *Bloem BR, Beckley DJ, Dijk JG, Zwinderman AH, Remler MP, Roos RA*. Influence of dopaminergic medication on automatic

postural responses and balance impairment in Parkinson's disease. Mov Disord 1996; 11(5): 509−21.

11. *Lewis SJG, Barker RA.* Understanding the dopaminergic deficits in Parkinson's disease: insights into disease heterogeneity. J Clin Neurosci 2009; 16(5): 620−5.
12. *Djurić-Jovičić M.* Inertial sensors signal processing methods for gait analysis of patients with impaired gait pattern [dissertation]. Belgrade: Faculty of Electrical Engineering, University of Belgrade; 2012. (Serbian)
13. *Hoehn MM, Yahr MD.* Parkinsonism: onset, progression and mortality. Neurology 1967; 17(5): 427−42.
14. *Fahn S, Elton RL.* Committee mot UD. Unified Parkinsons Disease Rating Scale. In: *Fahn S, Marsden CD, Goldstein M, Calne DB*, editors. Recent developments in Parkinsons disease II. Florham Park, NJ: Macmillan Healthcare Information; 1987. p. 153−63.
15. *Folstein MF, Folstein SE, McHugh PR.* Mini-mental state. A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975; 12(3): 189−98.
16. *Giladi N, Shabtai H, Simon ES, Biran S, Tal J, Korczyn AD.* Construction of freezing of gait questionnaire for patients with parkinsonism. Parkinsonism Relat Disord 2000; 6(3): 165−70.
17. *Podsiadlo D, Richardson S.* The timed "Up & Go": a test of basic functional mobility for frail elderly persons. J Am Geriatr Soc 1991; 39(2): 142−8.
18. *Djurić M.* Automatic recognition of gait phases from accelerations of leg segments.. Proceedings from the 9th Symposium on Neural network applications in Electrical Engineering; 2008 Sep 25−27; Belgrade: Neurel; 2008. p. 121−4.
19. *Sabatini AM, Martelloni C, Scapellato S, Cavallo F.* Assessment of walking features from foot inertial sensing. IEEE Trans Biomed Eng 2005; 52(3): 486−94.
20. *Djurić-Jovičić MD, Jovičić NS, Popović DB, Djordjević AR.* Nonlinear optimization for drift removal in estimation of gait kinematics based on accelerometers. J Biomech 2012; 45(16): 2849−54.
21. *Moore ST, MacDougall HG, Gracies J, Cohen HS, Ondo WG.* Long-term monitoring of gait in Parkinson's disease. Gait Posture 2007; 26(2): 200−7.
22. *Moore ST, Macdougall HG, Ondo WG.* Ambulatory monitoring of freezing of gait in Parkinson's disease. J Neurosci Meth 2008; 167(2): 340−8.
23. *Schaafsma JD, Balash Y, Gurevich T, Bartels AL, Hausdorff JM, Giladi N.* Characterization of freezing of gait subtypes and the response of each to levodopa in Parkinson's disease. Eur J Neurol 2003; 10(4): 391−8.

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