

Gait analysis in frequency domain for freezing detection in patients with Parkinson's disease

Haritz Zabaleta, Thierry Keller, José Félix Martí Massó

Abstract—Freezing of gait (FOG) is a common and disabling symptom of Parkinson's disease. It is an episodic and non predictable phenomenon that affects most commonly the gait in the form of start hesitation and sudden immobility. It often results in falls and consequent injuries reducing quality of life.

In this pilot study sensors measuring acceleration in 3 axes and angular velocity in 2 axes have been used to monitor foot, shank and thigh movements. Also the magnitude of acceleration was calculated for each 3-axis accelerometer. To determine changes in the power spectral density (PSD) the short time Fourier transform (STFT) was used.

The results showed significant shift of the PSD towards higher frequencies during FOG episodes ($p=0.00002$) in vertical linear acceleration and in the angular velocity of the heel ($p=0.00003$). 82,7 % of the FOG episodes were detected correctly using motion parameters obtained from the acceleration perpendicular to the coronal plane of the heel.

I. INTRODUCTION

THE freezing of gait (FOG) is a common and disabling symptom of Parkinson's disease (PD) and responds poorly to medical treatment. This episodic phenomenon is often incapacitating for the affected person both physically and psychologically because of injuries that could occur [1]. The embarrassment and discomfort which people may feel as a result of their freezing episodes may discourage their participation in public events, reduce their social contacts and exclude them from activities that they had previously enjoyed. Freezing of gait is likely to disturb balance and thereby represents a common cause of falls in people with Parkinson's disease. Falls are initially absent early in the course of the disease, but they become increasingly prevalent as balance becomes progressively impaired, and eventually disappear again when patients become progressively immobilized in late-stage Parkinson's disease [2].

It has been observed that FOG it is slightly more common in people whose initial Parkinson's symptoms include difficulties with gait and problems with balance [3].

It is also more likely to occur in late stages of PD and in people who have been on a treatment with levodopa (LD) for long periods. However, as freezing can occur in people who are not being treated with levodopa, the condition

cannot be simply described as a side effect of the medication. It has been suggested that other mechanisms in the brain besides dopamine might be involved in freezing. It is not clear what the cause of the freezing is, but it is known that it becomes worse when a person gets anxious, in crowded places, while crossing doorways, elevators and narrow spaces such as corridors or due to sudden change of the walking surface.

There are several techniques that detect FOG. While some investigations suggest the analysis of electromyographic (EMG) profiles as method to predict FOG [4], others, [4] and [5] suggest that motion signal analysis in the frequency domain can be useful for FOG detection. The goal of this pilot study is to determine which sensor placement is more suitable and which signal of the sensor is most suitable for FOG detection purposes using frequency domain analysis. In order to analyze this issue that several parameters have been taken into account; the dominant frequency, PSD Quartiles, power above and below the dominant frequency and the freeze index (FI) described in [5].

Within a standard 3D gait laboratory setting acceleration and angular velocity data were collected in 6 placements of the lower limbs while the participants performed some pre-defined FOG inducing tasks. The selected tasks were: straight walking test for 5 m, turn and return, walking test with obstacle avoidance, backwards walking test, sit-stand-walk test and a dual task while walking.

II. METHODS

A. Participants

Two participants (Table 1) diagnosed with PD were recruited by a neurologist at the Hospital of Donostia. The inclusion criteria was designed to include the PD affected patients that tended to have FOG episodes. Both participants had no cognitive impairment, were capable of adhering to the protocol requirements and to provide written informed consent. Their gait disturbance score was 3 and 4 (out of a maximum of 5) on the Unified Parkinson's Disease Rating Scale (UPDRS; item 29)[7], and Hoehn and Yahr stage IV for 'On' and 'Off' phase. The study was performed in accordance with the ethical standards of the Declaration of Helsinki.

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H. Z. and T. K. Authors are with the Health Unit in Fatronik Foundation, San Sebastian, Spain ({hzabaleta / tkeller}@fatronik.com).

J. F. M. M. is with the Neurology department of Hospital Donostia. ((e-mail: josefelix.maritmasso@osakidetza.net)

TABLE I
PARTICIPANTS IN THE PILOT STUDY

Participant	Age (years)	Onset (years)	H&Y 'off' ¹	H&Y 'on' ²
1	73	65	IV	IV
2	75	65	IV	IV
	LD ³ (morning)	LD ³ (total)	Adjunct PD meds	
	[mg]	[mg]		
1	50	200	Yes	
2	250	875	Yes	

¹ Hoehn and Yahr stage in 'On' phase.

² Hoehn and Yahr stage in 'Off' phase.

³ Levodopa

B. Experimental setup

To analyze gait and leg movements six locations were selected in the the lower extremities (Fig. 1). The heel sensors have been placed as nearest to the floor as possible in order to maximize de measured angular velocity. The calf sensors have been placed in the mid-point of the shank; equidistant to the bellow the malleolus head and the lateral malleolus bone. The thigh sensors have been placed in the mid-point of the thigh.

Each of the tracked points contains a three-axis accelerometer and a two-axis gyroscope. Also the kinematics of each of the points was recorded during each trial using 6 Hawk camera system (MotionAnalysis)[8].

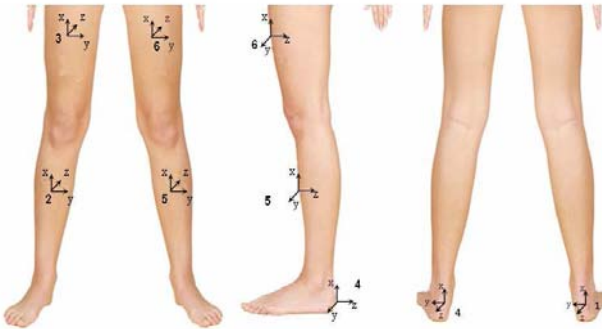


Fig. 1. Sensor axis convention: x axis: positive upwards y axis positive in the transversal axis leftwards in walking direction and z axis positive backward (opposite to walking direction)

Sparkfun IMU5 (Fig. 2) sensors were used to obtain kinematic data of each point. This small PCB board incorporates the new IDG300 dual-axis gyroscope and the Analog Devices triple axis ADXL330 accelerometer providing 5 axis of sensing (Roll, Pitch, X, Y, Z) in around 6 cm².

The IDG300 is an integrated dual-axis gyroscope with: integrated X- and Yaxis gyro on a single chip; full scale range of 500/sec; integrated low-pass filters [9]. On the other hand, the ADXL330 is a 3-axis accelerometer of a minimum full-scale range of 3 g [10].

The sensor signal naming convention is $S_{i,j}$, were i , from 1 to 6, is the number of the sensor (as shown in Fig. 1) and j , from 1 to 5, the signal output from the sensor (1 for vertical acceleration; 2 for lateral acceleration; 3 for the acceleration perpendicular to the coronal plane, 4 for lateral and medial rotation of the leg and 5 for the extension and flexion).

Video and data were time synchronized and collected at 200Hz and 1000Hz, respectively (EVaRT, Motion Analysis Corp.). The motion analysis system was

calibrated to manufacturer recommendations prior to each data collection session.

After the acquisition the data was labeled manually using the synchronized video acquisition.

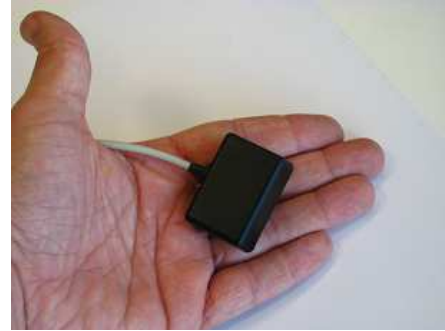


Fig. 2. IMU5 embedded in hand.

C. Trials

The tasks have been designed to provoke FOG during acquisition of kinematic data. Freezing is more likely to appear in tasks that require attention [1]-[3] like sharp turns, walking in crowded environments, doorways, etc.

The gait analysis trials took place at the Fatronik Foundation Health Division laboratory in San Sebastian, Spain during one whole medication cycle. The participants arrived to Fatronik in the morning without having taken their usual morning medication (10 to 11 hours after last medication intake). After performing the first cycle of trials, they could take their morning medication. This was done in order to monitor possible effects of the medication cycle in the participants performance.

Each cycle of trials comprised a circuit section, a repeated isolated task section (only if the participant got into FOG) systematically in one of the tasks of the circuit, and a dual task section.

This circuit was designed to reproduce the situations where FOG is more likely to appear. The circuit was divided into eight parts (Fig. 3). Starting from a quiet sitting position, the participant will stand-up and go (1); walk along a zigzag path (2); turn to right side (3); sit on the chair stand-up and go again (4); sharp turn with a doorway approach (5); avoidance two chairs and walk around them (6); another sharp turn (7); and finally sit down (8). Going through the circuit takes around 1,5 minutes.

If the participant got into FOG systematically in one of the above described tasks, this task was repeated isolated 2 times.

Some previous works ([11] [12] and [13]) note that people with PD have difficulties when they were instructed to perform a complex secondary task while walking. The regulation of gait variability and rhythmicity is apparently an automatic process that does not demand attention in healthy adults. In patients with PD, however, this ability becomes attention-demanding and worsens when subjects perform secondary tasks. Moreover, the associations between executive function and gait variability suggest that a decline in executive function in PD may exacerbate the effects of dual tasking on gait, potentially increasing fall risk.

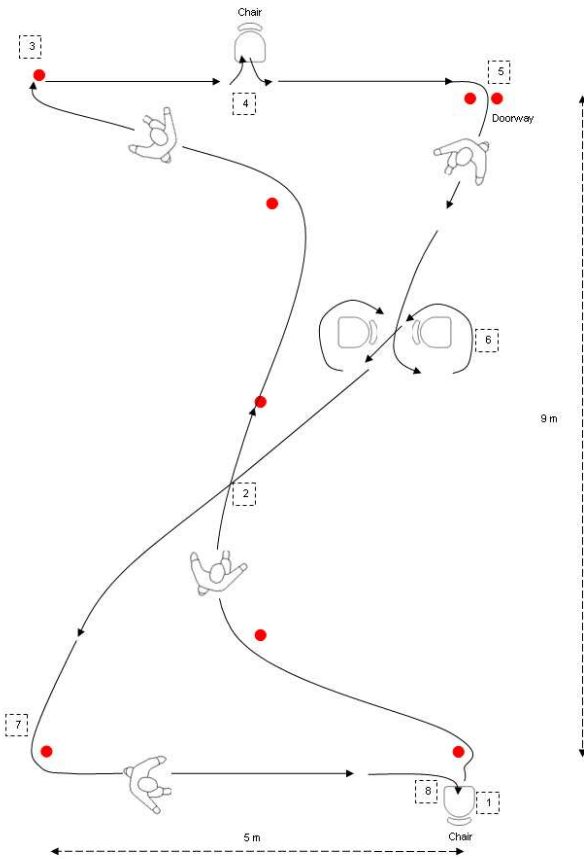


Fig. 3. Schematic of the performed circuit. 1. Sit to Stand; 2. Zig Zag walk; 3. Turn (right side); 4. Stand to sit (left side) count loud until 3 and Sit to stand; 5. Sharp turn right and doorway approach; 6. Obstacle avoidance; 7. Sharp turn (left side); 8. Stand to sit.

Therefore the participants performed a dual task. The control task is a straight line walk, 180° turn and another straight line walk as shown in the Fig. 4.

In our study the basic dual task will be the performed in three different forms:

1. The participant performs the control task without restrictions.
2. The participant performs the control task without stepping the lines marked on the floor.
3. The participant performs the control task without stepping the lines marked on the floor and performing the cognitive secondary task (participant had to repeat some strings of numbers backwards).

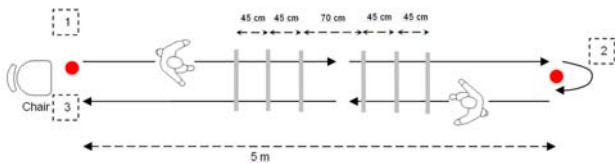


Fig. 4. Schematic of the performed circuit during dual task.

D. Signal Treatment

The resulting waveform was processed in Matlab using various spectral analysis techniques (FFT and STFT). First the signal is broken into overlapping frames and

then each frame is transformed into the frequency domain using the Fast Fourier Transform. In this way the PSD for each frame, which describes how the power of the signal is distributed with frequency is obtained. To analyze the distribution of the PSD several parameters have been taken into account; the dominant frequency, PSD Quartiles, power above and below the dominant frequency and the freeze index (FI) described in [5]. The FI was defined as the square of the area under the power spectra in the ‘freeze’ band, divided by the square of the area under the spectra in the ‘locomotor’ band.

III. RESULTS

The power spectrum up to approximately 2-3 Hz corresponds to the power of the oscillations that happen during voluntary movements like cyclic movement of walking. During FOG episodes, the power of the signal above this frequency increase, and the ones blow this frequency decrease. Therefore, change of the PSD of the movement towards higher frequencies can be interpreted as FOG (Fig. 5).

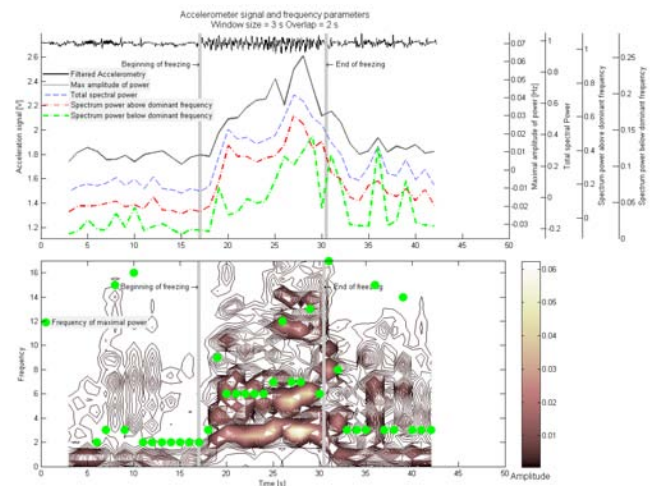


Fig. 5. PSD change during FOG. Between the gray lines the FOG occurs and principal PSD parameters change towards higher frequencies. Also the spectrogram of the signal is shown.

On the other hand, depending on which tracked point of the leg and what signal of the point we use, the characterization of the FOG will be different. In the Fig. 6 and Fig. 7, the difference in characterization of three situations is shown depending on the signal we used for it. In other words, FI will have a different behavior depending on the signal we use to calculate it and the placement of the sensor in the lower limbs.

Although PSD distribution changes depending on the placement of the sensor and the used signal, the differences of the FI in most of the cases remain significant (Table 2).

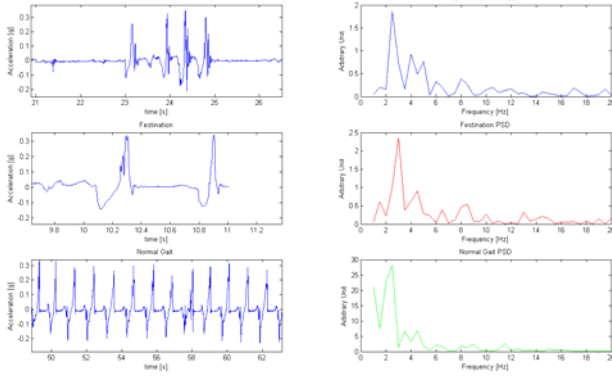


Fig. 6. Characterization of Start hesitation, Festination and Normal Walk using the horizontal acceleration of the right heel

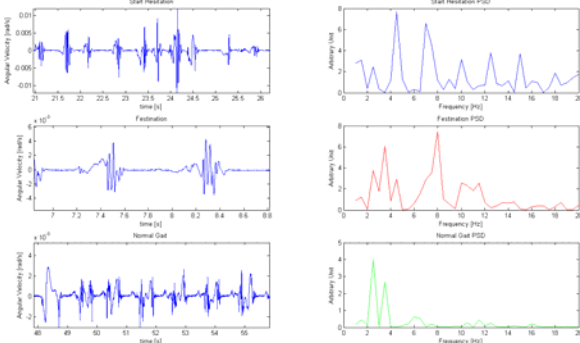


Fig. 7. Characterization of Start hesitation, Festination and Normal Walk using the angular velocity of the left shank in the sagittal plane.

TABLE II
FI DIFFERENCES BETWEEN STATES

Sensor	Freezing		Normal Walk	p value
	mean \pm SD			
$S_{4,3}$	0,1072 \pm 0,1538		15,94 \pm 18,7984	0,000231
$S_{1,3}$	0,0812 \pm 0,0971		6,2485 \pm 7,757	0,00043
$S_{2,5}$	0,7244 \pm 0,8552		3,7681 \pm 5,8767	0,00078
$S_{5,4}$	1,27164 \pm 2,1547		4,446 \pm 3,962	0,00085
$S_{2,1}$	0,1744 \pm 0,194		2,141 \pm 2,769	0,00131

After visualizing the videos, 8 FOG episodes could be identified with a mean duration of 5.125s [S.D. 4.48s].

Using the freeze index (FI) as classification variable, the classification of the signals was done using a linear classifier. The best results of classification were obtained with $S_{1,3}$. With freeze index obtained from the horizontal axis acceleration of the heel, 82,7 % of the FOG episodes were detected correctly. Using $S_{2,5}$ (the shanks angular velocity in the sagittal plane), 80,8 % of the FOG episodes could be detected.

The vertical acceleration of the leg (left and right heel, shank and thigh) could classify correctly between 63,4 and 69,2 % ($66,27 \pm 2,34$) of the FOG episodes, whereas using angular velocity in the sagittal plane between 67,3 and 80,8 % ($73,1 \pm 5,83$).

The worst results have been obtained using $S_{5,4}$ 51,1 % of well classified FOGs and $S_{1,4}$ with 54.5% of well classified FOGs.

IV. CONCLUSION

The results of this work show the importance of the placement of the sensor and sensing magnitude

(acceleration or angular velocity) in order to design a reliable FOG detection algorithm using PDS distribution analysis.

The angular velocity of the lower limbs proved to be the best classification variables. The acceleration of the heel perpendicular to the coronal plane was be the best classification variable of all.

The bad results obtained using the $S_{5,4}$ and $S_{5,4}$ are due to the fact that these correspond to mediolateral rotations of the heel and this movement is not present during FOG.

The PSD distribution analysis performed on the training set obtained discriminant functions able to classify a high percentage of the testing set series. These results permit to consider PSD distribution analysis as a promising methodology to study the FOG and medication effects in patients with PD.

This methodology will be validated by a larger number of patients, especially to improve the discrimination functions and the FOG detection accuracy.

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