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***Abstract*— Deep brain stimulation (DBS) implant represents an appropriate treatment for motor symptoms typical of Parkinson's Disease (PD). However, little attention has been given to the effects of different DBS stimulation frequencies on gait outcomes. Accordingly, the aim of this pilot study was to evaluate the effects of two different DBS stimulation frequencies (60 and 130 Hz) on gait spatio-temporal parameters, symmetry, smoothness, and variability in PD patients. The analysis concentrated on acceleration signals acquired by a magnetic inertial measurement unit placed on the trunk of participants. Sessions of gait were registered for three PD patients, three young and three elderly healthy subjects. Gait outcomes revealed a connection with both age and pathology. Values of the Harmonic Ratio (HR) estimated for the three-axis acceleration signals showed subjective effects provoked by DBS stimulation frequencies. Consequently, HR turned out to be suitable for depicting gait characteristics, but also as a monitoring parameter for the subjective adaptation of DBS stimulation frequency. Concerning the Poincaré analysis of vertical acceleration signal, PD patients showed a greater dispersion of data compared to healthy subjects, but with negligible differences between the two stimulation frequencies. Overall, the presented analysis represented a starting point for the objective evaluation of gait performance and characteristics in PD patients with a DBS implant.**

Keywords—Parkinson's Disease, DBS stimulation, inertial sensor, gait analysis, harmonic ratio, phase plot

I. INTRODUCTION

Gait is a complex motor behavior that involves different functions and abilities, and it can be identified as the primary activity in the daily life of a person [1]. Any dysfunction in the musculoskeletal and nervous systems can lead to a crucial alteration of gait pattern and correlated negative consequences such as pains, falls, and injuries. Among the neurodegenerative disturbs, Parkinson's Disease (PD) is a brain disorder characterized by a slowly expanding degeneration of neurons. PD leads to several motor disorders involving balance, posture, and gait [2]. Deep brain stimulation (DBS) represents a therapeutic solution based on electrical stimulation of the brain (subthalamic nucleus) by means of an implanted electrode [3]. DBS is common for the treatment of PD motor disorders and several studies demonstrated good/excellent results in the reduction of rigidity, bradykinesia, and tremor, as well as their daily fluctuations. In the past, DBS effects on body posture [4], [5], balance [6], and gait pattern [7] have been evaluated; however, results were non-significant or conflicting with previous ones. Possibly this is related to methodological and instrumental limitations [6], [7]. One other innovative aspect can be identified in the improvement of the DBS system from continuous and constant stimulations to adaptive ones [8], in order to meet the different needs and continually evolving symptoms in PD patients.

During the last decades, wearable technologies for the analysis of human movements have become important in several clinical applications [9], [10]. Among them, inertial measurement unit (IMUs) systems are a suitable alternative to the gold standard of optoelectronic systems. IMUs small size and practical usage allow overcoming the limits of laboratory setting, expensiveness, and post-processing time cost of other measuring systems. In the case of elderly and pathological subjects, easy-to-use characteristics of inertial systems have turned out to be strong advantages for gait monitoring. Several studies concentrated on the identification of the most reliable algorithm and repeatable set-up for the quantification of walking ability in healthy and pathological subjects [11], [12]. Considering gait spatio-temporal parameters as outcomes of interest, the use of one inertial unit positioned on the trunk revealed to be the best solution in terms of accuracy, repeatability, and ease of use [13]. Linear acceleration signals acquired with the IMU system can be post-processed to provide spatio-temporal parameters, such as Walking Speed, Stride Time, Step Time, differentiation of gait phases (Stance and Swing), but also specific indexes of stride smoothness, symmetry, and variability [14]. Investigation of these last variables might be fundamental to understand and quantify gait patterns in some pathologies, such as PD.

A commonly used index of gait symmetry [15] and smoothness [16] is the Harmonic Ratio (HR), which is the ratio between the amplitude of even and odd harmonics of the spectrum of a signal. Considering gait, the HR is based on the spectral analysis of the acceleration signals acquired by one IMU placed at the trunk level. Through the identification of heel strikes, the acceleration signal can be segmented into consecutive strides. Then the harmonic content of the signal is identified. A higher value of HR corresponds to a greater gait smoothness [15]. Several previous studies have adopted the HR estimation to measure gait asymmetry and lack of smoothness in patients, particularly in people with PD [17], [18]. Latt and colleagues [17] have analyzed acceleration patterns and HRs during gait in elderly PD patients with and without a history of falls, positioning inertial sensors on head and pelvis. In that study, HRs were used as indicators of upper

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body stability. Results pointed out a reduction of stability in PD fallers in all three planes. In 2018, Conway and colleagues [18] have adopted HRs to demonstrate a poorer trunk control during stair descent with respect to stair ascent in PD patients. Despite its wide usage, the lack of standardization in data acquisition and index estimation reduces HR reliability [19].

Considering other methodologies to investigate walking, Poincaré analysis (Phase plot) is an emerging quantitative-visual technique taken from nonlinear dynamics to analyze the variability of a specific parameter. In detail, this analysis produces scatterplots relating the value at an instant to the consecutive one. The Poincaré analysis presents numerous previous applications on biomedical signals [20], especially within electrocardiogram studies [21]. The Phase plot typically appears as an elongated cloud of points oriented along the line of identity. Subsequently, an ellipse can be fitted from the points distribution. Brennan and colleagues [21] have provided mathematical expressions that relate each objective measure obtained from the Poincaré plot geometry to identify a correspondence with the heart rate variability indexes. More recently, the Phase plot has also been adopted in walking analysis to evaluate gait smoothness and variability in elderly fallers [22], in post-stroke patients [23], and in PD patients [16]. Due to its cyclical behavior, good repeatability of gait pattern and small values of dispersion are expected in healthy subjects [21], while in the case of pathological subjects, some deviations may occur. Based on these parameters or temporal signals, a proper interpretation of data along short and long axes needs to be implemented to describe gait properties.

The principal aim of the current preliminary study concentrated on the investigation of deep brain stimulation effects with two different stimulation frequencies (60 Hz and 130 Hz) on patients affected by Parkinson's Disease. Gait outcomes were evaluated and compared with the ones recorded on young and elderly healthy subjects. Three-axis acceleration signals were recorded by a trunk-IMU set-up during walking sessions and post-processed. In detail, the analysis focused on the estimation of global spatio-temporal parameters (Walking Speed, Stride Time and Step Time), gait symmetry, smoothness, and variability parameters (Harmonic Ratios and Poincaré analysis).

II. Materials and Methods

A. Participants

Nine participants from three different categories were recruited for the present preliminary study:

- three healthy young (HY) subjects, one female and two males (age: range 25-27 years, BMI: range 23-25 kg/m^2) with no prostheses, musculoskeletal disturbs or neurological diseases;
- three healthy elderly (HE) subjects, two females and one male (age: range 65-69 years, BMI: range 22.6-30 kg/m^2) with no prostheses, musculoskeletal disturbs or neurological diseases;
- three PD patients with a DBS implant, two males and one female (age: range 56-70 years, time from PD diagnosis: range 19-23 years, time from DBS implant: range 7-14 years).

The study was approved by the Local Institutional Review Board for the healthy young and elderly subjects. Procedures were conformed to the Helsinki Declaration. For the pathological subjects, the study was approved by Hospital Ethics Committees. All participants gave their written informed consent before the experiment.

B. Instruments

The instrumentation adopted for the test consisted of one cable-driven magnetic inertial measurement unit MTx (Xsens, The Netherlands) containing a tri-axial accelerometer (range ± 5 G), a tri-axial gyroscope (range ± 1200 dps), and a tri-axial magnetometer (range ± 75 μT). An elastic band provided by the Xsens kit was used to fix the sensor on the trunk of participants at the level of L1 vertebra. The sensor was oriented with the vertical V-axis pointing downward, the medio-lateral ML-axis directed to the right side of participants, and the anterior-posterior AP-axis pointing in the opposite direction of the gait (Fig 1). The unit was connected via Bluetooth to the PC through the control system called Xbus Master. Data were acquired through the Xsens proprietary software MT Manager with a sampling frequency of 50 Hz.

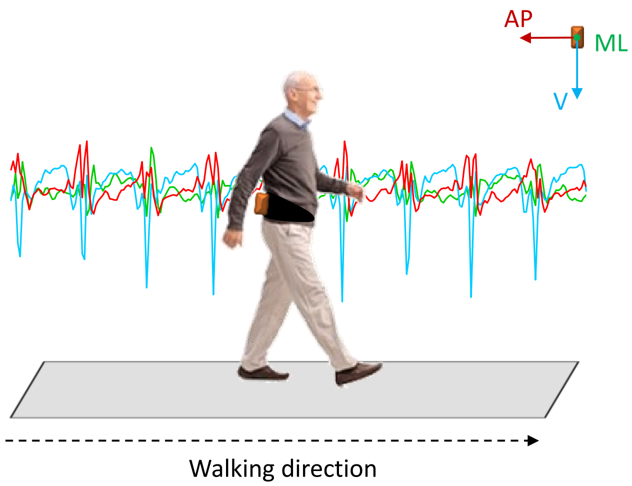

Fig. 1 Graphical representation of the IMU set-up and of the three axial acceleration signals during walking.

C. Protocol

Tests of HY and HE subjects were conducted in the same laboratory in the DIMEAS Lab – Politecnico di Torino. A linear path of 20 meters was traced on the floor. Participants were asked to walk barefoot back and forth along the path, at a self-selected comfortable speed. A range between 120 and 150 strides was recorded for each subject.

The test of PD patients was conducted in the specialized Movement Disorders Center of "Città della Salute e della Scienza" - Torino. Patients were asked to walk barefoot back and forth along a 7-meters path at a self-selected comfortable speed. The test was repeated with two different stimulation frequencies (60 Hz and 130 Hz) of the DBS implant, with a pause of thirty minutes between the two repetitions. A range of 40-60 strides was recorded for each of the three participants, based on clinical conditions during the experiment.

D. Signal processing and data analysis

Signal post-processing and data analysis were conducted with customized Matlab routines. For this study, only the accelerometer of the inertial unit was considered. Raw accelerations data were filtered with a low-pass second-order

Butterworth filter, with a cutoff frequency of 15 Hz prior to stride segmentation. According to [24], maximum deceleration points of the vertical (V) acceleration signal identified heel-strikes. Consequently, tri-axial acceleration signals were segmented in strides. Spatio-temporal parameters (Walking Speed, Stride Time, Step Time) were calculated and averaged for each participant, and then averaged for each category.

Considering acceleration signals separately for each axis, the Harmonic Ratio was estimated as an overall symmetry and smoothness index of gait. In the case of healthy gait, the acceleration presents only even harmonics in the antero-posterior (AP) and vertical (V) directions, and only odd harmonics in the mediolateral (ML) direction [19]. For AP and V directions, due to the biphasic nature of the signals, the HR is calculated as the ratio between the sum of the amplitudes of the even harmonics and the sum of the amplitudes of the odd harmonics. On the contrary, due to the presence of only one dominant acceleration peak within a stride cycle, the HR in ML direction is evaluated as the ratio between the sum of the odd harmonics amplitudes and the sum of the even harmonics amplitudes [23], [24]. The power spectrum of the signal was inspected in order to analyze the frequency content of the segmented signal and to define the number of harmonics to be considered [15]. The HRs of vertical (V) and antero-posterior (AP) accelerations were calculated by dividing the sum of the first 8 even harmonics amplitudes by the sum of the first 8 odd harmonics amplitudes. On the contrary, the HR of the medio-lateral (ML) acceleration was estimated as the ratio of the sum of the first 8 odd harmonics amplitudes and the sum of the first 8 even harmonics amplitudes [15]. HRs were assessed for each stride, then mean and standard deviation values were estimated intra-subject. In addition, mean and standard deviation values of HRs were calculated inside each category of participants.

Poincaré analysis using Phase plots was performed considering the vertical acceleration signal (V) for the evaluation of gait smoothness and gait variability. Considering signal segmentation in strides, the phase plot of signal V was obtained by relating the value at instant *i (x-axis)* to the value at instant *i+1 (y-axis)*. The cloud of data was fitted to an ellipse. In standard Poincaré plots, the dispersion of points perpendicular to the line of identity describes the level of the short-term variability (SD1, width of the short axis of the ellipse) [21]. The dispersion of points along the line of identity indicates the level of the long-term variability (SD2, length of the long axis of the ellipse) [21]. The ratio between the short and the long axes correlates these two measures. In this work, considering the geometrical characteristics of the fitted ellipse, the inclination (φ), the width (SD1), and the length (SD2) of the short and long axes respectively, and their ratio (SD1/SD2) were estimated. Finally, these parameters were averaged intra-subject, and then inter-subjects inside each category of participants. The Phase plot was depicted considering the ellipse averaged on all strides.

The same analysis was conducted for each subject and repeated twice for PD patients, one for each DBS stimulation frequency (60 Hz and 130 Hz).

III. Results

Mean and standard deviation values of Walking Speed, Stride Time, and Step Time are presented in Table I for the three categories of participants, separating the two DBS conditions of PD patients.

Table II contains HRs calculated for the vertical, anteroposterior, and mediolateral directions. In detail, for each category, intra-subject and inter-subjects mean and standard deviation values are reported.

Table III contains parameters of gait Phase plots expressed by the geometrical characteristics of the fitted ellipse (φ, SD1, SD2, SD1/SD2). In detail, for each category, intra-subject and inter-subjects mean and standard deviation values are reported.

Finally, Fig. 2 shows the Phase plots of Poincaré analysis obtained for each subject separately.

TABLE I. GAIT SPATIO-TEMPORAL PARAMETERS OF PARTICIPANTS

Gait spatio-temporal parameters
Mean (std)

	HY	***HE***	***PD_{60}***	***PD_{130}***
Walking Speed (m/s)	0.94 (0.09)	0.93 (0.13)	0.62 (0.04)	0.66 (0.03)
Stride Time (s)	1.10 (0.05)	1.13 (0.04)	1.26 (0.16)	1.31 (0.21)
Step Time (s)	0.55 (0.03)	0.58 (0.02)	0.68 (0.13)	0.65 (0.10)

HY = healthy young, HE = healthy elderly, PD_{60} / PD_{130} = Parkinson's Disease DBS 60/130 Hz

IV. Discussions

The main aim of this pilot study was to obtain a reliable and clinically useful estimation of gait outcomes in PD patients treated with DBS at different frequencies. A comparison with healthy young (HY) and elderly (HE) subjects was conducted.

TABLE II. GAIT THREE-AXIS HRS OF PARTICIPANTS

Gait Harmonic Ratios
Mean (std)

	HY			***HE***			***PD_{60}***			***PD_{130}***		
	S01	***S02***	***S03***	***S01***	***S02***	***S03***	***S01***	***S02***	***S03***	***S01***	***S02***	***S03***
HR_V	3.63 (0.98)	3.33 (0.95)	4.57 (1.13)	3.02 (1.29)	2.48 (1.52)	2.56 (1.30)	1.66 (0.77)	2.55 (1.03)	1.95 (1.15)	2.17 (0.81)	2.16 (0.86)	1.40 (0.62)
Mean (std)	*3.84 (0.65)*			*2.69 (0.29)*			*2.06 (0.46)*			*1.91 (0.44)*		
HR_{AP}	3.83 (0.53)	3.25 (1.22)	4.22 (1.39)	2.57 (1.20)	1.92 (0.94)	2.00 (0.87)	1.46 (0.77)	1.76 (0.77)	1.56 (0.81)	1.87 (0.85)	1.73 (0.55)	1.33 (0.55)
Mean (std)	*3.77 (0.49)*			*2.16 (0.35)*			*1.59 (0.15)*			*1.64 (0.28)*		
HR_{ML}	3.58 (1.29)	1.29 (0.28)	2.50 (0.83)	2.00 (0.79)	1.84 (0.66)	1.40 (0.45)	1.54 (0.63)	2.55 (1.05)	1.45 (0.48)	1.62 (0.57)	2.09 (0.74)	1.31 (0.56)
Mean (std)	*2.46 (1.15)*			*1.75 (0.31)*			*1.84 (0.61)*			*1.67 (0.40)*		

HY = healthy young, HE = healthy elderly, PD_{60} / PD_{130} = Parkinson's Disease DBS 60/130 Hz

TABLE III. GAIT GEOMETRICAL PARAMETERS OF ELLIPSE IN PARTICIPANTS' PHASE PLOTS

	HY			***HE***			***PD_{60}***			***PD_{130}***		
	S01	***S02***	***S03***	***S01***	***S02***	***S03***	***S01***	***S02***	***S03***	***S01***	***S02***	***S03***
φ (°)	44.12 (0.57)	43.55 (1.15)	43.55 (1.15)	42.40 (2.29)	41.83 (2.87)	42.40 (2.29)	41.83 (2.29)	42.97 (1.72)	42.40 (2.87)	42.97 (1.72)	42.97 (1.15)	37.82 (8.59)
Mean (std)	*43.74 (0.33)*			*42.21 (0.33)*			*42.40 (0.57)*			*41.25 (2.97)*		
SD1 (m/s^2)	2.51 (0.26)	3.81 (0.36)	2.65 (0.21)	3.63 (0.46)	4.94 (1.03)	3.98 (0.54)	3.68 (0.53)	2.96 (0.36)	3.64 (0.95)	3.57 (0.59)	3.21 (0.37)	5.82 (1.75)
Mean (std)	*2.99 (0.71)*			*4.18 (0.68)*			*3.42 (0.41)*			*4.20 (1.42)*		
SD2 (m/s^2)	12.31 (1.20)	10.13 (0.80)	10.32 (0.52)	8.07 (0.88)	10.65 (1.27)	8.38 (0.73)	8.58 (1.05)	6.78 (0.68)	10.55 (2.72)	8.21 (0.96)	6.97 (0.51)	11.12 (2.40)
Mean (std)	*10.92 (1.21)*			*9.03 (1.41)*			*8.64 (1.89)*			*8.77 (2.13)*		
SD1/SD2	0.20 (0.03)	0.38 (0.03)	0.26 (0.02)	0.45 (0.06)	0.46 (0.08)	0.48 (0.06)	0.43 (0.04)	0.44 (0.07)	0.34 (0.07)	0.43 (0.05)	0.46 (0.05)	0.53 (0.11)
Mean (std)	*0.28 (0.09)*			*0.46 (0.02)*			*0.40 (0.06)*			*0.47 (0.05)*		

Gait Poincaré analysis — Mean (std)

HY = healthy young, HE = healthy elderly, PD_{60} / PD_{130} = Parkinson's Disease DBS 60/130 Hz

The first part of the analysis concentrated on gait parameters: Walking Speed, Stride Time, and Step Time (Table I). The obtained values stressed a connection with both age and pathology. In detail, the Walking Speed decreased about 15% from HY (0.94 m/s) to HE (0.81 m/s), and about 20% from HE to PD (0.62 m/s for 60 Hz and 0.66 m/s for 130 Hz). As expected, comparing HY and HE, Stride Time and Step Time both increased by approximately 5% with age. Accordingly, comparing HE and PD, temporal parameters increased with pathology (about 10% for the Stride Time, 15% for the Step Time). These trends are consistent with previous literature studies [25], [26].

The HR indexes quantified the gait symmetry and smoothness along the three axes of IMU (Table II), expecting high values in the case of normal gait. Results showed a general decrease of HRs with age and pathology. Obtained values are in line with the literature. In particular, Latt et al. have studied PD upper body stability during gait [17], while Conway et al. have evaluated dynamic balance control in PD patients climbing stairs [18]. It is important to stress result fluctuations in relation to the severity and frequency of the impairment. DBS could be set by adjusting stimulation parameters in response to each patient's needs [8]. For this reason, the comparison between the two stimulation frequencies was done for each subject separately. In detail, for the PD patient S01, HRs revealed better results at 130 Hz and the highest value of HR was registered for the vertical acceleration (HR_V =2.17). On the contrary, for PD patients S02 and S03 HRs were higher at 60 Hz (max value: $HR_V = HR_{ML} = 2.55$ for S02, $HR_V = 1.95$ for S03). These outcomes suggest using HR not only for the evaluation of symmetry and smoothness during gait, but also as a suitable index for the subjective adaptation of DBS stimulation frequency in PD patients [8].

Gait symmetry, smoothness, and variability were also investigated considering the Phase plot obtained from the acceleration along the vertical axis of trunk-IMU (Table III and Fig. 2). The inclination φ of the ellipses is assumed as an index of gait symmetry. In the case of normal gait, cloud data are distributed along the line of identity (dotted black line in Fig. 2), and φ is expected to register values near to 45° in each ellipse. In general, all participants (HY, HE, PD) showed a good gait symmetry confirmed by φ mean values around 42°. The only exception was represented by S03 of PD subjects. This participant registered a good symmetry of gait with the DBS frequency of 60 Hz (42.40°), while he revealed a worsening of symmetry at 130 Hz (37.82°). Considering the width of ellipses (SD1), values resulted lower for HY (2.99 ± 0.71 m/s^2) with respect to HE (4.18 ± 0.68 m/s^2) and PD (3.42 ± 0.41 m/s^2 for 60 Hz, 4.20 ± 1.42 m/s^2 for 130 Hz). This greater dispersion of acceleration data related to age and pathology could be interpreted as a reduction of gait smoothness inside the stride. Considering the length of ellipses (SD2), values decreased from HY (10.92 ± 1.21 m/s^2) to HE (9.03 ± 1.41 m/s^2) and PD (8.64 ± 1.89 m/s^2 for 60 Hz, 8.77 ± 2.13 m/s^2 for 130 Hz). This aspect is due to the presence of lower positive and negative peaks in the vertical acceleration signal (both in HE and PD with respect to HY) and could be interpreted as a decrease of gait rhythm with age and pathology. The ratio SD1/SD2 summed up the relation between width and length of ellipses and, as expected [20], registered lower value for HY (0.28) compared to HE (0.46) and PD (0.40 for 60 Hz and 0.47 for 130 Hz). Concentrating on the comparison between the DBS frequencies, geometrical variables of Poincaré analysis resulted similar with negligible differences for PD patients S01 and S02. For the S03 subject, geometrical variables depicted better values in the case of 60 Hz stimulation (higher φ, lower SD1/SD2). Nevertheless, the graphical analysis of Phase plots (Fig. 2) well highlighted the dispersion of data in all PD patients compared to HE and HY. Moreover, plots of HY well depicted the data distribution along the line of identity. These trends are consistent with results discussed by Khandoker and coll. in a previous analysis concerning gait variability among healthy young, healthy elderly, and elderly fallers [22].

Thanks to the promising results, the presented investigation revealed to be an important methodology for the evaluation of gait symmetry, smoothness, and variability of PD patients in general and of those treated with DBS, proving sensitivity in capturing gait changes at different stimulation frequencies. In detail, the Poincaré analysis well highlighted differences among participants' categories (HY, HE, PD), while the HRs resulted more suitable for the comparison of DBS stimulation frequencies.

V. CONCLUSIONS

This research presented a preliminary investigation of DBS stimulation effects in patients with Parkinson's Disease during walking. Objective outcomes characterizing gait patterns were calculated from the acceleration signals measured by a trunk-IMU and were compared with outcomes from healthy young and healthy elderly subjects.

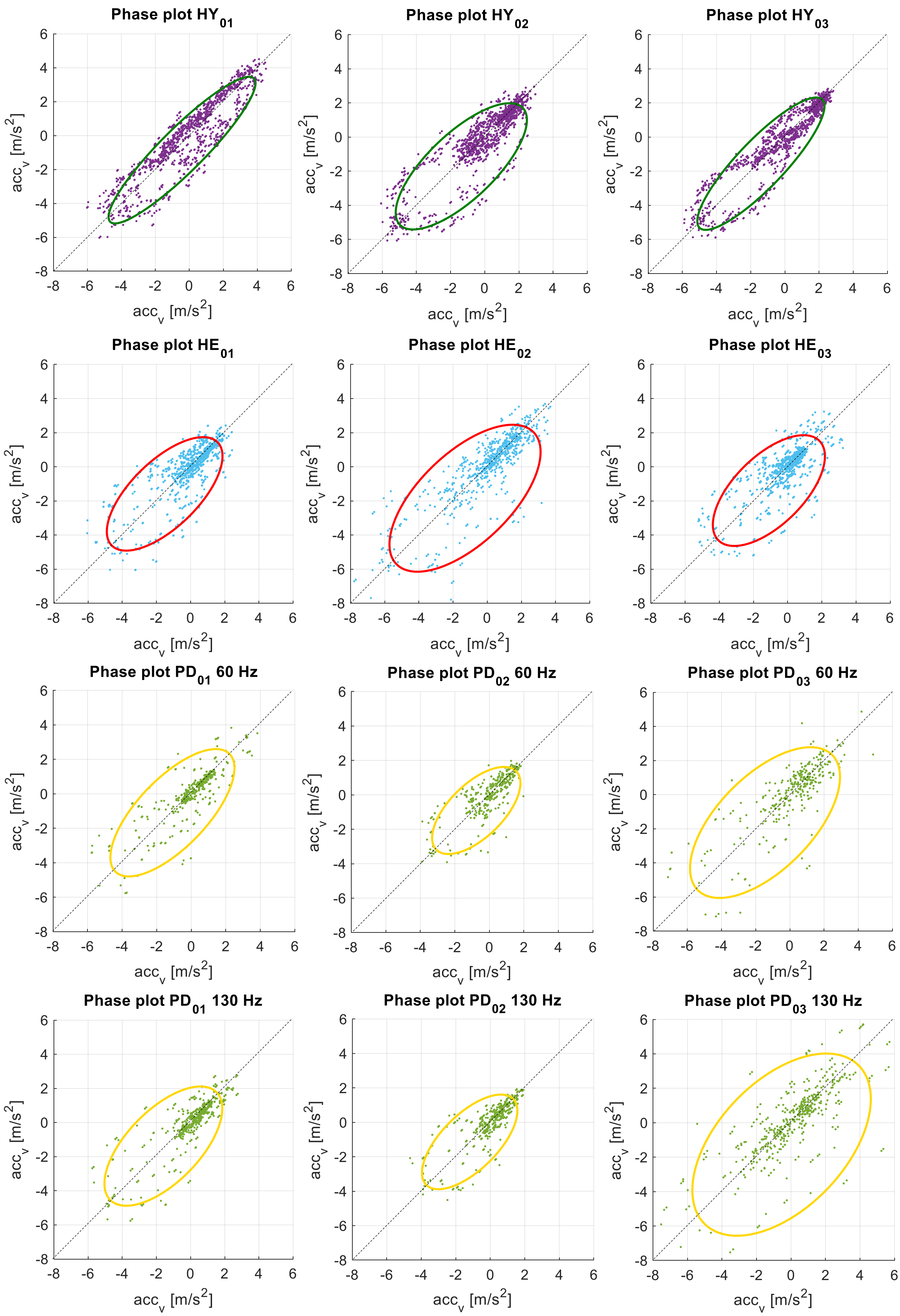

Fig. 2 Phase plots of Poincaré analysis obtained from the vertical acceleration (m/s^2) for each participant (HY = healthy young, HE = healthy elderly, PD = Parkinson's Disease).

In addition to the importance of analyzing gait symmetry, smoothness, and variability, results pointed out:

- the difference of gait outcomes between PD patients and control groups stressed by the Poincaré analysis;
- the different effect of the two DBS stimulation frequencies on gait smoothness and gait symmetry, especially pointed out by the quantification of HRs;
- the suitability of those parameters as monitoring values for a possible future development of the study towards the adaptive DBS stimulation.

Nevertheless, some limits might be underlined. Firstly, this work involved a limited number of subjects and a reduced number of gait repetitions. Moreover, the study concentrated on only two DBS frequencies, without considering the switch off condition as control. Future investigations with a larger population, a greater number of gaits and additional stimulation frequencies and switch off condition will be conducted. One other crucial aspect is the low frequency of data registration (50 Hz) that might have affected the quality and frequency content of signals. With additional tests, a higher sampling frequency should be considered. Finally, among future plans, a comparison of different IMU positions along the human spine may be investigated to describe a possible multi-IMUs set-up [27], suitable for pathologies involving the alteration of trunk posture and balance such as the Pisa's syndrome. Moreover, objective gait variables from IMUs could be correlated with subjective outcomes measuring the severity and progression of PD through clinical scales (MDS-UPDRS).

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