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A smart ink pen for spiral drawing analysis in patients with Parkinson's disease

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***Abstract*— Handwriting skills could be highly impaired in patients affected by Parkinson's disease (PD), and for this reason its analysis had always been considered relevant. In handwriting assessment, Archimedes spiral drawing is one of the most proposed tasks, due to its peculiar shape and ease of execution. In the last decades, digitizing tablets had been widely employed for the evaluation of the spiral performance, providing a cheap and non-invasive way to gather quantitative information, to be combined with the classical clinical examination. Despite this advantage, such approach cannot easily be adopted in an unsupervised scenario and lacks the natural feel of the traditional pen-and-paper approach. This work aims at overcoming these limitations by employing a smart ink pen, designed to write on paper and instrumented with inertial and force sensors, to automatically collect data related to spiral drawing execution of PD patients (n=30) and age-matched healthy controls (n=30). From the raw data, several time and frequency domains features were extracted and compared between the groups. The statistical analysis revealed some significant differences, showing less smooth acceleration and force profiles for PD patients. However, given the heterogeneous symptoms presented by the PD cohort, a detailed analysis of exemplifying PD patients was conducted, showing the ability of Archimedes spiral drawing to capture and quantify PD characteristic features.**

***Clinical Relevance*— Among the first clinical manifestations of the pathology, handwriting impairment appears in PD patients. It is often underestimated and not investigated properly. This easy-to-use tool could be very useful as a large-scale screening, but also for treatment efficacy evaluation and for the identification of PD subgroups.**

I. Introduction

Parkinson's Disease (PD) is one of the most common neurodegenerative disorder worldwide, with a reported 2-3% prevalence in the population over 65 [1]. Its cardinal motor symptoms are resting tremor, bradykinesia, rigidity, and postural instability [1]. When motor symptoms affect the dominant hand, patients may report worsening of handwriting as one of the initial signs [1]. For this reason, writing analysis has been proposed as a clinical tool in neurology [2-3]. Among the handwriting tasks proposed to patients, Archimedes Spiral drawing became popular, because its execution is easy and requires the activity of proximal and distal joints [4]. In addition, its performance can detect features of tremor without the necessity of allowing for stylistic differences of handwriting [4]. In addition, the Unified Parkinson's Disease Rating Scale (UPDRS) [5], which is the clinical scale most employed for PD assessment, includes the evaluation of traces produced by the patient. In particular, the clinician attributes a score ranging from 0 (normal) to 4 (severe) to the subject's handwriting skills. The main problems related to the visual inspection of handwriting/drawing tasks, but more in general to the clinical scale itself, are: i) the score dependence on the clinician's expertise and the lack of quantitative data; ii) the low frequency of visits during the year, caused by the limited resources of health care systems. The latter point is of fundamental importance for the patient's quality of life; indeed, PD symptoms evolve at a high rate and the medication should be adjusted accordingly. A proper solution should consider a way to collect objective data in a transparent way with good frequency [6].

The introduction of digitizing tablets, recording pen position and pressure on the screen, made quantitative analysis possible and revealed important aspects of handwriting in PD patients, like the lower force exerted on the writing surface or the lower fluency in the performance [7,8]. After their diffusion, the so called "Digitized Spiral Drawing" grew in popularity. Starting from the coordinates of pen contacts with the tablet screen, parameters able to characterize the execution were derived. In particular, [9] represented the starting point of this type of analysis, applying it to subjects affected by different motor disorders. Parameters related to the spiral spatial irregularity demonstrated to correlate with the corresponding clinical scales. The same rationale was applied in [10] for PD, demonstrating good correlation with UPDRS, and in [11] finding differences finding differences between spiral parameters of healthy subjects and PD patients. Several other studies [6,12-16] employed this method (i.e., spiral drawn on a touchscreen), supporting quantitative spiral analysis as an objective way for characterizing PD. The main reason for the success of such approach is the capability of providing quantitative information in an easy, noninvasive, and affordable way. However, supervision is necessary to manage the software during the acquisition, making this solution not so feasible to monitor patients in an unsupervised scenario. Moreover, the writing surface is not the natural one and tablets represent a technological barrier for most older adults. For these reasons, the tablet approach does not appear convenient for the ecological, possibly remote, monitoring of PD patients.

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The goal of the work is to propose an alternative method to quantify spiral drawing. A smart ink pen, presented in [17] and designed to write on paper, was used by PD patients and healthy control for data acquisition during spiral drawing execution on paper. Data were then processed to extract relevant features and a statistical analysis was conducted to investigate between-group differences. Given the heterogeneity of the available PD patients, some representative cases are presented in detail.

II. METHODS

A. Material

The smart ink pen is presented in detail in [17]. It looks like a normal ink pen, but it is enriched with sensors to quantitatively assess handwriting during traditional pen-and-paper tasks. It embeds an inertial measurement unit, comprising tri-axial accelerometers and gyroscopes, and a load cell connected to the pen tip. In this study, sensor data were acquired - with a sampling rate of 50Hz - and online transmitted via Bluetooth Low Energy to a custom app, which saves the raw signals in a .csv file

B. Participants and Protocol

Two groups participated in the study. PD patients, recruited by IRCCS Istituti Clinici Scientifici (ICS) Maugeri (Milan, Italy), and age-matched healthy controls, enrolled by Politecnico di Milano (Milan, Italy). Inclusion criteria for patients were confirmed diagnosis of PD and Mini Mental State Examination (MMSE) score ≥ 24. The presence of other disorders impairing handwriting and/or sight caused the patient's exclusion from the study. For controls, inclusion criteria were the lack of neurological, cardiovascular, or impairing musculoskeletal disease, and a MMSE score ≥ 24.

The protocol, equal for both groups, consisted in drawing a spiral with the smart ink pen on paper, starting from a given template (external diameter 6 cm, inter-loop distance 1.2 cm, five loops). The spiral task was chosen since it can be completed in a single, smooth movement, requiring the activation of all upper limb joints. Subjects were asked to start from the center of the template, but no constraints were imposed on the accuracy and on the speed of execution. The PD group performed the task with dominant and nondominant hands, while only the dominant hand was considered for the control group. All enrolled patients were evaluated by means of the UPDRS.

The protocol was approved by the Ethical Board of the Politecnico di Milano (study protocol n. 10/2018) for control subjects, and by the Ethical Board of ICS Maugeri for the PD group (2457 CE, 06/07/2020). All participants signed an informed consent to take part in the study.

C. Data Analysis

MATLAB® 2019b was used for data analysis and statistics. Spiral analysis can be divided into two main parts:

Spiral drawing execution in time-domain: Sensor data were pre-processed: the force signal (F) underwent a baseline removal and was leveraged for the segmentation into strokes (F>0), while the acceleration signals were filtered between 0.5 and 12Hz with a 4th order Butterworth filter, to remove the DC component, related to slow oscillations, and frequencies beyond the range of relevant tremor components. The 3D velocity profile was obtained through the integration of the acceleration signal. After that, for each stroke, the following indicators were computed and averaged over all strokes:

- Velocity: Average Velocity *(V AVG),* Number of Changes in Velocity *(NCV),* Mean of the difference between consecutive peaks in Velocity (*V_PeakDiff,* which considers the difference in absolute value between consecutive peaks in the velocity profile) [15].
- Acceleration: Number of Changes in Acceleration *(NCA)*
- Force: Average Force *(F AVG),* Force Overshoot *(F OVS,* a measure of force variability), Number of Changes in Force (*NCF*), Mean of the difference between consecutive peaks in Force (*F_PeakDiff,* see *V_PeakDiff)*.
- Fluency: Signal-to-Noise velocity peak difference (*SN_V_PeakDiff* which looks for high frequency oscillations in the velocity profile), and Squared Jerk *(SJ)*.

Spiral drawing execution in frequency-domain: the power spectral density (PSD) of the 3D acceleration, filtered between 0.5 and 12Hz, was extracted using the Welch's Method (500 samples window, 50% overlap). Power distribution was evaluated in three separate frequency bands, associated to different type of motion, thus obtaining the following indicators: Relative Power of Dyskinetic band (*RPW DYS*) (1-3Hz), PD tremor band (*RPW PD*) (4-7Hz) and physiologic tremor band (*RPW PHY*) (8-12Hz) [18].

As for statistics, normal distribution of indicators was checked by means of the Lilliefors test. Then, group-differences were assessed with Mann-Whitney (nonnormal features) and Unpaired t-test (normal features), with a 5% significance level.

III. RESULTS AND DISCUSSION

A total of 30 PD patients and 30 age-matched healthy controls participated in the study. No significant differences in age (p=0.96) and MMSE score (p=0.36) were found between the groups. Participants' characteristics are summarized in table I. For the PD group, UPDRS III score, related to the motor evaluation, is reported. The statistical analysis revealed some significant differences between the two populations in the time-domain indicators (Table II). As expected, fluency features demonstrated a reduced smoothness in the drawing execution for the PD group: *NCF*

TABLE I: PARTICIPANTS' CHARACTERISTICS

	PD	Controls
Gender	14 M, 16 F	11 M, 19 F
Handedness	30 Dx	30 Dx
Age [years]	72.8 ± 7.40	72.7 ± 8.48
MMSE	27.67 ± 1.68	28.07 ± 1.56
UPDRS III	19.50 ± 7.75	N.A.

TABLE II
BETWEEN-GROUP DIFFERENCES

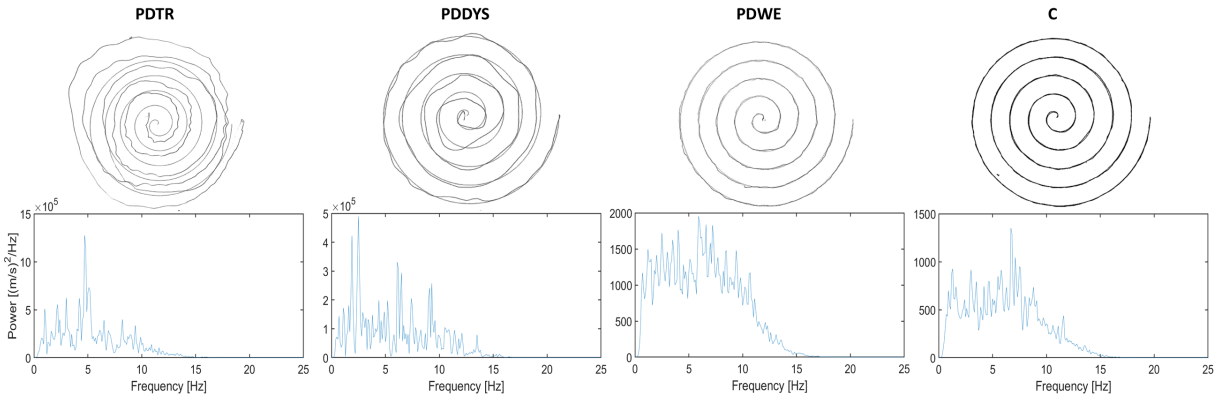
Time-domain Indicators					Frequency-domain Indicators				
Indicator	Normality	PD	Controls	p-val	Indicator	Normality	PD	Controls	p-val
V AVG [mm/s]	N	130.45 (116.48)	130.69 (95.43)	0.92	*RPW DYS*	Y	0.21±0.04	0.22±0.05	0.52
NCV	N	11.84 (1.48)	11.52 (1.32)	0.96	*RPW PD*	N	0.33 (0.04)	0.31 (0.05)	0.47
V_PeakDiff [mm/s]	N	28.66 (35.31)	23.46 (16.77)	0.06	*RPW PHY*	Y	0.24±0.03	0.24±0.04	0.50
NCA	Y	7.00±0.47	6.82±0.39	0.13					
F AVG [arbitrary unit]	Y	137.55±78.63	160.71±65.68	0.23					
F OVS [arbitrary unit]	N	55.43 (46.13)	60.19 (52.42)	0.15					
NCF	Y	3.81±0.91	3.35±0.68	0.02*					
F_PeakDiff	N	7.41 (5.78)	10.71 (10.48)	0.02*					
SN_V_PeakDiff	Y	1.90±0.28	2.02±0.23	0.10					
SJ [mm^2/s^5]	N	2.03E10 (5.09E10)	5.97E09 (1.45E10)	< 0.001*					

Results of the statistical analysis for the group comparison. Statistically significant differences are highlighted by *.
Mean ± standard deviation and median (interquartile ranges) are reported for normally distributed and not normally distributed variables, respectively. No measurement units are reported for dimensionless indicators.

and *SJ* were significantly higher for patients. A lower *F_PeakDiff* was found in PD. Additionally, in line with previous literature [7], *F AVG* resulted lower for patients, although not reaching statistical significance in this study. These findings suggest that subjects affected by PD tend to apply a more variable force on the writing surface, although reduced values of force are exerted.

No between-group differences emerged in terms of frequency domain indicators. However, despite the differences revealed by the statistical analysis, a detailed inspection of the spiral traces outlined by the PD patients enrolled in the study showed a strong heterogeneity of the available dataset of patients: some spirals presented a clear trembling activity, others were compromised by dyskinetic movements, but also drawings characterized by a good accuracy were present. This finding is confirmed by the overall increased inter-subject variability of the PD group indicators, compared to the control group (Table II).

Due to the heterogeneity of the patients' symptoms and conditions, a simple group comparison between pathological and healthy subjects may not be the most appropriate analysis to reveal alterations due to pathology. Therefore, three illustrative examples, each representative of a different spiral drawing performance by PD patients, were selected and carefully analyzed: a spiral trace showing tremor (PDTR), a spiral trace of a patient with dyskinetic signs (unstable tracts crossing the template, PDDYS), and a well-executed spiral (PDWE). In addition, an exemplifying control subject (C)



RPW DYS	0.21	**0.29**	0.18	0.19
RPW PD	**0.43**	0.28	0.32	0.33
SJ [mm^2/s^5]	**9.38e10**	**6.99e10**	5.35e9	2.5e9
NCF	**5.14**	3.12	4.35	4.71

Figure 1: From left to right: PDTR, PDDYS, PDWE, C. From top to bottom: Spiral traces, PSDs of acceleration and relevant indicators.

was also chosen for comparison. Fig. 1 shows the subjects' spiral traces, together with the PSD extracted from the acceleration signal during spiral execution, and relevant indicators. As shown in Fig.1, the spiral executed by subject PDTR is strongly compromised by the pathology. This is reflected in a neat PSD peak at frequencies related to parkinsonian tremor, which results in a high value of the *RPW PD* indicator. In addition, increased *NCF* and *SJ* are reported for this patient. However, looking at clinical scale, the patient is reported with low UPDRS tremor scores (Table III). As for PDDYS, spiral execution is affected by anomalies at lower frequencies. This is also clear from the power spectrum, which presents a peak at frequencies related to the dyskinetic component, resulting in an increased *RPW DYS* indicator, thus confirming the clinical scores (Table III). Also in this case, the lack of a smooth trace results in a high value of the *SJ* indicator. As for the third patient – PDWE – spiral drawing does not report evident anomalies. Accordingly, the PSD is homogeneously distributed over the relevant frequencies, without marked peaks. The same trend is observed in the PSD of the control subject (C).

The performed analysis was able to capture important characteristics of the produced drawings. However, there was not always correspondence between traces and clinical items related to tremor (e.g., PDTR and PDWE have the same tremor scores but clearly different traces). This is probably due to the scale low sensitivity in identifying clinical changes in the oscillations, especially with disease progression.

IV. Conclusion

The analysis of spirals drawn with the smart ink pen revealed peculiar aspects of PD population, considering both the comparison with healthy age-matched subjects and specific intra-group cases. Such approach, based on the natural execution of drawings using a simple tool, could be introduced during the classical clinical examination, to help overcoming some of the limitations related to the use of the scale only, but could also be employed for remote monitoring purposes. Further research should include the analysis of handwriting samples (letters, sentences, paragraphs) and consider other motor disorders which impair handwriting.

TABLE III: Exemplyfying Cases' Characteristics

	PDTR	PDDYS	PDWE	C
Age [years]	69	53	76	68
UPDRS III (0-56)	17	12	16	
Tremor UPDRS III (0-4)	1	1	1	
Hand tremor UPDRS III (0-4)	0	0	0	
Dyskinesia Time UPDRS IV (0-4)	0	2	0	
Dyskinesia Impact UPDRS IV (0-4)	0	3	1	

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