A common framework to evaluate Parkinson's disease in voice and handwriting

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Abstract— **Parkinson's disease is manifested as well in handwriting as in voice. Previous researches have carried out different procedures to estimate the dysfunctions of the illness in voice and handwriting separately. This paper proposes one parameter to evaluate the influence of the illness on both voice and handwriting as the symptoms affecting both has a common origin. Specifically, the parameter proposed is based on the Kinematic Theory of rapid human movements. It allows to quantify the deficits caused by Parkinson's disease in both handwriting and voice. The velocity profile obtained to characterize voice between the first and second formant is computed by a spatio-temporal approximation. In handwriting, the velocity profile is obtained from the sampled positions of the pen on a digital tablet. Once the velocity profile is derived, it is transformed to fit into the lognormal model in which similarities between voice and handwriting has been found for performance of these tasks by Parkinson's patients. The experiments with different databases of voice and handwriting recorded from different patients in different labs display encouraging results.**

Keywords—Sigma-lognormal model; kinematic theory of rapid movements; articulation; Parkinson; Voice; handwriting.

I. Introduction

Parkinson's disease (PD) is a neurodegenerative disease that has symptoms which manifest in deficiencies affecting both handwriting and voice. PD symptoms are the result of a dopaminergic deficiency characterized by the presence of two or more cardinal motor symptoms (i.e., bradykinesia, rest tremor, rigidity, and postural disturbances) [1]. PD is a slow progressive disease with a long duration where clinical treatment and rehabilitation can help to improve the quality of life. Therefore, an early diagnosis and continuous monitoring of the effects of treatments are important. PD has been monitored by recording handwriting and processing its signals and recording the voice and processing its signals.

In handwriting changes of the kinematic aspects of movements and the analysis of in-air movements have been proposed as useful methodologies to monitor and diagnose early the disease. [2]–[5]

On the other hand, in voice processing there have been recent studies about the evaluation of the voice of individuals with Parkinson's disease using the variability of the pitch, the voice rate and pausing [6]–[9] .

In the current paper, we propose using a common methodology to analyse handwriting and voice. As both voice and handwriting are complex tasks involving the neurological and muscular system, in which muscular system is synchronized to communicate an idea through sentences, words, and letters. When a person writes on a Wacom or other tablet device that allows capturing the temporal position of the pen during handwriting, the velocity information can be obtained and analysed. To this end, the Kinematic Theory of rapid human movements [10] is applied to divide a complex movement in simple movements (strokes), each one is modelled by a sigma-lognormal function and the complex movement is then the summation of all the parametrized sigma-lognormals. This theory has been applied in different fields to assess movements as it pertains to handwriting variations across time [11], [12]. Thus this model has allowed us to specify diagnostic systems for neuromuscular disorders [13], [14] and the assessment of risk factors for stroke risk [15].

In voice production, the resonating cavities modifiable by the articulatory organs allow the energy of the voice signal to be concentrated at certain frequencies (formants), due to oropharyngeal tract resonators. It is well known that the formants are related with the tongue-yaw reference centre (JTRC) [16]. Also, the JTRC is related with the first and second formant [17]. In recently studies [18]–[20], a relationship between the formants and the lognormal model have been shown.

The present work is intended to compare voice and handwriting production and the derived velocity signals as both tasks can be captured by a common parameter which can be validated to detect Parkinson disease. This validation of a common parameter in both domains reinforces earlier findings that could assist to develop a more reliable diagnoses.

II. FROM VOICE OR HANDWRITING TO VELOCITY

In order to get the kinematic signal from the voice, formants are calculated. The formant estimation is obtained by adaptive inverse filtering [21]. This computation has been carried out with a resolution of 15 Hz using an 8-order prediction-error lattice-ladder filter [22].

The first formant $F1$ is related to the longitudinal movement and the second formant $F2$ is related to the vertical movement. These movements can be correlated with the formants positions in the plane $F1$ vs $F2$ [16] as:

$$\begin{bmatrix}\Delta x\\ \Delta y\end{bmatrix} = \begin{bmatrix}c_{11} & c_{12}\\ c_{21} & c_{22}\end{bmatrix}\begin{bmatrix}\Delta F1\\ \Delta F2\end{bmatrix} \quad (1)$$

where Δx and Δy are the relative displacement from the previous position of the JTRC. c_{ij} are the weights of the combination matrix.

Once the displacement is calculated, the velocity signal $\vec{v}(t)$ is estimated as:

$$\overrightarrow{v_{voice}(t)} = \frac{\sqrt{\Delta x(t)^2 + \Delta y(t)^2}}{\Delta t} \quad (2)$$

In the case of handwriting, the patient is asked for write down on a tablet, in our case a WACOM tablet which record the position $x(t)$ and $y(t)$ of the pen on the tablet 200 times per second. As a result, the pen velocity can be worked out as:

$$\overrightarrow{v_{handw}(t)} = \sqrt{(x(t) - x(t-1))^2 + (y(t) - y(t-1))^2} \quad (3)$$

Both voice signals are normalized to mm/s.

III. FROM VELOCITY TO SIGMA-LOGNORMAL MODEL

This section is devoted to parametrize the velocity profile of both voice and handwriting signal using the Kinematic Theory of rapid movements framework. In this way, the velocity profile $\vec{v}(t)$ can be modeled as a linear combination of lognormals [23] as follows:

$$\vec{v}(t) = \sum_{j=1}^{M} \vec{v}_j(t; D_j, \tau_j, \mu_j, \sigma_j^2) \quad (4)$$

where the velocity profile of each stroke $v_j(t)$ is defined as:

$$\vec{v}_j(t; \tau_j, \mu_j, \sigma_j^2) = \frac{\vec{D}_j}{\sigma_j\sqrt{2\pi}(t-\tau_j)} exp\left\{-\frac{[ln(t-\tau_j)-\mu_j]^2}{2\sigma_j^2}\right\} \quad (5)$$

with t the basis of time, τ_j the time of stroke occurrence, D_j the amplitude of each stroke, μ_j the stroke time delay and σ_j the stroke response time, both on a logarithmic time scale .

Based on the facts that Parkinson patients perform shorter movements and have some difficulties to plan next movements, among all of the expected effect of the disease on the lognormal decomposition is a lower stroke logresponse time σ_j [4], [19]. Therefore, we propose as a common parameter to detect Parkinson disease in both voice and handwriting, the averaged the stroke logresponse time $\overline{\Delta\sigma}$ as defined in (6):

$$\overline{\Delta\sigma} = \frac{\sum_{i=1}^{M} |\sigma_i - \sigma_{(i-1)}|}{M} \quad (6)$$

It is expected that people with some degree of Parkinson disease will show a lower $\overline{\Delta\sigma}$ than healthy people.

IV. METHOD

A. Voice Database

A database comprising phonations from five PD patients selected by neurologists and five control subjects was used in this study. The subjects, with aged from 52 to 78 years old, were diagnosed with PD as grade 2 or 3. Each subject was asked to utter the vowel /a/ at the same normal loudness and their most natural way (modal phonation). Each sample of the database comprises the recording of the vowel /a/ from the Spanish vowel set ([a] from the International Phonetic Alphabet) uttered in a sustained way, each utterance lasting approximately two seconds, separated by silences from repeated utterances. The voice records were taken by a hand recorder at 16 KHz and 16 bits, in the neurologists' office. They were segmented automatically by an energy-based method and the central part of the phonation selected, avoiding the initial and final transients.

B. Handwriting database

A database comprising of seven individuals with Parkinson's disease and seven age-matched controls were used in this study. All patients were tested on medication. All participants had written six loops which progressed to the right (i.e., cursive connected '*llllll*') with an electronic pen. The participants were instructed to match the size of the cursive '*l*'s which were displayed before each trial. After each trial the performance of the participant was displayed between two lines which were 25 mm (i.e., 2.5 cm) apart, so the participant could see if s/he matched the required size. This condition was one of several size and speed conditions which were part of a much larger study. Each participant did repeat the writing task 8 times in which they tried to match the 25 mm size requirement.

The data were automatically segmented with a custom made segmentation procedure which searched for the first zero crossing in vertical velocity after the first full loop and thereafter searched for the first zero crossing in vertical velocity after the fourth full loop, i.e., each segment consisted of three loops per repetition (i.e., the connected second, third, and fourth loops of each trial).

C. Signal procesing.

To process the voice production samples, first the central part of the signal was isolated to avoid the transients, where the speed is higher in Parkinson's patients [20]. Second, the first and second formants were identified, after which the velocity was calculated as explained in section II.

Once the velocity signal of the voice and the handwriting samples was obtained, the procedure to estimate the parameter was the same, i.e., $v_{voice}(t)$ and $v_{handw}(t)$. The position signal data were fed into the sigma-lognomal estimator, where the signals were filtered with a cutoff frequency of 7 Hz. The lognormal parameters were calculated using the low-pass filtered signal as explained in section III. A new analytical signal was reconstructed from the estimated parameters as it is shown in Fig. 1 and Fig. 2.

V. RESULTS

A. Qualitatve comparison of Parkinson and normal voice and handwriting profiles

As a first step, we compared the low-pass filtered velocity profile (original) with the analytical one. As can be observed in Fig. 1, the analytical and the original seem similar. The SNR is 21.7 dB in PD and 25.38 dB in control, being SNR the error between the original and its reconstructed signal gives the reconstruction quality in the sigma-lognormal domain [23].

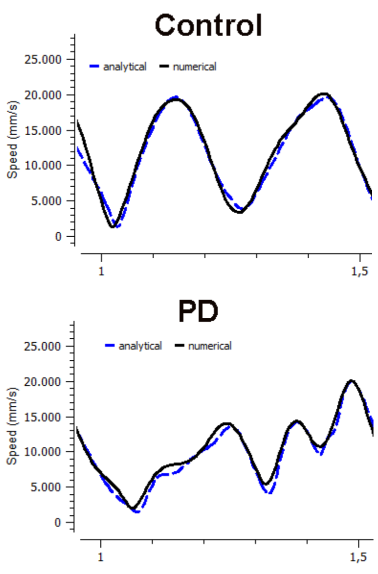

Figure 1. Speed profile of the handwriting of a healthy (above) and PD patient (below). Original speed profile (continuous black line) and Lognormal reconstructed speed profile (discontinuous blue line)

If we compare the handwriting signal (Fig.1) with the voice signal (Fig.2), we can observe that they are similar but the time between peaks is longer in handwriting, i.e., 0.35 s in handwriting and 0.08 s in voice production. This could be due to try keeping the tongue position at a constant target to utter the vowel /a/. Instead, in handwriting, the movement is fast and longer, where simple movements are joined. The overlapping of two consecutives lognormals depends on the initial time of each lognomal and on the stroke logresponse time, therefore, the longer is the movement also the longer will be the stroke logresponse time, and there will be more overlapping between lognormals, as it is explained in[24].

Comparing a control (Fig. 1 and Fig. 2 upper) with a PD (Fig. 1 and Fig. 2 down), one can observe how the velocity signal of the PD has more and shorter peaks and the variability of speed is also noticeable. When inspecting the voice signal it can be seen also that the speed is higher for the PD. This higher speed could be due to the disability of PDs to keep the tongue in the same position.

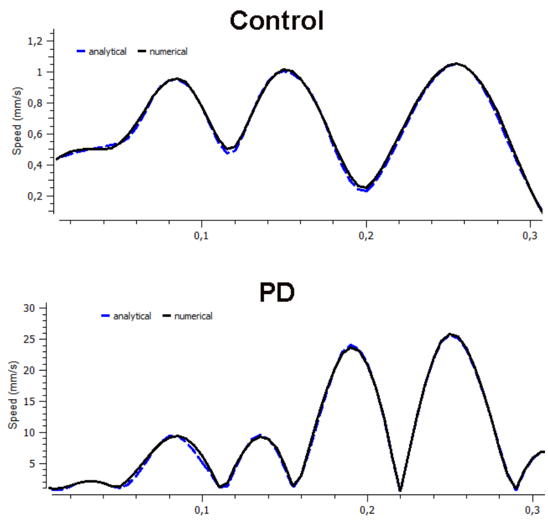

Figure 2. Speed profile of the voice of a healthy (above) and PD patient (below). Original speed profile (continuous black line) and Lognormal reconstructed speed profile (discontinuous blue line)

B. Quantitative comparison of voice and handwriting averaged stroke response time $\overline{\Delta\sigma}$.

The average of the values obtained for $\overline{\Delta\sigma}$ for the voice data and handwriting data for healthy controls and PD patients across the two databases are given in Table I, Table II, Figure 3 and figure 4. It can be clearly observed that the mean of the parameter $\overline{\boldsymbol{\Delta\sigma}}$ is lower for handwriting and voice production of PDs.

To evaluate whether a statistical difference exists between the $\overline{\boldsymbol{\Delta\sigma}}$ value of controls and PDs an ANOVA (Analysis of Variance) was performed (using the statistical toolbox of Matlab). The two groups were considered different when the residual p-value is close to 0 and statistically similar if the p-value is greater than 0.05 [25]. It was shown that the groups differed on their $\overline{\boldsymbol{\Delta\sigma}}$ values in both handwriting and voice (p-values were lower than 0.05). However, voice showed a larger difference than handwriting between the two groups, suggesting that voice production is more discriminative than handwriting. However, to verify this latter suggestion, this study should be repeated using voice and handwriting samples of the same participants.

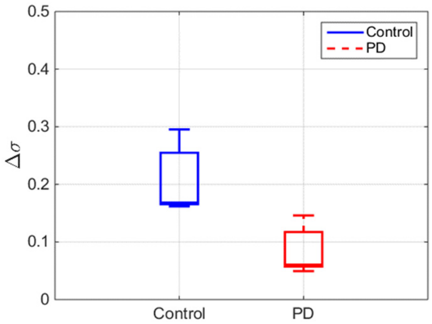

Figure 3. Box-plot of the averaged stroke response time $\overline{\Delta\sigma}$ for Control and PD patients in voice.

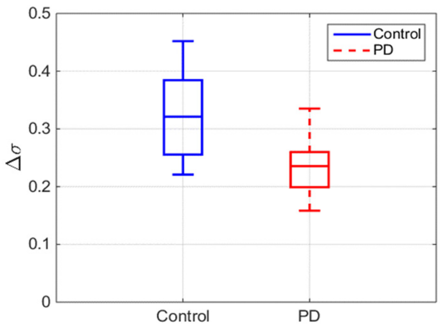

Figure 4. Box-plot of the averaged stroke response time $\overline{\Delta\sigma}$ for Control and PD patients in handwriting.

TABLE I. AVERAGE SIGMA: NORMAL VS. PARKINSON VOICES

	Control	PD	p-value
$\overline{\Delta\sigma}$	0.2	0.08	0.005

TABLE II. AVERAGE SIGMA: NORMAL VS. PARKINSON HANDWRITING

	Control	PD	p-value
$\overline{\Delta\sigma}$	0.32	0.23	0.04

VI. CONCLUSION

The results seem to validate that it is possible to use a common parameter to assess voice production and handwriting. Furthermore, the current study shows that Parkinson's disease affects the velocity profile of both handwriting and voice production.

Comparing these handwriting and voice productions, it seems that voice production is better to distinguish PDs from controls. This pattern of findings, could be due smaller movements and less inertia when using the tongue as compared to hand movements made when writing. These characteristics could affect the width of the lognormal and the separation between them.

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