DOI: 10.17469/O2111AISV000005

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Acoustic biomarkers of Parkinson's Disease: a pilot study on the *Italian Parkinson's Voice and Speech* dataset

Beyond the most well-known motor symptoms, Parkinson's disease can also affect patients' speech and language abilities. This article presents an acoustic analysis of the *Italian Parkinson's Voice and Speech* dataset, comprising recordings of 65 speakers from southern Italy (28 patients, 22 elderly healthy controls, and 15 young healthy controls). The results reveal significant differences between pathological and control subjects across several metrics, including jitter, shimmer, HNR, and the Higuchi fractal dimension. Significant alterations were observed in vowel metrics, with a marked decrease in tVSA and VAI, and an increase in FCR. Consistent with existing literature, the study also confirms the documented reduction in pitch variability among patients. To complete the analysis, two additional variables (UPDRS scores and biological sex) were taken into account; notably, opposing trends between men and women emerged on duration measures (distribution of pauses, sound segments, and measures related to speech rate).

Keywords: Parkinson's disease, Parkinson, hypokinetic dysarthria, clinical linguistics, phonetics.

1. *Introduction*

Parkinson's Disease (PD) is the second most common neurodegenerative disorder after Alzheimer's disease (Rusz, Cmejla, 2011). From a neurological perspective, it is characterised by the progressive loss of dopaminergic cells in the substantia nigra. Alongside the primary motor signs of muscular rigidity, bradykinesia, rest tremor, and postural instability, the symptoms of the disease include various speech disorders, globally referred to as hypokinetic dysarthria, which can be grouped into three major components: dysphonia, articulatory problems, and dysprosody. Since several of these characteristics tend to manifest in the initial phases of the condition (Rusz, Cmejla, Ruzickova & Ruzicka, 2011), conducting research on them proves to be worthwhile, as it may eventually contribute to the development of diagnostic tools in the future.

Regarding the dysphonic traits, the voice of PD patients is often reported as being soft, breathy, harsh, hoarse, rough, and aspirate. These alterations in voice quality can be attributed to laryngeal dysfunctions that can affect patients, such as the condition of vocal fold bowing initially described by Hanson, Gerratt & Ward (1984).

As for the articulation of segmental features, a general trend towards articulatory undershooting has been observed, resulting from the effects of hypokinesia and rigidity on active articulators (Robertson, Hammerstad, 1996; Hunker, Abbs, 1990; Dworkin, Aronson, 1986). The reduction of articulatory gestures induces

alterations in acoustic vowel metrics: the triangular Vowel Space Area (tVSA) and the Vowel Articulation Index (VAI) tend to lower, while the Formant Centralisation Ratio (FCR) increases (Skodda, Visser & Schlegel, 2011a; Skodda, Grönheit & Schlegel, 2012). As regards to consonants, some studies have identified devoicing and spirantization patterns: incomplete closure of the articulators can result in plosives being produced as fricatives and can lead to the loss of the plosive element in affricates, while fricatives tend to lose the [+strident] feature (Antolík, Fougeron, 2013; Logemann, Fisher, 1981).

Concerning prosodic features, there is strong agreement in defining parkinsonian speech as monotonous in terms of pitch and intensity. There are greater discrepancies, however, regarding duration measures; while some studies have reported a significant decrease in verbal rate for PD patients (Peacher, 1950, cited in Cohen, 2003), others have not found significant differences compared to control subjects. Moreover, some other studies have even identified a tendency towards accelerated speaking rates towards the end of sentences; this phenomenon has been likened to the festination of gait and is commonly referred to as "oral festination" (Moreau, Ozsancak, Blatt, Derambure, Destee & Defebvre, 2007). As a final point, research on the rhythmic characteristics of PD has suggested a drift towards isosyllabic features, regardless of the rhythmic classification of the analysed language (Liss, White, Mattys, Lansford, Lotto, Spitzer & Caviness, 2009; Lowit, Marchetti, Corson & Kuschmann, 2018): this is seemingly a result of parkinsonian bradykinesia, leading the patient to lengthen stable articulatory configurations (vowels) at the expense of more dynamic ones (consonants).

Most of the above-mentioned features manifest cross-linguistically, as proved by the convergence of works on different languages (e.g., English, German, French, Mandarin, Czech, and Spanish). Some studies have also been conducted on Italian speakers, especially from Southern Italy. Various aspects of PD speech in patients from Salento (Puglia) have been explored by Gili Fivela and colleagues, including prosodic modulation (confirming the tendency towards monopitch in Gili Fivela, D'Apolito & Di Prizio, 2020a), higher vowels, and Italian geminates (Gili Fivela., Iraci, Grimaldi & Zmarich, 2015; Gili Fivela, Zmarich, 2005). An interesting outcome of their studies, derived from the combination of kinematic and acoustic analysis, is the hypothesis involving widest tongue movements as a compensatory mechanism for reduced labialisation in rounded vowels (Gili Fivela, D'Apolito & Di Prizio, 2020b).

Mirarchi, Vizza, Tradigo, Lombardo, Arabia & Veltri (2017) have measured VAI and VSA in PD patients from Cosenza (Calabria, Italy). As has been found in previous studies from other languages, these appear to be significantly reduced in PD patients compared to control subjects. Another research group, composed of Maffia, Pettorino, and their colleagues from the University of Naples "L'Orientale", successfully combined two rhythmic measures (%V and V-to-V) and found a significantly higher %V in the examined PD groups, even in drug-naive patients

(Pettorino, Busà & Pellegrino, 2016; Maffia, De Micco, Tessitore & De Meo, 2020; Maffia, De Micco, Pettorino, Siciliano, Tessitore & De Meo, 2021).

The present study hopes to follow this research tradition, with the aim of broadening the landscape of Italian works on hypokinetic dysarthria. To pursue this objective, we analysed the *Italian Parkinson's Voice and Speech* dataset, a fairly extensive corpus of recorded speech, fully available online (Dimauro, Di Nicola, Bevilacqua, Caivano & Girardi, 2017). The next section of this article (§ 2) provides a description of the composition of the dataset, with a focus on the specific tasks that have been selected for our purposes. In the following paragraph (§ 3), methods and results of our analysis will be presented. A short discussion of our findings will then follow in § 4.

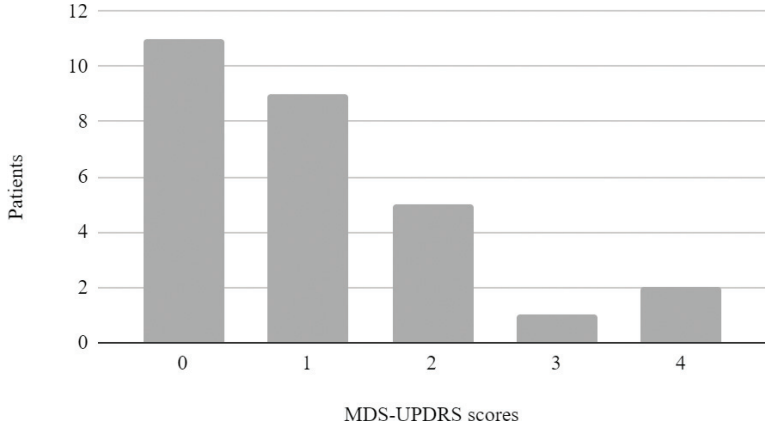
Although the previous literature has set certain expectations, which might have guided the interpretation of the results, we would describe our work as a mainly exploratory, not hypothesis-driven study. This choice is mainly related to the small size of our sample. Quantitative and statistical methods have been employed in all stages of the analysis, and the observation of statistical significance served the ultimate goal of uncovering potential new biomarkers for the disease.

2. Italian Parkinson's Voice and Speech*: description of the dataset*

All data were collected in 2017 in Bari (Puglia, Italy). A total of 65 speakers have been involved, divided into three groups: a first group of patients with Parkinson's disease (PPD) included 19 men and 9 women, whose ages ranged between 40-80 ($\mu = 67.2$); all of them came from the linguistic area of Bari, except from 1 male patient from Venice; a second group of 22 elderly healthy controls (EHC), 10 men and 12 women, age-ranging 60-77 ($\mu = 67.1$), all from the Bari area; a third group of young healthy controls (YHC), 13 men and 2 women, age range of 19-29 ($\mu = 20.8$), all of whom from Bari, except for 2 subjects from the Brindisi area. While we acknowledge the potential usefulness of including a third group (especially to understand age-related changes independent of pathology), our study specifically focused on the comparison between PPDs and EHCs.

All patients were receiving antiparkinsonian treatment and were in ON-state at the time of the experiment. The severity of the disease was examined by using the most common rating scales for motor examination: Hoehn & Yahr (HR) and MDS-UPDRS (Hoehn, Yahr, 1967; Movement Disorder Society Task Force on Rating Scales for Parkinson's Disease, 2003). According to the HR scale, all patients received a score <4, except for two patients with stage 4, and one patient with stage 5. More details are provided by the authors (Dimauro *et al.*, 2017) about UPDRS scores, whose distribution is depicted by the bar chart in Fig. 1.

Figure 1 - *Distribution of PPD subjects based on UPDRS scores*



The corpus comprises recordings of various speech tasks, defined by the authors as the best protocol for automatic speech analysis. These include, listed in order:

a. Two readings of a phonemically balanced text, spaced by a pause (30 sec).
b. Execution of the syllable /pa/ (5 sec), pause (20 sec), execution of the syllable /ta/ (5 sec).
c. Two series of phonations for each vowel (/a/, /e/, /i/, /o/, /u/).
d. Reading of a list of phonemically balanced words.
e. Reading of a list of phonemically balanced sentences.

Among the available materials, recordings of tasks a., c., and e. appeared to be the most useful for our purposes and were selected for further analysis (see § 3).

As regards to task c., the participants were asked to inhale as much air as they could and to maintain the vowel as long as possible for the first phonation; in contrast, the second phonation was uniformly set to a duration of 5 seconds. Presented below are the text and sentences the participants read for points a. and e.

Phonemically balanced text

IL RAMARRO DELLA ZIA. Il papà (o il babbo come dice il piccolo Dado) era sul letto. Sotto di lui, accanto al lago, sedeva Gigi, detto Ciccio, cocco della mamma e della nonna. Vicino ad un sasso c'era una rosa rosso vivo e lo sciocco, vedendola, la volle per la zia. La zia Lulù cercava zanzare per il suo ramarro, ma dato che era giugno (o luglio non so bene) non ne trovava. Trovò invece una rana che saltando dalla strada finì nel lago con un grande spruzzo. Sai che fifa, la zia! Lo schizzo bagnò il suo completo rosa che divenne giallo come un taxi. Passava di lì un signore cosmopolita di nome Sardanapalo Nabucodonosor che si innamorò della zia e la portò con sé in Afghanistan.

List of phonemically balanced sentences

Oggi è una bella giornata per sciare. • Voglio una maglia di lana color ocra. • Il motociclista attraversò una strada stretta di montagna. • Patrizia ha pranzato a casa di Fabio. • Questo è il tuo cappello? • Dopo vieni a casa? • La televisione funziona? • Non posso aiutarti? • Marco non è partito. • Il medico non è impegnato.

As emphasized by the authors, the text is sufficiently long and is designed to test the speakers' resistance, as it contains a high concentration of complex and similar phonemes in close proximity. In the same way, the list of sentences was carefully chosen to engage all the muscles that are needed to produce the Italian language sounds.

3. *Methods and results*

The analysis was conducted in three main steps: the first involved the observation of acoustic vowel metrics, following the example of Skodda *et al.* (2012), Rusz, Cmejla, Tykalova, Ruzickova, Klempir, Majerova, Picmausova, Roth & Ruzicka (2013), and Sapir, Ramig, Spielman & Fox (2010). For the second part of the study, we relied on the use of the *DLBs Computational Pipeline*, a valuable tool for the automatic extraction of pathological speech features, originally developed by Gagliardi and Tamburini (2022). Thirdly, we reused the data calculated by Toye and Kompalli (2021) – especially regarding jitter, shimmer, and HNR measures– and applied a statistical analysis comparable to that of the previous stages. Further details about methods and results for each of these steps are provided in the following subsections (§ 3.1, § 3.2, and § 3.3).

3.1 Vowel description

Although the appearance of articulatory problems is often described as more tardive than dysphonia and dysprosody (Pinto, Ghio, Teston & Viallet, 2010; Rusz, Cmejla, Ruzickova & Ruzicka, 2011), alterations in acoustic vowel metrics have been proven to manifest early in the disease progression (Rusz *et al.*, 2013; Skodda *et al.*, 2012), and there is strong agreement on the direction of their shifts in PD patients.

To explore these metrics, the series of vowel executions (/a/, /e/, /i/, /o/, /u/; see task c. in § 2) were taken into account. All recordings have been manually analysed by collecting values of the first two formants (F1 and F2) in *Praat*; for every speaker, arithmetic mean values between the two executions of each vowel have then been calculated. Formant values were measured within a time window, according to criteria of stability and representativeness, rather than a fixed temporal length. The results obtained were statistically compared by applying the non-parametric test of Wilcoxon-Mann-Whitney in R.

Tab. 1 represents the mean values and standard deviations of F1 and F2 for both PPDs and EHCs, as well as the results of the statistical comparison (p-values) between the two groups. To highlight the most relevant results, only statistically significant outcomes are shown. Tab. 2, on the other hand, shows the results of the measurements of tVSA, VAI, and FCR[1], based on the mean formant frequencies of the corner vowels /a/, /i/, /u/.

[1] For further details and formulas of tVSA, VAI, and FCR, see Skodda *et al.* (2012) and Sapir *et al.* (2010).

Table 1 - *Means and st. deviations of formant frequencies in PD speakers and elderly controls (SD values for each measure in brackets). P-values in the right column mark the degree of statistical significance according to the following rules: * if p-value ≤ 0.05; ** if p-value ≤ 0.01; *** if p-value ≤ 0.001; **** if p-value ≤ 0.0001*

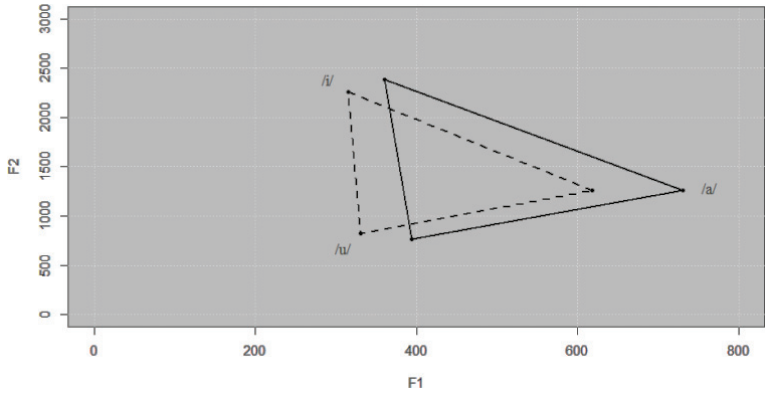
	PPD		*EHC*		*p-value*
/a/ F1 Mean	618.3746	(± 219.3455)	730.7576	(± 155.1223)	0.04236 *
/e/ F2 Mean	1829.374	(± 257.5197)	2033.51	(± 191.1282)	0.003334 **
/i/ F1 Mean	315.274	(± 79.84552)	359.9481	(± 59.97617)	0.002358 **
/u/ F1 Mean	331.0825	(± 62.36161)	394.0553	(± 49.10942)	0.000607 ***

Table 2 - *Triangular Vowel Space Area, Vowel Articulation Index, and Formant Centralisation Ratio for PPD and EHC*

	tVSA	*VAI*	*FCR*
PPD	209359.2	1.053374	0.94933
EHC	280145.1	1.119967	0.892883

As expected, the Vocalic Articulation Index (VAI) and tVSA are lower in PPDs compared to non-pathological subjects, confirming a tendency towards vowel centralisation in pathological subjects; conversely, the Formant Centralisation Ratio is higher in patients than in controls. A graphical comparison between triangular Vowel Space Areas for both the PPD and the EHC groups is provided in Fig. 2: as shown in the graph, the patients' area is visibly reduced compared to that of the EHC group, as well as the global mean value of F1.

Figure 2 - *Mean triangular Vowel Space Areas (tVSA) for the PPD group (dotted lines) and the EHC group (continuous lines)*



In order to refine the analysis, the additional variable of the speakers' sex has been taken into account. Tab. 3 shows the results of these further measurements, divided between male and female speakers. As in Tab. 1, p-values result from the statistical test of Wilcoxon-Mann-Whitney, comparing mean values of male and female patients to

the respective subgroups of elderly healthy controls of the same sex. Once again, only statistically significant results are presented.

Table 3 - *Means and standard deviations of formant values, divided between men and women. P-values result from the statistical comparison of PD subgroups with their respective controls of the same sex*

	Men			*Women*		
	PPD	*EHC*	*p-value*	*PPD*	*EHC*	*p-value*
/a/ F1 Mean	508.5833 (±161.222)	711.1058 (±121.3202)	0.002009 **	850.1561 (±121.778)	747.1341 (±182.3518)	0.1694
/a/ F2 Mean	1183.466 (±147.123)	1219.147 (±79.5595)	0.3077	1420.925 (±137.7207)	1289.934 (±122.8868)	0.04907 *
/e/ F1 SD	23.5133 (±18.22045)	13.5341 (±11.8644)	0.09439	7.1427 (±5.4647)	34.0311 (±27.7193)	0.04089 *
/e/ F2 Mean	1726.63 (±124.8017)	1892.996 (±151.1217)	0.00568 **	2046.28 (±332.8249)	2150.605 (±134.7093)	0.8078
/i/ F1 Mean	276.0183 (±33.9081)	350.2001 (±67.1847)	0.0000657 ****	398.1473 (±86.8523)	368.0714 (±54.9163)	0.6016
/i/ F2 Mean	2175.29 (±190.6583)	2300.147 (±149.8447)	0.04455 *	2444.188 (±407.8353)	2446.333 (±405.4428)	0.5538
/u/ F1 Mean	308.1545 (±54.9667)	383.7472 (±56.5358)	0.001665 **	379.486 (±49.4267)	402.6453 (±42.5673)	0.3451

The table reveals some sex-related differences: among men, in addition to the differences highlighted in Table 1, there is a further alteration in the second formant of /e/. For women, the only significant alterations pertain to the second formant of /a/ and the standard deviation of the first formant of /i/.

3.2 DLBs Computational Pipeline

As previously stated (§ 3), the second part of the analysis relied on the use of a pipeline for the automatic extraction of Digital Linguistic Biomarkers (DLBs), namely a set of acoustic and linguistic metrics that could potentially aid the identification of pathological speech (Gagliardi, 2023). The *Pipeline* has proved to be a promising tool for the detection of other pathologies (e.g., Mild Cognitive Impairment; see Gagliardi, Tamburini, 2021) and currently calculates a wide range of features, encompassing acoustic, rhythmic, lexical, and syntactic measures, as well as readability and linguistic inquiry and word count features. Coherently with our objectives and with the nature of the available data, solely the acoustic features were considered in this study. These are listed in Calzà, Gagliardi, Rossini Favretti &Tamburini (2021) and can be briefly described as follows:

– SILMEAN, SILMEDIAN, SILSD: mean, median and standard deviation of silent segments duration.
– SPEMEAN, SPEMEDIAN e SPESD: mean, median and standard deviation of speech segments duration (excluding silent segments).

- TRVSD: temporal regularity of voiced segment durations.
- VR: verbal rate, including silent segments.
- TPR: transformed phonation rate, calculated as arcsin√PR, where PR (phonation rate) is the ratio between total phonation time (speech time without pauses) and total locution time (speech time including pauses).
- SPT (Standardised phonation time): standardised phonation time, calculated as the ratio between the number of words and the duration of phonation (excluding silent segments).
- SPR (Standardised pause rate): ratio between words and silences in the audio sample.
- RMSEM e RMSESD: mean and standard deviation of the root mean square energy.
- PITCHM e PITCHSD: mean and standard deviation of pitch.
- SPCENTRM e SPCENTRSD: mean and standard deviation of spectral centroid, an acoustic correlate of the perceptual brightness of sounds.
- HFractDM e HFractDSD: mean and standard deviation of the Higuchi fractal dimension.

For this part of the analysis, tasks a. (two readings of a phonemically balanced text) and e. (reading of a list of phonemically balanced sentences) were selected. All data extracted from the corpus were adapted to fulfil the pipeline's requirements: audio files were converted to .wav/44.1KHz/16bit/Mono, and orthographic transcriptions (.txt, Unicode UTF-8) were provided.

Tables below present aggregate data for the PPD and EHC groups[2]. Measurements were carried out separately for each task; as for the other tables further down in this article, the degree of significance is indicated according to the same rules as Tab. 1. Notably, some of the metrics show a significant difference across all the tasks: SPEMEAN, SPEMEDIAN, SPT, PITCHSD, SPCENTRSD, FractDMEAN e HFractDSD (Tab. 4-6).

Table 4 - *Means, st. deviations and statistical comparison (PPDs vs EHCs) for the 1st text reading task*

	PPD		*EHC*		*p-value*
SPEMEAN	1.425933	(±0.55628)	0.982076	(±0.736492)	0.0362 *
SPESD	0.917477	(±0.33362)	0.642534	(±0.407299)	0.0223 *
SPEMEDIAN	1.263111	(±0.582036)	0.861851	(±0.72917)	0.0314 *
VR	2.154168	(±0.704509)	2.525489	(±0.437549)	0.0449 *
SPT	3.794013	(±3.247913)	8.64725	(±5.978701)	0 ****
PITCHM	148.4479	(±28.42092)	166.1551	(±28.08773)	0.0442 *
PITCHSD	23.95979	(±5.579796)	37.33001	(±8.963386)	0 ****
SPCENTRM	1916.485	(±823.4478)	2044.991	(±515.6468)	0.0391 *
SPCENTRSD	1560.532	(±428.6954)	1286.021	(±282.7223)	0.0346 *
HFractDMEAN	1.624539	(±0.090066)	1.829976	(±0.049112)	0 ****
HFractDSD	0.154929	(±0.024546)	0.085443	(±0.015314)	0 ****

[2] Only statistically significant results are shown.

Table 5 - *Means, st. deviations and statistical comparison (PPDs vs EHCs) for the 2nd text reading task*

	PPD		*EHC*		*p-value*
SPEMEAN	1.833724	(±0.530703)	1.221547	(±0.869531)	0.0112 *
SPESD	1.130024	(±0.30339)	0.812094	(±0.499486)	0.0117 *
SPEMEDIAN	1.699225	(±0.696153)	1.088312	(±0.902443)	0.0099 **
SPT	3.524875	(±0.573903)	7.606606	(±5.140292)	0.0012 **
PITCHM	145.1231	(±28.43825)	165.7067	(±27.40162)	0.0196 *
PITCHSD	22.62279	(±5.935683)	37.76195	(±8.418174)	0 ****
SPCENTRSD	1568.869	(±409.4062)	1276.227	(±279.6976)	0.0277 *
HFractDMEAN	1.623039	(±0.086177)	1.824355	(±0.048178)	0 ****
HFractDSD	0.155023	(±0.025143)	0.085367	(±0.016201)	0 ****

Table 6 - *Means, st. deviations and statistical comparison (PPDs vs EHCs) for the sentence reading task*

	PPD		*EHC*		*p-value*
SPEMEAN	1.709863	(±0.446501)	1.209864	(±0.812239)	0.01836 *
SPEMEDIAN	1.739127	(±0.55902)	1.170601	(±0.897708)	0.02078 *
VR	1.980705	(±0.492023)	2.37204	(±0.40088)	0.004044 **
SPT	3.044265	(±0.6706)	5.987555	(±3.285112)	6.414e-05 ****
PITCHSD	23.01193	(±6.222952)	32.20312	(±8.890534)	0.0002056 ***
SPCENTRSD	1697.961	(±585.1265)	1214.359	(±286.0436)	2.264e-05 ****
HFractDMEAN	1.641649	(±0.094701)	1.829654	(±0.051397)	3.491e-10 ****
HFractDSD	0.153559	(±0.023903)	0.077639	(±0.017954)	1.296e-11 ****

As in § 3.2, it was deemed useful to investigate some additional variables to assess their potential impact on the results. More specifically, we chose to consider the biological sex of the participants and, regarding patients, their score on a UPDRS rating scale. In Tab. 7-9, the subgroups of male and female PPDs are compared to respective controls of the same sex. These tables show opposing trends for male and female patients across some of the metrics: for example, SILMEAN, SILSD, and SILMEDIAN values prove to be higher in male patients and lower in female patients (compared to respective sex-matched controls), whereas SPEMEAN, SPEMEDIAN, and TPR values decrease in men and increase in women. Conversely, the Parkinson's effect is consistent across genders for other measures, such as PITCHSD and HFractDM (lower in both PPD groups), or SPCENTRSD and HFractDSD (always higher in PPDs than in controls).

Table 7 - *Male and female PPDs compared to their respective controls on the first text reading task*

	Men			*Women*		
	PPD	*EHC*	*p-value*	*PPD*	*EHC*	*p-value*
SIL MEAN	1.1734 (±0.4947)	0.9665 (±0.4888)	0.0071 **	1.0339 (±0.312)	1.8299 (±0.8279)	0.0029 **
SIL SD	0.5979 (±0.5156)	0.3668 (±0.3825)	0.0178 *	0.5058 (±0.3641)	1.1557 (±0.6358)	0.0084 **
SIL MEDIAN	1.0246 (±0.3466)	0.9291 (±0.3716)	0.0654	0.9111 (±0.167)	1.5475 (±0.7991)	0.0114 *
SPE MEAN	1.3003 (±0.5296)	1.6387 (±0.6516)	0.0293 *	1.72437 (±0.5324)	0.5282 (±0.31431)	0.0008 ***
SPE SD	0.8749 (±0.342)	0.9903 (±0.3326)	0.1164	1.0186 (±0.3099)	0.4018 (±0.2459)	0.001 ***
SPE MEDIAN	1.1235 (±0.5368)	1.5239 (±0.6773)	0.0249 *	1.5946 (±0.5822)	0.407 (±0.2218)	0.0005 ***
VR	2.2041 (±0.6078)	2.64004 (±0.2913)	0.0357 *	2.0355 (±0.9332)	2.4416 (±0.5032)	0.2197
TPR	0.8998 (±0.1896)	1.0083 (±0.2567)	0.0089 **	1.0349 (±0.2054)	0.5563 (±0.2159)	0.0009 ***
SPT	4.263 (±3.7757)	4.5526 (±2.6819)	0.383	2.6802 (±0.7133)	11.5067 (±6.1643)	0.0001 ****
PITCH SD	23.0117 (±5.7587)	39.3436 (±9.6425)	0.0002 ***	26.2115 (±4.7045)	36.1734 (±7.8735)	0.0102 *
SPCENTRSD	1568.122 (±362.359)	1123.302 (±200.7114)	0.0065 **	1542.506 (±586.8935)	1388.472 (±291.8508)	0.3839
HFractD MEAN	1.586 (±0.0742)	1.8023 (±0.0334)	0 ****	1.7161 (±0.0488)	1.8477 (±0.0519)	0.0003 ***
HFractD SD	0.1624 (±0.0203)	0.089 (±0.0129)	0 ****	0.1372 (±0.0258)	0.0837 (±0.018)	0.0004 ***

Table 8 - *Male and female PPDS compared to their respective controls on the 2nd text reading task*

	Men			*Women*		
	PPD	*EHC*	*p-value*	*PPD*	*EHC*	*p-value*
SIL MEAN	0.9683 (±0.1554)	0.8279 (±0.2419)	0.0074 **	0.9342 (±0.3269)	1.6359 (±0.6434)	0.009 **
SIL SD	0.34999 (±0.1146)	0.2915 (±0.2581)	0.0247 *	0.5508 (±0.549156)	1.0049 (±0.5903)	0.0641
SIL MEDIAN	0.9366 (±0.1594)	0.7947 (±0.1873)	0.0099 **	0.8449 (±0.1758)	1.3812 (±0.5329)	0.0192 *
SPE MEAN	1.7186 (±0.4746)	1.9449 (±0.7665)	0.1203	2.16002 (±0.588)	0.67902 (±0.4452)	0.0012 **
SPE SD	1.0708 (±0.2767)	1.1856 (±0.4403)	0.2285	1.2979 (±0.338)	0.53215 (±0.3363)	0.0013 **

	Men			*Women*		
	PPD	*EHC*	*p-value*	*PPD*	*EHC*	*p-value*
SPE MEDIAN	1.5739 (±0.69899)	1.8224 (±0.8903)	0.1631	2.0543 (±0.6035)	0.5377 (±0.3642)	0.0012 **
TPR	1.0127 (±0.0802)	1.0812 (±1.9425)	0.0152 **	1.1186 (±0.1816)	0.6397 (±0.2594)	0.0031 **
SPT	3.6803 (±0.489245)	3.9885 (±1.4963)	0.2685	3.0844 (±0.6068)	10.32015 (±5.2602)	0.0005 ***
SPR	6.1178 (±1.8423)	6.7308 (±1.9425)	0.2957	6.5906 (±2.4799)	5.1473 (±1.1319)	0.0482 *
PITCH SD	20.9433 (±5.2527)	37.8978 (±8.8225)	0.0003 ***	27.3814 (±5.4744)	37.66004 (±8.4977)	0.015 *
SPCENTRSD	1575.213 (±327.533)	1084.074 (±191.7497)	0.0025 **	1550.895 (±627.4434)	1420.341 (±250.262)	0.4108
HFractD MEAN	1.5838 (±0.0589)	1.8002 (±0.0286)	0 ****	1.7341 (±0.0396)	1.8425 (±0.0528)	0.0024 **
HFractD SD	0.1635 (±0.0191)	0.0857 (±0.0097)	0 ****	0.1309 (±0.0258)	0.0851 (±0.0202)	0.0024 **

Table 9 - *Male and female PPDs compared to their respective controls on the sentence reading task*

	Men			*Women*		
	PPD	*EHC*	*p-value*	*PPD*	*EHC*	*p-value*
SIL SD	0.4204 (±0.3124)	0.4094 (±0.3386)	0.7512	0.3604 (±0.339)	0.8938 (±0.6182)	0.02013 *
SPE MEAN	1.6630 (±0.3796)	1.7845 (±0.8259)	0.491	1.8094 (±0.5809)	1.5343 (±0.6182)	0.001524 **
SPE SD	0.8197 (±0.2056)	0.8621 (±0.2433)	0.5604	0.8679 (±0.1866)	0.7789 (±0.2691)	0.03142 *
SPE MEDIAN	1.7032 (±0.5202)	1.8197 (±0.9325)	0.458	1.8154 (±0.6657)	0.5881 (±0.4791)	0.001064 **
VR	2.0749 (±0.3662)	2.5209 (±0.3056)	0.002857 **	1.7805 (±0.6754)	2.2604 (±0.4388)	0.1153
TPR	0.9211 (±0.0914)	0.9704 (±0.25424)	0.2198	0.98797 (±0.1199)	0.6787 (±0.2255)	0.004096 **
SPT	3.3033 (±0.5277)	4.3815 (±2.0571)	0.2409	2.4939 (±0.6294)	7.19207 (±3.5848)	0.000111 ***
PITCH SD	21.0772 (±5.7944)	36.5242 (±9.6271)	0.000309 ***	27.1233 (±5.2554)	28.9623 (±7.04081)	0.5208
SPCENTRSD	1612.838 (±363.1613)	1055.049 (±141.0105)	0.00041 ***	1878.847 (±413.509)	1333.841 (±312.994)	0.007303 **
HFractD MEAN	1.6012 (±363.1613)	1.807 (±0.0349)	6.401e-07 ****	1.7276 (±0.0612)	1.8466 (±0.0564)	0.001524 **
HFractD SD	0.1599 (±0.0166)	0.0768 (±0.0127)	6.401e-07 ****	0.1402 (±0.0320)	0.0783 (±0.0216)	0.000714 ***

To evaluate the variation according to UDRPS scores (Tab. 10), PPDs were divided into three subgroups: patients with mild symptoms (scoring 0 or 1), moderate (2-3), and severe (UPDRS>3) symptoms; it should be noted that the comparison between the three groups was only possible for the first reading of the text, as patients with severe symptoms were unable to perform the second text reading and sentence reading task. The results from Tab. 10 show that, for many of the metrics, the difference becomes significant precisely in the transition to the most advanced stage of the disease.

Table 10 - *Comparison between UPDRS subgroups of patients, based on the 1st text reading task*

	Mild PD	*Moderate PD*	*Severe PD*	*p-values*		
				Mild vs Mod.	*Mod. vs Sev.*	*Mild vs Sev.*
SIL MEAN	1.1143 (±0.4186)	0.98898 (±0.3337)	1.9079 (±0.5566)	0.1276	0.0105 *	0.0367 *
SIL SD	0.5265 (±0.3832)	0.4406 (±0.4020)	1.4590 (±0.8361)	0.0945	0.0087 **	0.0393 *
SIL MEDIAN	0.9928 (±0.3237)	0.9057 (±0.1601)	1.4402 (±0.1912)	0.3605	0.0185 *	0.0216 *
SPE MEAN	1.4651 (±0.5571)	1.5828 (±0.5342)	0.6890 (±0.0093)	0.3605	0.0185 *	0.0216 *
SPE SD	0.9713 (±0.358)	0.9104 (±0.2563)	0.4723 (±0.0004)	0.4091	0.032 *	0.0168 *
SPE MEDIAN	1.2816 (±0.5696)	1.4748 (±0.5975)	0.5490 (±0.0166)	0.2212	0.0123 *	0.0256 *
TRV SD	0.4372 (±0.183)	0.5436 (±0.4058)	0.6865 (±0.0426)	0.3836	0.0593	0.032 *
VR	2.3026 (±0.544)	2.0959 (±0.8586)	0.8989 (±0.2011)	0.4091	0.032 *	0.0168 *
TPR	0.9376 (±0.1804)	1.0272 (±0.2045)	0.6165 (±0.0708)	0.2576	0.0139 *	0.0244 *
SPT	4.3412 (±4.0073)	2.8209 (±0.7136)	2.6759 (±0.0674)	0.0391 *	0.359	0.0742
SPR	5.1310 (±1.8984)	4.4894 (±2.0831)	1.8244 (±0.0203)	0.2688	0.0304 *	0.0086 *
PITCH SD	22.4547 (±5.1725)	26.3035 (±5.0885)	28.6058 (±10.2910)	0.0385 *	0.4629	0.1225
HFractD MEAN	1.6183 (±0.0884)	1.6745 (±0.0838)	1.5317 (±0.0713)	0.0834	0.0202 *	0.0856

3.3 Jitter, Shimmer, HNR

Since dysphonia has been shown to be among the initial indicators of speech impairment in PD (see Pinto *et al.*, 2010), exploring measures related to voice quality represents a particularly interesting research avenue. In 2021, Toye and Kompalli extracted some of these features (including jitter variants, shimmer variants, and

HNR[3]) from vowel execution recordings of the *Italian Parkinson's Voice and Speech* corpus; since the results of their measurement were made publicly available[4], it was possible to reuse them to supplement the present study. A statistical analysis was thus conducted on these data, following the same approach as the previous subsections: means and standard deviations were calculated for PPDs and EHCs, and the two groups were later compared by using the statistical non-parametric test of Wilcoxon-Mann-Whitney. Tables below illustrate the results obtained for each vowel on jitter measures (Tab. 11), shimmer measures (Tab. 12), and Harmonic-to-Noise Ratio (Tab. 13). Overall, the differences between the two groups were highly significant for all vocalizations in all shimmer and HNR measures, while, on the other hand, jitter measures showed statistical significance only for the three corner vowels /a/, /i/, and /u/.

Table 11 - *Jitter measures on vowel executions: means, standard deviations and statistical comparison (p-values) between PPDs and EHCs*

		Local Jitter	*Local Absolute Jitter*	*Rap Jitter*	*Ddp Jitter*
/a/	*Mean PPD*	0.005624 (±0.008486)	3.81e-05 (±0.0000643)	2.93e-03 (±0.005012)	0.008776 (±0.015036)
	Mean EHC	0.005838 (±0.003632)	3.94e-05 (±0.0000243)	0.00309 (±0.002142)	0.00927 (±0.006426)
	p-value	0.0328 *	0.0277 *	0.02155 *	0.02155 *
/e/	*Mean PPD*	0.006436 (±0.011325)	4.41e-05 (±0.0000844)	3.33e-03 (±0.006461)	0.009977 (±0.019384)
	Mean EHC	0.005312 (±0.004151)	3.61e-05 (±0.0000251)	0.002794 (±0.002399)	0.008382 (±0.007197)
	p-value	0.4352	6.01e-01	0.2894	0.2894
/i/	*Mean PPD*	0.003832 (±0.001592)	2.44e-05 (±0.0000116)	1.89e-03 (±0.000879)	0.005679 (±0.002636)
	Mean EHC	0.00831 (±0.010047)	5.27e-05 (±0.0000626)	0.00457 (±0.005837)	0.013711 (±0.01751)
	p-value	0.04365 *	0.04401 *	0.0215 *	0.0215 *
/o/	*Mean PPD*	0.005128 (±0.002545)	3.47e-05 (±0.0000197)	2.64e-03 (±0.001265)	0.007921 (±0.003796)
	Mean EHC	0.005525 (±0.004662)	3.75e-05 (±0.0000317)	0.002925 (±0.002681)	0.008774 (±0.008042)
	p-value	0.2467	5.31e-01	0.1479	0.1479

[3] A complete description of these features can be found in the Appendix of Toye, Kompalli (2021).
[4] https://github.com/aeesha-T/parkinsons_prediction_using_speech.

		Local Jitter	*Local Absolute Jitter*	*Rap Jitter*	*Ddp Jitter*
/u/	*Mean PPD*	0.003602 (±0.002028)	2.30e-05 (±0.0000137)	1.82e-03 (±0.00122)	0.005458 (±0.00366)
	Mean EHC	0.007342 (±0.008565)	4.71e-05 (±0.0000571)	4.71e-05 (±0.005042)	0.011704 (±0.015125)
	p-value	0.01048 *	0.02357 *	0.005963 **	0.005963 **

Table 12 - *Shimmer measures on vowel executions: means, st. deviations and statistical comparison (p-values) between PPDs and EHCs*

		Local Shimmer	*Local db Shimmer*	*apq3 Shimmer*	*apq5 Shimmer*	*Dda Shimmer*
/a/	*Mean PPD*	0.027403 (±0.021298)	0.25964 (±0.214383)	0.013286 (±0.010428)	0.015221 (±0.011861)	0.039859 (±0.031283)
	Mean EHC	0.072828 (±0.04221)	0.671414 (±0.371165)	0.037256 (±0.024488)	0.044148 (±0.028025)	0.111767 (±0.073464)
	p-value	2.2e-16 ****	2.2e-16 ****	3.594e-15 ****	2.20e-16 ****	3.59e-15 ****
/e/	*Mean PPD*	0.029551 (±0.022644)	0.282237 (±0.231909)	0.013932 (±0.010352)	0.015913 (±0.011252)	0.041796 (±0.031055)
	Mean EHC	0.059624 (±0.046414)	0.551995 (±0.397508)	0.029488 (±0.025365)	0.03815 (±0.037496)	0.088465 (±0.076095)
	p-value	1.40e-06 ****	4.48e-07 ****	5.66e-06 ****	3.58e-07 ****	5.66e-06 ****
/i/	*Mean PPD*	0.019129 (±0.013484)	0.18677 (±0.156311)	0.009133 (±0.007239)	0.010786 (±0.007944)	0.027398 (±0.021716)
	Mean EHC	0.052676 (±0.048381)	0.510718 (±0.441095)	0.025479 (±0.025769)	0.032395 (±0.035177)	0.076437 (±0.077308)
	p-value	2.74e-10 ****	1.65e-10 ****	9.60e-08 ****	1.366e-09 ****	9.60e-08 ****
/o/	*Mean PPD*	0.03095 (±0.01932)	0.289764 (±0.194466)	0.015355 (±0.009475)	0.017472 (±0.010994)	0.046065 (±0.028426)
	Mean EHC	0.058774 (±0.046212)	0.544526 (±0.412815)	0.027491 (±0.023018)	0.036019 (±0.033853)	0.082473 (±0.069054)
	p-value	6.83e-05 ****	4.23e-05 ****	0.001512 **	6.25e-05 ****	0.001512 *
/u/	*Mean PPD*	0.021482 (±0.019223)	0.201214 (±0.180082)	0.010756 (±0.010824)	0.012315 (±0.012971)	0.012315 (±0.032473)
	Mean EHC	0.048298 (±0.04619)	0.464424 (±0.418607)	0.022219 (±0.02524)	0.029579 (±0.034524)	0.066658 (±0.075719)
	p-value	1.71e-07 ****	1.26e-07 ****	6.26e-06 ****	3.01e-07 ****	6.26e-06 ****

Table 13 - *Harmonic-to-Noise Ratio on vowel executions: means, st. deviations and statistical comparison (p-values) between PPDs and EHCs*

	HNR		
	Mean PPD	*Mean EHC*	*p-value*
/a/	25.05944 (±8.191305)	16.28696 (±6.634543)	6.29e-13****
/e/	22.99675 (±7.757845)	18.7804 (±7.405272)	0.0003349***
/i/	27.49632 (±7.136836)	20.16619 (±7.762003)	1.04e-06****
/o/	23.8211 (±8.654639)	21.28797 (±7.730056)	0.03745*
/u/	30.44595 (±6.649103)	23.60019 (±9.587023)	5.22e-05****

4. *Discussion*

The results of our research are generally consistent with previous literature on parkinsonian speech: while dysphonia is commonly identified as one of the earliest signs of hypokinetic dysarthria (see § 3.3), our analysis also highlights spectral measures as some of the most significantly altered features. More specifically, patients in our sample showed lower means and higher variability on the Higuchi Fractal Dimension, as well as significantly greater variability in the central spectroid measure.

In addition to these metrics, the data gathered from Toye and Kompalli (2021) allowed us to extend the analysis to jitter, shimmer, and HNR: results on jitter variants were significant on the three corner vowels (/a/, /i/, /u/), while shimmer and HNR demonstrated high statistical significance across all vowel executions (/a/, /e/, /i/, /o/, /u/). Surprisingly, however, the variation in these metrics did not follow the expected patterns, as HNR yielded a higher value in Parkinson's patients, whereas the measures of spectral variability were greater in control subjects. This result, which we judge as noteworthy, prompts the need to conduct further studies on larger samples and with more attention to consistent data collection procedures.

Regarding speech segment articulation, our work confirms previous findings from foreign literature on vowel articulation indices and supports the first measurements conducted on an Italian-speaking population by Mirarchi *et al.* (2017), thereby reinforcing the validity of these metrics for the Italian language. In fact, the Vowel Articulation Index (VAI) decreases in pathological subjects of our sample, while FCR increases and the tVSA appears to be reduced, to such an extent that the difference is graphically visible in Fig. 2; another insight that can be drawn from the graph concerns the significantly lower values in PD patients' F1, likely due to reduced mobility of the jaw. Further analysis on biological sex, moreover, reveals a potential gender effect: vowel production appears especially impaired in male patients, while almost no relevant differences were shown by the comparison between female patients and their respective controls. It should be noted that the structure of the corpus at our disposal enabled the collection of formant frequencies on pure vowel execution tasks, eliminating other complexity factors related to rhythmic structure (e.g., the position of the syllable within wider prosodic units) or coarticulation:

positive results on this simpler execution mode, in which speakers could exclusively focus on good vowel articulation, can thus be considered further proof of the relevance of VAI, FCR, and tVSA as acoustic biomarkers. In general, based on the observation of vowels, we can conclude that the study of hypoarticulation of speech segments yields promising signals: further investigation in the future could include the extension of the analysis to consonant production, following the example of Antolík, Fougeron (2013).

Concerning prosody, our findings align with previous literature on pitch variability, indicating a significant reduction in patients of our sample. This reduction contributes to the perceived monotony which is commonly reported as a feature of parkinsonian speech.

As for duration measures, the difficulties of identifying consistent patterns of variation have already been discussed in § 1: rather than a uniform strategy, patients seem to adopt a range of different compensatory methods, including reduced speech rate, oral festination, or alterations in the distribution of pauses. In our corpus, these discrepancies appear to arise with the introduction of biological sex as an independent variable: in fact, different trends are found for male and female PPDs when compared to respective controls. For female patients, an increase in speech segment duration (SPEMEAN and SPEMEDIAN) is detected in all tasks, while the average total duration of silences (SILMEAN, SILMEDIAN) is reduced; as a result, a significant rise in Transformed Phonation Rate (TPR) and Standardised Pause Rate (measures inversely correlated with pauses) is observed, as well as a decrease in SPT. Results from male PPDs, on the other hand, vary in the opposite direction, with an increase in pause-related measures (SILMEAN and SILMEDIAN, along with SILSD) at the expense of speech segment durations (SPEMEAN and SPEMEDIAN), resulting in a decrease in TPR and VR. The overall interpretation of these data suggests that female patients exhibit a less disrupted speech pattern, characterised by longer speech segments and fewer pauses, while male patients would tend to produce shorter rushes of speech punctuated by long pauses. Interestingly, a similar result can be found in Skodda, Visser & Schlegel (2011b), who reported a highly significant reduction of pause durations in female patients; however, to our knowledge, gender effects on dysprosody have not been investigated before on Italian speakers.

Lastly, an observation can be made about the evaluation of UPDRS subgroups. As already stated in § 3.2, the comparison between the three subgroups was only possible for the first reading of the text since patients with more severe symptoms did not manage to execute the subsequent tasks. The difficulty in completing the protocol is – in itself – proof of the association between motor symptoms and speech impairment; this observation is further supported by data from the first reading of the text, as for many of the metrics (SILMEAN, SILSD, SILMEDIAN, SPEMEAN, SPESD, SPEMEDIAN, VR, TPR, SPR, HFractDM) the analysis clearly distinguishes patients in the most advanced stage from the two previous groups. In this regard, it is also worth mentioning that TRVSD (Temporal regularity of voiced segments) increases across the subgroups, making the comparison between

early- and later-stage patients significant: this result could be interpreted as consistent with previous studies on the rhythmic features of PD dysarthria, which have demonstrated an increase in %V and more regularity in patients' syllable durations.

5. *Conclusions*

Overall, the study successfully analysed various aspects of parkinsonian speech, contributing to the flourishing body of Italian research in the field. Our three-staged analysis revealed several differences between pathological subjects and controls: some of our findings, such as the results on pitch and vowel metrics, fully align with previous literature, while some others (outcomes on jitter, shimmer, and HNR) contradict the expectations and require further investigation. Furthermore, some novel elements have been introduced, notably a focus on spectral measures related to voice quality and the inclusion of gender effects on prosody, which, to the best of our knowledge, had not been previously investigated in the Italian language context.

Several research paths remain unexplored and could be addressed in future works. First of all, while the current study is mainly focused on quantitative methods, we deem it useful to extend the analysis to qualitative approaches which could eventually involve various features, ranging from consonant production to prosody and intonation. A second improvement to our work would consist in the expansion of the corpus, by including a larger number of speakers and additional tasks (e.g., spontaneous speech). Computational methods could also be implemented, by using the most significant measures as input features for classification algorithms: achieving promising outcomes in this domain would certainly pave the way for the development of automatic tools in support of the diagnosis. As a final point, among other variables that could possibly be explored, it is noteworthy to mention the response to surgical procedures such as Deep Brain Stimulation. As far as we know, there is a lack of Italian studies on this subject, while conflicting results can be inferred from foreign literature – including a worsening in speech impairment. We believe that further research (even on limited cohorts) is needed on this topic, as it could offer important arguments for or against this kind of treatment.

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