VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2025.1.11
Vibrations in Physical Systems, 2025, 36(1), 2025111

Acoustic methods in diagnosis of Parkinson's disease

Filip ULMANIEC[1], Maciej KŁACZYŃSKI[2], Karolina PORĘBSKA[3], Małgorzata DEC-ĆWIEK[3]

[1] AGH University of Science And Technology, Acoustic Engineering Graduate Student
[2] AGH University of Science And Technology, Department of Mechanics and Vibroacoustics
[3] Jagiellonian University Medical College, Department of Neurology

Corresponding author: Maciej KŁACZYŃSKI, email: maciej.klaczynski@agh.edu.pl

Abstract The article discusses the usefulness of speech signals in the context of screening or objectively monitoring the progress of Parkinson's disease (PD) treatment. The AGH team developed an application for a mobile device (smartphone), which uses the built-in microphone to record the acoustic signal during a phonetic test performed by the patient. The research task was to identify parameters estimated from the time courses of the speech signal that objectively and statistically significantly differentiate the states of Parkinson's disease. Ultimately, nine different acoustic parameters were selected, and their usefulness was statistically examined to determine the significant difference between the studied groups. Voice parameters of individuals with Parkinson's disease (27 people) were compared with a control group of healthy individuals (15 people). The difference in voice between patients with low and high levels of disease severity on the Hoehn-Yahr scale was also examined. Inference was conducted using the Mann-Whitney U test, suitable for the given sample size and group imbalance. The obtained research results and conducted analyses show a high potential for diagnostics based on the speech signal, which can be combined with upper limb tremor diagnostics in the recognition of early-stage PD, thus providing the possibility of facilitating doctors' work in the context of objectively monitoring the adopted therapy.

Keywords: Parkinson's disease, vibration diagnostics, signal analysis, accelerometer, parameterization.

1. Introduction

1.1. Research motivation

In Poland, around 8,000 people are diagnosed with Parkinson's disease each year, and a total of about 90,000 people have been diagnosed nationwide. Globally, approximately 8.5 million people have been diagnosed, and the WHO reports that, at this rate, 12 million patients will be struggling with Parkinson's disease (PD) by 2040. It affects 1% of adults over the age of 60, and up to 4% after the age of 80. Men are 1.5 times more likely to suffer from the disease than women [1, 2]. The classic symptoms of PD belong to so-called parkinsonism. This is a set of symptoms typical of PD, which can also appear in the course of other conditions, such as a brain tumor or carbon monoxide poisoning [3]. Currently, there is no clinical test available to confirm the diagnosis of PD. Therefore, in light of the symptoms alone, without additional specialist examinations and prolonged clinical observation, it is unlikely that PD can be diagnosed [3, 4]. Making diagnosis difficult, as the symptoms intensify with the progression of the disease, sometimes very slowly, gradually over a few years. The initial common diagnosis of the disease is based on the identification of at least two of the three classic symptoms of parkinsonism [4, 5]: resting tremor, bradykinesia (slowness of movement), and increased muscle tone. Other symptoms indicating the occurrence of PD include: autonomic disorders, micrographia, changes in handwriting, olfactory disturbances, constipation, which can precede the classic onset of the disease by up to 10 years, depression and anxiety, postural disturbances, weakened cognitive functions, dementia syndrome, and speech pathology. Published works to date [6 – 12] indicate that PD, being a progressive neurodegenerative disorder, manifests not only through characteristic motor symptoms but can also affect various aspects of voice function. Currently, the methods of treating PD are diverse, although there is still no cure that allows for the complete recovery of the patient. Pharmacological therapy remains the most common form of treatment, but other therapeutic options are also available, surgical procedures, including rehabilitation, and innovative approaches such as music therapy or phonation rehabilitation. The application of therapy is dependent on the moment of disease detection. Ideally, treatment should begin when symptoms have not yet appeared, providing the possibility of dopamine compensation through the activation of appropriate regenerative mechanisms. Treatment always considers various aspects, primarily the patient's age and the planned duration of therapy. Although PD remains incurable to this day, numerous studies are continuously being conducted to understand its mechanisms and search for effective treatment methods. Scientists around the world focus on developing innovative therapeutic approaches, utilizing the latest discoveries in neurology, genetics, and molecular biology.

1.2. Purpose of research

The primary goal of the research conducted by the AGH and UJ team is to contribute to the development of new diagnostic technologies that would be less invasive and more accessible to a wider group of patients, as well as to better understand the mechanisms affecting voice changes and upper limb tremors in the course of Parkinson's disease. The AGH team created an application for a mobile device (smartphone) [10], which uses the built-in microphone and accelerometer to record sound pressure level and the amplitude values of hand vibration accelerations in three directions during a phonetic test spoken by the patient. The research task is to find parameters estimated from the time courses of hand vibration acceleration signals (resting measurement) and speech that objectively and statistically significantly differentiate the states of Parkinson's disease. This publication aims to demonstrate a relationship between Parkinson's disease and the voice of the patient, using acoustic methods based on psychoacoustic parameters. The overarching goal is to create an accessible mobile system to support diagnosis and, most importantly, remote evaluation of patients' rehabilitation and treatment progress by the medical team.

2. Methodology

2.1. Speech disorders in Parkinson's disease

Pathological language behaviors, known as speech disorders, encompass a wide range of issues, from minor speech defects to complete loss of speech or communication ability. They are often a result of the malfunctioning of articulatory organs, which can be caused by Parkinson's disease. Among individuals suffering from this disease, 75-89% experience speech disorders. These are often one of the first symptoms, yet most patients are unaware of these issues. The main causes of speech disorders among Parkinson's patients are problems with articulation and speech fluency. James Parkinson, in describing these disorders, noted that they do not affect the patient's intellectual capacity. The speech of a Parkinson's patient is characterized by respiratory, articulatory, and phonatory disorders, resulting from damage to the subcortical nuclei (extrapyramidal system), primarily the striatum and the globus pallidus. The primary speech disorders associated with PD include dysarthria, aprosodia, and dysprosody (monotonous speech, lack of modulation, problems with rhythm and accentuation), impaired articulation of consonants and vowels, voice loss, palilalia (involuntary repetition of words), and many other difficulties. The speech of Parkinson's patients is often perceived as emotionally limited, both due to the characteristics of speech and personality changes that cause the patient to appear less engaged or interested. To assess speech disorders, various criteria and methods need to be applied. These include an interview that should cover the duration of the disease, the nature of speech disorders as perceived by the patient, and the condition of speech before the onset of the disease. Speech therapy examination is also necessary, including the assessment of the efficiency of articulatory organs such as the lips, teeth, tongue, hard palate, soft palate, and jaw, as well as articulation analysis. Tools for adult speech assessment, such as the Frenchay Dysarthria Assessment (FDA) questionnaire, can be used for this purpose. Additionally, assessments can be conducted using the Voice Handicap Index (VHI) questionnaire by Jacobson, Johnson, and Grywalski, which helps to understand the impact of speech disorders on the quality of life of individuals with Parkinson's disease. Phoniatric examinations and acoustic analysis are also significant, as is the evaluation of cognitive function disorders and the degree of the patient's depression [13, 14].

2.2. Description of the research project and the methods used

In this study conducted in collaboration between the Neurology Clinic of the Jagiellonian University and Department of Mechanics and Vibroacoustics AGH University in Krakow, a proprietary mobile application [10] and an MI 5s smartphone running on Android 8.0, equipped with a microphone and an accelerometer were used. The sampling frequency for the speech signal was 44100 Hz, and for the vibration amplitude signal, it was 400 Hz. In the research presented in this manuscript, only audio recordings were used. The analysis of the resting hand vibration signal and the kinetic test is the subject of another article. The application can be started and stopped using the REC/STOP function, and the audio signal is saved in WAVE files. Patients diagnosed with Parkinson's disease were qualified for the study at the Neurology Clinic of the Jagiellonian University in Krakow. Qualification was based on a specialist doctor's diagnosis following the United Kingdom Parkinson's Disease Society Brain Bank Criteria (UK PDS BBC), and the disease stage was determined according to the Hoehn-Yahr scale. In this study, 27 patients were examined, among them, 14 were women and 13 were men, with an average age of 67 years. Among the 27 patients diagnosed with Parkinson's disease, the following were classified: 7 patients in stage 1 PD - slightest ailments, 9 patients in stage 2 PD, 4 patients in stage 3 PD, 5 patients in stage 4 PD, and 2 patients in stage 5 PD - greatest ailments. The control group consisted of 15 healthy individuals aged between 22 and 70 years, with an average age of 57 years, including 4 women and 11 men. The research material was collected between 2022 October and 2023 July. In collaboration with the Neurology Clinic of the Jagiellonian University, a methodology for conducting the entire study process was established:

1. Qualification for the study – Specialist doctors qualified patients diagnosed with Parkinson's disease whose stage was determined by the international Hoehn-Yahr scale. Patients with coexisting diseases that could affect qualification or study outcomes were excluded.
2. Presentation of the process and preparation – Patients were informed both orally and in writing about the study procedure to ensure they understood all steps, minimizing unnecessary stress and allowing them to become familiar with the application and its operation. Instructions covered study requirements, including proper positioning and actions to be taken.
3. Main study – Three tests were conducted: two in static form and one in dynamic form. For the static tests, patients were seated on a couch, with their back and head supported against a wall, and hands resting on the couch without touching their legs to avoid interference. The smartphone with the application was placed in the patient's right hand, and recording began just before the test to avoid vibrations from handling or pressing the REC/STOP button. The patient counted aloud from one to ten, allowing for the recording of their speech while focusing on counting to minimize stress-induced tremors. This also standardized the test duration to about 10 seconds, depending on counting speed. After counting, the recording was stopped similarly to how it was started. The second test mirrored the first, with the patient holding the smartphone in the left hand. The dynamic test lasted around 10 seconds as well: the patient held the smartphone in a relaxed hand, hanging along the body. Recording began as the hand was lowered, and the patient counted from one to ten while moving slowly around the room. Some patients were excluded from this part of the study due to limited motor skills or physical disabilities.
4. Validation of recording correctness - Recordings were checked for external disturbances. a. Re-recording – Some recordings were repeated due to premature or delayed recording start/stop or external disturbances.
5. Data collection – Summarized information included each patient's disease stage, age, and gender.

The study was conducted in a closed room in the presence of the examiner, the patient, and one person close to the patient, which significantly impacted the comfort and ease during the test.

2.3. PD assessment scales

Based on a comprehensive clinical analysis, the diagnostician is required to make a decision regarding the presence of the disease, its progression, and classification. The most commonly used scales for assessing the progression of Parkinson's disease are the Hoehn & Yahr scale, the Schwab & England scale, and the Unified Parkinson's Disease Rating Scale (UPDRS). The Hoehn & Yahr (H&Y) scale numerically defines the patient's disability and disease stage from 1 to 5:

- stage 1 – unilateral involvement, usually with minimal or no functional impairment,
- stage 2 – bilateral involvement or midline involvement without impairment of balance,
- stage 3 – first signs of impaired righting reflexes. Evident postural instability, such as when turning or when pushed from a standing position with feet together and eyes closed,
- stage 4 – fully developed disease, severely disabling; the patient is often able to walk but is unable to stand unassisted,
- stage 5 – patient is confined to a wheelchair or bed unless assisted [3].

2.4. Research material preemphase and parametrization

Audio signal recordings were made using the recording application [10] with the built-in microphone of a smartphone, sampling at a frequency of 44100 Hz, and saved to files in *wave* format. Using the REAPER software, the files were imported and normalized, then converted from stereo to mono in the MATLAB environment, after which *smoothdata* function was used to improves the signal-to-noise ratio.

There are several well-known and validated parameters for describing audio signals, including speech signals, which are described and used in many publications. In this study, a total of nine parameters were used, which, based on the literature, were deemed crucial in the process of acoustic signal analysis and were based on psychoacoustic assessment. The starting point for this decision was the observation that an experienced diagnostician can detect speech deformations in a patient during a conversation at a check-up visit. Therefore, the hearing and experience (knowledge base) of the doctor could be applied in the digital analysis of pathological speech deformed by PD. The parameterization was mostly performed using MATLAB and the *MIRtoolbox* library [15] dedicated to extracting features from audio files. Analyses of the speech signal used the full bandwidth made possible by the sampling frequency. Additionally, the *Parselmouth Praat Scripts in Python* library created by David R. Feinberg [16] was used. The software was utilized thanks to the MIT License. Calculations were mainly carried out using the *Parselmouth library* based on algorithms from the *Praat* program [17]. With all these tools, parameter calculation and further analysis could be performed in an accessible and reliable manner.

In this study, speech signal parameterization methods were applied to the following forms:

Loudness level [phones] – Loudness and loudness level are perceptual attributes of sound. Due to differences among people, measurements of loudness [sones] and loudness level [phones] should be considered statistical estimators. It is characterized by equal-loudness contours, which show sound pressure levels of sounds with the same loudness level [18]. The calculation method for the Loudness parameter was performed according to the Zwicker method defined in ISO-532-1 [19].

Sharpness [acum] – measures the "sharpness" of sound and depends on the high-frequency content in the sound spectrum. It primarily evaluates the timbre of the sound [18], and is a measure derived from loudness, with its values depending on the "weighting" method. The calculation was based on the guidelines of DIN 45692 [20].

Roughness [asper] – Roughness is related to the perception of sound roughness, especially with small frequency differences. Roughness increases with modulation frequency, so it is noticeable in sounds with frequencies close to each other [18]. The Roughness algorithm defines a value of 1 asper for a 1 kHz tone at 60 dB with 100% amplitude modulation at 70 Hz. Calculations were performed based on the guidelines [17, 19].

Fluctuation [vacil] – refers to perceptual changes in sound associated with slow amplitude or frequency modulations [21]. The strength of fluctuation has a band-pass characteristic, with a maximum around 4 Hz modulation frequency. Calculations were based on the guidelines [19, 21].

Brightness [spectral energy] – this term refers to the perceptual quality of sound that determines how "bright" or "sharp" a sound is. Brightness is related to the proportion of high frequencies in the sound spectrum. Sounds with more energy at higher frequencies are usually perceived as brighter.

Flatness [spectral flatness] – relates to how sound energy is distributed across different frequencies in the spectrum. Sound is considered "flat" if its energy is evenly spread across all frequencies.

Harmonics-to-Noise Ratio (HNR) – the ratio of harmonic energy to noise energy in the sound signal. A high HNR indicates a pure, less noisy sound [17]. Calculations were performed using a correlation method with the algorithm proposed by Paul Boersma [22].

Local Jitter [%] – the mean absolute difference between consecutive fundamental frequencies from cycle to cycle of the speech signal, divided by their mean value [17]. This measure is used to assess voice quality and stability, measuring how regularly the vocal cords vibrate.

Local Shimmer [%] – the mean absolute difference between consecutive fundamental amplitudes from cycle to cycle of the speech signal, divided by their mean value [17]. This measure is used to assess amplitude fluctuations in the voice.

3. Statistical analysis of results

All audio files representing recordings from patients and the control group were parameterized according to the description in section 2.4. Importantly, for each subject, three recordings were parameterized – two static tests and one dynamic test. Ultimately, the analyzed database consisted of 84 records from individuals diagnosed as PD and 45 records from healthy individuals. Based on this data, the Kolmogorov-Smirnov normality test was conducted using MATLAB - *kstest* function. The function returns a decision on whether there is sufficient evidence to reject the null hypothesis *H0* – that the data is normally distributed. If $h = 0$, the null hypothesis *H0* is accepted; if $h = 1$, there is evidence to reject *H0* in favor of *H1* – that the data is not normally distributed. A significance level of $\alpha = 0.05$ was assumed, meaning a 5% chance of rejecting the null hypothesis H0 when it might actually be true is accepted. Low p-value results, lower than the set alpha threshold for this test, challenge the validity of *H0*. The test was performed separately for individuals with diagnosed PD and for healthy individuals. The null hypothesis *H0* was rejected in all cases.

Given that the analyzed data did not follow a normal distribution, non-parametric testing using the Mann-Whitney U test, which is the non-parametric equivalent of the Student's t-test for independent samples, was employed for further analysis. This test examined whether there were statistically significant differences between each parameter for the control group and the patient group. Results are presented in Table 1. The same test was also used to examine relationships within the patient group, but across different stages of the Hoehn-Yahr scale. Voice parameters of patients with disease progression at stages 1 to 3 were compared with individuals diagnosed at Hoehn-Yahr stages 4 and 5. Results are presented in Table 2. A significance level of $\alpha = 0.05$ was used for calculations. An additional condition justifying the use of this test is the lack of requirement for equal-sized data sets. In the Mann-Whitney U test, the median plays a significant role as it is used as a reference point for the overall data distribution in each group.

Table 1. Results of Mann-Whitney U Test, Parkinson's disease (PD) vs Control Group (CG).

Parameter	Recognition	Median	Median absolute deviation (MAD)	p-value	Hypothesis	Statistical difference between data
Loudness	PD CG	27.56 28.62	3.57 2.96	4.50e-01	H=0	No
Sharpness	PD CG	1.11 1.11	0.09 0.08	1.25e-01	H=0	No
Roughness	PD CG	0.14 0.13	0.04 0.05	7.74e-01	H=0	No
Fluctuation	PD CG	0.57 0.67	0.2 0.19	1.11e-02	H=1	Yes
Brightness	PD CG	0.35 0.32	0.09 0.09	1.46e-01	H=0	No
Flatness	PD CG	0.06 0.06	0.02 0.01	5.99e-01	H=0	No
HNR	PD CG	6.93 8.98	1.82 1.97	3.11e-07	H=1	Yes
Local Jitter	PD CG	0.03 0.02	0.01 0.01	4.92e-07	H=1	Yes
Local Shimmer	PD CG	0.14 0.13	0.03 0.03	1.31e-01	H=0	No

Based on the decision regarding the null hypothesis presented in Table 1, statistically significant differences were observed for three parameters: Fluctuation, HNR, and Local Jitter. These differences were evident when comparing the control group and the patient group. Regarding differences based on the disease progression stage, i.e., Parkinson's disease stages 1, 2, and 3 vs. stages 4 and 5, statistically significant differences were found for three parameters: Brightness, HNR, and Local Shimmer.

The analysis of results was conducted only for parameters showing statistically significant differences. According to theory, the Fluctuation parameter value for the patient group should be higher compared to the control group. However, data in Table 1 show that situation is reversed. For the Brightness parameter and the difference between disease stages, the value of this parameter is higher for stages 1, 2, or 3 compared to stages 4 and 5. This indicates a lower amount of energy in higher frequencies for the more advanced stages of Parkinson's disease. Another parameter that showed statistically significant differences was HNR, for which the results align with the theory. As seen in Table 1, lower HNR values were observed in the patient group, indicating speech disorders. These results suggest moderate speech quality, as the ratio of harmonic energy to noise is low. For comparisons across Parkinson's disease stages (Table 2), lower HNR values were anticipated for patients with more advanced stages. The observed results may primarily be attributed to the disproportionate number of recordings from individuals in earlier stages compared to those in advanced stages. The next two parameters, Local Jitter and Local Shimmer, relate to the stability of glottal function. Local Jitter refers to fluctuations in the periodicity of vocal fold vibrations, with higher values indicating greater irregularity. As expected, higher values were observed in the patient group (Table 1). Conversely, Local Shimmer reflects fluctuations in the amplitude of vocal fold vibrations. When comparing disease stages (Table 2), a lower value of Local Shimmer was observed in advanced stages compared to stages 1, 2, and 3.

Table 2. Results of Mann-Whitney U Test,
Parkinson's disease stage 1,2,3 (PD 1 2 3) vs. Parkinson's disease stage 4 and 5 (PD 4 5).

Parameter	Recognition	Median	Median absolute deviation (MAD)	p-value	Hypothesis	Statistical difference between data
Loudness	PD 1 2 3 PD 4 5	27.31 28.34	3.87 2.66	9.46e-01	H=0	No
Sharpness	PD 1 2 3 PD 4 5	1.15 1.06	0.08 0.08	3.43e-03	H=1	Yes
Roughness	PD 1 2 3 PD 4 5	0.13 0.15	0.04 0.04	1.58e-01	H=0	No
Fluctuation	PD 1 2 3 PD 4 5	0.59 0.51	0.2 0.22	6.55e-01	H=0	No
Brightness	PD 1 2 3 PD 4 5	0.37 0.29	0.8 0.06	1.34e-03	H=1	Yes
Flatness	PD 1 2 3 PD 4 5	0.06 0.06	0.02 0.03	8.02e-01	H=0	No
HNR	PD 1 2 3 PD 4 5	6.84 7.70	‘1.95 1.5	1.53e-02	H=1	Yes
Local Jitter	PD 1 2 3 PD 4 5	0.03 0.03	0.01 0.01	9.78e-02	H=0	No
Local Shimmer	PD 1 2 3 PD 4 5	0.15 0.12	0.03 0.03	7.59e-03	H=1	Yes

4. Summary

The purpose of this study was to prove the existence of a relationship between Parkinson's disease and the voice of a patient. Based on the results and the described statistical analysis of results, it was observed that such relationships exist for certain parameters. A parameterisation of the acoustic signal to 9 parameters was proposed for the study material collected in the pilot study - 27 patients diagnosed with Parkinson's disease i.e. 7 patients in stage 1 PD, 9 patients in stage 2 PD, 4 patients in stage 3 PD, 5 patients in stage 4 PD, and 2 patients in stage 5 PD. The control group consisted of 15 healthy individuals. Statistical differences at the significance level of $p=0.05$ were confirmed using the non-parametric Mann-Whitney U test for three parameters - Fluctuation, HNR, and Local Jitter - in differentiating the control group from the patient group, and for three parameters - Brightness, HNR, and Local Shimmer - in differentiating Parkinson's disease stages 1, 2, and 3 vs. stages 4 and 5. Several factors may have influenced these results. One possibility is the lack of a true relationship between certain parameters and the examined groups. Not all preselected parameters may be effective for describing the intended relationships. Another factor is the small sample size, which reduces the likelihood of detecting significant differences. With only 27 patients studied, the ability to capture subtle voice abnormalities was limited. Additionally, the quality of the recordings may have impacted the results. The recordings were made in clinical settings, where external factors often interfered with data quality. Despite efforts to enhance the recordings, some files still contained noise and interference, potentially affecting parameter measurements. While the study results are moderately promising, they highlight the need for a larger dataset. In the medical field, studies often involve thousands of samples, whereas this study was limited to only 27 patients. Further research with larger sample sizes is necessary to strengthen these findings.

Ethical supervision

The research was approved by The Bioethics Committee of the Jagiellonian University (review no. 1072.6120.271.2019 of 21 Nov 2019).

Acknowledgments

The work was created as part of research project of Department of Mechanics and Vibroacoustics no. 16.16.130.942 AGH and CMUJ in Krakow.

Additional information

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Global Burden of Disease 2021: Findings from the GBD 2021 Study; Institute for Health Metrics and Evaluation (IHME), Seattle, WA: IHME, 2024
2. Global Health Estimates; WHO, https://cdn.who.int/media/docs/default-source/gho-documents/global-health-estimates/ghe2019_cod_methods.pdf?sfvrsn=37bcfacc_5 (accessed on 1.07.2024)
3. B. Thomas, M. Flint Beal; Parkinson's disease; Human Molecular Genetics, 2007, 16(R2), R183–R194; DOI: 10.1093/hmg/ddm159
4. Parkinson’s Disease: Causes, Symptoms, and Treatments; https://www.nia.nih.gov/health/parkinsons-disease (accessed on 1.07.2024)
5. S. M. Stahl; Fundamentals of psychopharmacology. Theory and practice. T. 2. (in Polish); Gdańsk: Via Medica, 2009
6. L. Ali, C. Zhu, M. Zhou, Y. Liu; Early diagnosis of Parkinson’s disease from multiple voice recordings by simultaneous sample and feature selection; Expert Systems with Applications, 2019, 137, 22–28; DOI: 10.1016/j.eswa.2019.06.052
7. J.S. Almeida et al.; Detecting Parkinson’s disease with sustained phonation and speech signals using machine learning techniques; Pattern Recognition Letters, 2019, 125, 55–62; DOI: 10.1016/j.patrec.2019.04.005
8. A. Benba, A. Jilbab, A. Hammouch; Voice assessments for detecting patients with Parkinson’s diseases using PCA and NPCA; Int J Speech Technol, 2016, 19(4), 743–754; DOI: 10.1007/s10772-016-9367-z
9. P. Gillivan-Murphy, N. Miller, P. Carding ; Voice Tremor in Parkinson’s Disease: An Acoustic Study; J Voice, 2019, 33(4), 526–535; DOI: 10.1016/j.jvoice.2017.12.010
10. M. Chronowski, M. Kłaczyński, M. Dec-Ćwiek, K. Porębska, K. Sawczyńska; Speech and tremor tester - monitoring of neurodegenerative diseases using smartphone technology; Diagnostyka, 2020, 21(2), 31-39; DOI: 10.29354/diag/122335
11. M. Chronowski, M. Kłaczyński, M. Dec-Ćwiek, K. Porębska; Parkinson’s disease diagnostics using AI and natural language knowledge transfer; Diagnostyka, 2024, 25(1), 2024103; DOI: 10.29354/diag/176931
12. M. Heijmans, J.G.V. Habets, C. Herff et al.; Monitoring Parkinson’s disease symptoms during daily life: a feasibility study; npj Parkinsons Dis., 2019, 5, 21; DOI: 10.1038/s41531-019-0093-5
13. A.P. Krysiak; Language, speech, and communication disorders in Parkinson’s disease (in Polish); Neuropsychiatria i Neuropsycholgia, 2011, 6(1), 36-42
14. W. Pawlukowska, K. Honczarenko, M. Gołąb-Janowska; Nature of speech disorders in Parkinson disease (in Polish); Neurologia i Neurochirurgia Polska, 2013, 47 (3), 263-270; DOI: 10.5114/ninp.2013.35566
15. MIRtoolbox Version 1.10.0.0 by Olivier Lartillot; https://www.mathworks.com/matlabcentral/fileexchange/24583-mirtoolbox (accessed on 13.12.2023)
16. Parselmouth – Praat in Python, the Pythonic way; https://parselmouth.readthedocs.io/en/stable/ (accessed on 19.12.2023)
17. Praat: doing phonetics by computer; https://www.fon.hum.uva.nl/praat/ (accessed on 13.12.2023)
18. A. Fastl; The Psychoacoustics of Sound-Quality Evaluation; Institue of Man-Machine-Communication, 1997, 83, 754-764
19. ISO 532-1:2017(E); Acoustics – Methods for calculating loudness – Part 1: Zwicker method, 2017
20. DIN 45692:2009; Measurement Technique for the Simulation of the Auditory Sensation of Sharpness, 2009
21. H. Fastl, E. Zwicker; Psychoacoustics: Facts and Models; Springer Science & Business Media, 2013

22. P. Boersma; Accurate Short-Term Analysis of the Fundamental Frequency and the Harmonics-to-Noise Ratio of a Sampled Sound; Institue of Phonetic Sciences, 1993, 17, 97-110