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Application of vibration diagnostics to monitor the progression of Parkinson's disease

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Abstract The paper presents the results of a pilot study to determine the applicability and feasibility of using a method for processing and analyzing acceleration signals of upper limb tremors in the context of screening and objectively monitoring the progression of Parkinson's disease (PD) treatment using a smartphone-embedded accelerometer. The study involved 27 individuals diagnosed with PD at various stages of the disease as determined by the Hoehn-Yahr scale, and 15 healthy individuals as the control group. The study analyzed hand tremors by recording accelerations in three directional components: *x*, *y*, and *z*, applying appropriate normalization and parameterization. The analyzed quantities were maximum value (MV), root mean square (RMS), crest factor (CF), and peak-to-average ratio (PAPR). The statistical analysis using the Student's t-test showed that CF is the least differentiating parameter for disease states, while PAPR is the most differentiating. The obtained study results and conducted analyses demonstrate the significant potential of vibrational diagnostics of the upper limbs in diagnosing PD, and the possibility of facilitating the specialist doctor's work in the context of objectively monitoring treatment progress, not only in a contact manner but also remotely.

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

1. Introduction

Modern society faces the challenge of a significant aging population, both in Poland and globally. Trends presented by the Statistics Poland show that by 2050, individuals over the age of 60 may constitute up to 40.4% of the entire Polish population [1]. The trend of an aging society is experiencing a significant increase, over 150% in the next 30 years. With the increasing percentage of people aged 60 and older in society, the number of individuals affected by neurodegenerative diseases also rises. One of the most common and very difficult to diagnose in its early stages is Parkinson's disease. In Poland, over 100 cases per 100,000 people are diagnosed annually, and in 2021, about 90,000 people were recorded as having this disease [2], with 4 out of 100,000 people dying from it annually [3]. According to forecasts, these numbers may double by 2040. Parkinson's disease is a chronic, rapidly progressing neurodegenerative disease characterized by profound and selective loss of dopaminergic neurons in the nigrostriatal pathway, closely related to motor function. These neurons, located in the basal ganglia—an area of the brain controlling movement—produce dopamine in healthy individuals, but in patients with the disease, they may die or become damaged. When this happens, they produce less dopamine, which directly affects movement associated with the disease [4] [5]. The clinical picture and symptoms vary between patients, even at the same stage of the disease. Four main symptoms are distinguished: tremor of the hands, legs, jaw, and head; muscle stiffness, especially in areas where they have been tense for a long time; bradykinesia, or slowness of movement; tendency to fall, disturbed balance, and coordination [6], and other symptoms such as depression and emotional disturbances; difficulty swallowing, speaking, or chewing; urinary problems, constipation; skin problems; sleep disturbances; and loss of smell [7]. Motor changes in Parkinson's disease usually affect one part of the body or at the beginning, one limb. Resting tremor occurs in 70.5% of individuals affected by PD, characterized by a frequency range of 2-7 Hz, and is most pronounced in this position [8]. Currently, Parkinson's disease is considered the disease with the fastest-growing number of cases among all neurodegenerative diseases worldwide

Vibroacoustics is a key research area that enables the assessment and analysis of the performance of mechanical structures by monitoring their vibrational response. Focusing solely on vibration diagnostics, one must consider the theory of vibrations, encompassing both linear and nonlinear aspects in the realm of deterministic and random phenomena. Vibrations not only occur in isolated machines but are also present in everyday life [9]. Studies on human body vibrations are significant both in the context of human-machine interaction and in predicting vibrations of the human body. Vibration diagnostics in relation to the human body is applied not only in the ergonomic design of machines but also in medical diagnostics. Analyzing human body vibrations allows for the identification of potential health problems and can be useful in diagnosing motor system disorders or assessing the impact of external factors on the human body. Numerous studies conducted over the past two decades have shown significant potential in using speech signals for PD diagnosis, with classification accuracy reaching nearly 100% [10–15]. The impact of PD on human speech is well documented. Symptoms include voice tremors and stuttering, and as the disease progresses, speech may become completely unintelligible. In the case of limb tremors, it is less studied in terms of automated diagnostics, but some approaches have been undertaken, such as using a touch panel to measure writing disturbances [16] or using mobile devices to monitor gait [17] and hand vibrations with a smartphone attached to the hand [18] as well as using the digital Parkinson's movement diary (adPMD) based on an accelerometer along with an application [19]. Currently, smartphones are equipped not only with increasingly high-quality microphones but also with a whole set of sensors, including three-directional accelerometers, which can be used for technical or medical diagnostics tasks. Therefore, an approach was proposed to use the acceleration signal recorded with a mid-range Android device.

The aim of this pilot study is to determine the applicability and feasibility of using a method for processing and analyzing acceleration signals of upper limb tremors in the context of screening and objectively monitoring the progression of Parkinson's disease (PD) treatment using mobile devices (smartphones). The ultimate goal is to implement a mobile monitoring system for Parkinson's disease, aiming to construct a comprehensive tool for remote measurement and analysis of parameters characteristic of patients with this neurodegenerative disease. This system has the potential not only to effectively monitor motor symptoms but also to provide diagnostic data to physicians and enable patients to actively participate in monitoring their health. Another objective is to evaluate the effectiveness of such a system in clinical practice.

2. Methodology

2.1. Description of research project and applied methods

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 [14] and a MI 5s smartphone operating on Android 8.0, equipped with an accelerometer with a sampling frequency of 400 Hz, were used. The maximum sampling frequency for this smartphone was used because of the observing possible components other than in the standard limb vibration frequency range. This was also due to the ease of use of the signal decimation procedure. The application can be started and stopped using the REC/STOP function, while the recording of vibration acceleration signals in three directional components is saved in ASCII files. The impact of the transducer's mass (with a smartphone weighing approximately 100–150 g) on hand movement dynamics should be considered. According to the guidelines of EN ISO 5349-2:2021 standard [20] regarding the measurement of mechanical vibrations transmitted through the upper limbs, if the transducer's mass does not exceed 5% of the mass of the tool to which it is attached, its influence can be considered negligible. The total mass of the upper limb (including the arm, forearm, and hand) accounts for approximately 5–6% of body weight [21]. For example, a person weighing 70 kg, this corresponds to about 3.5–4.2 kg. In this case, the smartphone's mass represents less than 5% of the limb's mass, suggesting that its impact on hand movement dynamics is negligible. Additionally, the study will be conducted at different stages of treatment using the same smartphone each time, ensuring that any potential influence of its mass remains constant throughout the experiment. Patients diagnosed with Parkinson's disease at the Neurology Clinic of Jagiellonian University in Krakow were qualified for the study. Qualification was based on the specialist physician's diagnosis according to the United Kingdom Parkinson's Disease Society Brain Bank Criteria (UK PDS BBC), and the stage of the disease was determined according to the Hoehn-Yahr scale.

The primary goal of the research is to develop a method for monitoring the treatment progress of patients with Parkinson's Disease (PD); therefore, the patient will ultimately be consistently assessed using a sensor mounted in a mobile device. 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. Four of them were women, and 11 were 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 research process was established:

1. qualification for the study – specialist doctors qualified diagnosed patients whose disease stage was determined by the international Hoehn-Yahr scale. Patients did not have comorbidities that could affect the qualification or results of the study.
2. process explanation and preparation – patients were informed about the entire study process both orally and in writing so that they were aware of all the steps, which also helped eliminate unnecessary stress. They were familiarized with the application and its operation. Patients were instructed about the requirements during the study, such as the appropriate position and actions to be performed.
3. main study – three tests were conducted: two in a static form and one in a dynamic form. Patients were instructed to sit on a couch, rest their back and head against the wall, and place their hands on the couch so that they did not touch their legs, which could interfere with the study by damping or falsely increasing vibrations. Initially, the smartphone with the application was placed in the patient's right hand, and the recording was started just before the test to avoid external vibrations associated with handling the smartphone or pressing the REC/STOP button by the patient. The patient counted aloud from one to ten, allowing for the recording of the patient's speech and helping them focus on counting, which could positively affect the study by reducing stress, a significant cause of increased tremors. This also standardized the duration of each test, which lasted about 10 seconds depending on the counting pace. When the patient finished counting, the recording was stopped using the REC/STOP button, similar to how it was started. The next stage mirrored the first, only changing the patient's hand to the left. A dynamic test was also conducted, lasting about 10 seconds like the static tests. The patient held the smartphone with the recording application running in a relaxed hand, lowered along the body. The recording started when the hand was lowered, and then the patient began counting from one to ten while walking slowly around the room. Some patients were excluded from this part of the study due to limited mobility or physical disability.
4. validation of recording accuracy – recordings were validated for external noise or vibrations. a) re-recording – some recordings had to be repeated due to starting or stopping too early or too late or due to external vibrations.
5. data collection – summarizing information about the patient such as disease stage, age, and gender.

The study was conducted in a closed room in the presence of the researcher, the patient, and a close relative of the patient, which significantly affected the comfort and ease of the test.

2.2. 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 [5].

2.3. Research material

The files obtained using the recording application [14] with an accelerometer sampling at a frequency of 400 Hz were ASCII files containing information on accelerations in three directional components: x, y, and z, which provided a spatial representation of the patient's hand movement. Ultimately, using MATLAB software, the source data were placed in structural arrays along with medical descriptions. For further research, only recordings from the static test, conducted at rest, were used. Figures 1-5 show the range of

motion for sample subjects at each stage of the H&Y scale of disease progression and a healthy individual during the examination. Visual observation clearly shows changes and increases in amplitude of displacement for left and right hands in the spatial dimensions, indicating the potential for recognizing Parkinson's disease using these signals.

a) b)

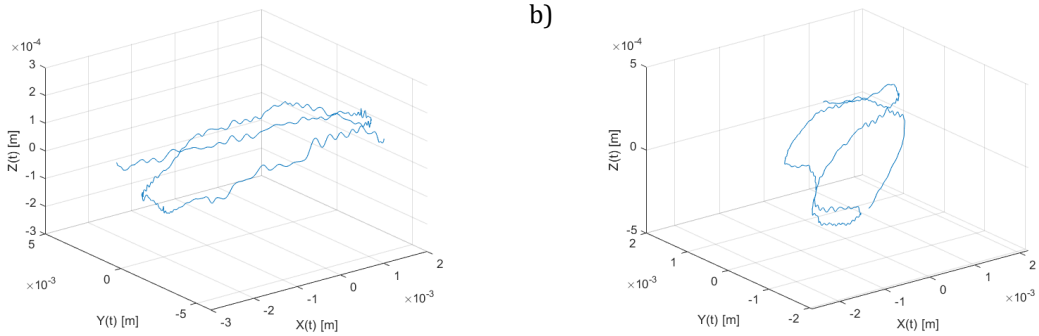

Figure 1. Diagram of the amplitude of displacement for a healthy person (a) left hand (b) right hand.

a) b)

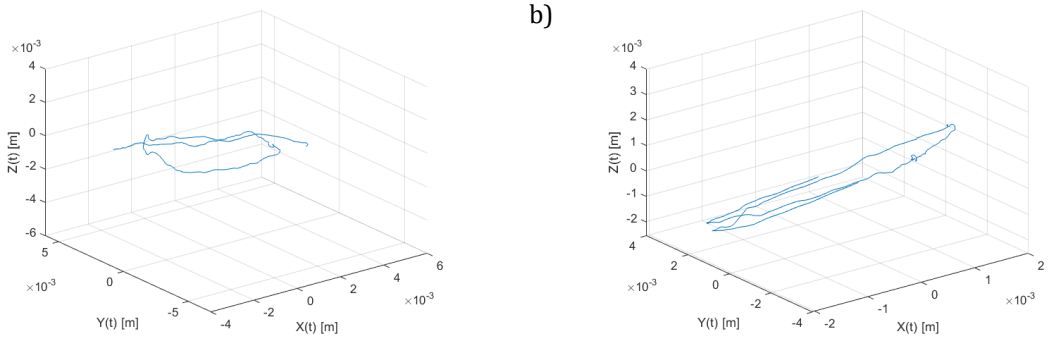

Figure 2. Diagram of the amplitude of displacement for a person with stage 1 PD (a) left hand (b) right hand.

a) b)

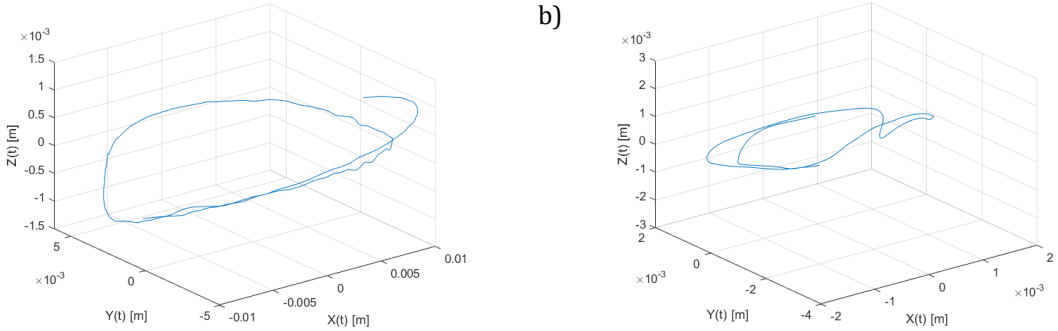

Figure 3. Diagram of the amplitude of displacement for a person with stage 2 PD (a) left hand (b) right hand.

a) b)

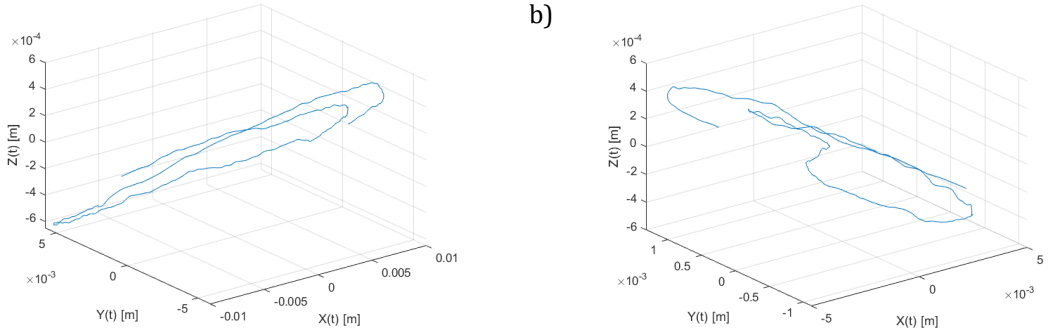

Figure 4. Diagram of the amplitude of displacement for a person with stage 3 PD (a) left hand (b) right hand.

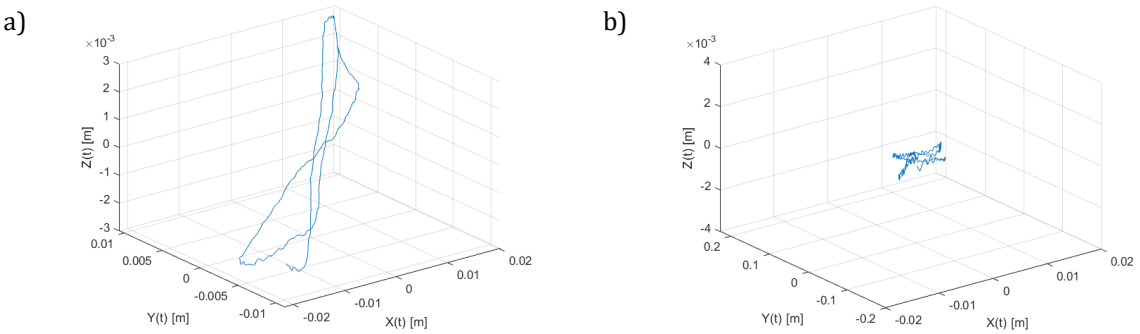

Figure 5. Diagram of the amplitude of displacement for a person with stage 4 PD (a) left hand (b) right hand.

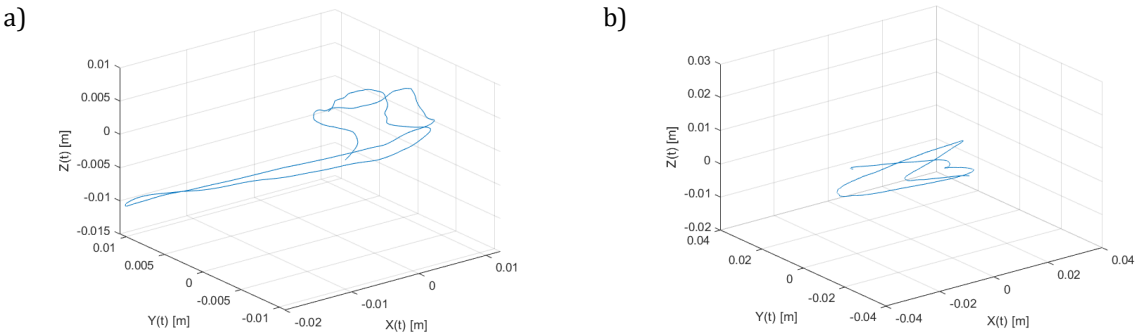

Figure 5. Diagram of the amplitude of displacement for a person with stage 5 PD (a) left hand (b) right hand.

2.4. Parameterization

There are many known methods for analyzing and parameterizing vibroacoustic signals used in technical diagnostics [9]. In this study, signal parameterization methods from an accelerometer embedded in a smartphone were applied in the time domain, specifically:

Maximum value (MV) – is the maximum value from the acceleration waveform of the vibration amplitude:

$$a_{\max} = \max|\boldsymbol{a}(N)|, \tag{1}$$

where $\boldsymbol{a}_{\max}$ is the maximum value [m/s^2], and $\boldsymbol{a(N)}$ represents the signal tested in a limited number of N samples.

Root Mean Square (RMS) – it is a statistical value that allows estimation of the magnitude of the measured quantity, particularly useful when instantaneous values differ in sign, and is represented by the following formula:

$$a_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}[a_n]^2}\,, \tag{2}$$

where a_{RMS} is the root mean square value [m/s^2] , N is the number of samples, and a_n represents the signal samples.

Crest Factor (CF) – it is a value representing the peak factor, which is a shape parameter of the signal indicating the ratio of the maximum value to RMS value. When it is 1, it means there is no peak value; higher factors indicate peak values and it is represented by the following formula:

$$a_{CF} = \frac{a_{\max}}{a_{\mathrm{RMS}}}, \tag{3}$$

Peak-to-Average Ratio (PAPR) – it is a value that represents how much the maximum power of the signal differs from its average power. When this value is high, it means that the signal has significant fluctuations. It is expressed in decibels using the following formula:

$$\mathrm{PAPR} = 10\log_{10}\left(\frac{P_{\max}}{P_{\mathrm{avg}}}\right) = 10\log_{10}\left(\frac{(\max|\boldsymbol{a}(N)|)^2}{\frac{1}{N}\sum_{n=1}^{N}[a_n]^2}\right)\ [\mathrm{dB}], \tag{4}$$

where, PAPR stands for the ratio of a signal maximum power to its average power, $P_{\max}$ is maximum power, P_{avg} is average power.

3. Results

3.1. Import and preprocessing of data

All data recorded on the device in ASCII file format were imported using a specifically written in MATLAB script. The data were grouped into four categories for ease of presentation: right hand of the patient, left hand of the patient, right hand of the healthy individual, and left hand of the healthy individual. Each recording was shortened by three seconds to mitigate potential disturbances from starting and stopping the recording, such as button presses or patient distractions. To account for potential premature start of recording, the first 400 samples (equivalent to one second) were removed. Additionally, any disturbances caused by the end of the recording, such as handing the smartphone back to the examiner, were accounted for by removing 800 samples (equivalent to two additional seconds). The processed data were presented in tables, all converted into matrices with a width of 3 (corresponding to *x*, *y*, and *z* directions), and a length representing the duration of the recording, where each line corresponded to 0.0025 seconds.

3.2. Normalization

In the first stage of the signal normalization procedure, the constant component was subtracted for each direction (*x*, *y*, and *z*) and each recording, as described below.

$$\boldsymbol{a}_i^{norm} = \boldsymbol{a_i} - \overline{\boldsymbol{a}}_i, \tag{5}$$

where $\boldsymbol{a}_i^{norm}$ in [m/s²] represents the preliminarily normalized amplitude traces for the *i*-th direction (*x*, *y*, and *z*) of vibration signal $\boldsymbol{a}_i$ and $\overline{\boldsymbol{a}}_i$ denotes the mean amplitude of acceleration for the *i*-th direction of vibration. Subsequently, to reduce dimensionality and parameterize the data, equation (6) was used to obtain the amplitude of the normalized resultant vector:

$$\boldsymbol{a}_w^{norm} = \sqrt{(\boldsymbol{a}_x^{norm})^2 + \left(\boldsymbol{a}_y^{norm}\right)^2 + (\boldsymbol{a}_z^{norm})^2}, \tag{6}$$

3.3. Results of parameterization

Table 1 shows maximum amplitude value of hands tremor for individual patients and the control group. This parameter represents the highest instantaneous amplitude value in a given signal, indicating the largest deviation of vibration for the respective patient.

Table 1. Maximum amplitude values of acceleration vibrations for healthy individuals and patients.

	Control group			PD		
No.	a_{max} left hand	a_{max} right hand	No.	a_{max} left hand	a_{max} right hand	H&Y scale
1	5.93	0.56	1	5.67	0.75	1
2	0.30	0.30	2	0.49	0.80	1
3	0.36	0.41	3	4.11	7.40	1
4	0.76	0.60	4	0.55	0.88	1
5	0.48	0.22	5	0.40	0.83	1
6	0.24	0.37	6	0.52	0.36	1
7	0.32	0.24	7	0.53	0.68	1
8	0.23	0.62	8	1.23	7.07	2
9	0.30	0.45	9	23.37	6.51	2
10	0.60	0.40	10	0.40	0.49	2
11	0.33	0.40	11	0.32	0.51	2
12	0.33	0.31	12	0.28	0.64	2
13	3.23	0.32	13	0.00	1.41	2
14	0.37	0.41	14	2.16	0.00	2
15	0.29	0.60	15	0.56	1.77	2
			16	0.35	0.57	2
			17	0.64	0.97	3
			18	0.57	1.14	3
			19	15.25	7.36	3
			20	3.43	2.29	3
			21	12.31	26.24	4
			22	0.60	0.81	4
			23	0.70	3.16	4
			24	0.69	0.91	4
			25	12.21	10.71	4

	Control group			PD		
No.	a_{max} left hand	a_{max} right hand	No.	a_{max} left hand	a_{max} right hand	H&Y scale
			26	5.00	9.23	5
			27	0.52	8.47006	5

Table 2 presents the root mean square (RMS) values for the recorded individuals. This value represents the amplitude of the signal in a way that allows for comparison with signals of constant amplitude, i.e., signals with unchanging vibrations, and facilitates the interpretation of the signal's power.

Table 2. Root mean square value of acceleration vibrations for healthy individuals and patients.

	Control group			PD		
No.	a_{rms} left hand	a_{rms} right hand	No.	a_{rms} left hand	a_{rms} right hand	H&Y scale
1	0.96	0.23	1	0.72	0.26	1
2	0.1	0.12	2	0.19	0.25	1
3	0.11	0.13	3	0.75	1.41	1
4	0.21	0.21	4	0.17	0.32	1
5	0.11	0.08	5	0.13	0.21	1
6	0.08	0.1	6	0.13	0.11	1
7	0.12	0.08	7	0.15	0.17	1
8	0.09	0.16	8	0.42	1.96	2
9	0.12	0.17	9	1.62	1.05	2
10	0.22	0.16	10	0.13	0.18	2
11	0.1	0.14	11	0.14	0.18	2
12	0.11	0.12	12	0.11	0.27	2
13	0.23	0.13	13	0.00	0.65	2
14	0.14	0.15	14	0.93	0.00	2
15	0.11	0.13	15	0.29	0.98	2
			16	0.11	0.19	2
			17	0.24	0.27	3
			18	0.17	0.29	3
			19	3.13	2.25	3
			20	1.16	0.72	3
			21	2.27	5.12	4
			22	0.21	0.26	4
			23	0.13	1.05	4
			24	0.17	0.21	4
			25	4.39	4.69	4
			26	1.38	1.42	5
			27	0.16	1.15	5

Table 3 presents crest factor values, which indicate how much the signal fluctuates relative to its average value.

Table 3. Crest factor value of acceleration vibrations for healthy individuals and patients.

No.	Control group			PD		
	a_{CF} left hand	a_{CF} light hand	No.	a_{CF} left hand	a_{CF} right hand	H&Y scale
1	6.15	2.46	1	7.87	2.88	1
2	2.91	2.58	2	2.58	3.15	1
3	3.30	3.09	3	5.45	5.26	1
4	3.52	2.84	4	3.33	2.73	1
5	4.35	2.71	5	3.06	3.85	1
6	3.13	3.71	6	4.01	3.18	1
7	2.58	2.94	7	3.62	4.04	1
8	2.51	3.87	8	2.96	3.61	2
9	2.43	2.65	9	14.42	6.21	2
10	2.79	2.49	10	2.98	2.77	2
11	3.21	2.91	11	2.34	2.79	2
12	2.98	2.57	12	2.62	2.34	2

No.	Control group		No.	PD		
	a_{CF} left hand	a_{CF} light hand		a_{CF} left hand	a_{CF} right hand	H&Y scale
13	13.95	2.51	13	0.00	2.16	2
14	2.58	2.78	14	2.31	0.00	2
15	2.63	4.80	15	1.89	1.80	2
			16	3.31	3.01	2
			17	2.61	3.54	3
			18	3.32	3.88	3
			19	4.88	3.27	3
			20	2.96	3.17	3
			21	5.42	5.13	4
			22	2.91	3.07	4
			23	5.30	3.02	4
			24	3.95	4.32	4
			25	2.78	2.28	4
			26	3.63	6.50	5
			27	3.33	7.37	5

Table 4 presents the values of peak-to-average ratio - indicating the fluctuations in signal power, represented in decibels.

Table 4. Peak-to-average ratio value of acceleration vibrations for healthy individuals and patients [dB].

No.	Control group		No.	PD		
	PAPR left hand	PAPR right hand		PAPR left hand	PAPR right hand	H&Y scale
1	37.37	-119.49	1	83.87	-47.50	1
2	-1224.20	-911.19	2	-206.66	-38.70	1
3	-979.58	-553.00	3	36.80	13.92	1
4	-68.37	-121.28	4	-238.22	-14.46	1
5	-778.67	-2576.48	5	-571.70	-53.05	1
6	-2561.55	-1037.99	6	-500.96	-844.94	1
7	-816.37	-2190.59	7	-328.16	-155.24	1
8	-1749.42	-229.12	8	14.43	5.65	2
9	-828.87	-286.56	9	99.45	37.83	2
10	-114.09	-385.06	10	-549.90	-231.69	2
11	-1157.23	-504.27	11	-636.97	-221.70	2
12	-931.80	-843.01	12	-1219.51	-62.36	2
13	362.44	-708.58	13	0.00	9.22	2
14	-506.47	-435.92	14	8.96	0.00	2
15	-1074.61	-373.87	15	-67.10	5.85	2
			16	-970.46	-163.88	2
			17	-83.60	-5.22	3
			18	-200.47	16.85	3
			19	4.41	4.49	3
			20	11.74	18.83	3
			21	6.83	1.77	4
			22	-131.01	-35.42	4
			23	-226.70	11.87	4
			24	-136.72	-23.42	4
			25	1.49	1.09	4
			26	9.31	12.88	5
			27	-288.45	49.83	5

4. Analysis of results

4.1. Statistical analysis

The maximum amplitude values of vibrations for healthy individuals are at the decimal level, except for two measurements of the left hand which may constitute significant errors due to accidental shaking of the hand. Outlier data were excluded from the statistical calculations according to the three sigma rule. For healthy

individuals, the range of results for the left hand, excluding large values (due to significant errors), is from approximately 0.23 to 0.76 m/s^2, while for the right hand, it ranges from 0.22 m/s^2 to about 0.62 m/s^2. For individuals diagnosed with Parkinson's disease, the minimum value for vibrations in the left hand is 0.28 m/s^2 (at stage 2 of the disease) and the maximum is over 23.37 m/s^2 (at stage 2). In the right hand, vibrations range from 0.36 m/s^2 (at stage 1) to over 26.24 m/s^2 (at stage 4). Analyzing RMS values, we can exclude significant errors observed in the maximum values. The minimum RMS value for the left hand of a healthy individua`l was less than 0.08 m/s^2, and the maximum RMS value did not exceed 1. For the right hand, the minimum was 0.08 m/s^2, and the maximum was only 0.23 m/s^2. The minimum RMS value for a patient diagnosed with Parkinson's disease at stage H&Y 2 was just over 0.11 m/s^2, up to more than 4.39 m/s^{2}for a patient at stage H&Y 4. The crest factor, which relates to the shape of the signal, reflects the relationship between the maximum value and the RMS value.

It showed similar analyses but with greater differences in the crest factor itself, which can aid in more detailed mathematical analysis. The lowest crest factor values for healthy individuals were 2.43 m/s^2, and the highest was over 6 m/s^2. There was also a crest factor reaching nearly 14, which is a significant deviation from the norm and should be ignored. For patients, the crest factor starts at 1.8 m/s^2 and the highest value exceeds 14 m/s^2. The height of this coefficient helps determine the dynamics of the signal itself; characteristics of sick individuals are significantly more dynamic and "spiky," as confirmed by crest factor calculations. Peak-to-average ratio value are in ranges from a minimum of -2561 dB to a maximum of over 37 dB for healthy individuals. For patients, this range starts at about -1219 dB and ends at a maximum value about 99 dB. This coefficient is the most challenging to analyze due to the wider range of PAPR ratios in healthy individuals compared to patients. It would not affect diagnosis during this analysis because observing only this coefficient does not allow for determining the range specific to patients.

4.2. Student's t-test

Using the Student's t-test without checking the normality of the data distribution can be problematic, but is acceptable in some cases, such as: large sample size ($n > 30$) or equality of groups and homogeneity of variances. Comparing two groups, it is important that their numbers are similar and their variances are similar. If these conditions are not met, it is better to use other tests, such as the Mann-Whitney U test for independent data or the Wilcoxon test for dependent data. Statistical analysis was conducted using MATLAB software. To compare patients and healthy individuals across separate categories for the right and left hand and each parameter, the sample size was reduced to fifteen due to the limited number of controls in order to keep the Student's t-test applicable. The analysis included fifteen patients with Parkinson's disease: 5 with stage 1 and 2 PD in the H&Y scale, 3 with stage 3 PD, and 1 each with stage 4 and 5 PD, as well as 15 healthy individuals in the control group. Patients with the most significant deviations in statistical analysis were excluded. In the t-test analysis, four parameters *h* showed a logical value of 0, while four showed a logical value of 1. No significant difference was found in the comparison of patients and healthy individuals for the following: maximum amplitude values of left hand tremor, crest factor in the left and right hands tremor, and RMS value in left hand tremor. Significant differences were observed in the analysis of signals from sick and healthy individuals for: maximum values of the right hand tremor, RMS value of the right hand tremor, and PAPR for both hands tremor. The probability values for this analysis were lowest for the PAPR ($p=0.0013$) and RMS ($p=2.47e-07$) parameters for right-hand vibrations, providing substantial evidence against the null hypothesis, meaning there is a significant difference between the sick and healthy groups. The highest probability values were observed for the crest factor ($p=0.66$) of left-hand vibrations and the maximum vibration value of the left hand ($p=0.12$).

4.3. Mann-Whitney U test

Before performing non-parametric statistical analyses, the Shapiro-Wilk test was conducted to check the normality of the distribution of the analyzed variables. The entire dataset from individuals diagnosed with PD was examined, including 27 recordings of right hand tremors and 27 recordings of left-hand tremors. The null hypothesis H0 assumed that the distribution of the given variable is normal, while the alternative hypothesis H1 assumed that the distribution is not normal. A significance level of $\alpha = 0.05$ was adopted. As a result of the normality tests conducted for the control group and the parameters maximum amplitude values ($p=0.22$), RMS ($p=0.46$), and PAPR ($p=0.506$) of the right-hand tremor, there was no reason to reject the null hypothesis H0. For the PD group, only for the parameter crest factor ($p=0.055$) of the right-hand tremor was there no reason to reject the null hypothesis H0. Considering the results of the Shapiro-Wilk test, the Mann-Whitney U test, a non-parametric equivalent of the Student's t-test for independent samples, was used for further analysis. A significance level of $\alpha = 0.05$ was adopted too. No significant differences

were found when comparing patients and healthy individuals for the crest factor parameter of the tremor in both hands (p=0.56 for left hand tremor, p=0.1 for right hand tremor). Significant differences were observed in the analysis of signals from patients and healthy individuals for the parameters: maximum amplitude value, RMS, PAPR, and tremors in both hands.

5. Discussion

Many parameters proved to be very useful in attempting to analyze patients, but it is their collective use that may assist clinicians in diagnosing Parkinson's disease. The parameter showing the most significant differences and highlighting the greatest patient vibrations was the maximum value, though it has the downside of potentially detecting a single vibration that may not be related to Parkinson's disease, but rather to an incorrectly conducted test. RMS value shows very small differences between patients despite different stages on the H&Y scale, often patients with lower stages of Parkinson's disease had lower RMS values than those with higher stages. The crest factor indicates the dynamics and shape of the developed vibration signals but does not always clearly indicate the presence of the disease. Analyzing all values for healthy individuals was at a very similar level, allowing differentiation from the values of vibrations of sick individuals, though it would be challenging to determine the disease stage. Also the Student's t-test and Mann-Whitney U test reveals significant information comparing the analytical value of each coefficient in vibration diagnostics. The least useful was the crest factor, while PAPR was the most useful, despite not showing larger differences between sick and healthy individuals in statistical analysis. Additionally, differences between measurements of the right and left hands should be highlighted. Among the group with greater fluctuations, the signals from the right hand exhibited higher amplitudes. Parkinson's disease often manifests unilaterally, as these studies confirmed. 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).

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Additional information

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