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SPECTRAL PARAMETERS FOR FINGER TAPPING QUANTIFICATION [*]

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Abstract. *A miniature inertial sensor placed on fingertip of index finger while performing finger tapping test can be used for an objective quantification of finger tapping motion. Temporal and spatial parameters such as cadence, tapping duration, and tapping angle can be extracted for detailed analysis. However, the mentioned parameters, although intuitive and simple to interpret, do not always provide all the necessary information regarding the subject's motor performance. Analysis of frequency content of the finger tapping movement can provide crucial information about the patient's condition. In this paper, we present parameters extracted from spectral analysis that we found to be significant for finger tapping assessment. With these parameters, tapping's intra-variability, movement smoothness and anomalies that may occur within the tapping performance can be detected and described, providing significant information for further diagnostics and monitoring progress of the disease or response to therapy.*

Key words: *frequency analysis, finger tapping, Parkinson's disease.*

1. INTRODUCTION

Patients with Parkinson's disease (PD) exhibit severe motor problems; therefore objective assessment of their movements is crucially important for diagnostics and evaluation of progress of the disease. Frequency analysis is widely used for such assessment of Parkinsonian patients. Some usual frequency-derived measures obtained from Fast Fourier Transform (FFT), such as amplitude, median power frequency, power dispersion, and power

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percentage within the 4–7 Hz frequency range were used for quantification of hand tremor [2]. Body-area inertial sensing system and signal processing based on filter-bank analysis and cross correlation were used for the interpretation of tremor frequency and energy [3]. One study proposed a new technique for tremor detection from gyro data [4] that comprises Empirical Mode Decomposition and the Hilbert Spectrum, introducing the concept of instantaneous frequency in the field of tremor.

Frequency-derived measures were extracted from the results of the Welch's averaged modified periodogram method of spectral estimation performed on the acceleration data and used for assessment of stride-to-stride variability in PD patients and healthy controls in real-life settings [5]. They defined four parameters for the main peak of the power spectral density function: its frequency, the amplitude, the width at half of its amplitude and the slope from the point of the peak's maximum to the point of half of the peak's amplitude. Body motion of PD patients was also assessed by using a maximum-likelihood-estimator-based fractal analysis method for triaxial accelerometer data [6]. Freeze of gait in patients with PD was quantified from the power spectral density of the shank acceleration [7]. Researchers defined a new index, named Frequency Ratio as the square of the total power in the 3–8 Hz band, divided by the square of the total power in the 0.5–3 Hz band. Results showed that the defined parameter can be used for better differentiation between patients than traditional gait spatial measures.

Although spectral components hidden in the performed movement can indicate motor impairment [8], Fourier analysis is not the most effective tool for the analysis of transient behavior or discontinuities that are typical for human movement. In such case, time-frequency algorithms can provide detailed analysis of signal's frequency content over time, allowing detection of localized features in specific time moments.

Time-frequency algorithms Short-Time Fourier Transform (STFT), and Wavelet Transform (WT) have already been used in many studies in the field of human movement [9]-[11]. Detection of transient episodes and tripping in inertial data can be performed with both STFT and discrete Wavelet transform [12]. However, wavelets proved to be superior at describing anomalies, pulses and other transient events that start and stop within a movement signal [13]. Parameters expressing main frequencies, pattern decrement and activity volume of the basic finger tapping rhythm and vigor of the performed movements were extracted from the coefficients of the results of continuous wavelet transform performed on gyro signals, providing classification between PD patients and healthy subjects [14].

Neurological disorders, including Parkinson's disease [15], can affect smoothness of the patient's motor performance. Because of that, objective measure of movement smoothness can be a very important segment of the assessment of the patient's motor abilities. It was shown that frequency analysis can provide information about movement smoothness by analyzing the spectral arc length (SPARC) [16].

Repetitive finger tapping represents one of the descriptive characteristics of the patient motor ability that is included in Unified Parkinson's disease rating scale (UPDRS test, e.g., Fahn et al, 1987 [17]). In clinical practice, the finger tapping performance is often validated visually, which results in a low diagnostic resolution [18]. However, using the appropriate instrumentation, such as miniature inertial sensors, finger tapping performance can be quantified, allowing the objective assessment of specific characteristics or changes in the finger tapping pattern over time [19]-[20].

Our goal is to offer a new method for the objective quantification of finger tapping performance that is regularly used for assessment and visually estimated by physicians. We suggest a set of frequency derived parameters that can provide the assessment of tapping's rhythmic behavior, vigor of its performance, intra-variability, tremor and motor blocks. In this way, the quantitative assessment of repetitive finger tapping performance can be obtained thus providing support in monitoring of the patient's condition, response to therapy as well as in differential diagnostics of Parkinsonism.

2. METHODS AND MATERIALS

Instrumentation

The instrumentation includes an inertial sensor unit comprising a 3D gyroscope L3G4200 (STMicroelectronics, USA) [21]. In our system, the small sized (10x12 mm) and lightweight (3 g) sensor is placed on a fingertip of the subject's index finger (Fig. 1). The sensor is connected to its sensor control unit (SCU), positioned on the forearm, by thin, light, flexible and loose cable. The designed instrumentation and mounting concept secure that movement path and range are not hindered in any aspect. Different technical and mounting solutions (sensor gloves, wireless sensors) have also been considered, however, all of them showed certain shortcomings in terms of size, weight (e.g. having wireless sensor on fingertip requires mounted battery which increases the size and weight), limited performance and tactility (gloves), as well as hygiene and price.

The signals are collected by SCU and wirelessly transmitted to a remote computer. Custom-made graphical user-friendly interface, which is developed in CVI (CVI 9.0, NI LabWindows, USA), controls the data acquisition, storing and provides export (ASCII comma separated value (CSV) format) for further analysis.

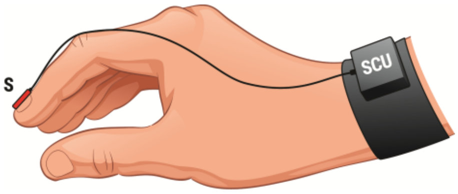

Fig. 1 System setup: sensor (S) positioned on fingertip connected to sensor control unit (SCU) mounted on the subject's hand.

Experiments

Twenty patients with Parkinson's disease (Age: 61,39±9,7), and twelve age and gender matched controls (Age: 56,53±9,13) were enrolled in this study. During the performance, subjects were sitting comfortably in a chair, with their hand placed in front of them. As the part of the test, they repeatedly tapped index finger and thumb as rapidly and as widely as possible for 15 s, as described in [19]. Each recording began and ended with their fingers closed at the "zero-posture". For each subject, three trials per affected hand were recorded. A resting period of one minute in between was given; because fatigue may compromise the performance.

The study was performed at the Neurology Clinic, Clinical Centre of Serbia, Belgrade in accordance with the ethical standards of the Declaration of Helsinki. All the participants gave informed written consent prior to the participation in the study.

Signal processing

Angular velocity was recorded using digital gyroscopes with the sampling frequency f_s=200 Hz, calibrated and directly processed by custom-made Matlab script (Matlab 7.6.0., R2008a). The examples of recorded signals for one healthy control (CTRL) and two PD patients are presented in Fig. 2.

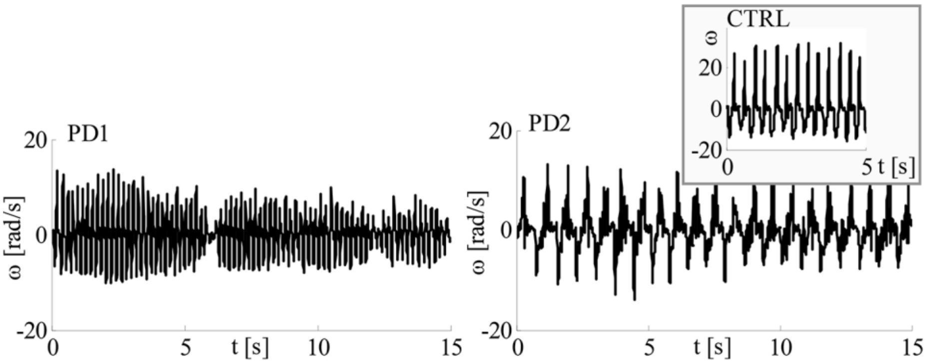

Fig. 2 The examples of recorded gyro signals for: two PD patients and one CTRL subject.

Firstly, tapping performance was described with parameters typically used for tapping description [19]:

- duration of the taps t_T – expressed in seconds,
- tapping cadence c_T – expressing the number of taps in the observed 15 s long sequence,
- angle that index finger forms relative to the “zero posture” of the fingers α_T – expressed in degrees.

Additionally, Continuous Wavelet transform (CWT), Welch's averaged modified periodogram method of spectral estimation and Spectral Arc Length method (SPARC) [16] were applied on the observed 15 s long sequences of the signal. The methods were performed for the frequency range between 0.01 and 20 Hz (the frequency increment 0.01 Hz), covering the complete possible spectral content of finger tapping.

Continuous wavelet transformation

Continuous wavelet transformation based on FFT algorithm was applied on the 15 s long sequences of the gyro signal. For this application, we used a mother wavelet from complex Morlet Wavelet family, with center frequency f_0=1 Hz and time-frequency resolution σ=0.7.

The Fourier transform of wavelet function was found for each scale (reciprocal of each frequency from the defined band 0-20 Hz) and multiplied by the representation of the gyro signal in the frequency domain. Complex CWT coefficients were obtained using the inverse Fourier transform and then normalized with the weighting function i.e., by dividing the coefficients by the square root of the scale. The final result is obtained in the form of matrix, with the same time resolution Δt=5 ms ($\Delta t=1/f_s$=1/200 Hz) as the original gyro signal (no additional interpolation or down sampling were performed).

The examples of obtained CWT coefficients, presented in the shape of a 3D scalogram, are shown in Fig. 3. The scalogram represents an original color-coded illustration of wavelet coefficients. For this application, we used Jet colormap, where small amplitudes are represented with the cold color tones (starting from navy blue), whereas warmer colors (ending with dark red) follow the increase of the amplitude.

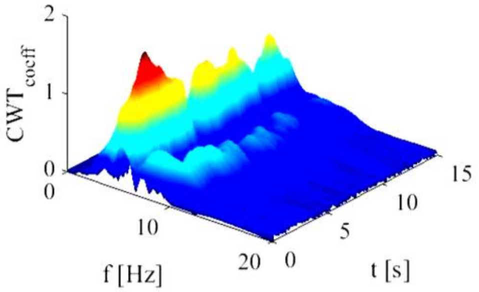

Fig. 3 3D representation of CWT coefficients. An example is given for patient PD1.

In order to observe temporal changes of tapping activities, we defined cross-sectional area perpendicular to the t-axis (CSA-T_{tot}) [14]. CSA-T_{tot} was calculated by summing the absolute values of CWT coefficients, and finally expressed as percent of the maximum energy of CSA-T_{tot} characteristic. By introducing two thresholds at 50 and 25% (light and dark dashed grey lines in Fig. 4, respectively), we found signal parts where tapping performance was compromised causing energy loss below two defined levels.

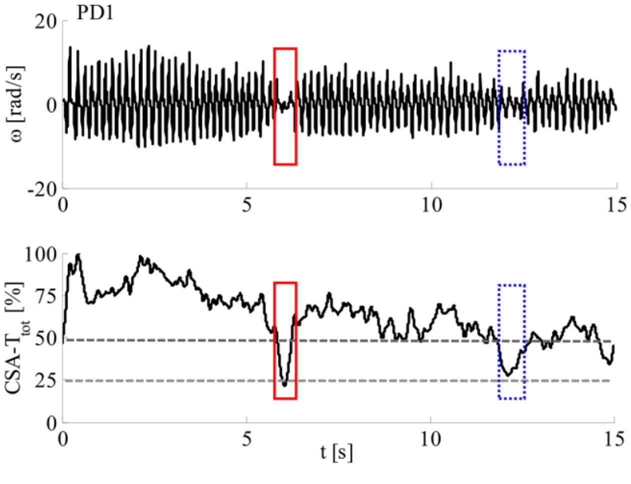

Fig. 4 Representative example of CSA-T_{tot} [%] distribution given for one PD patient. Light and dark dashed grey lines mark two defined thresholds at 50 and 25%, whereas dashed blue and solid red rectangles outline signal parts with energy loss below defined levels (50 and 25%, respectively).

In this way, tapping performance can be described regarding the disturbance of its basic rhythmic behavior e.g., motor blocks. We introduced two parameters representing the duration of the detected anomalies, expressed in seconds (CWT<50 and CWT<25, respectively).

Welch's method of spectral estimation

Power spectral density was calculated with Welch's method of spectral estimation. For this application, a window size of 800 samples and overlap between the windows of 50% were applied. A FFT length was 2 times the next higher power of 2 of the signal length.

For each subject, we extracted four parameters for the main peak i.e., the dominant harmony of the obtained power spectral density function (Fig. 5) [5]:

- the frequency of the peak – f;
- the amplitude of the peak – h;
- the width of the peak at half of its amplitude – w (the red lines in Fig. 5);
- the slope of the peak, calculated from the point of half of the peak's amplitude to the peak's maximum point – s (the blue lines in Fig. 5).

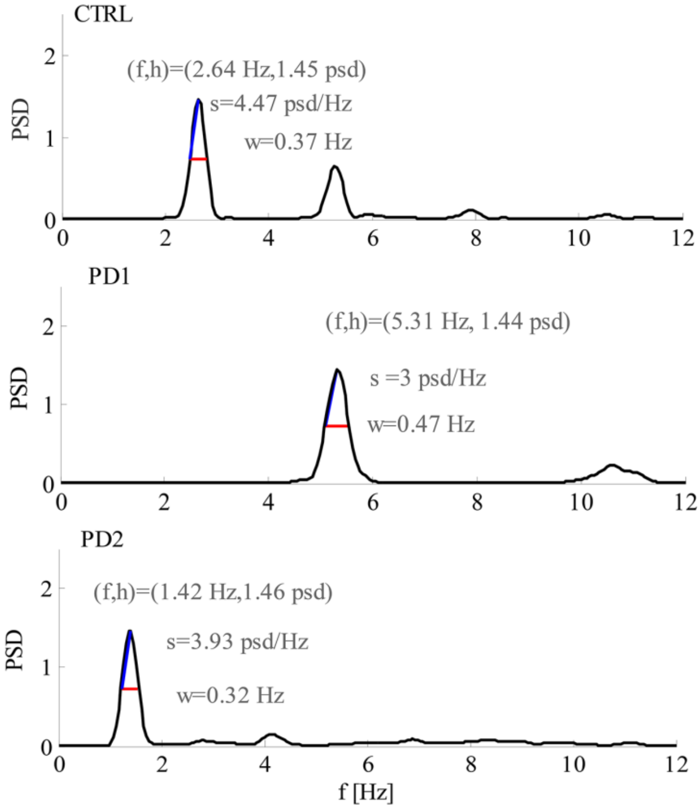

Fig. 5 Representation of power spectral density function. Blue line marks slope of the peak, whereas red line shows width of the peak at half of its amplitude. The examples are given for: one CTRL subject (top panel) and two PD patients (middle and bottom panels).

SPARC method for assessment of tapping smoothness

Spectral Arc method is used for the assessment of smoothness of signals describing any rhythmic sensorimotor behavior [22]-[24]. SPARC method applied here is modified Spectral Arc Length method, defined in [16]. It represents the signal smoothness as a single scalar, by calculating the arc length of the Fourier spectrum within the defined frequency range of a given velocity. Final value of this parameter was expressed as negative logarithm of the calculated arc length. Bigger values correspond to greater smoothness.

Smoothness was calculated for the upward trend of the taps, because it corresponds partially to both opening and closing but it doesn't include the moment when fingers are closed, which may cause some changes in the signal and thus introduce error. The procedure was repeated for all the taps, which were previously segmented. For each subject we calculated the total measure of tapping smoothness, expressed as descriptive statistics (average ± std.dev), and the trend of change in smoothness across all segmented taps, represented by the slope of the fitted linear regression line across the corresponding smoothness characteristic (the red dashed line in Fig. 6).

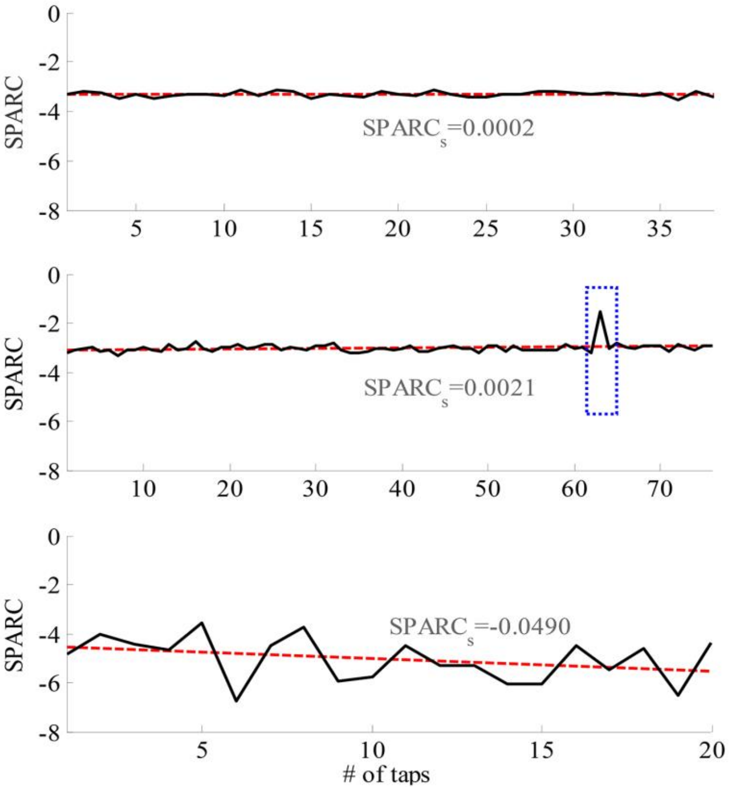

Fig. 6 SPARC smoothness characteristic with corresponding slope (red dashed line) for one CTRL subject (top panel) and two PD patients (middle and bottom panels). Dashed blue rectangle marks detected change in movement smoothness.

Statistical analysis

The two groups were compared using the t-test for two independent samples (if both groups satisfied the normal distribution) or Mann-Wilcoxon test (if the distributions were not normal). Statistical significance was determined with 2-tailed tests when $p<0.05$. Statistical analysis was performed in SPSS v17.0 (Chicago, IL).

3. RESULTS

By observing the examples of recorded gyro signals (Fig. 2), one can notice that the healthy subject had rapid and vigorous performance. Patient PD1 performed even more rapidly, but less vigorously, less rhythmically and with noticeable amplitude changes within the signal, as the consequence of motor block that occurred during the performance. On the other hand, the patient PD2 had slower and non-smooth but more rhythmical tapping performance. Results summarized for all the participants showing descriptive statistics (average ± std.dev) for the parameters expressing duration of tapping performance, tapping cadence and angles, as well as the statistical differences between the two groups are given in Table 1. Distributions of the introduced parameters are shown in Fig. 7.

Although those parameters show statistically significant differences between the groups (the grey shaded cells in Table 1), they cannot provide information about changes in tapping shape and the appearance of specific transient events, and therefore they are not suitable for the detection or description of such noticeable characteristics of tapping performance. Because of that, the evaluation of tapping pattern needs to be supplemented with the frequency analysis of gyro data.

Table 1 Descriptive statistics of finger tapping duration, cadence and angle for both CTRL and PD subjects

Param.	CTRL (av±std)	PD (av±std)	p-value
t_T [s]	0.32 ± 0.07	0.65 ± 0.41	0.001
c_T [taps/s]	49.00 ± 13.02	30.40 ± 17.22	0.001
α_T [°]	61.88 ± 18.18	39.53 ± 18.74	0.024

In order to provide the complete analysis of tapping data, we applied CWT, SPARC and Welch's method of spectral estimation on the 15 s long sequences of the signal.

Continuous Wavelet transformation has an important role in the detection and localization of anomalies that may appear within movement signal. Patient PD1 had some changes in the tapping motion which are obvious from the raw gyro signal (marked with the solid red rectangle in Fig. 4).

By using the CWT method, this disturbance can be described in terms of the degradation level (below 25% of the maximum performing energy) and duration. However, the suggested technique allowed detection of another not so noticeable tapping "anomaly" (marked with the dashed blue rectangle, around 12 s), which could be left unnoticed otherwise. By combining CSA-T_{tot} function with a color-coded illustrative representation of CWT coefficients such as 3D scalogram (Fig. 3), clinicians can assess anomalies in tapping performance, localize them in time and evaluate the duration and severity of those disturbances.

By using parameters extracted from Welch's algorithm of spectral estimation, tap-to-tap variability can be assessed. SPARC algorithm allowed calculation of tapping smoothness and its decrement in time. The combined frequency analysis of all three performed methods can provide clinicians with crucial information about tapping performance that can be used for further analysis, or assistance in diagnostics.

The applied analysis is summarized in Table 2, showing descriptive statistics (average ± std.dev) for the listed frequency parameters for all the subjects, as well as the statistical difference between the two groups.

The statistically significant difference between PD patients and healthy subjects was found for all the parameters (except slope of SPARC). In addition, for all CTRL subjects the value of CWT<25 parameter was equal to zero, indicating that none of them had severe energy loss below 25%, as opposed to PD patients who demonstrated the appearance of those anomalies in duration up to 5 s long. This indicates that CWT based evaluation is suitable for finger tapping quantification, with potential for differential diagnostics.

Table 2 Descriptive statistics of CWT, Welch and SPARC based parameters of finger tapping for both CTRL and PD subjects

Param.	CTRL (av±std)	PD (av±std)	p-value
CWT<50 [s]	1.02 ± 1.49	5.23 ± 3.26	<0.001
CWT<25 [s]	0.00 ± 0.00	0.94 ± 1.74	0.023
f [Hz]	3.47 ± 0.92	2.10 ± 1.21	0.002
h [psd]	1.34 ± 0.29	1.14 ± 0.39	0.039
s [psd/Hz]	3.42 ± 0.70	2.90 ± 1.09	0.042
w [Hz]	0.39 ± 0.04	0.42 ± 0.07	0.041
SPARC	-3.13 ± 0.13	-3.69 ± 0.70	0.001
$SPARC_S$	-0.0005 ± 0.003	-0.03 ± 0.05	0.373

The distributions of CWT<50 and four PSD based parameters for two groups of subjects (CTRL and PD) are shown in Fig. 7.

SPARC smoothness parameter distributions are presented for 10 randomly selected healthy subjects and 10 PD patients with different patterns of tapping performance and shown in the form of a boxplot in the bottom panel in Fig. 7.

Based on the presented results of the applied SPARC analysis, it can be seen that healthy subjects have small intra- and inter-subject variability of tapping smoothness. On the other hand, patients with PD have wider range of SPARC index within their tapping patterns (intra-variability) as well as within the group (inter-variability). This cognition proves that SPARC parameter is suitable for the analysis of tapping performance and has potential for differential diagnostics.

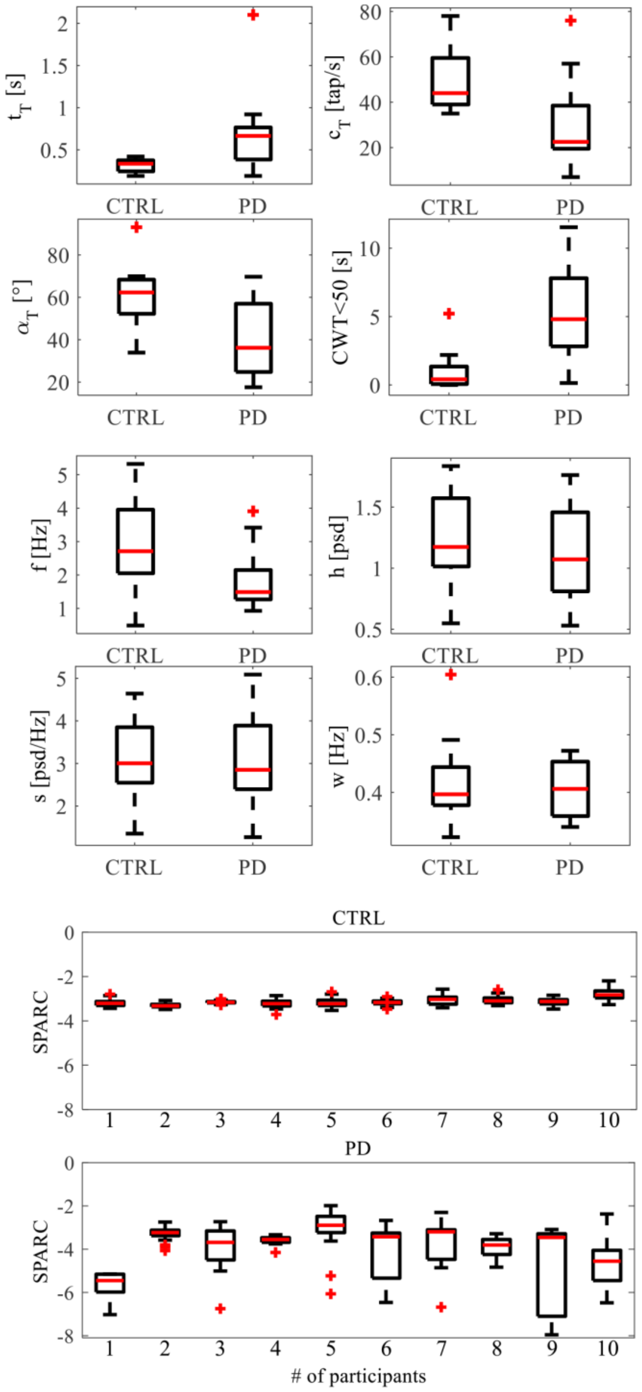

Fig. 7 Boxplot representation of all listed parameters for both CTRL subjects and PD patients.

4. DISCUSSION AND CONCLUSION

Tapping performance can be described with temporal and spatial parameters, describing tapping duration and cadence and angle between fingers at maximum opening. Although the mentioned characteristics of tapping performance can be used for distinction between healthy individuals and patients (Table 1), they are not suitable for the detailed analysis of changes that may occur within tapping performance, movement variability and smoothness. Therefore, the analysis should be supplemented with other techniques that can provide such evaluation of tapping performance. In this paper, three frequency based methods were applied on gyro signal acquired from one miniature sensor mounted on the subject's index finger, and the results of performed techniques are used for quantification of finger tapping performance.

By implementing Continuous Wavelet transform, the frequency content of signal can be observed over time (Fig. 3), but also analyzed in terms of energy changes that can be useful for anomaly detection (the solid red rectangle in Fig. 4). Two CWT based parameters expressing the duration of energy loss below 50% and 25% proved to be statistically different between groups (the grey shaded cells in Table 2).

In previous research studies, the smaller slope and larger width of the dominant frequency within Welch's power spectral density function were defined as indicators of the greater signal intra-variability. The most prominent peak of the PSD function was explained with f, h, s and w parameters which proved to be statistically different between the two groups of subjects (the grey shaded cells in Table 2). For PD group, the smaller slope and higher values of width parameters comparing to CTRL group, indicate prominent tapping intra-variability for PD patients. This discovery agrees with the result from Weiss et al, performed on gait data [5].

SPARC based parameter provide the assessment of movement smoothness, whereby bigger values indicate smoother movements. In this paper, it was demonstrated (Table 2, Fig. 7) that PD patients have decreased movement smoothness, with statistically significant difference from healthy subjects. By implementing this method, patient's motion smoothness and its decrement in time can be assessed. Also, the combined analysis of these methods allows detection of some changes (the dashed blue rectangle in Fig. 4 and Fig. 6), which aren't obvious from the gyro signal, and therefore can be overlooked.

Based on the presented analysis, finger tapping can be quantified in terms of its rhythmic behavior, the vigor of its performance, tapping intra-variability, tremor and motor blocks that can occur within the tapping performance. These methods allow monitoring of patient's response to therapy and progress of the disease, and comparison with other evaluated patients. In the future, defined parameters will be complemented with additional parameters which can provide the complete assessment of tapping movement. Designed methodology will be implemented for automated differential diagnostic system.

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