Frequency analysis of repetitive finger tapping – extracting parameters for movement quantification

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Best Section Paper Award

Abstract—**In clinical practice, the finger tapping movement is often validated visually, thus resulting in a coarse diagnostic resolution. However, by using miniature inertial sensor mounted on fingertip of index finger, finger tapping performance can be quantified, allowing objective assessment of specific characteristics or changes in the finger tapping pattern over time. Various parameters such as cadence, tapping duration, speed, and tapping angle can be extracted for detailed analysis of patient's motor performance. However, the listed parameters, although intuitive and simple to interpret, do not always carry all necessary information regarding subject's motor performance. Here we present kinematic parameters extracted from spectral analysis that are significant for finger tapping assessment. With these parameters, tapping's intravariability, movement smoothness and anomalies that occur within the tapping performance can be identified and observed, providing significant information for further diagnostics and monitoring progress of the disease of response to therapy.**

Index Terms— **frequency analysis, finger tapping, Parkinson's disease**

I. INTRODUCTION

Frequency analysis is widely used for assessment of motor abilities of Parkinsonian patients. Hand tremor is often quantified with some usual frequency-derived measures obtained from Fast Fourier Transform (FFT), such as amplitude, median power frequency, power dispersion, and power percentage within the 4–7 Hz frequency range [1]. By using some other methods, such as filter-bank analysis, cross correlation and new method comprising Empirical Mode Decomposition and the Hilbert Spectrum, it is possible to obtain even more information about tremor that can be useful for clinicians [2]-[3].

Frequency-derived measures were also 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 Parkinson disease (PD) patients and healthy subjects [4]. They defined four parameters for the main peak of the power spectral density function: the 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. Power spectral density was also used to analyze freezing of gait in PD patients [5]. Researchers defined 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 defined parameter can be used for better differentiation between patients than traditional gait spatial measures.

Most behavioral actions require the detection of localized features in specific time moments. In these applications, the frequency analysis can be performed by time-frequency algorithms Short-Time Fourier Transform (STFT), or Wavelet Transform (WT) [6]-[7]. Time-frequency algorithms allow analysis of signal's frequency content over time. Due to that fact, those methods are far more efficient than Fourier analysis whenever a signal is dominated by transient behavior or discontinuities such as human movement. Both STFT and discrete Wavelet transform were used in the detection of transient episodes of freezing behavior and tripping in inertial data. [8]. Wavelets were superior at describing anomalies, pulses and other transient events that start and stop within a movement signal [9]. 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 [10].

Frequency analysis can also provide information about movement smoothness, which is often impaired in patients with PD and other neurological disorders [11]. Movement smoothness can be assessed by analyzing the spectral arc length (SPARC) [12].

Repetitive finger tapping represents one of the descriptive characteristics of the patient motor ability that is included in

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Unified Parkinson's disease rating scale (UPDRS test, e.g. Fahn et al, 1987). In clinical practice, the finger tapping performance is often validated visually, which results in a rough diagnostic resolution [14]. However, using the appropriate instrumentation, such as miniature inertial sensors, finger tapping performance can be quantified, allowing objective assessment of specific characteristics or changes in the finger tapping pattern over time [15]. This approach can provide detailed spectral analysis of the movements, and reveal spectral components hidden in the performed movement indicating possible motor impairment and assisting in further diagnostics [16].

Here we suggest a set of frequency derived parameters that can provide detailed assistance in PD diagnostics and monitoring progress of the disease or response to therapy.

II. METHODS AND MATERIALS

A. Instrumentation

One miniature (10x12mm) and lightweight inertial sensor comprising a 3D gyroscope L3G4200 (STMicroelectronics, USA) was placed on a fingertip of the index finger, allowing subjects to perform tapping test with in a most natural manner. Sensor was wirelessly connected to a remote computer, where a custom-made graphical user-friendly interface developed in CVI (CVI 9.0, NI LabWindows, USA) controlled data acquisition [17].

B. 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. They were asked to repeatedly tap index finger and thumb, as rapidly and as widely as possible for 15 s, as described in [18]. Three trials per affected hand were recorded for each subject, with a resting period of one minute in between. 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.

C. Signal processing

Gyroscope signals were recorded with the sampling frequency f_s=200 Hz. Acquired signals were calibrated and directly processed by custom-made software (scripts written in Matlab 7.6.0., R2008a). Examples of recorded gyro signals for one healthy control (CTRL) and two PD patients are presented in Fig. 1.

Continuous Wavelet transform (CWT), Welch's averaged modified periodogram method of spectral estimation and Spectral Arc Length method (SPARC) 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.

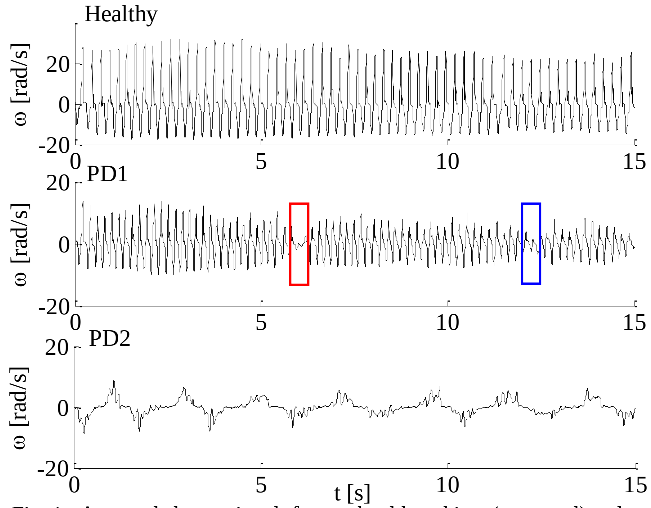

Fig. 1. A recorded gyro signals for one healthy subject (top panel) and two PD patients (middle and bottom panels).

1) Continuous Wavelet transformation

For this application, we applied continuous wavelet transform based on FFT algorithm, as used in [10]. The representation of wavelet function obtained using the FFT was calculated based on the scale (reciprocal of each frequency from the defined band) and multiplied with the gyro signal in frequency domain. Applying the inverse FFT, complex coefficients of CWT in the form of a matrix were obtained. Results were normalized by dividing the coefficients with square root of the scale. Time resolution of the result was 5 ms. For this application, we applied a mother wavelet with center frequency f_0=1 Hz and time-frequency resolution σ=0.7, from complex Morlet Wavelet family.

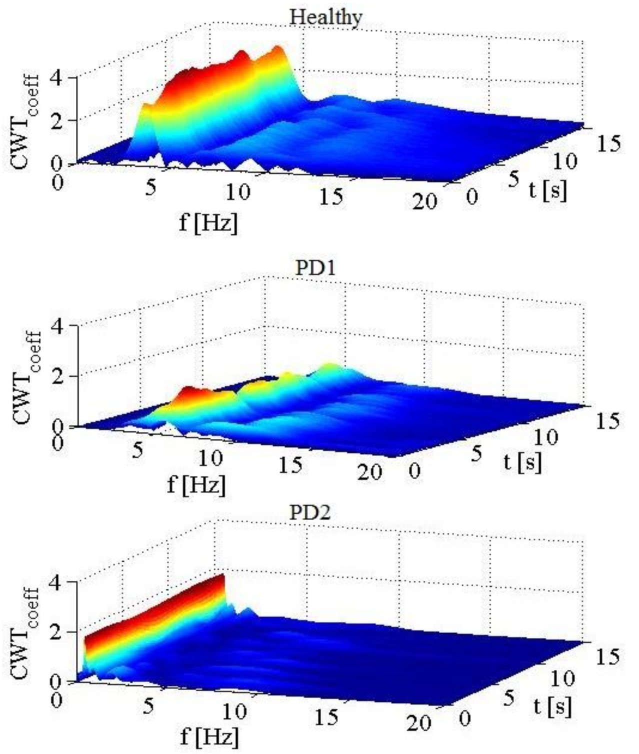

Fig. 2. 3D scalogram showing CWT coefficients and frequency content in time, example for one healthy and two PD patients.

Examples of obtained CWT coefficients, presented in a form of 3D scalogram, are shown in Fig. 2.

By summing the absolute values of CWT coefficients, we calculated cross-sectional area perpendicular to the t-axis (CSA-T_{tot}) [10]. Final CSA-T_{tot} characteristic was expressed as percent of the maximum energy of CSA-T_{tot} characteristic. For each sample, we found parts of the signal with energy loss below 50 % or 25 % (dark and light grey lines in Fig. 3b, respectively). This can be used for finding signal parts were tapping performance was disturbed regarding its basic rhythmic behavior, e.g. motor blocks.

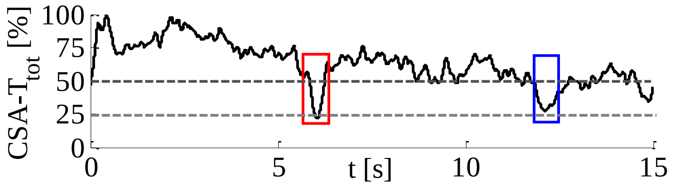

Fig. 3. CSA-T_{tot} [%] distribution for subject marked PD1 in Fig.1; light and dark grey lines mark energy loss below 50 and 25 % respectively.

2) Welch's method of spectral estimation for assessment of tapping intravariability

For this application, we applied Matlab built-in function called “pwelch”. We used a window size of 800 samples, with a 50% overlap between the windows. 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 (dominant harmony) of the obtained power spectral density function (Fig. 4) [4]: the frequency f, the amplitude h, the width w (at half of peak’s amplitude) and the slope s (calculated from the peak maximum to the point of half of the peak’s amplitude). Weiss et al. showed that smaller slope and higher width for PD patients indicate more prominent stride-to–stride intravariability [4].

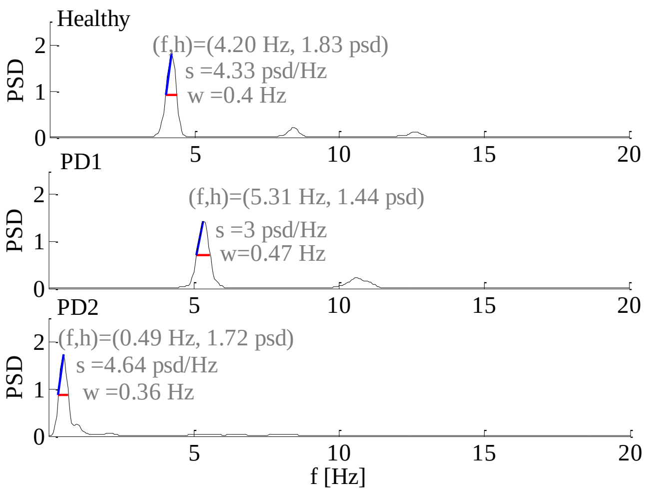

Fig. 4. Power spectral density of finger tapping sequence for one healthy subject and two PD patients, showing peak’s frequency and amplitude (f, h), slope (s) and width at half of peak's amplitude (w).

3) Spectral Arc Length method for assessment of tapping smoothness

SPARC method is a modified Spectral Arc Length method, defined in [13]. It represents the signal smoothness as a single scalar, by calculating the arc length of the Fourier spectrum within the defined frequency range (form 0 to 20Hz) of a given angular velocity. Bigger values correspond to greater smoothness.

We repeated procedure for all taps, which were previously segmented. For each subject we calculated total measure of tapping smoothness, expressed as descriptive statistics (average±std.dev), and trend of change in smoothness across all segmented taps, represented by the slope of the fitted linear regression line across the corresponding smoothness characteristic (Fig. 5).

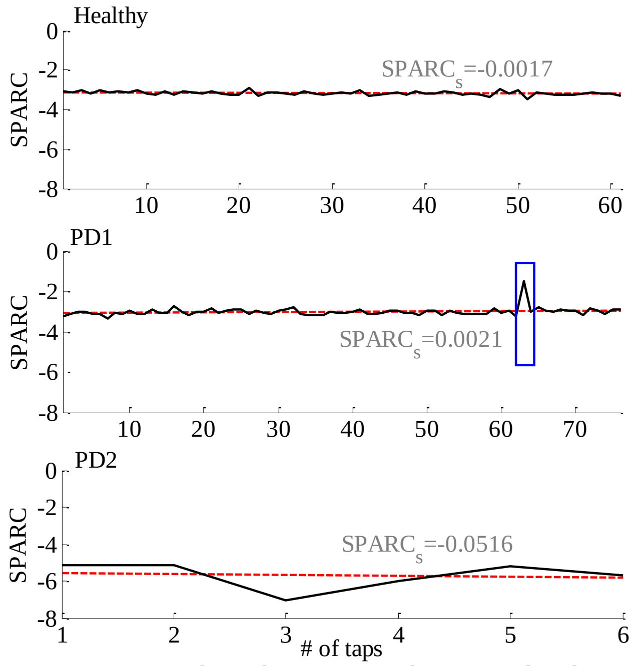

Fig. 5. SPARC smoothness characteristic with corresponding slope (red dashed line) for one healthy subject and two PD patients.

D. *Statistical analysis*

The two groups were compared according to the mean values using 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).

III. Results

By observing the examples of recorded gyro signals (Fig. 1), one can notice that healthy subject had rapid and vigorous performance, patient PD1 also performed rapidly and vigorously (nut less than healthy subject), however less rhythmical and with noticeable amplitude changes within the signal, as a consequence of motor block that occurred during the performance. The patient PD2 had slow and unsmooth but more rhythmical tapping performance. By observing some of the usual parameters, such as mean velocity, tapping duration, etc., clinicians cannot detect nor quantify such noticeable characteristics of tapping performance. In order to obtain such evaluation, frequency analysis of gyro data should be performed. Due to those facts, we applied CWT, SPARC and

Welch's method of spectral estimation on the 15 s long sequences of the signal. By using CWT we can detect and localize anomalies within tapping signal (marked with red rectangle in Fig 3). Although some signal changes were visible in patient PD1 even from the raw gyro data (tapping performance marked with red rectangular, around 6s), the second tapping "anomaly" (marked with blue rectangular, around 12s) could skip unnoticed without implementation of the suggested CTW method. By combining CSA-T calculation and an intuitive graphical representation such as 3D scalogram of CWT, clinicians can perform assessment of anomalies in tapping pattern, analyze the severity of such movements and localize them in time.

Tap-to-tap variability can be assessed with Welch's algorithm, while tapping smoothness and its decrement in time can be accessed with SPARC algorithm. By combining results from all three performed methods, clinicians can have crucial information about tapping performance that can be used for further analysis, or assistance in diagnostics.

The applied analysis is summarized in Table 1, showing descriptive statistics (average±std.dev) for the listed frequency parameters for all participants, as well as the statistical difference between the two groups.

TABLE I
DESCRIPTIVE STATISTICS OF WELCH AND SPARC BASED PARAMETERS OF FINGER TAPPING FOR PD PATIENTS.

Param.	**CTRL (av±std)**	**PD (av±std)**	**p-value**
f	3.47 ± 0.92	2.10 ± 1.21	0.002
h	1.34 ± 0.29	1.14 ± 0.39	0.039
s	3.42 ± 0.70	2.90 ± 1.09	0.042
w	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 statistical analysis showed all parameters (except slope of SPARC) have statistically significant differences between patients with PD and healthy subjects.

Results presented in Fig. 6 show distribution of PSD based parameter for two groups: healthy subjects and PD patients.

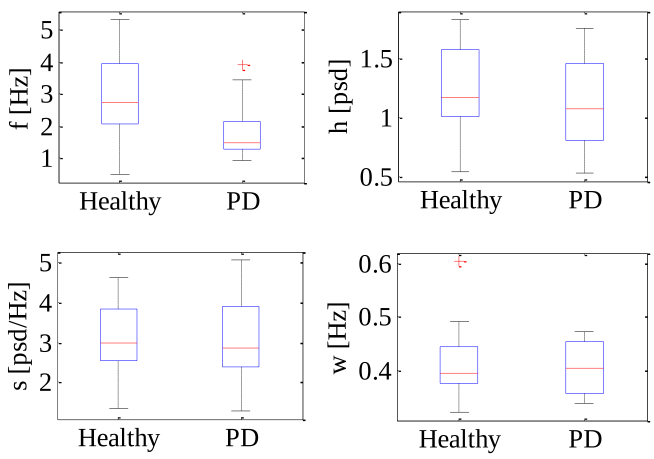

Fig. 6. Boxplot representation of PSD based parameters for healthy subjects and PD patients.

SPARC smoothness parameter distributions among 10 healthy subjects and 10 PD patients are shown in form of a boxplot in Fig. 7.

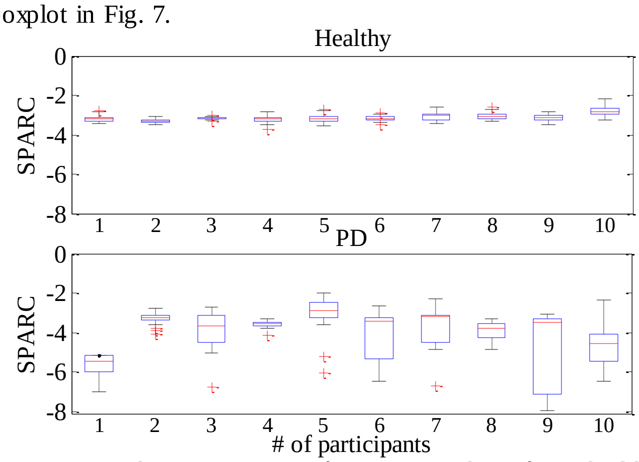

Fig. 7. Boxplot representation of SPARC smoothness for 10 healthy subjects and 10 PD patients (upper and lower panels, respectively).

SPARC analysis showed that healthy subjects have small intra- and intersubject variability of tapping smoothness, while PD patients have wider ranges of SPARC index within their tapping sequences (intravariability) as well as among themselves (intervariability). This proves the SPARC parameter suitable for analysis of tapping performance and its potential for differential diagnostics.

IV. DISCUSSION AND CONCLUSION

We have presented results of performed frequency analysis applied on gyro signal acquired from one miniature sensor mounted on subject's index finger, used for finger tapping movement quantification.

CWT based results allow us to observe frequency content of signal over time (Fig 2), but also to analyze signal in the terms of energy changes that can be useful for anomaly detection (marked with red rectangle in Fig 3). In previous studies, greater signal intravariability was defined with smaller slope and larger width of the most prominent peak within the power spectral density function obtained with Welch's algorithm. Parameters describing f, h, s and w of the most prominent peak of the PSD function were found significantly different between two groups (grey shaded cell in Table 1) with smaller values of slope and width parameters for PD group, meaning greater tapping intravariability for PD patients, which agrees with the results from Weiss et al, performed on gait data [4]. Smaller values of SPARC based parameter correspond to smoother movements. We demonstrate (Table 1, Fig 7) that PD patients have decreased movement smoothness, with statistically significant difference from healthy subjects. This method can help accessing patient's motion smoothness and its decrement in time. Also, common analysis of these methods allow detection of some changes (blue rectangle in Fig 3 and Fig 5), that aren't visible in the gyro signal, thus can be overlooked.

In this way, finger tapping can be quantified, in the terms of its rhythmic behavior, vigor of its performance, tapping intravariability, tremor and motor blocks that can occur within the tapping performance. This method allows monitoring of patient's response to therapy and progress of the disease, and comparison with other evaluated patients. Future work would include implementation of the defined parameters for automated differential diagnostic system.

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