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Smartphone-based Evaluation of Movement Disorders: Quantitative Measurements vs Clinical Assessment Scores

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Abstract— **With an ever-growing number of technologically advanced methods for the diagnosis and quantification of movement disorders, comes the need to assess their accuracy and see how they match up with widely used standard clinical assessment tools. This work compares quantitative measurements of hand tremor in twenty-three Parkinson's disease patients, with their clinical scores in the Unified Parkinson's Disease Rating Scale (UPDRS) which is considered the "gold standard" in the clinical assessment of the disease. Our measurements were obtained using a smartphone-based platform, which processes the phone's accelerometer and gyroscope signals to detect and measure hand tremor. Our results suggest relatively strong correlation between the patients' UPDRS scores and the signal metrics applied to the measured signals.**

I. Introduction

Researchers frequently look for new ways to facilitate the work of physicians and doctors, for the purposes of increased accuracy, speed or accessibility. Towards that end, smartphones and smartphone-like devices offer a tantalizing platform since they contain embedded motion sensors, including accelerometers and gyroscopes, making it possible to detect even slight displacements of the device. Moreover, phones that feature such sensors are now commonplace, and it is relatively easy to utilize a smartphone to detect movement anomalies that appear in disorders such as Parkinson's. Accelerometers have been used successfully for characterizing tremor [1] and are particularly useful in measuring "resting" tremor (i.e., with the patient's hand being at rest against their body), and thus objectively quantifying one of the condition's predominant attributes. However, the advent of new technology does not remove the need for existing qualitative clinical assessment methods administered by a physician; on the contrary, it appears that clinical assessment will continue to be a mainstay in the diagnosis and tracking of movement disorders. Concerning Parkinson's disease in particular, clinical assessment typically uses the so-called UPDRS (Unified Parkinson's Disease Rating Scale) scoring method [2], in which the physician assigns numerical scores based on qualitative observations of the patient in various postures.

This paper is a continuation of our previous work [3]; its main contribution is a statistical comparison between signal-based methods of quantifying Parkinsonian tremor using a smartphone, and the UPDRS scores assigned by a physician specialist. We acquired new accelerometer and gyroscope signals from an iPhone "worn" by twenty-three patients and computed various signal metrics concerning the acceleration and rotation rate of the device. We then computed the correlation (Pearson product-moment) between the metrics under consideration and the patients' UPDRS scores. Our results indicate a strong correlation with high statistical significance.

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II. Background

A. Parkinson's Disease

Parkinson's disease is neurodegenerative in nature and heavily associated with movement disorders, such as involuntary tremor (limbs and face), bradykinesia, postural instability and rigidity [4]. The involuntary tremor is mostly periodic and is perhaps the most widely recognized symptom by the non-physicians. The disease's initial clinical features are caused by the loss of dopaminergic function in an area of the midbrain named the substantia nigra pars compacta. Parkinson's affects approximately 1% of the population over 55 years of age, being the second most common neurodegenerative disorder after Alzheimer disease [5]. Of course the disease comprises other symptoms as well, of nonmotor nature, such as executive dysfunction, bradyphrenia and memory problems [6].

B. UPDRS

The most widely used clinical method used to quantify the symptoms is the UPDRS [2]. It does not require any special equipment and involves observing the patient in various postures and "standardized" movements and tasks, and "grading" their performance on a scale of 0-4, 0 being normal, 1 slight, 2 mild, 3 moderate and 4 severe. The scale as it was introduced has four main sections:

1. Mentation, Behavior and Mood,
2. Activities of daily living,
3. Motor and
4. Complications

The UPDRS soon became the gold standard reference scale [7]. However, there has been criticism that it mostly focuses on the motor-related symptoms of the disease, and that it suffers from ambiguities [7]. Following a proposal from the Movement Disorder Society Task Force on Rating Scales for Parkinson's Disease [7], a new scale has been devised, MDS-UPDRS, which consists of four parts [8]:

1. Nonmotor experiences of daily living,
2. Motor experiences of daily living,

3. Motor examination and
4. Motor complications

Detailed instructions for testing and data acquisition accompany the MDS-UPDRS questionnaire in order to increase uniformity among caregivers. The Movement Disorder Society has even implemented an MDS-UPDRS smartphone application to help clinicians record their patients' scores.

Although from the point of view of medical practitioners the face-to-face interaction with the patients provided by the UPDRS rating process is very "rich" in information, it is nevertheless a subjective exercise, depending heavily on the clinician's experience, knowledge, objectivity and accuracy.

C. *Smartphone-Based Quantification of Tremor*

Over the past decade there has been extensive research on devices which can be used to objectively quantify tremor. Many efforts involved the use of wearable accelerometer sensors to record data and then transmit them over a wire or wirelessly to a PC, where numerical methods such as spectral analysis could be used to characterize the tremor [9], [10], [11], [12], [13], [14]. The majority of the implementations have limitations revolving around the cost of the hardware and the expertise required to use it. Furthermore, even wireless sensors can only transmit data within a limited range, so the recipient of the signal must be in close proximity.

The use of the embedded sensors in smartphones has introduced new accessibility options, without sacrificing efficiency, with the added bonus of the gyroscope, which is present in an increasing number of devices. LeMoyne et al. [15] where the first to introduce the use of a smartphone to collect acceleration data through an application installed on the device and send the data via e-mail to a remote computer for post-processing.

In earlier work [3], we used [15] as a point of departure and built a similar smartphone-based diagnostic tool for the detection and tracking of movement disorders. The novelty of our effort was that it was completely web-based, requiring from the patient nothing more than tapping on a web link while having the phone mounted on his/her hand. Moreover, ours is the only implementation that uses both the accelerometer and the gyroscope embedded in a smartphone. Being web-based, our tool [REFERENCE TO LINK HERE!] is independent of the operating system on the device and works on iPhone as well as on Android v4.4 devices.

A very similar approach to ours was taken by the authors of [16]: an application collects the acceleration data from an iPhone and posts them online for assessment, while the presence of a physician on site is not necessary. More recently, other researchers used a BlackBerry Storm phone to measure tremor, implementing the signal processing algorithms on-board the device with good results [17].

III. Experimental Setup & Software

The twenty-three subjects participating in this study were all Parkinson's disease patients recruited from the outpatient clinic of the 1st Department of Neurology at the Aristotle University of Thessaloniki. All agreed to participate in this research after a detailed explanation of its aims and of the testing procedure. All patients were under treatment. In this work we are initially interested in resting tremor so we asked the subjects to "wear" an iPhone (fitted on a glove as in [3]) on top of their hand while sitting in a chair comfortably and resting both their hands on their lap, keeping that position for 30 seconds. The device was mounted on both their hands alternately, and each test was repeated twice for each subject. Immediately prior to data collection, an experienced physician examined each subject and recorded their UPDRS scores, which were to be correlated with our quantitative measurements.

To collect our acceleration and rotational velocity signals for this work we used a setup similar to [3]:

1. An iPhone 4S with iOS 6 or later, with Internet access enabled,
2. A web site to collect data from the phone's sensors,
3. A web server to host the site and store the measurements,
4. Software for processing the signals received at the server.

Our web-based application (web-app) is intended for use on any smartphone equipped with an accelerometer and/or a gyroscope. We expect that by combining acceleration and rotation rate data we may be able to improve detection of movement disorders by accessing rotational components of hand tremor.

The web-app consists of three php files (index, machine, main). When the user visits the appropriate URL [18] using their phone, they are asked to enter an identifier, which does not have to be their name, the type of posture they will be in (hands extended, hands at rest, hands in action or hands in front of the chest), and the hand (left or right) their device is on. The user then presses a virtual button (link), which will result in a php session being created and, after a 3 second-delay, the readings from the sensors will automatically start being recorded. The recording procedure lasts 30 seconds, however the user can interrupt it at any time. The work in [3] used 12-second recorded signals. Here, we decided to increase the duration to 30 seconds after experimentation that showed that the longer signal gave vastly improved results under spectral analysis. Once the recording of the accelerometer and gyroscope readings is done, the data are transmitted to the server as simple text files for post processing.

Although when we collected our first samples in 2011 the only smartphone to incorporate JavaScript APIs [19] to access the accelerometer and gyroscope was the iPhone, the latest version of Android (4.4, Kit Kat) has added this feature to its web browser, making every Android phone with the required sensors a suitable platform for our implementation "out of the box".

IV. Processing & Analysis

From the data obtained, we formed each subject's acceleration vector, $\alpha(i) = \left[\alpha_x(i), \alpha_y(i), \alpha_z(i)\right]^T$ (in *m/s*^{2}) and rotation rate vector $\omega(i) = \left[\omega_x(i), \omega_y(i), \omega_z(i)\right]^T$ (in *deg/s*), with *i* denoting discrete time.

One of the biggest problems we faced in [3] was the low, nonadjustable sampling rate of 20*Hz* the iPhone offers when sampling through JavaScript. That fact directed us towards simple metrics extracted from the signals, such as their energy. These simple metrics allowed us to distinct

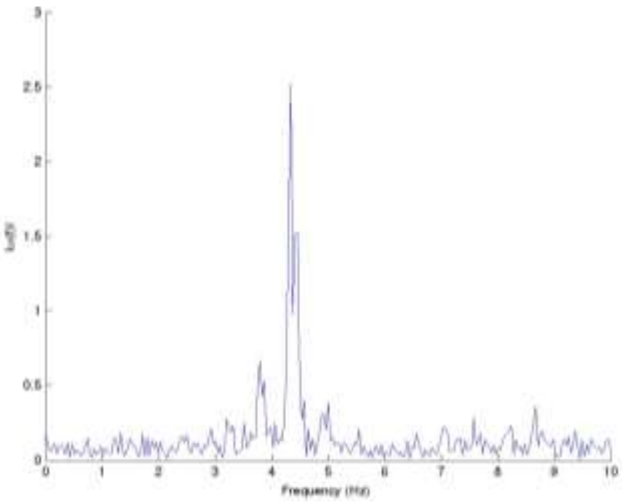

Fig. 1. Spectral analysis (Fourier Transform) of the magnitude of the rotation rate vector for one patient. No filters have been applied to the signal.

successfully patients from healthy participants in [3]. Here, we opted for longer signals, in an effort to compensate for the phone's low nominal sampling rate of 50*ms*. The spectral analysis of the rotation rate vectors indicates that the sensors can identify the resting tremor of a Parkinson's disease patient relatively accurately (Fig 1).

A. *Signal Metrics and Correlation Analysis*

As stated in [17] the UPDRS, although used to characterize tremor and classify patients' symptoms, is not specifically designed to quantify tremor amplitude. However, since it is being used to widely, we are interested in examining whether patients' UPDRS scores correlate well for a set of simple signal metrics detailed below. For this reason, we did not "improvise" a new scale (as in [17], for example) but rather considered the UPDRS motor "components" 20b and 20c which correspond to Tremor at Rest Right Hand, and Tremor at Rest Left Hand.

We computed four different metrics for each accelerometer and gyroscope signal obtained for each patient:

$$mag_{\alpha} = \sum_1^N \|\alpha(i)\|^2 \quad \text{and} \quad mag_{\omega} = \sum_1^N \|\omega(i)\|^2 \;, \quad (1)$$

$$sd_{\alpha} = \sum_{i=1}^{N-1} \sum_{\kappa \in \{x,y,z\}} |\alpha_{\kappa}(i) - \alpha_{\kappa}(i+1)| \;, \quad (2)$$

$$mAmp_{\omega} = \sum_{\kappa=\{x,y,z\}} \max_{4 \leqq \xi \leqq 7} \widehat{\omega_{\kappa}}(\xi) \;, \quad (3)$$

Where: mag_{α} and mag_{ω} are the sums of squared magnitudes of the acceleration, and the rotation rate vector respectively and sd_{α}, is the sum of absolute differences in the acceleration vector, summed over each of the three axes, *x*, *y*, and *z*. To compute $mAmp_{\omega}$ metric we initially obtained the magnitude of the Fourier transform of each of the three components of the rotation vector $\omega(i)$. We then determined each component's maximum in the 4-7*Hz* spectrum (that range being consistent with the frequency of Parkinsonian tremor) and summed the three maxima. Each patient performed two trials per hand, and each of the metrics (1)-(3) was averaged over both trials, giving us an average score for each patient's right hand and another average for their left hand. We kept left/right-hand averages distinct (as opposed to averaging all scores for both hands) because UPDRS scores are similarly categorized on a left-hand/right-hand basis.

In order to analyze the correlation between the UPDRS scores of the patients and each of the metrics detailed above, we computed the Pearson correlation coefficients between the patients' metric(s) (separately for right vs left hand) and their UPDRS scores (for the resting tremor of the respective hand). The coefficients (*r*) and their corresponding p-values (*p*) are shown in Table 1, with one row devoted to each of the metrics used. We observe that, at a very comfortable confidence level of 1%, the hypothesis that there is no correlation between the UPDRS scores and the metrics is rejected. The metric showing the highest correlation to the UPDRS scores is sd_{α}, where the correlation coefficients are 0.7706 (right hand) and 0.8793 (left hand) with high statistical significance. Given the qualitative/subjective manner in which UPDRS scores are assigned by the physician, a value of *r* above 0.7 suggests a strong correlation with our metrics, while the near-zero p-values indicate a strong statistical significance.

TABLE I. CORRELATION COEFFICIENTS BETWEEN EACH METRIC AND THE UPDRS SCORES

Metrics	**Coefficients**			
	Right Hand		***Left Hand***	
	r	***p***	***r***	***p***
mag_{α}	0.7003	0.0002	0.7034	0.0002
mag_{ω}	0.6975	0.0002	0.7967	0
sd_{α}	0.7706	0	0.8793	0
$mAmp_{\omega}$	0.7564	0	0.8517	0

Observing the values in Table 1, there is better correlation between UPDRS scores and all the metrics for the patients' *left* hand, while all patients were right-handed. One possible interpretation could be that the patients' dominant (right) hand is better at supporting the weight of the device while "controlling" tremor than their non-dominant hand. However, this is something that requires further investigation.

In Figure 2 we show how the UPDRS scores of the 23 patients, correlate to their $mAmp_{\omega}$ metric (3). The linear trend line has a slope of *a*= 5.0258, calculated from

$$\mathrm{a} = r\frac{\sigma(m)}{\sigma(u)} \;, \quad (4)$$

where *u* is the vector of UPDRS scores, *m* is the vector of *mAmp* values and σ is the standard deviation of each variable.

V. Conclusions and Ongoing work

We explored the correlation between the UPDRS components III.20.b and III.20.c, used by clinicians to assess Parkinsonan tremor, and simple metrics derived from the accelerometer and gyroscope of a smartphone, mounted on the hand(s) of 23 Parkinson's disease patients. In our analysis we used Pearson product-moment correlation as opposed to concordance correlation coefficients because we were primarily interested in exploring the validity of our smartphone-based method for quantifying hand tremor. We do not advocate the "replacement" of the UPDRS clinical test by any means, but are interested in seeing the sensors of a ubiquitous device such as a phone, together with our software being used to assist the physician, providing him with an objective method to quantify resting hand tremor efficiently, accurately and remotely. Our analysis showed that our metrics correlate well to the UPDRS scores reported by an experienced specialist physician. These results along with our previous research [3] motivate our ongoing efforts to explore the potential of smartphones as a tool for remote evaluation of movement disorders. We are already in the process of improving our web-app, adding a real-time presentation of the results to the patient (as well as a remotely-located physician) following the collection of the signals, while we continue to conduct further clinical trials to determine better signal metrics. Further studying of left-handed patients' is also of interest, in order to investigate the possible relationship between left/right-hand dominance and the correlation coefficients discussed in this study.

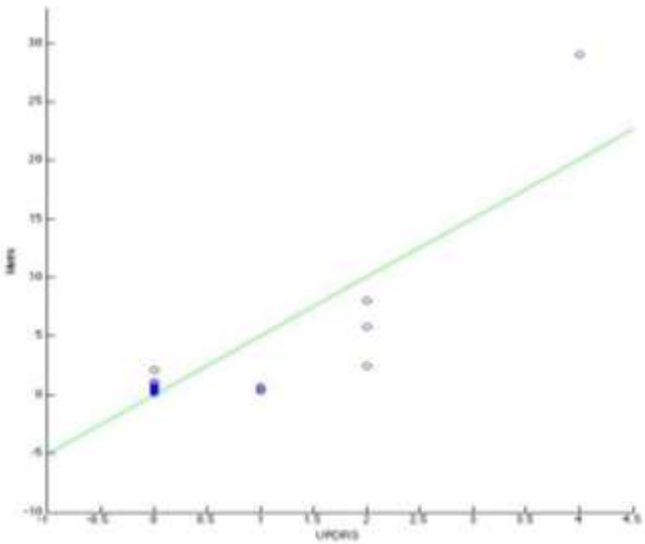

Fig. 2. Correlation Analysis. The metric (y axis) is the sum of maximum amplitudes of the rotation rate vector (sum of all three axes) in the spectrum of 4-7*Hz*.

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