Mobile health: assessment of upper limb motor function via a drawing test on a mobile device

Maciej Komosinski
maciej.komosinski@cs.put.poznan.pl

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Poznan University of Technology, Institute of Computing Science

Abstract

This paper describes and compares experiences with two generations of devices that can acquire pen movement data from a drawing test. The first part of this work summarizes methods introduced earlier that analyze data acquired using a graphics tablet from healthy subjects and people with Parkinson's disease before and after surgery. These methods can discriminate groups of patients and can assess improvements after surgery. The second part of this work presents the implementation of analogous methods that estimate hand tremor and drawing smoothness on a commercially available mobile tablet. Both approaches and applications are compared, and differences in goals and in characteristics of these devices are enumerated.

1 Introduction

This work belongs to an increasingly broad trend of human studies that involves the use of widely available hardware, human–computer interfaces, and dedicated software in order to obtain an objective, numerical evaluation of characteristics of a tested person. Popular computer peripheral devices such as a microphone, a camera, a touch screen or a mouse (a manipulator) with many degrees of freedom are accurate enough to be used in medical diagnostics. This is captured by the *mobile health* term: public health and the practice of medicine can be supported by broadly available devices such as tablets, smartphones, and PDAs.

This paper consists of two parts:

- Sect. 2 summarizes methods introduced in [1] of processing of data acquired using a graphics (digitizing) tablet (Fig. 1, left) from healthy subjects and people with Parkinson's disease before and after surgery. A few numerical measures have been proposed there that evaluate movement of a pen while a person is drawing on the tablet. These measures have been further investigated to see if specific characteristics and features of hand and arm movement allow to discriminate groups of patients and to assess improvements after surgery.

- Sect. 3 describes the implementation of methods that estimate hand tremor on a commercially available mobile tablet (Fig. 1, right), which has been done by the author in 2013. The characteristics of the mobile tablet device and slightly different goals required the development of another measures than those described in Sect. 2.

Figure 1: Two types of tablet devices. Left: a graphics tablet similar to the one used for data acquisition and experiments in Sect. 2. Right: a sample mobile tablet (here Samsung Galaxy Note 10.1) that can run an app described in Sect. 3.

2 A graphics tablet and Parkinson's disease patients

To estimate the quality of measures that would reflect the quality of the upper limb motor function, recorded data have been used from patients before and after neurosurgical procedures of pallidotomy and thalamotomy. 37 recordings have been considered (24 for pallidotomy and 13 for thalamotomy). Anonymized file names are shown in the table below.

Before pallidotomy	After pallidotomy
01________3182_10KRLP.mtb	02________3182_11KRLP.mtb
02________0753_10MRLP.mtb	04________0753_11MRLP.mtb
01________4998_10MRLP.mtb	02________4998_11MRLP.mtb
02________4739_10MRLP.mtb	03________4739_11MRLP.mtb
01________1594_10MLLP.mtb	03________1594_11MLLP.mtb
02________1594_10MRLP.mtb	04________1594_11MRLP.mtb
01________6154_10MLLP.mtb	03________6154_11MLLP.mtb
02________6154_10MRLP.mtb	04________6154_11MRLP.mtb
01________1897_10MLLP.mtb	03________1897_11MLLP.mtb
02________1897_10MRLP.mtb	04________1897_11MRLP.mtb
01________0097_10MLLP.mtb	03________0097_11MLLP.mtb
02________0097_10MRLP.mtb	04________0097_11MRLP.mtb
01________0816_10MRLP.mtb	02________0816_11MRLP.mtb
01________5185_10KLRP.mtb	03________5185_11KLRP.mtb
02________5185_10KRRP.mtb	04________5185_11KRRP.mtb
03________0157_11MLRP.mtb	04________0157_11MRRP.mtb
01________7562_10KLRP.mtb	03________7562_11KLRP.mtb
01________2577_10MLRP.mtb	03________2577_11MLRP.mtb
02________2577_10MRRP.mtb	04________2577_11MRRP.mtb
01________2857_10MLRP.mtb	03________2857_11MLRP.mtb
02________2857_10MRRP.mtb	04________2857_11MRRP.mtb
01________7123_10KLRP.mtb	02________7123_11KLRP.mtb
01________3936_10MLLP.mtb	03________3936_11MLLP.mtb
02________3936_10MRLP.mtb	04________3936_11MRLP.mtb

Before thalamotomy	After thalamotomy
02________3557_10MRLT.mtb	03________3557_11MRLT.mtb
02________2116_10MRLT.mtb	04________2116_11MRLT.mtb
01________1554_10MLLT.mtb	03________1554_11MLLT.mtb
01________7196_10MRLT.mtb	02________7196_11MRLT.mtb
02________1735_10MRLT.mtb	03________1735_11MRLT.mtb
01________6770_10MLLT.mtb	03________6770_11MLLT.mtb
02________6770_10MRLT.mtb	04________6770_11MRLT.mtb
01________8353_10MRLT.mtb	02________8353_11MRLT.mtb
01________4914_10MLLT.mtb	03________4914_11MLLT.mtb
02________4914_10MRLT.mtb	04________4914_11MRLT.mtb
01________2531_10MLRT.mtb	03________2531_11MLRT.mtb
01________1715_10MLRT.mtb	02________1715_11MLRT.mtb
02________1792_10MRRT.mtb	04________1792_11MRRT.mtb

Control groups of healthy subjects:

For pallidotomy

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41________0_ORCH.htd
18________0_ORCH.htd
50________0_ORCH.htd
10________1_ORCH.htd
50________1_OLCH.htd
50________1_ORCH.htd
20________0_OLCH.htd
20________0_ORCH.htd
10________0_OLCH.htd
10________0_ORCH.htd
99________9_OLCH.htd
99________9_ORCH.htd
35________0_ORCH.htd
17________0_OLCH.htd
17________0_ORCH.htd
22________0_ORCH.htd
21________0_OLCH.htd
39________0_OLCH.htd
39________0_ORCH.htd
16________0_OLCH.htd
16________0_ORCH.htd
23________0_OLCH.htd
12________1_OLCH.htd
12________1_ORCH.htd
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For thalamotomy

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19________1_ORCH.htd
22________0_ORCH.htd
18________0_OLCH.htd
38________0_ORCH.htd
31________0_ORCH.htd
42________1_ORCH.htd
42________1_ORCH.htd
28________0_ORCH.htd
44________0_OLCH.htd
44________0_OLCH.htd
36________0_OLCH.htd
24________0_OLCH.htd
37________0_ORCH.htd
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Five low-level methods have been proposed and verified that quantitatively estimate hand tremors. These methods are called low-level because they are simple and reflect primary features of the recorded signal. The way they are aggregated into a single value per recording is also simple. These measures do not take into account the specific shapes that were drawn and they work for the entire recording, so they are non-contextual and global.

For all measures, only the samples where the pen touches the tablet surface are considered. Tablet sampling rate was 200Hz.

In most charts presented in this paper, the vertical axis shows the z statistic of the Wilcoxon signed-rank test for pairs[1] before–after surgery. The horizontal axis shows values of the first parameter of a given method (which is the frequency of estimation of a given movement parameter or the distance of movement of the pen). Individual lines (series) on charts usually correspond to the second parameter of a method. Additional horizontal lines are auxiliary (zero or levels of statistical significance).

[1] http://faculty.vassar.edu/lowry/ch12a.html

2.1 Variability of the direction of movement – method p_{dir}

Calculating $p_{dir}(f, angle\_threshold)$ estimates how many times the change in the direction of movement exceeded some threshold. There are two parameters of this method: frequency f – how often changes of movement are detected, and the threshold, $angle\_threshold$. The idea is to calculate the number of "too big" changes in direction in the path that is drawn. This number is calculated independently for a large range of frequencies (horizontal axis in charts). The f frequency is constant for the entire recording.

Base sampling frequency, $F = 200$ Hz.

Interval Δt to compute direction changes for frequency f, $\Delta t = \frac{F}{f}$.

Direction of movement $dir(p_A, p_B)$ yields an angle of pen movement between two points A and B.

Direction change for a point recorded at time t,

$$dir\_change^*(t) = |dir(p_t, p_{t+\Delta t}) - dir(p_{t+\Delta t}, p_{t+2\Delta t},)|$$

Detection of direction changes exceeding $angle\_threshold$,

$$dir\_change(t, angle\_threshold) = \begin{cases} 1 & \text{if} \quad dir\_change^*(t) > angle\_threshold, \\ 0 & \text{otherwise.} \end{cases}$$

Average ratio of changes of direction for the entire test of n points,

$$p^*_{dir} = \frac{\sum_{t=1}^{n-2\Delta t} dir\_change^*(t)}{n - 2\Delta t}$$

and analogously, average ratio of changes of direction exceeding $angle\_threshold$,

$$p_{dir}(angle\_threshold) = \frac{\sum_{t=1}^{n-2\Delta t} dir\_change(t, angle\_threshold)}{n - 2\Delta t}$$

Figs. 2 and 3 show the differences Δ_{dir} in values of movement parameters for individual patients before and after surgery (for $angle\_threshold = 90°$).

$$\Delta_{dir} = p^{before}_{dir}(90°) - p^{after}_{dir}(90°)$$

Positive differences mean that before the surgery, there were more tremors (for a given f) than after surgery. Based on this information, Wilcoxon test statistics are computed (Figs. 4 and 5). One can see that, especially for pallidotomy, most patients had less tremors for f higher than about 10Hz, which is also demonstrated by statistical significance values. More detailed analysis can be found in [1].

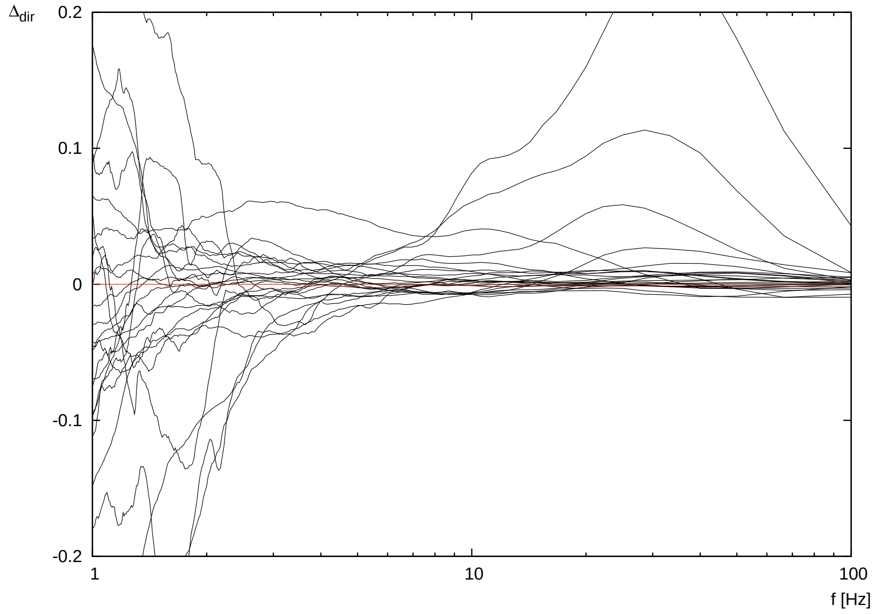

Figure 2: Differences Δ_{dir} of movement parameter p_{dir} for angle threshold 90°. Lines are individual patients that underwent pallidotomy.

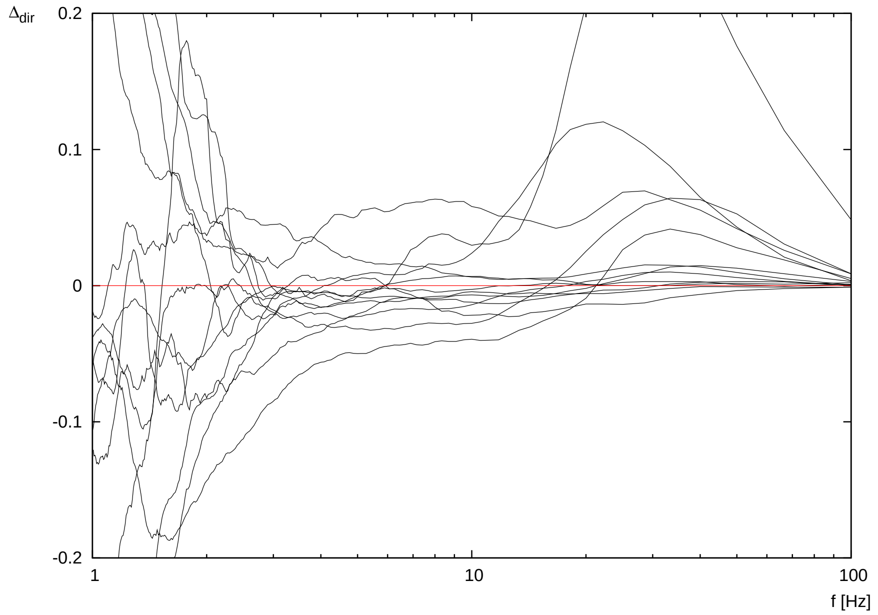

Figure 3: Differences Δ_{dir} of movement parameter p_{dir} for angle threshold 90°. Lines are individual patients that underwent thalamotomy.

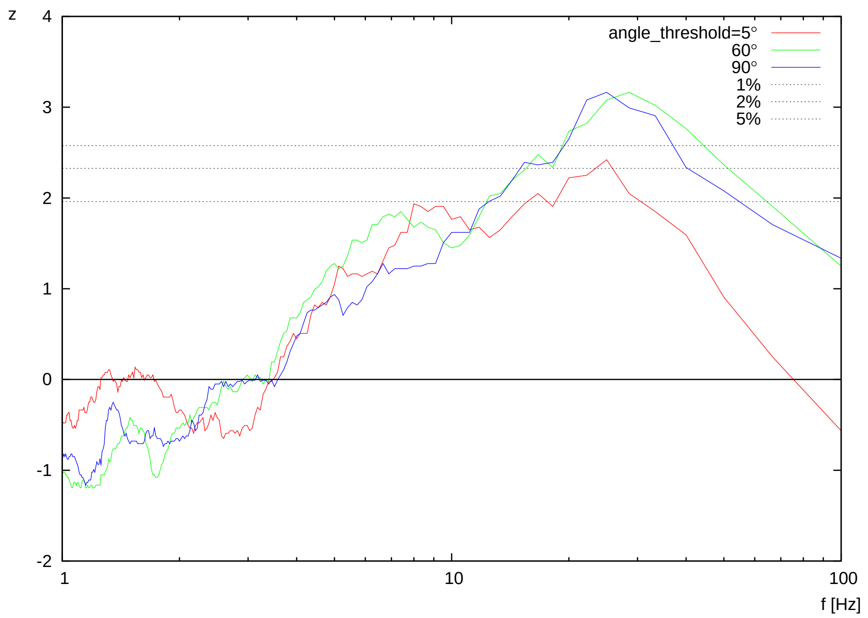

Figure 4: Statistical significance of differences in p_{dir}, pallidotomy.

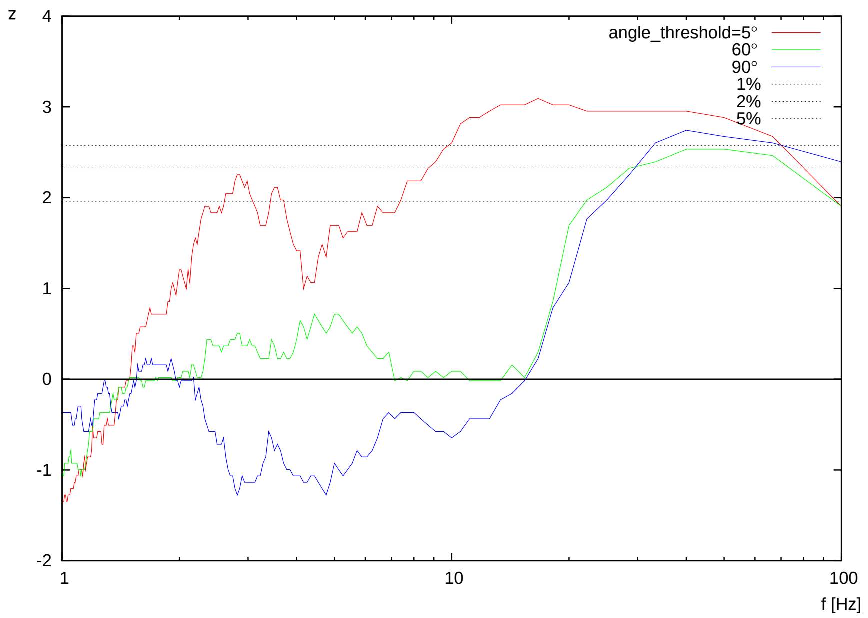

Figure 5: Statistical significance of differences in p_{dir}, thalamotomy.

Comparing charts in pallidotomy and thalamotomy (Figs. 4 and 5), one can see that the characteristics of these surgical procedures and patients that were assigned to these procedures are different. A broader discussion is presented in [1].

Fig. 6 shows the values of the Wilcoxon statistic for averaged values of angle changes (without thresholding). This chart also shows that both procedures eliminate tremors of higher frequencies.

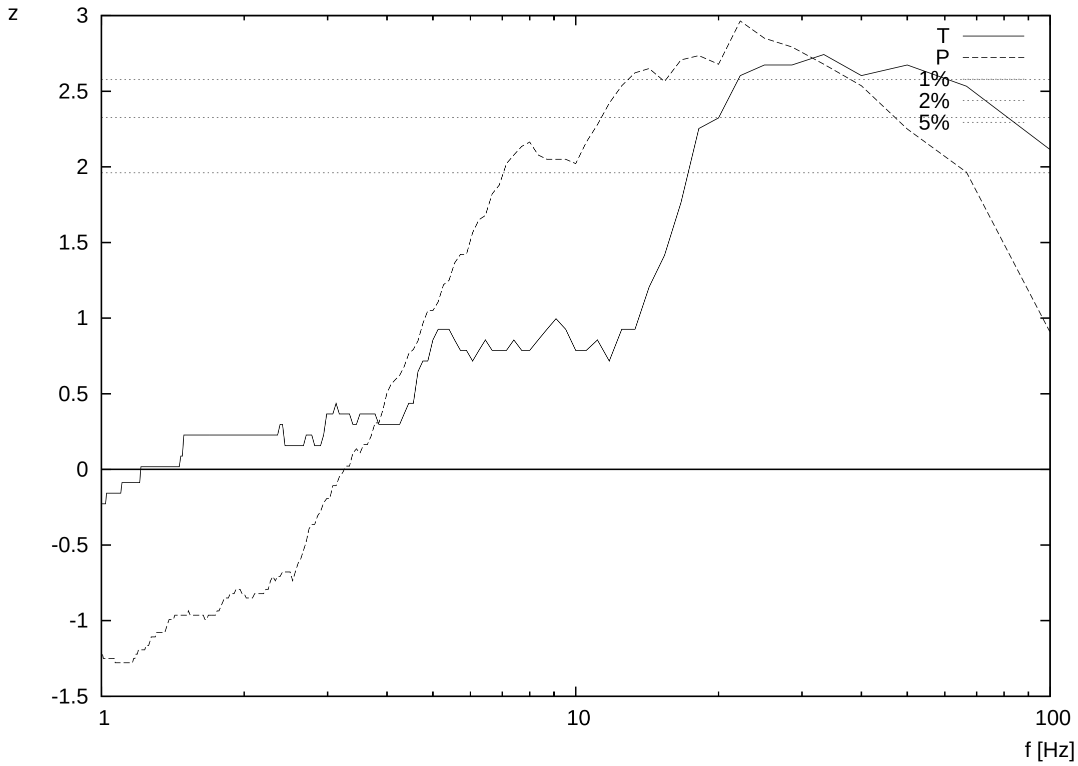

Figure 6: Statistical significance in differences in value of p^*_{dir}, pallidotomy and thalamotomy.

2.2 Variability of the velocity of movement – method p_{vel}

This method is analogous to p_{dir}. The difference is that we calculate subsequent lengths that the pen moved (given the constant tablet sampling rate, lengths correspond to velocities). For each pair of subsequent sections, we calculate the ratio of smaller to larger. This is therefore a measure of an instantaneous acceleration. As before, we calculate how many times this ratio is lower than a given threshold. Just as before, this method has two parameters: $p_{vel}(f, velocity\_ratio\_threshold)$.

The distance between two points A and B is $dist(p_A, p_B)$. The distance is a measure of velocity given the constant sampling rate. Let's put $vel(t) = dist(p_t, p_{t+\Delta t})$.

Velocity change for point recorded at time t,

$$vel\_change^*(t) = \frac{\min(vel(t), vel(t + \Delta t))}{\max(vel(t), vel(t + \Delta t))}$$

Detection of velocity changes exceeding $velocity\_ratio\_threshold$,

$$vel\_change(t, velocity\_ratio\_threshold) = \begin{cases} 1 & \text{if} \quad vel\_change^{*}(t) < velocity\_ratio\_threshold, \\ 0 & \text{otherwise.} \end{cases}$$

Fig. 7 demonstrates that both pallidotomy and thalamotomy yielded a decrease in velocity variability (so pen speed was stabilized). For thalamotomy and higher sampling frequencies, the difference in pen movement before and after surgery is radical. More detailed analysis can be found in [1].

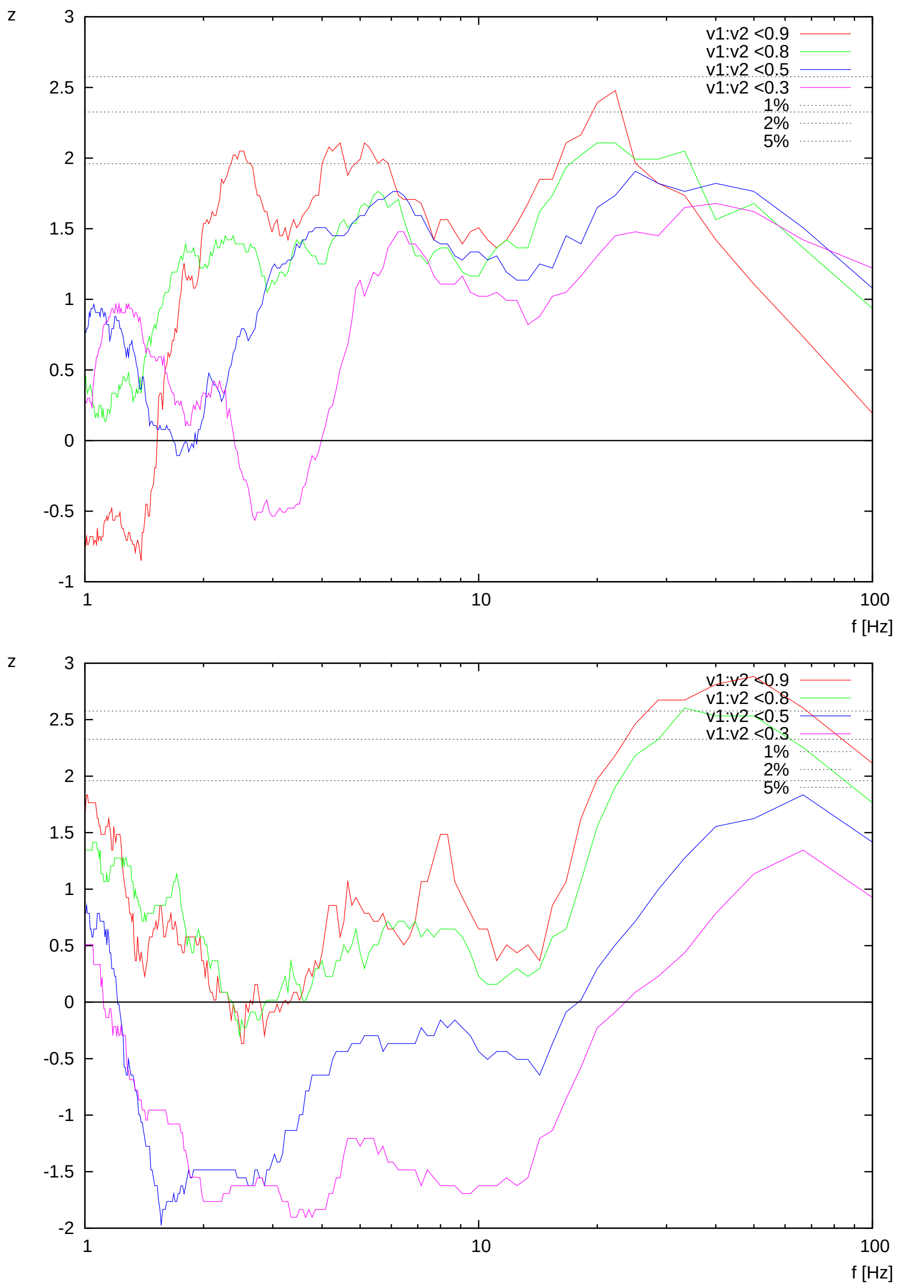

Figure 7: Statistical significance in differences in value of p_{vel}, pallidotomy (top) and thalamotomy (bottom).

2.3 Variability of pen tilt – method p_{tilt}

This method turned out to be a poor discriminator of patients before and after surgery (Fig. 8). A more detailed analysis is provided in [1].

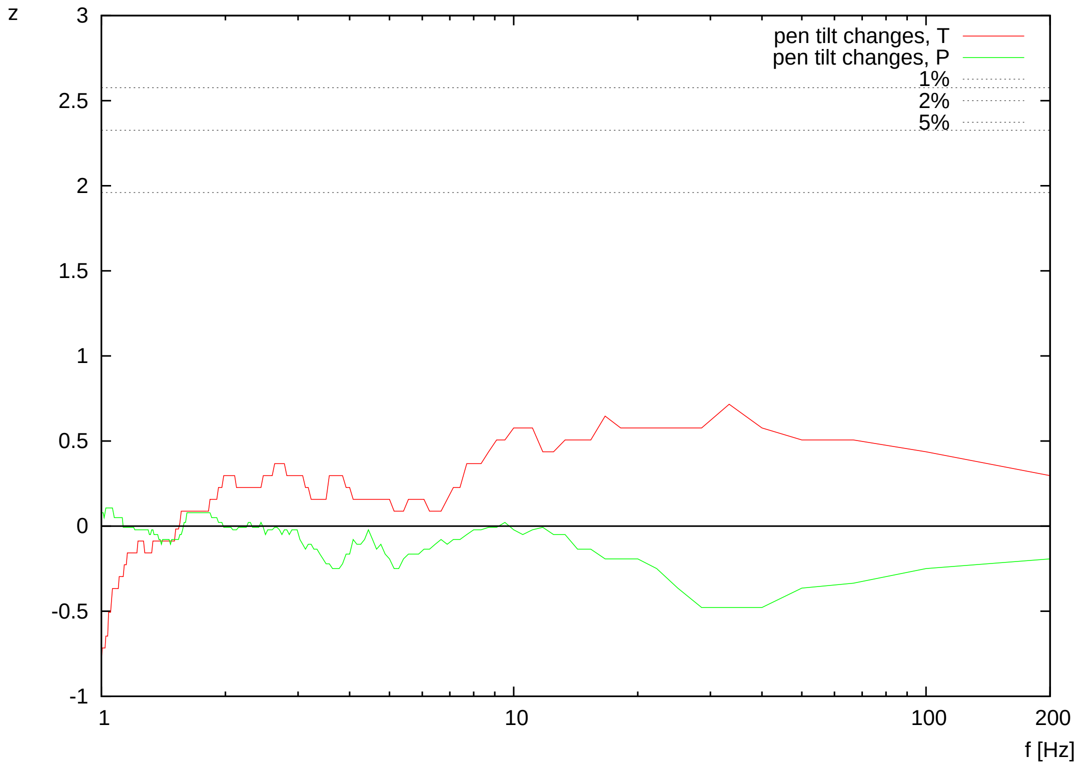

Figure 8: Minor statistical significance of differences in value of p_{tilt}, pallidotomy and thalamotomy.

2.4 Variability of pen pressure – method $p_{pressure}$

For this method, based on the value of z (Fig. 9), it is possible to tell which kind of the procedure (pallidotomy or thalamotomy) was performed. A more detailed analysis can be found in [1].

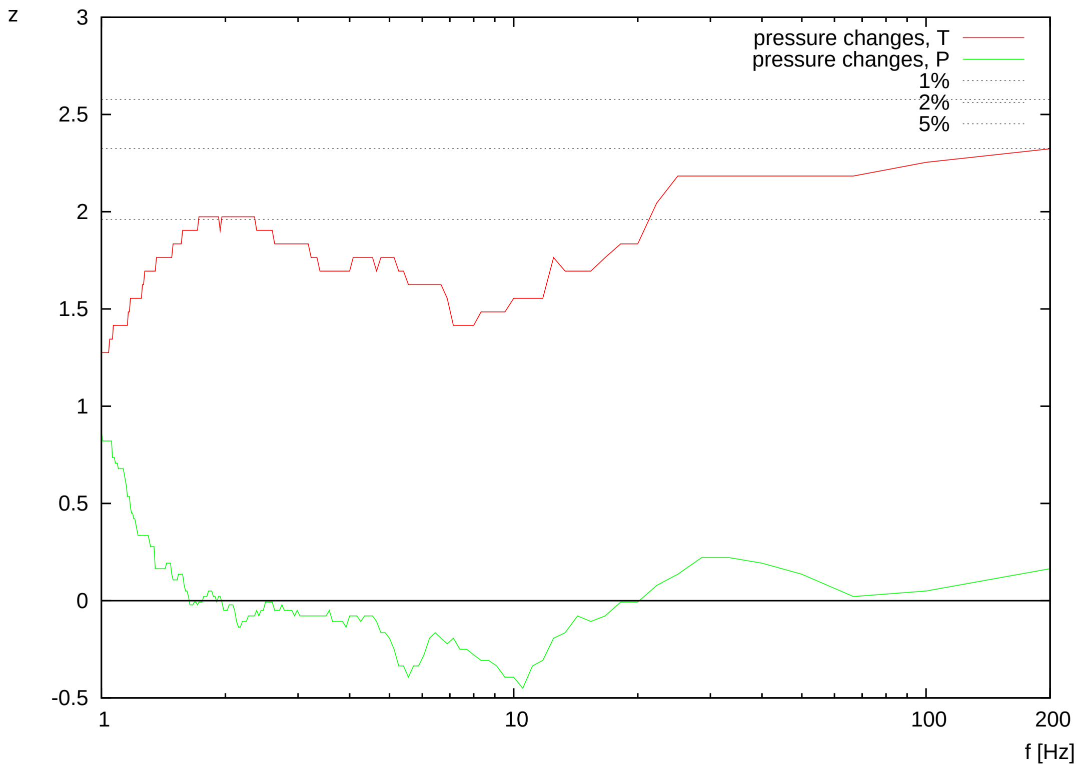

Figure 9: Statistical significance of differences in value of $p_{pressure}$, pallidotomy and thalamotomy.

2.5 Smoothness of the path drawn – method p_{smooth}

To determine $p_{smooth}(dist)$, we approximate subsequent locations of the pen with a polynomial of degree 2 to see how far the actual points are from the smoothed regression curve. If a pen is moved smoothly, the points will be close to the smooth curve. If pen movements are rapid and sharp, distances of points from the regression curve will increase. To follow the behavior of earlier measures ("the more tremors, the higher the value"), to evaluate a drawing we compute the average of $(1 - R^2)$, where R^2 reflects goodness of fit.

The only parameter of this method, $dist$, is the distance the pen must have been moved to evaluate smoothness of such an individual part of a drawing (Fig. 10).

As one can see, thalamotomy caused pen movements to become smooth – both for small (shorter than 1cm) sections of the drawn contour and for longer than 2cm. Pallidotomy on the other hand eliminated only little tremors – after surgery, lines drawn by patients had no oscillations of high frequency (less than 0.5cm), but larger oscillations remained and became more pronounced.

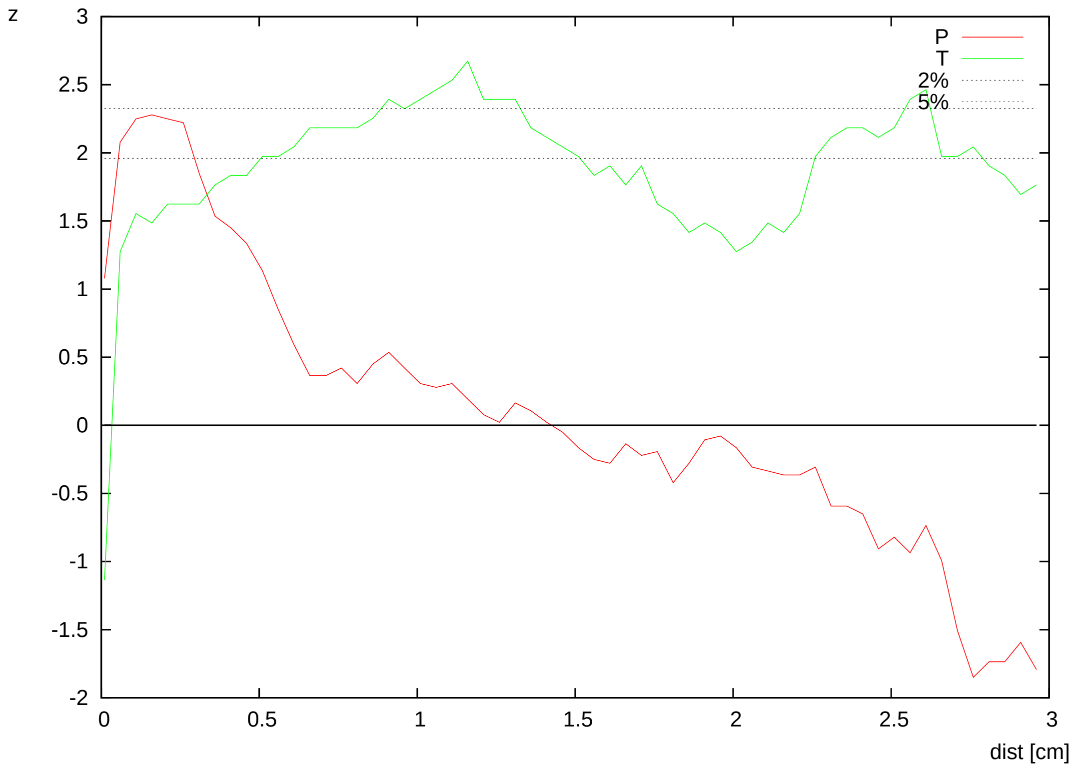

Figure 10: Statistical significance of differences in value of $p_{smooth}(dist)$, pallidotomy and thalamotomy. Horizontal axis shows $dist$.

2.6 Conclusions

Simple methods described in this section could discriminate between patients before and after surgery in a statistically significant way. It was possible even given the fact that the data was highly imperfect. Comparing averages and using values of the control (healthy) group are described in [1].

These methods have been implemented in the java language as command-line programs. They are portable and can be used for batch processing or as a part of another system, or can cooperate with other modules.

3 Mobile tablet application

The graphics tablet used for experiments in the previous section provided sufficient detail and accuracy of data to precisely analyze the characteristics of pen and hand movement. Such capabilities become now available in mainstream mobile devices – smartphones and tablets equipped with a pen; some of the much earlier devices (PDAs) had a "stylus" and they were already capable of detecting binary touch/no touch, but not pressure or pen tilt. In 2013, the author developed a mobile application (id: com.mooncoder.tremblinghand, Fig. 11) for Android Samsung Galaxy Note devices, which was since December 2013 available for free in the Samsung (Galaxy) Apps store for users with compatible devices.

This application helps detect and measure hand tremor and related disorders. Using "S-Pen" (the stylus for Samsung Galaxy devices), users draw four specific shapes and

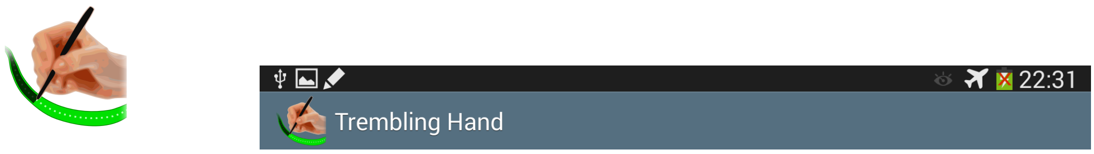

Figure 11: The icon and the top bar of the Trembling Hand application.

then see how accurate and smooth their strokes are.

There were a number of important differences to the experiences described in Sect. 2 that needed to be taken into account when designing the application for a mobile device:

- the group of target users is different: it is a large population of mostly healthy, mostly young users
- the goal of the application is different: in most cases, it has nothing to do with pallidotomy and thalamotomy
- usage scenarios are different – no controlled experiment conditions, no supervisor, probably a distracting environment; the application should be robust against human errors and cheating
- the characteristics of the device is different:
  - there are many devices that can vary in parameters (size, time and spatial resolution, precision, delays)
  - some parameters (like stylus tilt) cannot be recorded
  - devices have displays, so information can be updated in (almost) real time.

Following current standards, the mobile application had to obey usability recommendations, had to be designed so that it can be used intuitively and had to avoid distracting the user while the test is drawn. I have performed a number of testing sessions to identify usage problems, and tried a number of measures that could be reliably computed from data that could be acquired on such devices. Ultimately, I have selected two criteria (smoothness and precision) and decided to avoid aggregating these two factors, presenting them on a 2D chart instead. Other measures are also computed and they would provide additional information that could be included in a multi-criteria evaluation, but these two factors turned out to be most important for a basic screening test, and selected as the best indicators of drawing accuracy and hand tremor.

When users begin a test, an animation demonstrates the way the test should be completed (Fig. 12, left). Then the application waits for the user to start drawing. Successful completion is confirmed (Fig. 12, right).

Should users have problems with following the target green path, a message is displayed and problematic places are clearly indicated in red (Fig. 13).

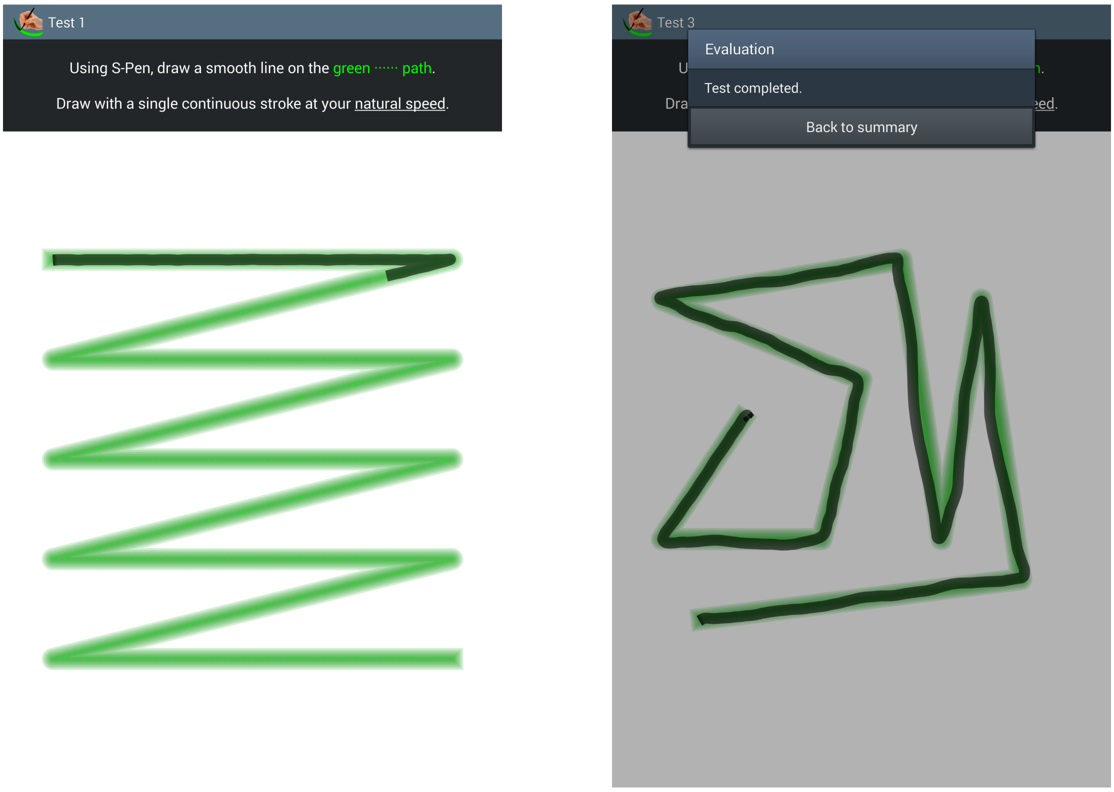

Figure 12: Drawing a test.

Figure 13: Indicating problematic places on the target path.

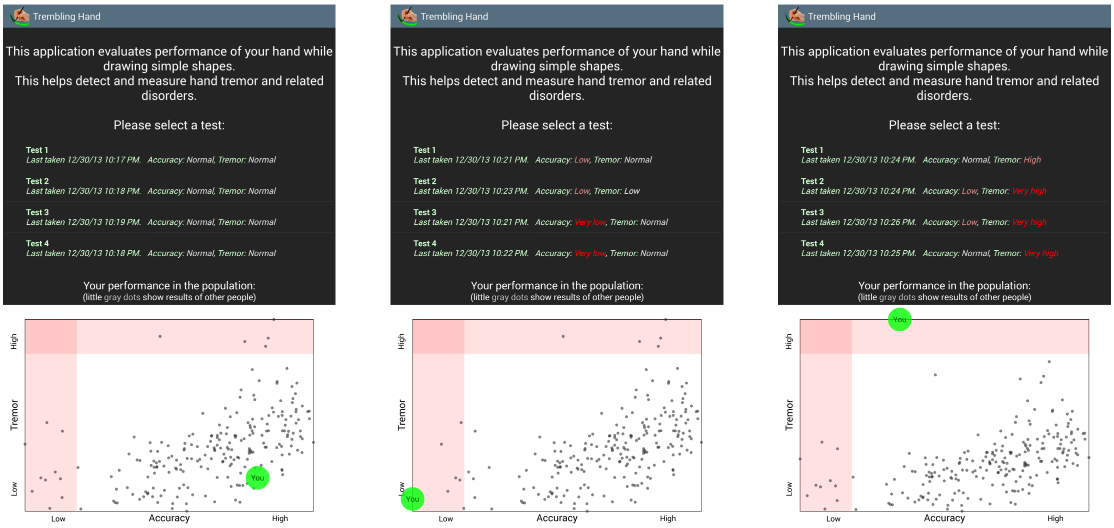

Figure 14: Performance results. Left: an excellent result – low tremor and high accuracy. Middle: a result of a person who could not follow the path accurately. Right: medium accuracy and a very high hand tremor.

The application uses specialized algorithms to evaluate the drawings numerically. This allows users to compare their own results to the results of other healthy people. Trembling Hand does not display a specific diagnosis. It rather demonstrates evaluations in both textual and graphical form to the user so that they can see their own results, repeat tests, and take action if their performance is poor.

After users complete all four tests, their performance is shown in a chart as a large green "You" sign overlaid on results provided by other healthy people (Fig. 14). Aggregated, anonymized results are sent to a remote server so that they can be analyzed by scientists and the population's "cloud of points" that is displayed for reference can be potentially enriched by every test that is taken.

Using menu, users can always clear all results either for privacy reasons, or to start taking tests again (Fig. 15).

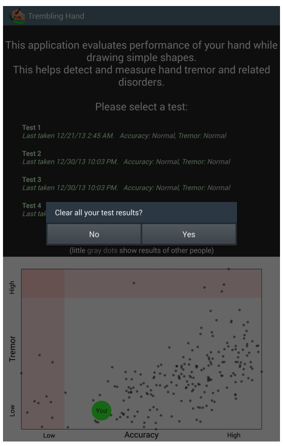

Figure 15: Clearing results.

3.1 Summary

Health and fitness are increasingly important in the modern society. The range of disorders that affect hand movement is large and their causes differ, including various brain disorders, sensory and motor problems, nerve degeneration, and cognitive deficits. The most popular of these is probably Parkinson's disease. Trembling Hand allows any owner of a compatible device to privately perform individual tests, and to anonymously compare their performance with others. This is a quick and simple screening test at no additional cost. People can even share one device to take drawing tests. This is the main advantage of the application: it increases personal health awareness and enables people to perform a simple screening test at home, with no additional costs.

Despite sophisticated concepts that are hidden under the hood of this application, results are displayed in a simple form, and the user interface is very friendly. The GUI does not contain distracting elements and is kept clear so that users can focus on tests and on understanding of their results. This is especially important for elderly people, or for younger people with various deficits.

The advantage of tablets with a screen is that they display the target shape so that users can immediately and continuously see if they are performing well. This also allows the application to provide feedback to users when they pick the pen up while drawing, or when their drawing cannot be accepted because it does not resemble the desired shape. This was not possible with digitizing graphics tablets (Sect. 2), so the testing procedure took more time and was more complex.

Trembling Hand is lightweight and it could even work on lower-end devices with smaller screens (it can adapt to various screen sizes, resolutions and pixel densities), but a large screen enables acquiring high-quality data and feeling natural when drawing shapes.

Even though the task of drawing shapes seems simple (and it is used by many Paint-like apps and games), data captured by such devices is of sufficiently high quality and high resolution, which opens up a way for a meaningful data analysis, processing, and – finally – visualization. This indicates a new trend where popular devices will be able to measure diverse aspects of human behavior, and applications with embedded artificial intelligence algorithms will be able to detect early symptoms of various disorders. Trembling Hand is a novel example of such applications.

References

[1] Maciej Komosinski. Podstawowe parametry ruchu piórka w teście rysunkowym i ich zastosowanie w diagnostyce motoryki kończyn górnych (Low-level properties of pen movement in a drawing test and their application in diagnosis of upper limb motor function). Research report RB–04/08, Poznan University of Technology, Institute of Computing Science, 2008. URL: `http://www.cs.put.poznan.pl/mkomosinski/research/parkinson-ocena-drgan-tablet.pdf`.