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Quantitative Analysis in the Digital Luria's Alternating Series Tests

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***Abstract*—The focus of the present research is on the kinematic features describing performance of the tested individual during the digital Luria's alternating series tests. First goal is to demonstrate that the features computed for the Parkinson Disease patients differ from those of healthy individuals. The secondary goal is to find the subset of features allowing to distinguish disorders on the level of motion planning from those on the level of motion execution. There are two novel properties of the proposed approach, which distinguish it from the previously published techniques. The first one is, that digital Luria's alternating series tests consist of different exercises targeted to distinguish disorders on the different levels, planning the motion and executing the motion. The second one is, that the set of kinematic features which is usually used in this area will be complimented by Motion Mass parameters describing amount and smoothness of the motion.**

I. Introduction

Parkinson's disease (PD) is the neurodegenerative disease that causes disorders on the different levels of motion planning and execution [1]. In spite of the fact that PD is one of the most common neurological diseases, there is no way to cure it. Moreover, precise diagnosing is very complicated task [2]. Recent technological developments has triggered research directed on the levels of gross and fine motor performances. The present paper concentrates its attention on the analysis of fine motor performance observed during the digital Luria's alternating series tests [3]. The main goal of the present research is to select the set of kinematic parameters and features, describing performance of the individual during the digital Luria's tests, allowing to diagnose PD.

Analysis of the fine motor performance has been used in the different areas of neurology and psychology long before the digital age. Different tests were performed by means of pen and paper, whereas the assessment were done by the neurologist or psychologist. Such settings inevitably lead to the presence of the subjective component in any assessment. The other drawback of the pure human based assessment are the limits of human perception, like inability to measure velocities and accelerations or pressure applied by the pen tip on the paper. Introduction of the digitized tables and later tablet PCs has sparked the interest to apply these devices to the analysis of fine motor skills. Main principles and parameters to record with digitized tables were outlined in [4]. Later those procedures has been adopted for the diagnosis of different neurologic diseases like PD [5] or schizophrenia [6] and other studies in the area of neurology [7]. Drawing and handwriting are the most popular exercises to measure different kinematic parameters and pressure, whereas Archimedes spiral seems to dominate in drawing exercises [8], [9] and [10]. The idea to analyse tracing of different patterns to distinguish PD from the other disease causing tremor was suggested in [11]. Some contributions report the results targeted either to analyze more specific type of disease or certain type of kinematic disorder. For example hand writing is analyzed in [12] to assess drug induced parkinsonism. Kinetic tremor is analyzed with respect to the age in [13]. Fine motor based approach to monitor development of the PD is proposed in [14].

The novelty of the approach proposed in the present paper has two key components. The first one is the digital Luria's alternating series tests, in the best knowledge of the authors there is no results available for this type of tests. Luria's alternating series tests consist of a number of different exercises, requiring different complexity of the motion planning. This allows to distinguish disorders on the different levels related to motion planning and execution. Within frameworks of the present research three of Luria's alternating series tests is will be used: continuing the series, copying the series and tracing the series. The second novel component is the set of kinematic parameters used to describe the motions. In addition to the selection of commonly used parameters, Motion Mass parameters [15] describing amount and smoothness of the motion will be used. The reason to add those parameters is that they were successfully used to describe differences in limb motions between the PD patients and healthy individuals (controls) [16]. The working hypothesis of the present research is, that fine motor motions of the PD patients, recorded by means of the tablet PC equipped with the stylus, during the

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digital Luria's alternating series tests differ from those of the healthy individuals. This should be reflect by the values of the kinematic parameters describing the motions. Also particular values describing performance of the particular individual should indicate if the disorder occurs on the level of planning the motion or on the level of executing the motion.

The rest of the paper is organized as follows. Necessary background knowledge about PD, Luria's alternating series tests and commonly used methods is provided in the Section II, the same section contains formal problem statement. Methodology, soft- and hard-ware tools are described in the Section III. Main results are present in Section IV. Conclusions and the possible directions of further research are drawn in the last section.

II. Background and problem statement

According to Luria, purposeful movement is the output of multilevel planning process [3]. It presumes certain goal to be accomplished. The first stage is the general planning, this level answers the question why and how some action should be performed. On the second level, concrete motion patterns are generated on the basis of general plan. These motion patterns are referred as *motion melodies* [3]. Motion melodies are the sequences of the motions, ordered in time, which should allow accomplishment of the goal. On the third level "orders" are generated to the direction of the spinal cord. On this level, melody of the motions is implemented. The present work is targeted towards detecting disorders on the second and third levels. Digital Luria's alternating series test are selected for this purpose.

The first Luria's alternating series test: *tracing the series* requires one to follow the periodic pattern. Tested individual asked to follow periodic pattern, for example sinusoidal line see "Fig 5" or the line consisting of the strait segments "Fig 4" (here and after referred as *PL - line*), with the pen. The second Luria's alternating test: *coping the series* requires one to copy periodic pattern. Pattern is drawn on top of the paper and tested individual is asked to draw the same on the bottom of the paper see "Fig 2 and 3". The third test: *continuing the series*, requires one to continue periodic pattern (PL line). Few segments of the pattern are drawn on the paper and tested individual is asked to continue the pattern see "Fig 1". In a non digitalized case, the neurologist or psychiatrist does assessment visually. If all the tests are problematic for the tested individual then the disorder is most likely on the third level where motion melody is outputted to the spine. Some of the Luria's tests are quite simple and do not require to generate complicated motion melodies. If the problem appears only during the third (more complicated test), and either do not appear at all or less severe for a simpler tests, then most likely disorder is on the second level where motion melodies are generated.

Unlike the human neurologist, computer perceives and processes the information by means of different numeric data. This leads the necessity to assign the set of numeric parameters or features describing how good tested individual was able to follow, copy and continue the lines. Tablet PC is able to record current position of the pen (stylus) in screen coordinates, current time and pressure applied to the stylus. Therefore, any goodness parameters should be defined on the basis of these attributes. This leads the following problem statement.

A. Formal problem statement

The present research targets two goals:

1) Select the set of kinematic parameters, to describe movements of the stylus tip during the digital Luria's series alternating tests, such that the values of the parameters would differ significantly for the groups of PD patients and controls.
2) Investigate behaviour of the selected set to identify the disorders on different levels of motion planning and implementation.

III. Methods and Tools

The work flow used during the present studies adopts commonly used scheme [4]. Data acquisition is performed on a tablet computer running Android OS equipped with application designed by the work group. It allows practitioner to specify the code of the patient and switch between different tests. Lines (patterns) to follow are prepared in such a way to allow approximately five cycles to continue and follow. In "Fig 1 - 5" thin dashed line represent the "etalon" to continue, copy or trace and thick line represent the result produced by typical PD patient. Designed application records Descartes coordinates of the stylus tip, pressure of the pen on the tablet screen and the time stamp. In the framework of the present studies, digital Luria's tests were given to the tested individuals in the reversed order. Continuing the series, copying the series and then tracing the series, such setting allows to minimize fatigues influence on the test results. Collected data then transferred to PC and processed in MATLAB environment. After the basic preprocessing which includes conversion of the coordinates to millimeters and artifacts removal three sets of the parameters are computed. The first set contains the feature selection commonly reported in the literature [8]. The second set are the motion mass parameters [15] adopted for the case of fine motor analysis. The third group are the measures commonly used to describe similarity between the trajectories and other sequential data. Namely mean square error MSE or the measure frequently used in machine learning area, dynamic times warping (DTW) [17], [18]. While the last set is well known and do not require special discussion, the first two sets are explained below.

A. Commonly used parameters

More than twenty years of research has resulted in the fact, that original set of four parameters proposed by [4] has grown significantly to nineteen parameters studied by [8]. In addition to kinematic parameters: velocity, acceleration, jerk, number of strokes and pressure [8], suggest to consider their horizontal and vertical components. Also specific features describing number of directional changes in velocity and acceleration are proposed. Within the frameworks of present research mean

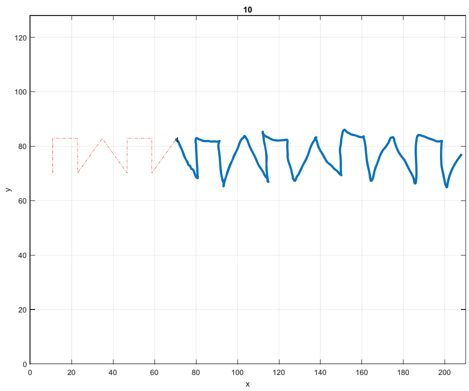

Fig. 1. PD patient continuing ”PL” line

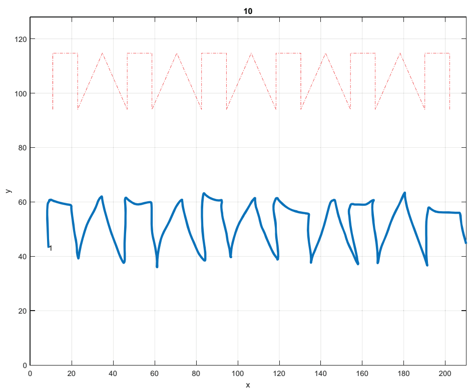

Fig. 2. PD patient copying PL line

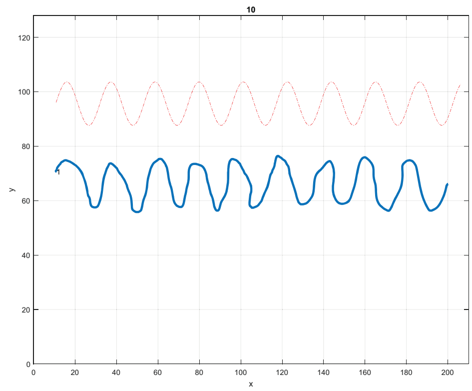

Fig. 3. PD patient copying sinusoidal line

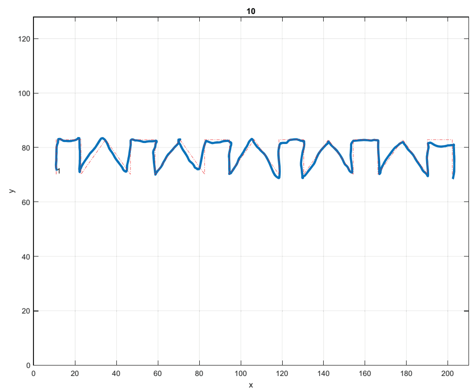

Fig. 4. PD patient tracing PL line

values of velocity $\overline{V}$, acceleration $\overline{A}$, jerk $\overline{J}$, directional change $\overline{D}$, strokes number S and pressure $\overline{P}$ are analyzed along with the motion mass parameters and measures of trajectory similarity.

B. The notion of Motion Mass

Motion mass parameters were introduced by [15] and [19] to describe amount and smoothness of the motion of a limb or some other group of joints. In its original version the motion mass was defined as a tuple of four values: trajectory mass, acceleration mass, combined Euclidian distance and length of the motion in time. The first parameter denoted by L_T is the sum of the lengthes of trajectories of each joint of interest. This parameter describes total amount of the movements performed. Acceleration mass requires one to compute absolute values of the accelerations at each observation points and sum their absolute values.

$$A_T = \sum_{i=1}^{n} |a_i| \tag{1}$$

where a_i acceleration computed at the ith observation point. Acceleration mass describes the smoothness of the motion. Lesser acceleration mass corresponds to the smoother motions. Combined Euclidean distance denoted by E_T is a sum of the Euclidian distances between the beginning and ending locations for each joint. Together with time t, Euclidean distance allows to normalize first two parameters. Later in [16] original set was complimented by the velocity mass:

$$V_T = \sum_{i=1}^{n} |v_i| \tag{2}$$

where v_i velocity computed at the ith observation point. Also the ratios of the acceleration and velocity masses to the combined Euclidean distance were added.

$$R_A = \frac{A_T}{E_T}, \quad R_V = \frac{V_T}{E_T} \tag{3}$$

This tuple of the motion mass parameters is denoted by M_T

$$M_T = \{L_T, A_T, V_T, E_T, R_A, R_V, t\}. \tag{4}$$

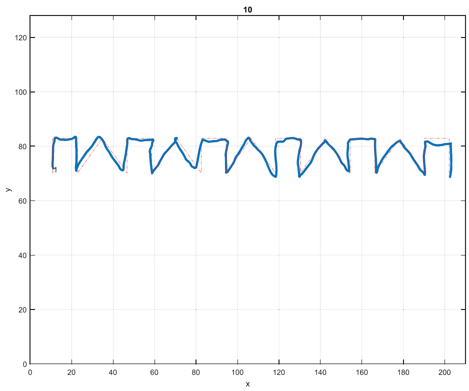

Fig. 5. PD patient tracing sinusoidal line

There are two considerations to take into account while adopting motion mass parameters for the case of fine motor motions. The first one is that space is limited by the size of the tablet screen and trajectories to follow are predefined. This make ratios (3) less informative compared to the gross motor case. The second one concerns the way controls perform the tests. Many of them artificially slowed down their motions to achieve a better precision in copying and tracing the lines. In order to "punish" such activity corresponding value of the motion mass parameters per second will be used. The following motion mass parameters has been chosen for the present research: trajectory length L_T, acceleration mass A_T, velocity mass V_T, length of the action in time t and ratios of the first three parameters to time L_T/t, A_T/t, V_T/t . While on the first view this may seem to be a simple averaging, one may easily check that this is not the case. In order to describe amount of the changes in pressure, direction and jerk by analogy to the velocity and acceleration masses *pressure mass*, *angular mass*, and *jerk mass* together with their ratios to time are introduced as follows.

$$P_T = \sum_{i=1}^{n} |p_i| \tag{5}$$

where p_i is the pressure measured at time instance i. Corresponding ratio to time will be denoted as P_T/t.

$$D_T = \sum_{i=1}^{n} |d_i| \tag{6}$$

where d_i is the angle between the direction at time instance i and time instance $i-1$. Corresponding ratio to time will be denoted as D_T/t.

$$J_T = \sum_{i=1}^{n} |d_i| \tag{7}$$

where j_i is the jerk at time instance i . Corresponding ratio to time will be denoted as J_T/t. Together with the measures of trajectory similarity and commonly used parameters this bring total amount of the parameters to be compared to twenty two. For each exercise, these parameters may be presented in the form of matrix, where rows correspond to the different individuals and columns to the different parameters. On the final step of the work flow the values of those parameters are treated as the samples representing PD patients on the one side and controls on the other. Ability to distinguish between the PD patients and controls on the basis of particular parameter is verified by means of two sample t-tests.

IV. Main Results

Some recent results already report application of the sophisticated machine learning algorithms to cluster and classify kinematic parameters observed during fine motor exercises [8]. Obviously machine learning techniques are more sophisticated in clustering and classification compared to classical statistical approaches. Nevertheless, simple statistical hypothesis based comparison has its advantages. First of all it does not require to chose and tune the values of hyper parameters, common in many machine learning techniques. Also statistical hypothesis testing is easer to interpret. Within the frameworks of present studies comparison of kinematic parameters will be performed in two steps. The first step is devoted to the comparing test wise the values of kinematic and pressure parameters between PD patients and controls. Then attention will is shifted towards comparing the changes between tests. Namely on the both sides (PD patients and controls) the differences between the following and tracing will be computed and compared. From the initial selection of twenty two parameters, quite many had to be dropped because their values appeared to be indistinguishable. Overall DTW similarity, motion mass and their alike parameters allow to distinguish PD patients from the controls in the majority of cases, whereas mean values of kinematic parameters did not change much between the PD patients and controls. For each test and each parameters the values computed for the PD patients and controls are compared in the following way. The null hypothesis H_0 is that the data in the samples representing PD patients and controls comes from independent populations with equal means, and the alternative hypothesis H_1 is that the data describing PD patients and controls comes from populations with unequal means. Tables I - IV summarize the results of two-sample t-tests at $\alpha = 0.05$ and $\alpha = 0.1$ significance levels.

A. Comparison of the PD patients and controls

Parameters compared below are computed on the basis of the data captured for the right hand of PD patients and controls. In the case of continuing PL line Jerk mass, ratio of the dynamic time warping to the time length of the motion and angular mass are different at $\alpha = 0.05$ significance level. Remaining parameters trajectory length, ratios of velocity mass and acceleration mass to time and strokes number are different with $\alpha = 0.1$ significance levels. See Table I.

In spite of the fact that copying PL line test is based on the same type of the line, the set of distinguishable parameters is

TABLE I
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS FOR CONTINUING THE SERIES TEST.

Parameter	p-value	t-statistic	α
J_T/t	0.0201	-2.5067	0.05
DTW/t	0.0105	-2.7954	0.05
D_T	0.0265	2.3788	0.05
L_T/t	0.0718	-1.8914	0.1
V_T/t	0.0534	-2.0244	0.1
A_T/t	0.0552	-2.0244	0.1
S	0.0549	2.027	0.1

TABLE II
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS FOR TRACING THE SERIES TEST, CASE OF PL LINE.

Parameter	p-value	t-statistic	α
DTW	0.0942	1.7494	0.1
D	0.0853	1.8015	0.1

different. Note that measure of trajectories similarity is present here. Later indicates the difference in the shapes of trajectories, see Tables II and III. Copying sinusoidal line appears to be slightly more complicated. Which resulted in the fact that three parameters differ significantly whereas the one of the at $\alpha = 0.05$ significance level. Tracing the series demonstrate similar results to copying the series with the slight change in the set of distinguishable parameters. Surprisingly tracing the sinusoidal line did not demonstrate significant difference between fine motor skills of PD patients and controls.

B. Comparison of copying and tracing the series tests

The previous subsection has clearly indicated that there may be difference between the same line drawn by the testee during different exercises. For example PL lines drawn by PD patients, during copying the series test were distinguishable from those drawn by controls by a greater number parameters than PL lines drawn during tracing the series tests. This leads the idea to compare PL and sinusoidal lines drawn by the same individual. The testing procedure is the same as for the previous case.

Results presented in the Tables V- VI indicate that in the both cases, PD patients and controls drawing of the PL differs a lot between different cases. Whereas less difference observed in drawing sinusoidal lines see Tables VII - VIII.

TABLE III
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS FOR COPYING THE SERIES TEST, CASE OF SINUSOIDAL LINE.

Parameter	p-value	t-statistic	α
D_T	0.0464	2.1102	0.05
t	0.0761	1.8612	0.1
DTW	0.0507	2.0670	0.1

TABLE IV
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS FOR TRACING THE SERIES TEST, CASE OF PL LINE.

Parameter	p-value	t-statistic	α
D	0.0191	2.5291	0.05
DTW	0.0739	1.8765	0.1
DTW/t	0.0960	1.7390	0.1

TABLE V
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS OF PD PATIENTS, COMPARISON OF COPYING AND TRACING TESTS, CASE OF PL LINE.

Parameter	p-value	t-statistic	α
D_T	0.0279	2.3296	0.05
V_T	0.0182	2.5204	0.05
DTW	3.3934e-06	5.8758	0.05
DTW/t	2.4989e-07	6.9033	0.05
L_T/t	0.0606	1.9616	0.1
A_T	0.0596	1.9694	0.1
J_T	0.0506	2.0494	0.1

TABLE VI
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS OF CONTROLS, COMPARISON OF COPYING AND TRACING TESTS, CASE OF PL LINE.

Parameter	p-value	t-statistic	α
D_T	0.0042	3.2710	0.05
T_L	2.0938e-06	6.8449	0.05
V_T	5.4854e-06	6.3556	0.05
A_T	0.0409	2.2023	0.05
DTW	5.5765e-05	5.2368	0.05
DTW/t	2.3849e-06	6.7778	0.05

V. CONCLUSIONS

Main result of the present paper describe the set of the kinematic and pressure parameters allowing to distinguish PD patients from controls on the basis of the digital Luria's alternating series tests. Digital Luria's alternating series tests have not been used before in conjunction with digital testing framework. Also unlike many other tests the battery of the digital Luria's series alternating tests allows not only to distinguish PD patient from the control but also indicates if the disorder occurs on the level of motion planning or motion implementation. The fact that for each test set of the distinguishable parameters varies is in pair with previously reported results. Also it supports the second working hypothesis of the

TABLE VII
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS OF PD PATIENTS, COMPARISON OF COPYING AND TRACING TESTS, CASE OF SINUSOIDAL LINE.

Parameter	p-value	t-statistic	α
DTW	1.7971e-06	6.1224	0.05
DTW/t	1.1757e-04	4.5256	0.05

TABLE VIII
DISTINGUISHABLE KINEMATIC AND PRESSURE PARAMETERS OF CONTROLS, COMPARISON OF COPYING AND TRACING TESTS, CASE OF SINUSOIDAL LINE.

Parameter	p-value	t-statistic	α
DTW	3.0039e-08	9.2333	0.05
DTW/t	8.2558e-06	6.16335	0.05

present research, that differences in values of the parameters reflect the disorders on the different levels of motion planning and execution. The second set of tests also indicates that fine motor performances differ more for the case of PL line which will be taken into the account for future studies.

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