

# The Modified Drawing Test for Assessment of Arm Movement Quality

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**Abstract**— The cerebrovascular accident often results in motor impairment of one of the upper limbs, hence, compromising the quality of life of stroke survivors. Rehabilitation aims to restore the movement abilities of the paralyzed/paretic upper limb. An important element in rehabilitation is to apply a quantified measure of the quality of movement, in order to follow the recovery and select the most appropriate therapeutic modality. We developed a method that uses data recorded during planar movements and outputs an objective measure that relates to the smoothness, velocity and precision of the movement. This method is universal, in a sense that hand position can be recorded by any available means (e.g., robot assistant, digitizing board, motion tracking systems, etc). The method follows the Drawing Test, but generates results that show the ability of the patient to make point to point movements and track the presented trajectory. The method is based on measurements of hand position during movement along a target path in form of a 2 cm wide rectangle. The patient's task is to move the hand along the target path as quickly as possible, with as few contacts (collisions) with the sides of the path. This paper addresses the aspects of automatic detection of parameters that quantify the quality of movement (speed, smoothness and precision). The use of this method is presented with 10 patients.

## I. INTRODUCTION

THE CEREBROVASCULAR ACCIDENT in the frontal cortex affects motor areas, and patients develop, among other problems, upper limb (UL) disability because of spasticity, muscular weakness, and disturbed muscle synergies [1]. The UL movement assessment is a qualitative and quantitative procedure, by which the quality of a patient's UL motor skills are evaluated. An objective quantification of UL disability contributes to better understanding of patient condition, and in addition could serve as a measure of efficacy of the rehabilitation treatment. In most cases, the assessment of UL functional and motor abilities is a subjective evaluation performed by clinicians. Functional ability tests of the UL typically use the following: dexterity and speed of single-hand movements; dexterity and speed of both hands (hand movements, picking up objects,

unbuttoning and buttoning, etc.); ability to write; and squeezing a dynamometer for measuring muscle strength [2-5].

In clinical trials evaluating functional electrical therapy, the first version of the Drawing Test (DT) was introduced as a measure of coordination of the elbow and shoulder joints during a functional task in tetraplegic and hemiplegic patients [6]. This DT required that a subject tracks on a digitizing board the 20 cm long sides of a square in the horizontal plane. The score was the ratio between the areas of the drawn square and the target square (20 cm x 20 cm). The test was validated in humans with no known motor disability [7]. The drawing of the square was found to be a complex task since it combined cognitive effort, while changing the direction of the movement, and motor skill. In order to eliminate the cognitive load when changing the direction of the movement, the DT was modified [8]. This version of DT was simple; it required that a subject makes self-paced radial, point-to-point movements within his/her horizontal working space. The score of the new DT measured the error of the end point during the point to point movement, and the difference in the direction of the line connecting the starting and ending point compared to the direction of the realized movement.

Recently, other similar methods for assessment of ability to control upper limb (UL) movements have been investigated. A haptic robot based method was presented by Bardorfer and colleagues [9]. In this work, subjects were assessed based on their performance in a maze tracking task. The maze was presented on a screen, while haptic properties of maze walls were provided by the OMNI robot. Another simple method for movement evaluation in post stroke rehabilitation introduced by Krabben and coworkers [10] is analysis of shape and size of circles drawn in horizontal plane. This method was later modified to robotic evaluation of reaching workspace with variable gravity compensation [11].

Here we describe quantitative metrics for assessing the movement quality, based on the measurements of hand position during the tracking of a rectangular path of a size achievable by the patient.

## II. METHODS AND MATERIALS

### A. Subjects

After extensive research with healthy individuals, tests were conducted with ten stroke survivors with right side hemi-paresis. Thirty healthy individuals (11 female, 19 male, age 25±4) were asked to participate in the study in order to

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evaluate normative values for used metrics. Both patients and healthy individuals provided signed informed consent, which was approved by the local ethics committee of the Clinic for Rehabilitation. Basic patient data is presented in Table I. Patients were asked to perform the test before and at the end of the three week rehabilitation program, which involved stretching exercises, muscle facilitation, strengthening activities, and practicing functional movements with the affected arm/hand.

TABLE I. BASIC PATIENT DATA

Age [Y]	62	38	61	65	62	68	52	57	59	61
Months after stroke	5	7	19	4	9	4	13	14	17	15
Fugl-Meyer	35	32	51	24	50	38	30	29	36	32

### B. Testing Procedure

The patient testing was supervised by an experienced therapist from the Clinic for Rehabilitation "Dr Miroslav Zotović", Belgrade, Serbia. The testing procedure comprised drawing a square based on the presented template, a 2-cm wide rectangular path. The path is formed by two concentric squares, with the side difference of 4 cm. The task is to complete the rectangular path (all four sides) as fast and precise as possible. The size of the template is determined by the initial measurement of subject's ROM. Movements started from the proximal contra lateral corner, proceeding to the distal contra lateral corner, and continued to cover the complete rectangular path. Subjects performed movements while seated, with their trunk secured in a harness, preventing any compensatory body movements. They held a handle with a broad smooth base, which enclosed a magnetic pen. The broad smooth base allowed stability and minimized friction with the work surface. The magnetic pen position was captured by Intuos 4 XL drawing board (Wacom, WA, USA), with sampling frequency of 100Hz and resolution of 0.05mm. The testing setup is shown in Fig 1.

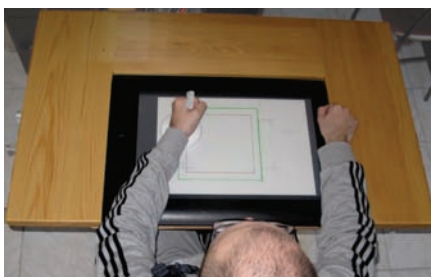


Fig 1. Testing setup

### C. Outcome Measures

The outcome measure of this test comprises three objective measures: movement speed, movement precision error and movement smoothness. The average speed was calculated as the ratio of length of a single side of the square and the time used to complete that side. The precision error was calculated as the area of transgressions outside the path. Areas enclosed by the drawing and template lines outside the path were detected, counted, and measured automatically, using the image processing methods. Precision error was defined as the total area of transgressions multiplied by their number, normalized with respect to the area of the template square. Example of transgression detection is presented in the right panel of Fig 2, marked with red color. Smoothness measure was defined as a function of four smoothness parameters proposed in [12].

### D. Data Analysis

These movement characteristics were evaluated for each of the square sides; therefore it was necessary to segment square drawing into four sides. The drawn shapes seldom looked exactly like a square, and were never drawn in four strokes, which made the movement segmentation a challenging task. For this purpose, an iterative algorithm which automatically detects "square vertices" was developed.

The algorithm consists of three steps depicted in the left panel of Fig 2. The first step in this algorithm is to detect the points where each of the central lines (AB, BC, CD, DA) is crossed for the first time. The next two steps are repeated for each vertex, and will be explained on the example of B (Fig 2). As stated earlier, the size of the template square was smaller than patient ROM; therefore patients should be able to, at least, reach each side of the square. The second step is based on this fact. Here, an iterator starts from the previously determined point of BC crossing and moves backwards, until it reaches the point where the X coordinate (dominant direction of segment) crosses the X coordinate of B vertex of the inside square template. This point is the "first landmark" (LM1). Around it, we search for the closest point where the Y coordinate (non-dominant direction) crosses the inside template vertex. This is the "second landmark" (LM2). The vertex is determined in the third step. It is the point closest to the landmarks where velocity has a local minimum.. Usually it is the point with zero speed, but there are instances where subjects do not pause at the vertex (e.g. point C, shown in Fig 2).

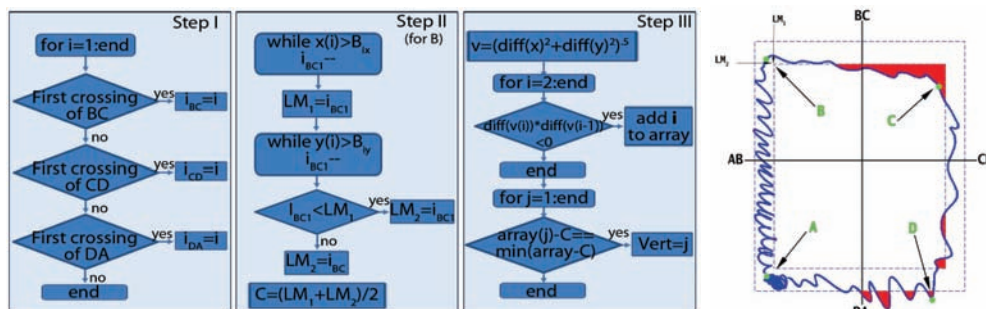


Fig 2. Algorithm for vertex detection (left) and an example of drawing with detected vertex (right). Detected vertices are labeled A, B, C and D, while landmarks from the given example at point B are labeled LM1 and LM2. Transgression areas are presented in red color.

Once the vertex indexes are identified, the algorithm for calculating **Speed** for each side is trivial, and comes down to:

$$Speed(i) = \frac{L \cdot F_s}{Iv(i+1) - Iv(i)} \quad (1)$$

where  $Iv(i)$  is the index of the  $i^{th}$  vertex,  $L$  is the length of the path segment, and  $F_s$  is sampling frequency.

The **precision error** was calculated using the image processing algorithm. The first step of this algorithm was to plot the drawing of the given side, along with the internal and external model squares, and transform the plotted image into a binary image. In order to ensure the continuity of the drawing, both ends of the drawn side are connected by straight lines to the appropriate vertices of the path central line (Fig 3. left).

Identification of areas outside the external square was performed by morphologically filling the binary image, and then removing pixels enclosed by the outer square from the obtained shape. Hence, all the transgressions outside the external square remain as objects in the binary image (Fig 3. middle). In order to identify areas inside the internal square, the original binary image was first cropped to size of the internal square. The side of square opposite to the side in question was deleted, and the remaining binary image was morphologically filled. After removing the pixels belonging to the remaining internal square, the remaining objects represent the transgressions (Fig 3. right). Total area of transgressions was calculated through pixel count of all objects outside and inside the model. Finally, precision error of the  $i^{th}$  side can be calculated as follows:

$$Precision\ error(i) = e^{(A_o + A_i) \cdot (N_o + N_i)} \quad (2)$$

where,  $A_o$  and  $A_i$  are total areas of transgressions, and  $N_o$  and  $N_i$  are numbers of individual transgressions (outer and inner, respectively).

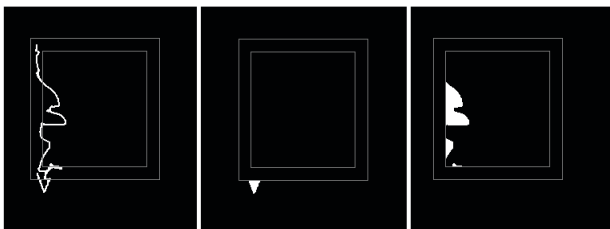


Fig 3. Steps in determining precision error: Binary image of one side drawing and model squares (left), transgressions from the outer side (middle), and transgressions from the inner side (right).

The **smoothness measure** was calculated as a function of four movement parameters proposed in [10], normalized with respect to average performance of healthy individuals. Smoothness of the  $i^{th}$  side was calculated as:

$$Smoothness(i) = e^{(J_h + J_i)} + e^{(P_h - P_i)} + \frac{V_i}{V_h} + \frac{T_i}{T_h} \quad (3)$$

where  $J_i$  is the ratio of mean negative jerk (third derivative of position) and peak velocity of the  $i^{th}$  side;  $P_i$  is the number of peaks in the velocity profile of the  $i^{th}$  side;  $V_i$  is the ratio

of mean velocity and peak velocity of the  $i^{th}$  side; while  $T_i$  is the ratio of area under the velocity profile and its convex hull [10]. Terms  $J_h=1.15$ ,  $P_h=1$ ,  $V_h=0.5$  and  $T_h=0.9$ , areheuristically determined normal values of observed parameters.

We also present a score which takes into account **speed**, **smoothness** and **precision error** metrics. It is calculated as

$$Score = \frac{Speed \cdot Smoothness}{Precision\ error} \quad (4)$$

**Speed** is given in m/s, **smoothness** is in percentages, while the **precision error** and **score** are numerical values in ranges  $[1, +\infty)$  and  $[0, 1]$ , respectively.

The entire testing procedure is supported by custom made software with user friendly interface (Fig. 4) which enables simple testing, and instant access to results. In order to expedite the testing procedure, only basic commands and the **score** are provided in the main window, shown in top panel of Fig. 4. Additional analysis of the performed movement is supported by the software, and can be accessed in the "Detailed results" window, shown in bottom panel of Fig. 4.

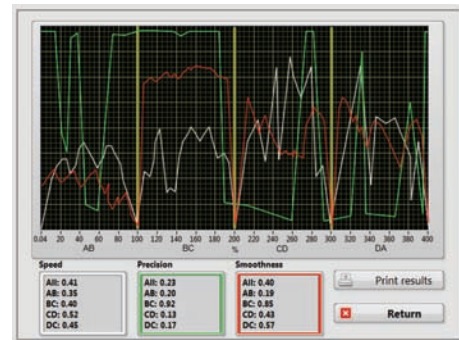
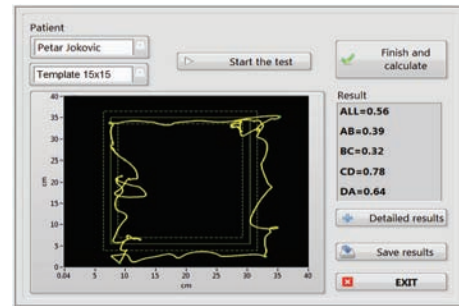


Fig 4. User friendly software interface. Main window provides intuitive comands for the testing procedure and the **score** (top panel). Individual metrics can be examined by the operator in the "Detailed results" window (bottom panel).

### III. RESULTS

Ten hemiparetic patients performed the drawing test before and after the three week long therapy program. Test results are presented in Fig 5.

Based on the two-tailed T test ( $df=18$ ,  $\alpha=0.05$ ,  $T_{critical}=2.1$ ), prior to therapy, **speed** in the AB segment was significantly lower in comparison to all other segments ( $p<0.02$ ). **Speed metrics** in segments BC and DA are similar and significantly higher than **speed** in CD ( $p<0.05$ ). **Smoothness** of movements performed in the AB segment

was significantly lower than in other segments ( $p < 0.04$ ), which all have similar **smoothness**.

There were no significant differences in **precision error** between different segments.

When all metrics are taken into account, the lowest **score** was obtained in the AB direction ( $p < 0.02$ ), while all other segments have higher **scores**, similar to each other, except in CD segment where **score** is significantly lower than in DA ( $p < 0.04$ ).

After therapy, the **speed**, while generally higher, had the same distribution through segments. The AB segment was significantly lower in comparison to all other segments ( $p < 0.04$ ). **Speed** segments BC and DA are similar and significantly higher than **speed** in CD ( $p < 0.05$ ). On the other hand, **precision error** decreased in all segments, which were similar to each other. **Smoothness** in the DA segment became significantly higher than in other segments ( $p < 0.05$ ), which were similar to each other. The **score** in segment DA was significantly higher than in other segments ( $p < 0.02$ ), while the score in AB was significantly lower ( $p < 0.05$ ).

All metrics show improvement in all segments of the test, as well as in overall performance. All **speed** improvements were significant ( $p < 0.05$ ), except in the DA segment. Improvements in **smoothness** were significant in AB ( $p = 0.03$ ) and DA segments ( $p = 0.04$ ). **Precision error** improvement was not significant in any segment. On the other hand the improvement of **score** was significant in all segments ( $p < 0.04$ ).

#### IV. DISCUSSION

Due to spasticity and disturbed muscle synergies, stroke survivors find movements which include shoulder and elbow extension especially challenging [1]. This method measures speed and precision of four different hand movements in the horizontal plain.

As shown by the results of this pilot study, some of these movements are more indicative than the others. It is observed that segments AB and CD were especially challenging for subjects, whereas segment DA was the least troublesome, prior to therapy. This fact was used by Eder et al. who successfully assessed UL movements by observing the AB segment only [8]. On the other hand, improvement due to therapy is significant in all segments, which is strongly reflected in the combined score, but is not consistent in each individual metric. Therefore, obtaining information about each segment may allow more comprehensive analysis of current patient condition and progress.

The main advantage of the method suggested by Eder et al. is its simplicity, which makes it practical for clinical use. Any involvement of the operator in data analysis (e.g. manual selection of regions of interest, manual segmentation, etc), prolongs the testing time and imposes additional burden on medical staff, making the test less efficient, and less desirable in everyday practice.

The proposed modified drawing test comprises algorithms embedded in software, which performs complete data analysis automatically. The algorithm for vertex detection segments the drawing with high accuracy, which allows calculation of results for each segment and the entire test. When the subject completes the test, results are instantly shown to the operator, along with the drawing on which the detected vertices are presented (Fig. 4.). The software enables analysis of UL movements in each segment individually, but also analysis of interdependent relations between different movements, as well as at transition from one segment to the other.

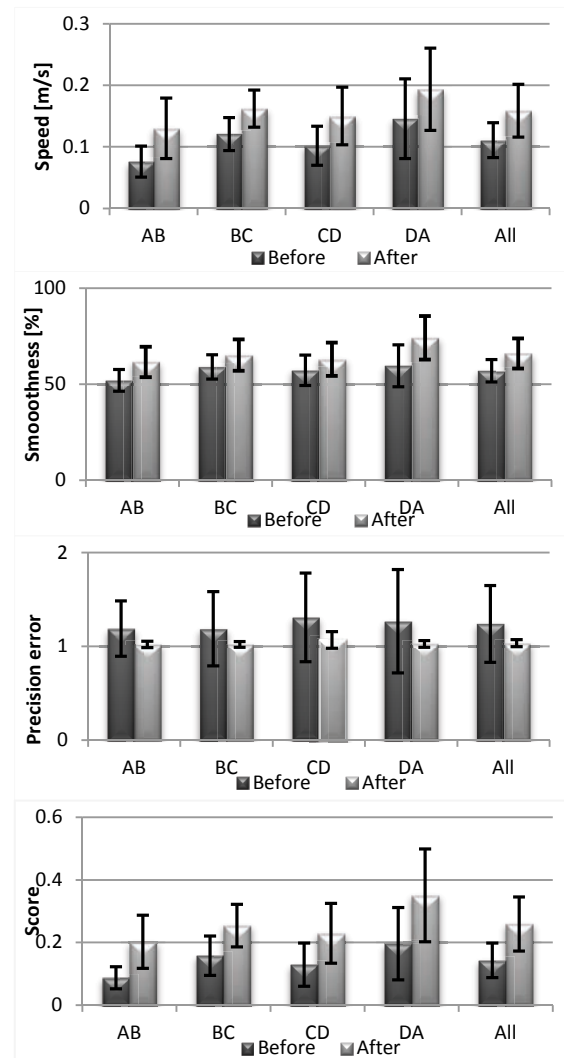


Fig 5. Modified drawing test group results (mean and st. dev.), before and after the rehabilitation program. Speed, smoothness, precision and overall score are presented, top to bottom, respectively.

#### V. CONCLUSION

The results of this pilot study show significant increase of proposed metric scores after therapy, thus suggesting that the method is sensitive to motor control improvement which occurs during rehabilitation treatment. Based on its comprehensiveness and simplicity of use, we propose usage of the Modified Drawing Test as a useful tool in quantitative assessment of UL disability and measure of efficacy of the rehabilitation treatment.

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