Computer Methods and Programs in Biomedicine 238 (2023) 107621

Contents lists available at ScienceDirect

Computer Methods and Programs in Biomedicine

journal homepage: www.elsevier.com/locate/cmpb

A smart tablet application to quantitatively assess the dominant hand dexterity

Alessandra Angelucci[a,*], Marco Damiani[c], Andrea Aliverti[a], Marina Scarlato[b]

[a] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milano, Italy
[b] Department of Rehabilitation, Istituto Clinico Quarenghi, San Pellegrino Terme, Bergamo, Italy
[c] Neurorehabilitation Unit, Istituto Clinico Quarenghi, San Pellegrino Terme, Bergamo, Italy

ARTICLE INFO

Article history:
Received 3 April 2023
Revised 24 May 2023
Accepted 24 May 2023

Keywords:
Digital health
Dominant hand
Hand dexterity
NHPT
Neurodegenerative disorders

ABSTRACT

Background and objective: The Nine-Hole Peg Test (NHPT) is the most used test to assess hand dexterity in clinical practice and is considered the gold standard but only evaluates the time needed to complete the task. The aim of this work is to describe a graphic test on a smart tablet to assess in a quantitative as well qualitative way the dominant hand dexterity and to validate it in a cohort of neurological subjects and healthy controls.

Methods: The task consists in asking the subject to connect with a graphic line the start and the end point of a pre-defined path, with two different widths, in the most precise and fastest way possible. The path is constituted by a 'meander' and a 'spiral' part. The subjects perform the task on a smart tablet with a capacitive pen four times. The three parameters of interest considered at each trial are the execution time, length path, and number of interactions with the border. The app automatically computes these three parameters and stores the completed test files. The results of the digital graphic test are compared to the NHPT results. Healthy and pathological subjects are compared to each other, and performances obtained in different repetitions are compared to assess the learning effect in each population.

Results: 53 subjects with a definitive diagnosis of neurodegenerative/genetic neurological disorders (34 men, mean age 59.1 $\pm$ 16.1) and 78 healthy controls (33 men, mean age 42.5 $\pm$ 16.3) were recruited. Among the pathological subjects, 31 also performed the NHPT. The graphic test clearly distinguish between the two populations for all parameters of interest. Moreover, compared to the gold standard NHPT, time has a moderate positive correlation ($r = 0.57$, $p \leq 0.001$), whereas interactions and length have a strong positive correlation ($r = 0.81$, $p \leq 0.001$) and ($r = 0.69$, $p \leq 0.001$), respectively.

Conclusions: The proposed digital test can measure in an accurate, quantitative and qualitative way dominant hand disability and can result more informative with respect to the gold standard NHPT. In homogeneous cohort of subjects (for example affected by multiple sclerosis or Parkinson disease), the digital test can be used as an outcome measure in clinical trials as well as a tool for monitoring disease progression at the dominant hand level.

1. Introduction

Dexterity is defined as a manual ability requiring a rapid coordination of fine and gross movements, basic abilities developed through experience, learning, and training [1]. Any alteration or reduction of dexterity due to aging, diseases, or injuries has a disabling effect on the execution of daily activities. In this digital world, also many new technologies improving accessibility for people with disabilities are based on hand dexterity, such as mobile telephones, smart devices, and home automation solutions. In almost all neurological diseases, there is a dominant hand impairment impacting functional independence and activities of daily living.

Assessing dexterity alteration is therefore crucial for establishing disability. There are different validated tests to assess it. Most of them can only give a qualitative evaluation; others use only quantitative measures based on a time limit, inducing a floor effect. These tests are divided into three groups: tests to functionally evaluate several activities to assess the upper limbs performance, time trials based on a single task that needs to be completed, and questionnaires administered to the patients.

Time trials that require the repetition of a single task include the Nine Hole Peg Test (NHPT) [2], the Buttoning Test (BT) [3], the Box and Blocks Test (BBT) [4], the Minnesota Manual Dexterity Test

* Corresponding author.
E-mail address: alessandra.angelucci@polimi.it (A. Angelucci).

https://doi.org/10.1016/j.cmpb.2023.107621
0169-2607/

(MMDT), the Workability Rate of Manipulation Test [5], and the Twenty-Five Hole Peg Test (TFHPT) [6].

Among the tests listed, the NHPT is by far the most used in clinical practice [7]. This test is administered by asking the patient to take the pegs from a container, one by one, and place them into the holes of a board with 9 holes, as quickly as possible. Participants must then remove the pegs from the holes, one by one, and replace them back into the container. Scores are based on the time taken to complete the test activity, recorded in seconds; there is a time limit of 300 s to complete the test. There are however several limitations of the NHPT. Once the test has been performed, only a score remains, without further possibility to review exactly how the patient did in each phase of the test; it is not possible to distinguish between subjects that are slow but precise and subjects that take more time due to imprecisions or difficulties in performing the task itself. Finally, the presence of a time limit introduces a floor effect on people with severe upper limb dysfunctions [8].

To overcome such limitations, we developed a new graphic test on paper and validated against the NHPT [9]. Both the NHPT and the paper graphic test require short time and no training to be completed, and are inexpensive. The paper graphic test was composed by three paths, each one composed by two configurations: the first part is meander-shaped, the second is an Archimedean spiral. From the bottom to the top of the paper, the width of the paths becomes smaller to increase difficulty. The subjects have to connect a continuous line inside the path determined by black borders in the most precise and fastest way possible. The aim is to connect the two black points, the starting and the ending one, without touching or crossing the borders. The test is performed twice to evaluate a possible learning effect between the two repetitions. Each path is manually timed by an operator, thus causing variability. In the validation study of the graphic test on paper [9], three parameters were analyzed, among which total time, total length, number of touches and crossings of the borders, namely interactions. The comparison between the NHPT and the time showed a strong positive correlation ($r = 0.71$, $p < 0.001$) whereas touches and crossing ('interactions' with the borders) a weak positive one ($r = 0.35$, $p = 0.01$). Times and interactions, however, were not correlated, showing that the paper test could be performed fast without much concern for the quality of execution. The graphic test allows to distinguish between a slow but precise performance and a fast but imprecise performance, thus providing additional information with respect to the NHPT, where the time to complete the task takes into account both the time to pick the peg and the trajectory to reach the hole.

The aim of the present work is to provide an evolution of the original graphic test, now digital, on a smart tablet, and to validate it in a cohort of subjects with neurological diseases and healthy controls. The three parameters taken into consideration are still the execution time, length, and interactions (touching or crossing path borders) occurred . Time is a parameter of interest in many gold standard tests. Length is a relevant information, being an indicator of quality of execution of the graphic line, or of the presence of tremors or other involuntary movements. The number of interactions is also an indicator of the quality of the hand control, in particular planning and sequencing movementsand therefore of the global performance. Moreover, the digital version facilitates the preservation of the tests providing the picture of the task performed and therefore the follow-up.

2. Materials and methods

2.1. Materials

The following devices were used: a 10″ screen size Android tablet (Lenovo M10 Plus), and a capacitive pen to draw lines on the tablet. It was necessary to use a glove to obtain palm-rejection, not featured by the tablet selected for the work. The used glove is composed by an external layer of Elastane, a middle layer of cotton wool and an internal layer (in contact with the palm of the hand) of stretch jersey.

Android Studio was employed to develop the actual application. The entire backend architecture of the application exploits Google Firebase services. Firebase Authentication was used to manage the authentication of the users, only through personal email and password. Firebase Realtime Database is a cloud-hosted NoSQL database. Data is stored as JSON and synchronized in real time to every connected client. It was used to store data related to tests, patients, and practitioners and to synch them with all possible connected tablets. Firebase Storage was used to manage the savings and the backup of the file of the tests already submitted.

2.2. Methods

2.2.1. Data collection

All 131 subjects recruited gave written informed consent to participate in the study. The present study was approved by the Papa Giovanni XXIII Hospital Ethical Committee (approval number 40/22).

All subjects enrolled in the study wore the previously described glove while using the tablet. The experimental setup is shown in Fig. 1.

Enrolled subjects were first allowed to get familiar with the glove, the capacitive pen, and the tablet, by means of pre-training paths. Especially non digital natives and subjects with neurological disease performed maximum three pre-training paths, a triangle, an exagon and a circle, to get used to the tablet. Those attempts were not recorded. Then there was a pop up window with written instructions saying that the starting and the ending point had to be connected, the test was a time trial, and finally that borders could not be touched or crossed.

Then, subjects were asked to follow four test paths: a first 'wide' test, then a 'narrow' test, a second 'wide' test, and a second 'narrow' test, where 'wide' and 'narrow' refer to the path width.

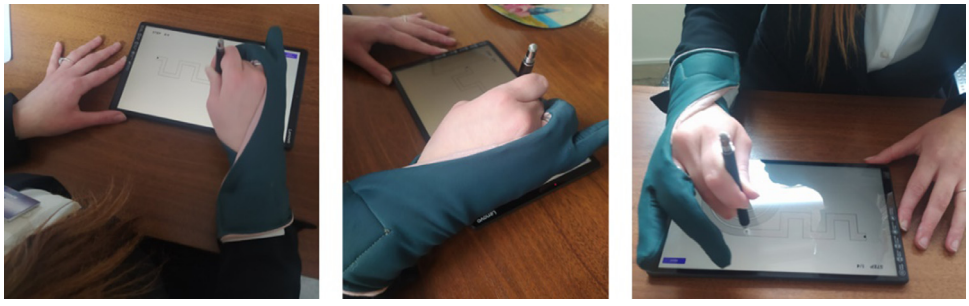

Fig. 1. Experimental setup: smart tablet app and subjects wearing a glove to achieve palm-rejection.

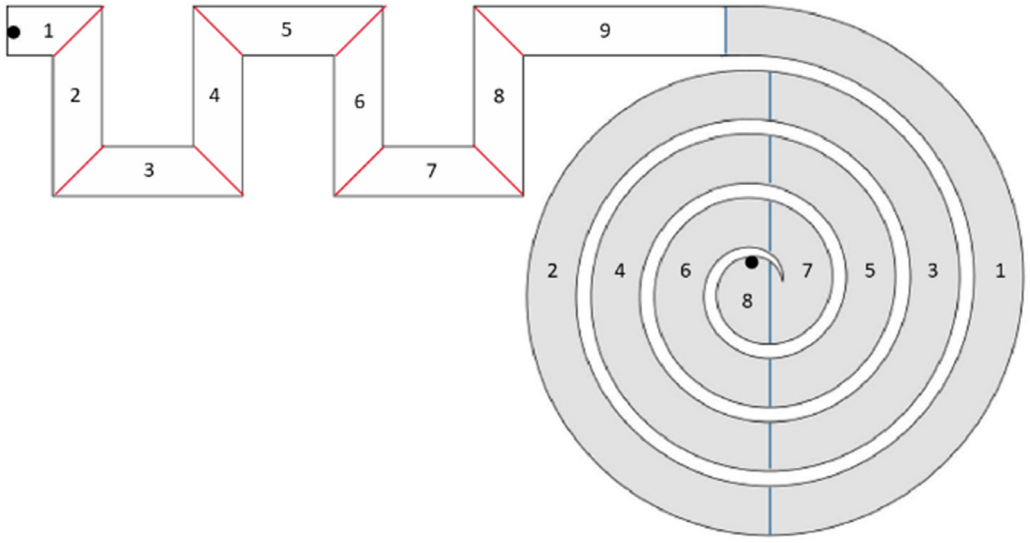

Fig. 2. Subdivision of border and internal corridor through separators (red and blue lines).

During the same day, 31 subjects with neurological diseases also performed with the dominant hand the NHPT twice, and the best time out of the two was made available for validation purposes.

2.2.2. Image pre-processing

The objective of the pre-processing is to elaborate the baseline image of the single paths and assign to each pixel specific labels. To detect the starting and ending points, pixels composing these buttons are labelled differently. To detect the passage from the meander to the spiral tract, pixels of the line dividing the two parts are labeled separately. For each pixel of the path's contour, it is indicated if it is part of the upper or lower border, if it is part of the meander or spiral part and which sector it belongs to. Sectors are different segments of the path, divided as shown in Fig. 2. Moreover, separators, indicated in red and blue in Fig. 2, are computed and pixels composing each of them are labeled differently based on sequential numbers, so that each pixel will address a single separator univocally. Lastly, with the same labeling system, also pixels inside the 'corridor' are acquired, but only those having at least one side in contact with black contours. This is needed to detect whether the line enters or exits the path after a border is touched.

2.2.3. Application development

When opened, the first activity called by the application is the 'Launching activity', appointed to check if the device is connected to an available network. If this control is successful, the application starts a new activity: if the user is already logged in, the software will start the 'Visualization activity', otherwise the 'Registration/Login activity' will display first. The 'Visualization activity' displays two main fragments, or tabs. One fragment allows the visualization of the list of patients tested; if one item of the list is pressed, another fragment displaying the list of tests submitted by the selected patient will be loaded. If a test in this second list is clicked, a new fragment will appear, showing data belonging to that test chosen. The other fragment-tab shows some buttons for the triggering of some specific functionalities. Here, if the user presses the button to start the acquisition of a new protocol, the application starts the 'Test activity', which is the one dedicated to managing all phases concerning the test protocol. Inside this activity, many fragments are displayed in sequence: the first fragment allows the registration of patient's data (ID, sex, age); the second fragment manages the training phase, aimed at getting the patient used to drawing on the tablet's touch screen. The second fragment also includes a pop up window with written instructions saying that the starting and the ending point have to be connected, the test is a time trial, and finally that borders cannot be touched or crossed. The third fragment is the one managing the actual test: it scrolls through the four sub-tests of the protocol and manages the extraction of parameters. The four sub-tests are in the following order: first repetition of the 'wide' path, first repetition of the 'narrow' path, second repetition of the 'wide' path, and second repetition of the 'narrow' path. The last fragment is the one handling the upload of files in remote repositories. After the upload is over, the user can go back to the 'Visualization activity', which works as the Home Page of the entire application when the user is logged in. This architecture is shown in Fig. 3.

2.2.4. Processing for parameters extraction

During the execution of the test protocol, the application elaborates images of the sub-tests completed, to extract parameters for the evaluation of individuals' performances. The process is composed by two threads running in parallel. One thread is responsible for the calculation of 'Length' and 'Time' parameters. The fundamental step is to find at which coordinate (*T point*) of the image space the patient crossed the line dividing the meander and spiral parts. Found this, the distance covered in the meander is calculated by summing, up to the *T point*, distances of consecutive couples of points composing the line drawn by the subject and acquired by the Android system. The same is done for the remaining part of points to retrieve distance covered in the spiral tract. For each point acquired a time instant is associated: the time spent in the meander is the difference between time instant for the first point and that of *T point*. The difference of time instants of *T point* and last point is the time spent in the spiral part.

The other thread is the one implementing the off-line tracking system, which parses lines traced by the subject and locates each point with respect to sectors composing paths of the graphic test. Since the beginning of the exercise is forced to be at the starting button, it is possible to suppose as starting conditions that the line is 'inside' the corridor and in the first sector of the meander part. For each pixel composing lines some evaluations are performed. The algorithm checks if that pixel considered is overlapping one of the separators: if true, knowing the current position of the line and knowing which separator has been crossed, the algorithm easily retrieves the new sector in which the drawn line is entering. If false, the procedure checks if the pixel considered is overlapping

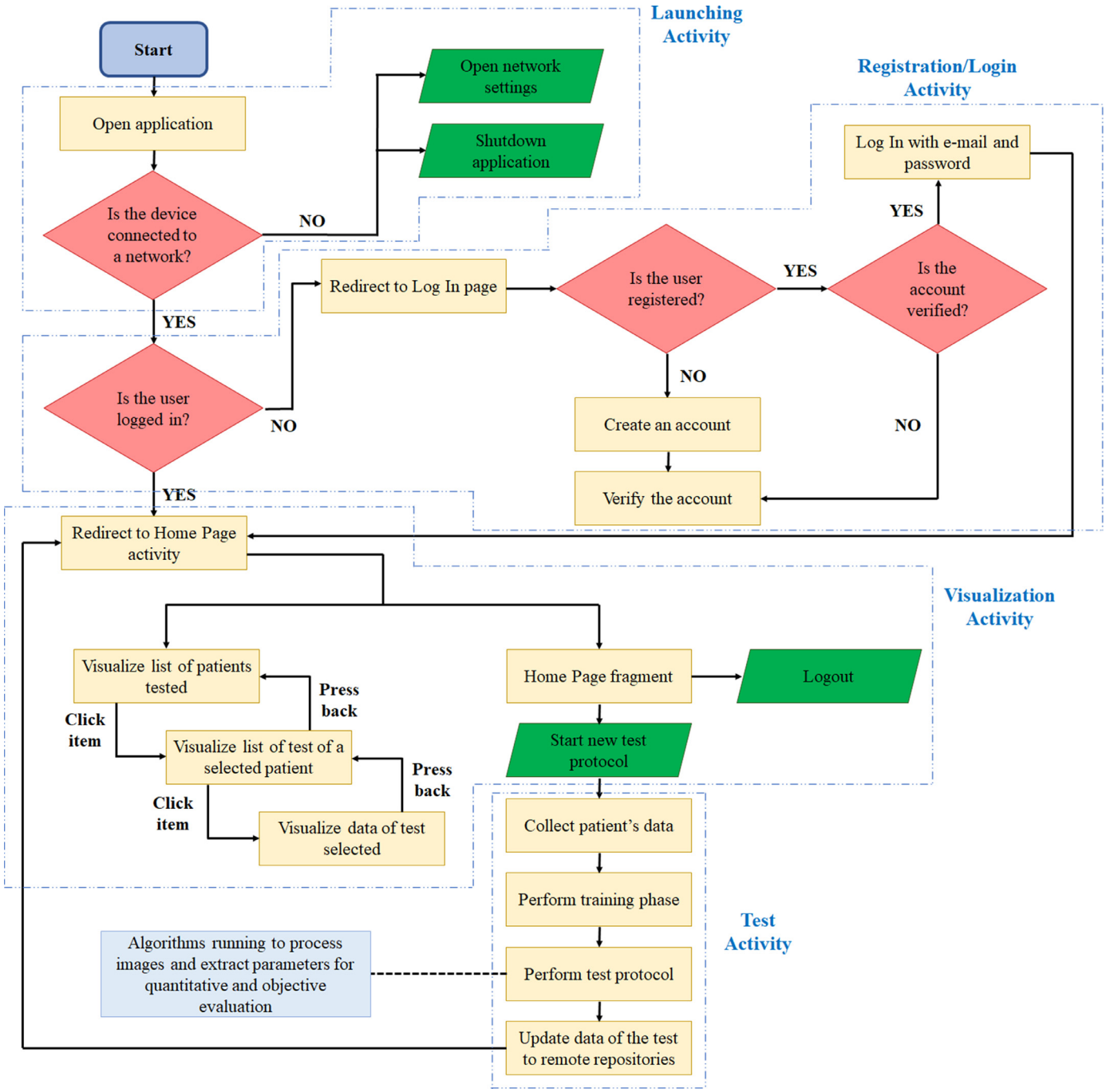

Fig. 3. Flowchart of the application.

one of the pixels of the contour. If false, all checks are negative, so the algorithm passes to consider the next pixel of lines. If it is true that there is overlapping with the contour, the algorithm checks the following points until it finds a point not belonging to the border (*X point*). Once the X point is found, the process checks if it overlaps one of the pixels belonging to the 'corridor' and which have been extracted during the pre-processing. If this check is true, it means the line is currently inside the corridor; if before touching the contour it was already inside, that interaction with the border is counted as 'border touch interaction', if it was outside that interaction with border is counted as 'border crossed interaction', and the location of the line turns to be 'outside'. If the *X point* is not contained inside the corridor, the reasoning is reversed (the border is either touched from outside or crossed from the outside to the inside). Therefore, with this mechanism the algorithm can track, pixel by pixel, the position of the lines and it is able to extract the number of times there are interactions with the contours. The sum of these interactions gives an overview of how precise the execution of each task has been.

2.2.5. Statistical analysis

An ad hoc software written in the Python programming language and based on the tools for statistics of the SciPy library [10] was used. The main characteristics of the distributions (median, inter-quartile range, mean, standard deviation, maximum, minimum) were computed for times, lengths, and interactions in

Table 1
Characteristics of the test population.

Label	Disease	Total participants	Age mean ± std [years]	Men / women participants	NHPT available
0	Healthy controls	78	42.5 ± 16.3	33 / 45	–
1	Ataxic syndromes	10	42.2 ± 13.1	2 / 8	3
2	Multiple sclerosis	10	54.1 ± 9.1	6 / 4	10
3	Stroke	7	75.6 ± 12.8	7 / 0	4
4	Parkinson's Disease	7	70.7 ± 9.8	4 / 3	3
5	Polyneuropathies	11	60.7 ± 14.6	10 / 1	6
6	Other Neurological Diseases	8	59.6 ± 11.05	5 / 3	5

Table 2
Test results – Time [s].

Population	Path	Median	Inter-quartile range	Mean	Standard deviation	Maximum	Minimum
Healthy	Wide	38.08	19.49	40.95	13.75	89.38	9.19
	Narrow	46.90	19.53	50.17	15.99	97.45	8.72
Pathological	Wide	69.70	30.47	75.78	29.51	165.04	32.73
	Narrow	80.63	30.16	84.51	27.31	147.18	42.28

the case of healthy and pathological subjects. Data are divided by path size, i.e., 'wide' or 'narrow'.

Healthy subjects were compared to pathological subjects on their performances divided by 'wide' and 'narrow' path (time, length, and interactions). After the Shapiro-Wilk test to check for normality, the tests chosen were the independent samples *t*-test for normal distributions and the Whitney U Test for non-normal distributions.

To assess the learning effect between the first and the second test, the paired distributions of the total time, length, and interactions in the first and in the second sheet were checked for normality with the Shapiro-Wilk test. Due to the non-normality of the distributions, the Wilcoxon signed-rank test was used to assess if there was any statistically significant difference. The learning effect was tested separately for healthy and pathological subjects.

For some pathological subjects, also NHPT results were available. Only NHPT results for the dominant hand were considered. After assessing the non-normality of the NHPT results distribution, the Spearman's correlation coefficient was computed between total time and NHPT, total length and NHPT, and total number of interactions and NHPT.

3. Results

3.1. Subjects affected by neurological diseases versus healthy controls

A total of 53 subjects with a definitive diagnosis of genetic or neurodegenerative disease (34 men, mean age 59.1 ± 16.1) and with the dominant hand always affected were recruited as well as 78 healthy controls (33 men, mean age 42.5 ± 16.3). The two cohorts were not aged matched. Among the pathological subjects, 31 also performed the NHPT.

The cohort of subjects with neurological disease was a mixed population regarding the disability grade and the anatomical pathway involved in order to represent the clinical variety. The characteristics of the population are summarized in Table 1.

The digital version of the graphic test, as the previous paper version, allows to distinguish between controls and pathological performances for all the tree parameters. Moreover, also in this digital version the narrow path requires longer time of execution for all subjects.

Tables 2, 3 and 4 summarize the results obtained by healthy and pathological subjects. The reported parameters are the following for each distribution: median, inter-quartile range, mean, standard deviation, maximum and minimum. All parameters in these tables represent the aggregated results of the first and second test repetition without distinction. All the distributions analyzed were not normal according to the Shapiro-Wilk test. When control subjects were compared with the Mann Whitney Test to pathological subjects on each parameter, there was always a statistically significant difference (time, length, and interactions, both for the 'wide' and the 'narrow' path) with $p<0.001$ in all cases. This differs from the results obtained on paper [9], where length was not significantly different between healthy and pathological subjects. These difference can be due to the different softwares measurement. Bigger and more homogenous (for example same disease) sample size group are needed to confirm this data.

It must be noted that the median value of interactions in the 'wide' path is slightly higher than the value in the 'narrow' path in the case of pathological subjects, as it emerges from Table 4. The values are very similar to each other, and in fact there is no statistically significant difference between the two distributions ($p = 0.17$).

Boxplots of the 'wide' and 'narrow' paths, with the first and second test aggregated, are reported for time, length, and interactions for all the diseases in Fig. 4.

All pathological subjects regardless of pathology required more time for drawing the line into the narrow path with the polyneuropathy and OND groups less changing in the two conditions. Interestingly, the interactions with borders are more in the wide path than in the narrow one as if the reduced width works as a binary. Finally, the low interactions number of the multiple sclerosis group is to be noted. That is probably relates to the small size

Table 3
Test results – Length [mm].

Population	Path	Median	Inter-quartile range	Mean	Standard deviation	Maximum	Minimum
Healthy	Wide	1493.25	40.42	1498.92	74.11	1808.21	1005.14
	Narrow	1498.61	33.52	1499.33	92.78	1830.9	810.46
Pathological	Wide	1589.39	175.76	1613.99	123.74	1955.88	1418.52
	Narrow	1563.33	132.47	1606.68	121.66	2016.70	1390.59

Table 4
Test results – Interactions.

Population	Path	Median	Inter-quartile range	Mean	Standard deviation	Maximum	Minimum
Healthy	Wide	0.0	1.0	2.5	8.1	52	0
	Narrow	0.0	0.0	1.9	6.2	42	0
Pathological	Wide	13.0	33.0	19.3	20.5	84	0
	Narrow	10.0	20.0	13.8	18.2	102	0

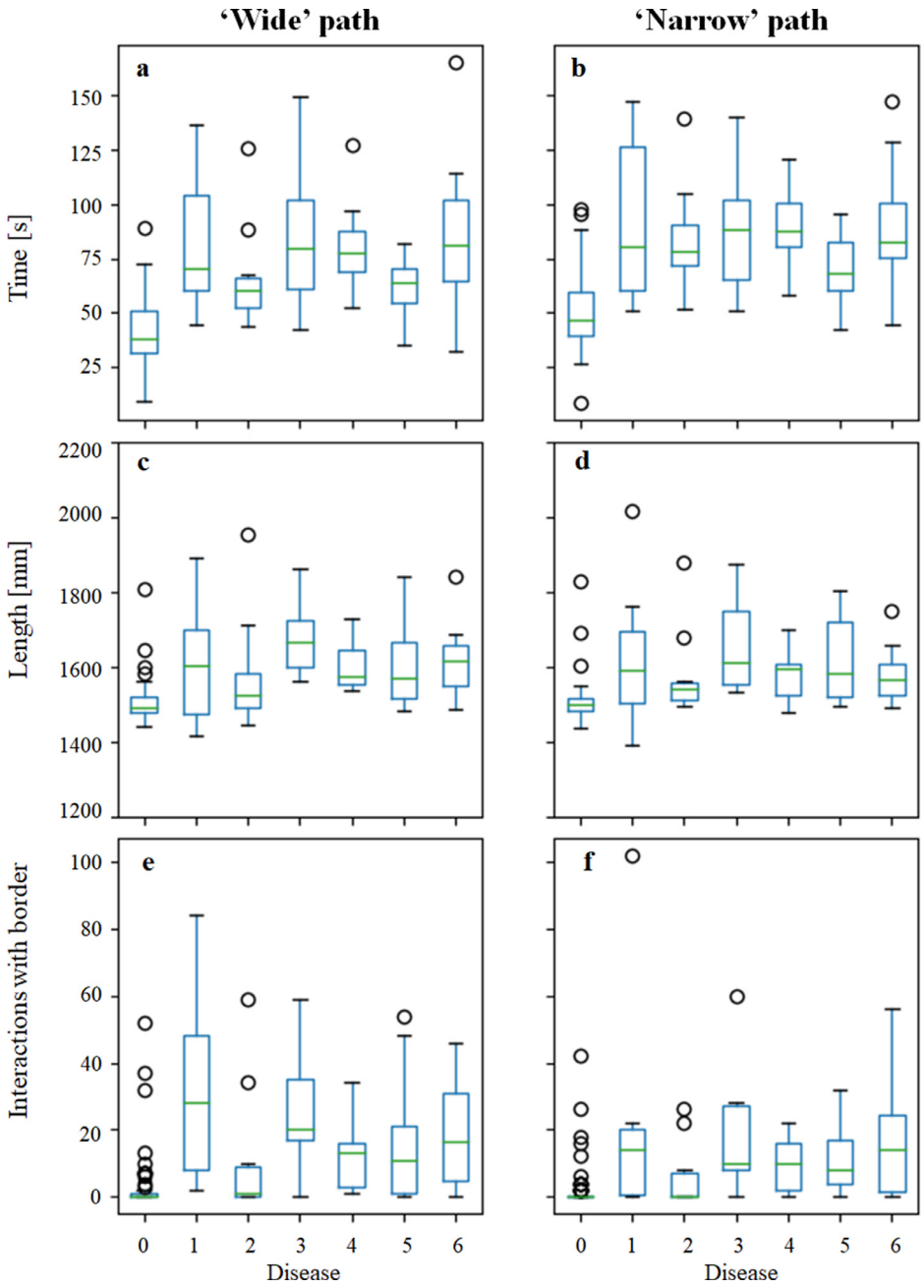

Fig. 4. Boxplot of the results divided by diseases in terms of (a) time on the 'wide' path, (b) time on the 'narrow' path, (c) length on the 'wide' path, (d) length on the 'narrow' path, (e) interactions on the 'wide' path, (f) interactions on the 'narrow' path. The diseases are the following: 0 – healthy subjects; 1 – ataxic syndromes; 2 – multiple sclerosis; 3 – stroke; 4 – Parkinson's disease; 5 – polyneuropathies; 6 – Other Neurological Diseases.

group because multiple sclerosis with the extreme clinical variability in terms of anatomical involvement from motor to sensory to ataxic deficit is expected to determine very different performances. Regarding the stroke and the Parkinson's disease group, although the two groups are the smaller ones, they are also the older ones. We have demonstrated in the previous study on paper that in the healthy control there was a direct correlation between total time of execution of the graphic test and the age, so this aspect has to be considered.

Moreover, visual inspection of the graphic tests can provide insights on the performance of the subjects in addition to the quantitative analysis, as shown in Fig. 5. The tablet app allows to longi-

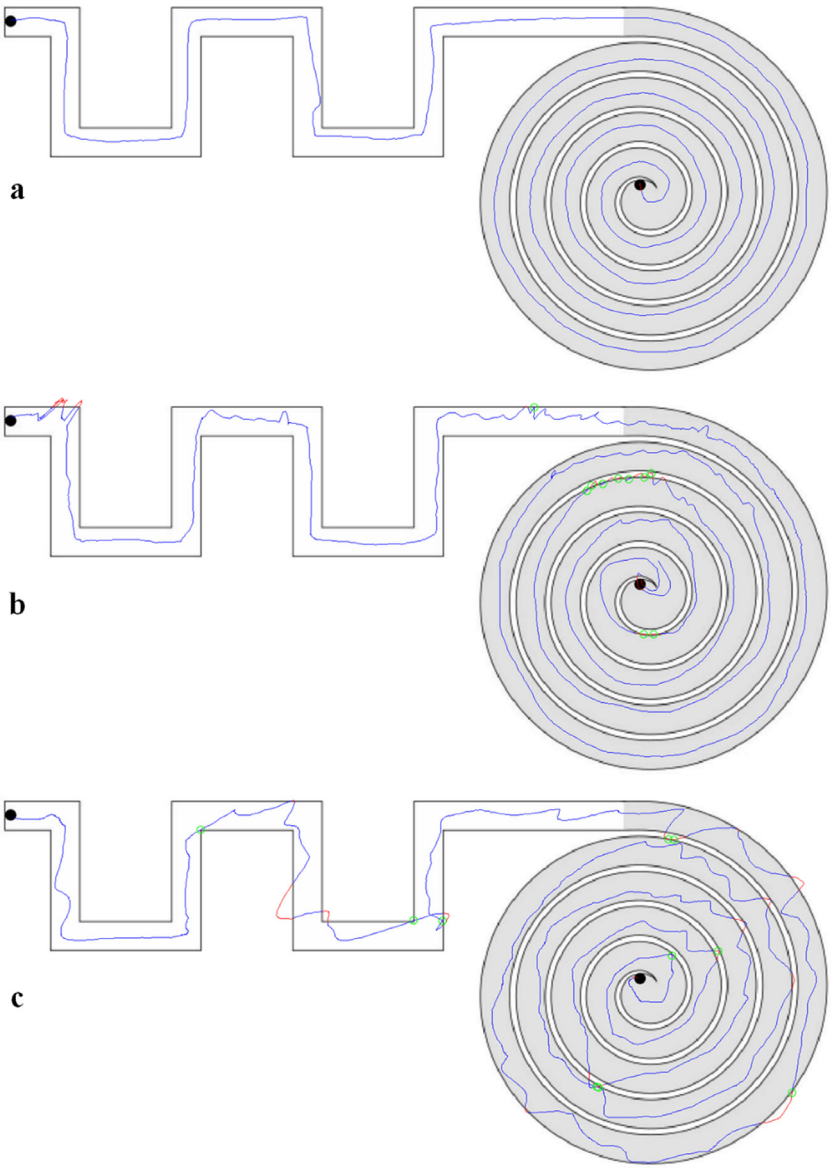

Fig. 5. (a) Test performed by a healthy subject; (b) Test performed by a patient with Parkinson's Disease; (c) Test performed by a patient with an ataxic syndrome (Friedreich's ataxia). All tests are the first repetition of the 'narrow' path as downloaded from the tablet. The green points highlight the interactions; the line drawn by the subjects is red when outside of the predefined path, otherwise it is blue.

tudinally store data for multiple patients, so it is possible to follow up each single patient.

3.2. Learning effect

Results of the analysis to assess if a learning effect is present are reported in Table 5. The medians are referred to the sum of the parameter in both paths, e.g., 'median 1' for the time is the median of the total time ('wide' and 'narrow' path) in the first repetition. The distributions that may be normal according to the Shapiro Wilk test are in italic in the Table. All comparisons were done with non-parametric tests due to the small samples.

A learning effect is present in the time parameter in the two cohorts, but not for length and interactions. The small samples size of the different diseases group limits considerations. In two groups, subject with polyneuropathy or ataxic syndromes, the reduces time executions between the two set of trials involve more interactions but still it is not possible to conclude if that is related to increased rapidity or instead increased fatigue.

3.3. Nine hole peg test results

Correlations between total time and NHPT, total length and NHPT and number of interactions and NHPT are shown in Fig. 6a, 6b and 6c, respectively. Time and NHPT have a moderate positive correlation ($r = 0.57$, $p \leq 0.001$), while interactions and NHPT have a strong positive correlation ($r = 0.81$, $p \leq 0.001$). These two results confirm what was obtained in the paper version in terms of statistical significance, while the different strength of the correlation is likely due to the small sample size. In this work, also the length displays a strong positive correlation with the NHPT ($r = 0.69$, $p \leq 0.001$). The dots displayed in red correspond to two subjects that did not complete the NHPT. In their case, the maximum value of 300 s was considered.

4. Discussion

The present work illustrates and validates a tablet app to perform a graphic test to quantitatively and qualitatively assess the

Table 5
Learning effect in healthy and pathological subjects.

Diseases	Parameter	Median 1	Median 2	p-value
Healthy controls	Time [s]	45.04	39.54	$p<0.001$
	Length [mm]	1500.21	1495.78	$p<0.001$
	Interactions	0.0	0.0	n.s.
Ataxic syndromes	Time [s]	*76.92*	*71.09*	n.s.
	Length [mm]	1536.68	1618.63	n.s.
	Interactions	19.0	*25.0*	n.s.
Multiple sclerosis	Time [s]	*72.32*	67.02	$p = 0.04$
	Length [mm]	1530.89	1534.90	n.s.
	Interactions	0.5	0.5	n.s.
Stroke	Time [s]	*84.79*	*78.5*	n.s.
	Length [mm]	1595.38	*1687.32*	n.s.
	Interactions	*23.0*	*12.0*	n.s.
Parkinson's Disease	Time [s]	*91.3*	*74.08*	$p = 0.03$
	Length [mm]	1583.57	1563.62	n.s.
	Interactions	*10.0*	11.0	n.s.
Polyneuropathies	Time [s]	*71.73*	*65.11*	$p = 0.005$
	Length [mm]	1610.02	1530.09	n.s.
	Interactions	6.0	*13.0*	n.s.
Other Neurological Diseases	Time [s]	*83.50*	*77.12*	n.s.
	Length [mm]	1599.62	*1561.51*	n.s.
	Interactions	*16.5*	*15.5*	n.s.

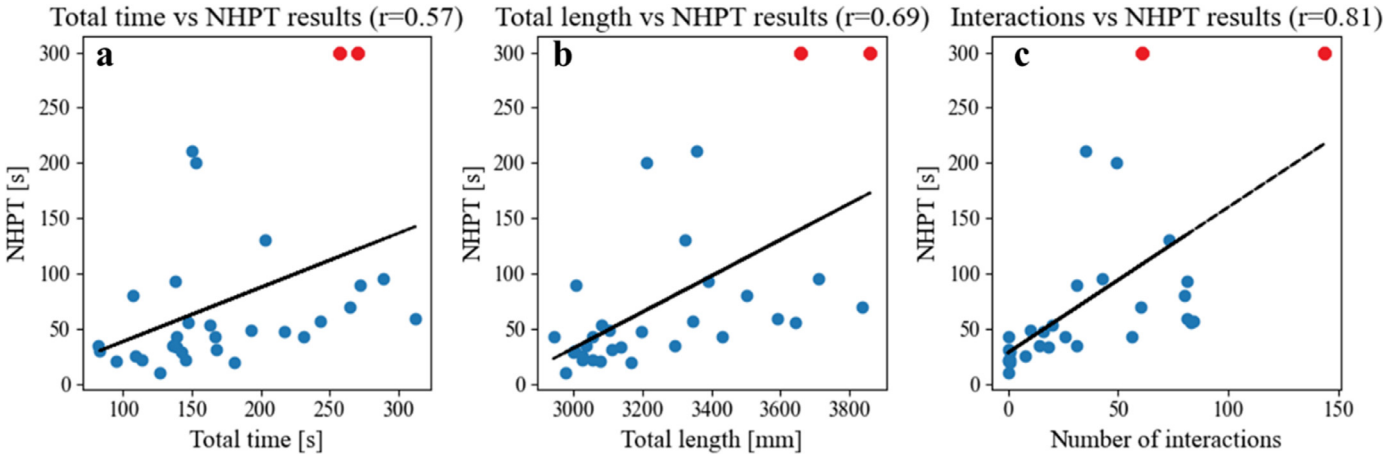

Fig. 6. (a) Correlation between total time and NHPT; (b) Correlation between total length and NHPT; (c) Correlation between number of interactions and NHPT. The red dots correspond to two subjects that did not complete the NHPT in the maximum time, so the default value of 300 s was considered.

dexterity of the dominant hand. The final goal is to establish a new and robust outcome measure to monitoring disease progression over time. The graphic test was designed for a neurological population in order to test different motor abilities and coordination. In fact, the path is formed by two parts requiring rapid changes in direction and continuous circular movements, respectively. The software developed for the analysis can separate the three parameters - time, length and interactions - for each part of the path in order to establish if there is a specific pattern of drawing and making errors for specific neurological populations. There are ongoing studies to clinically validate the graphic test in bigger size disease group.

Moreover, the two widths of the path are aimed at increasing the difficulty and avoid ceiling effects, especially for subjects with minimal impairment of the dominant hand. Nevertheless, in the present study, the interactions are unexpectedly more frequent in the wide path than in the narrow one in the cohort of pathological subjects. That differs from the results obtained in the graphic test on paper and definitely needs to be confirmed in larger cohorts of patients.

The repetition of the task twice has multiple potential meanings: evaluating learning effect, checking for consistency, and evaluating the fatigue. The graphic test is a complex task requiring integration between perceptual and motor information.

In this study, we have demonstrated that the digital version of the graphic test works, although some optimization in terms of sotware are still required, and we validated the test, since the results obtained by healthy and pathological subjects differ statistically for all three parameters, execution time, length and interactions. Moreover, the graphic test correlates well with the gold standard NHPT. The results of the correlations between time and NHPT and between interactions and NHPT confirm what was obtained in the paper version in terms of statistical significance, while the different strength of the correlation is likely due to the small sample size. The positive correlation between length and NHPT not only confirms what was obtained in the paper version, but also show that measuring the length provides an additional information with respect to the performance.

The main limit of the graphic test in the present study is that is restricted to the dominant hand. Many neurological diseases do not involved upper limbs in a symmetrical manner, from stroke to multiple sclerosis. A specular version of the graphic test to be performed with the left hand could be a solution, although it is reasonable to expect an increased variability in the three parameters

also for control healthy subjects due to the low dexterity of the non-dominant hand.

The need to turn the paper test [9] into a digital format came from the several problems faced during the previous trial. One of the bulkiest operations was the digitalization process. In fact, the automatic analysis must be always performed through computational algorithms, thus a digital format must be available. This process was performed by scanning piles of paper tests by means of traditional scanners, facing a time-consuming procedure. For this reason, whenever a scanning went wrong, the corrupted image was discarded in a subsequent phase. Moreover, the procedure was not always performed with the same instrument, leading to inconsistencies in terms of image quality and resolutions. In addition, scanners always introduce a certain level of noise, forcing a more complex processing and approximation to extract parameters of interest. These problems are overcome by the Android application, since everything is provided in a digital format. This allows a higher accuracy in parameters extracted, since no approximation or filtering of images is necessary. Moreover, the Android system can physically acquire points composing the lines drawn by patients, without considering the spreading of ink on a sheet, which generates variability. In fact, the test on paper did not provide statistically significant differences on length, but with a digital version of this software this new parameter is significantly different between healthy and pathological subjects and shows correlation with the gold standard NHPT too. An increase in length means that a subject deviated from the ideal, central path, possibly because of errors while performing the test, tremors, or involuntary movements of the dominant hand.

Another advantage is that while in the paper version the time is measured by an operator, introducing inaccuracy and operator dependency in time measurements, in the newer version time is measured by the Android system directly triggered by events occurring externally, guaranteeing repeatability.

Other positive aspects of the application can be found in its backend architecture: this structure allows to have data available in real-time, right after a test is submitted and loaded in remote repositories. Working with synchronized repositories allows to share data with other specialists and to retrieve those data to make them available inside the application itself, to be consulted by practitioners which want to review the history of a particular patient. Thus, this tool can be intuitively used for follow-up and for tracking the progress over time.

An issue of the digital version is related to the friction between capacitive pen and tablet's screen, which is very low, making the 'drawing' exercise quite different from the paper version. In particular, we observed more difficulties for pathological subjects to center exactly the starting dot on the tablet's screen compared to the starting dot on paper. We are considering to enlarge the dot or to make the starting point crossing the line closing the path. In any case, this aspect could be improved by adding a system able to increase the sensation of friction experienced while drawing on a paper sheet. Furthermore, during this study patients had to wear a glove to participate in the test because the used tablet does not implement palm rejection. Using a glove, however, affects the writing experience and the comfort of the subjects. A future development consists in using an active pen for automated palm rejection.

Other improvements to be addressed are the creation of an optimized version of the algorithm for the parameters extraction, as well as the realization of a cleaner and higher quality image of the test, which could make the pre-processing phase more accurate, leading to a better evaluation of results and, thus, to a better assessing of the dominant hand dexterity.

In conclusion, this graphic test on smart tablet can become a valid tool to assess hand dexterity in neurological population with light or pronounced hand impairment.

Declaration of Competing Interest

Alessandra Angelucci, Andrea Aliverti and Marina Scarlato are co-inventors of an industrial design application on the graphic test described in the paper.

References

[1] C.G. Canning, L. Ada, N.J. O'Dwyer, Abnormal muscle activation characteristics associated with loss of dexterity after stroke, J. Neurol. Sci. 176 (1) (2000) 45–56.
[2] V. Mathiowetz, K. Weber, N. Kashman, G. Volland, Adult norms for the nine hole peg test of finger dexterity, Occup. Ther. J. Res. 5 (1) (1985) 24–38.
[3] Y.S. Cheong, et al., Validity of the buttoning test in hand disability evaluation of patients with stroke, Ann. Rehabil. Med. 42 (1) (2018) 18–25, doi:10.5535/arm.2018.42.1.18.
[4] N.J. Seo, L.R. Enders, Hand grip function assessed by the box and block test is affected by object surfaces, J. Hand Ther. 25 (4) (2012) 397–405, doi:10.1016/j.jht.2012.04.004.
[5] Y.C. Wang, R. Wickstrom, S.C. Yen, J. Kapellusch, K.A. Grogan, Assessing manual dexterity: comparing the work ability rate of manipulation test with the minnesota manual dexterity test, J. Hand Ther. 31 (3) (2018) 339–347, doi:10.1016/j.jht.2017.03.009.
[6] F. Granström, M. Hedlund, B. Lindström, S. Eriksson, Test-retest reliability of the twenty-five-hole peg test in patients who had a stroke, BMJ Open 9 (12) (2019) 1–7, doi:10.1136/bmjopen-2019-032560.
[7] "Nine-Hole Peg Test | RehabMeasures Database" https://www.sralab.org/rehabilitation-measures/nine-hole-peg-test (Accessed December 11th, 2021).
[8] A. Sunderland, D. Tinson, L. Bradley, R.L. Hewer, Arm function after stroke. an evaluation of grip strength as a measure of recovery and a prognostic indicator, J. Neurol. Neurosurg. Psychiatry 52 (11) (1989) 1267–1272.
[9] A. Angelucci, A. Tettamanti, E. Sarasso, M. Filippo, A. Aliverti, M. Scarlato, Validation of a graphic test to quantitatively assess the dominant hand dexterity, PLoS One 17 (8) (2022) e0271889, doi:10.1371/journal.pone.0271889.
[10] P. Virtanen, et al., SciPy 1.0: fundamental algorithms for scientific computing in python, Nat. Methods 17 (3) (2020) 261–272.