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An extended drawing test for the assessment of arm and hand function with a performance invariant for healthy subjects

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ABSTRACT

Impaired hand motor function resulting from neurological, psychiatric or orthopaedic disorders affects patients of all ages. Existing hand function assessment methods, e.g. rating scales, accelerometers and electromyographical devices, are often time-consuming to administer, subjective in interpretation and/or expensive. Graphonomic tests are gaining popularity as a way of avoiding these drawbacks while relating directly to writing and drawing. Here we present a computerized Extended Drawing Test (EDT), which improves on an earlier Drawing Test for stroke patients in three ways. First, it assesses isolated proximal arm movement using a graphics pen in a puck-like pen holder, and in addition combined arm and finger dexterity in movements using a normal writing grip. Secondly, we calibrated our test against 186 healthy subjects (3–70 years), finding significant age- and handedness-related differences in both speed and accuracy of drawing. Thirdly, to simplify assessment we devised an overall performance measure using a variant of Fitts' Law combining speed and accuracy, which we found to be age-independent for healthy subjects above 3 years of age. This result enables us to provide age-independent performance norms using both hands, with and without the pen holder. These norms may assist quantification of specific arm dysfunction by comparing patient performance with the healthy norms, and also by comparing within-patient performance in the dominant and non-dominant hands with and without the pen holder. Using our freely available software, this new test will allow clinicians to rapidly assess arm and hand function across a wide range of patient categories and ages.

1. Introduction

Patients of all ages can be affected by impaired arm and hand motor function following, e.g. neurological, psychiatric or orthopaedic disorders. Impaired hand motor function is typically assessed using subjective rating scales such as the Action Research Arm Test (ARAT), the Nine Hole Peg Test (NHPT), the Purdue Pegboard Test, the Box and Block Test (BBT) or the Wolf Motor Function Test (WMFT) used in neurorehabilitation (Simpson and Angus, 1970; Schädler et al., 2006). More recently, assessments have also been performed using technologies such as accelerometers (Green, 2007) and electrophysiological recordings including motor or somato-sensory evoked potentials (MEP, SSEP), electromyographical (EMG) or neurographic and reflex recordings (Curt and Dietz, 1999). These assessments have disadvantages such as being time-consuming or difficult to administer, providing low accuracy and/or being expensive to purchase (Mergl et al., 1999). There is thus a need for innovative assessments to enable rapid, precise, objective and reliable evaluation of the course of training and convalescence. One potential solution to this problem lies in the use of graphonomic tests, first formalized in a 1982 workshop at the University of Nijmegen (The Netherlands) as "a concept denoting the scientific and technological efforts involved in identifying relationships between the planning and the generation of handwriting and drawing movements, resulting in visible traces on paper (or on electronic media with electronic pens)" (Van Gemmert and Teulings, 2006).

Recently, new methods using graphics tablets, linked to a computer recording the data, have opened up new and reliable ways of assessing upper limb motor function. Applied in a variety of clinical and research fields, these methods have been shown to be usable for regular assessment of hand motor function. A study measuring the coordinates of handwriting movements on graphics tablets using a pen as well as the pressure at the pen tip in healthy subjects revealed significant age and verbal intelligence effects, but no gender or handedness effects (Mergl et al., 1999). Graphics tablets have also been used to measure the intensity of ataxic symptoms in multiple sclerosis patients compared to healthy subjects. The results of a test involving tracing a pre-drawn '8' and tapping as fast as

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possible using a pen were found to correlate with the NHPT and could be used to distinguish patients from controls (Erasmus et al., 2001). Kinematics of handwriting using graphic tablets have also been assessed in patients with mild cognitive impairment (MCI), presumed to be a precursor to Alzheimer's Disease (AD) (Schröter et al., 2003). Both MCI and AD patients were found to exhibit a loss of fine finger motor ability. In schizophrenic patients a graphonomic test involving repetitive movements has revealed reduced performance in patients compared to healthy subjects (Jahn et al., 1995). Another study in schizophrenic patients using a graphics tablet with a regular computer mouse assessing arm movements in a pointing task on a computer screen found a movement planning deficit compared to controls (Carnahan et al., 1997). By drawing superimposed concentric circles, even very small hand motor dysfunctions have been detected in schizophrenic patients using graphonomic tests (Tigges et al., 2000). Another advantage of graphonomic tests is that, in principle, the exact trajectories performed can be recorded in detail for future re-analysis and development of new assessments and/or comparison with older studies.

Another assessment, the so-called Drawing Test (Eder et al., 2005), has been proposed to assess coordination abilities in post-stroke hemiplegic subjects. In this test, subjects draw vertical lines on a graphics tablet from one defined point to another, by means of a puck held in each hand in turn. Patient measurements using the Ashworth clinical scale of spasticity (Ashworth, 1964) have been found to correlate highly with performance in the Drawing Test. A variant of the Drawing Test, in which patients follow the sides of a square in both clockwise and anticlockwise directions, has been used in a battery of assessments for evaluating the efficacy of functional electrical stimulation on arm function in hemiplegic stroke patients (Popovic et al., 2004). In that study the Drawing Test scores were correlated with other measures, such as the Fugl-Meyer Assessment, related to the use of the paretic arm and hand.

Because of its simplicity, its independence of the ability to write or to draw geometric figures, its applicability in individuals of different ages and its demonstrated relevance for clinical assessment, the Drawing Test has potential for wider application to both assessment of stroke recovery and possibly for evaluating other hand and arm motor disorders. However, the test currently lacks data from healthy subjects as a reference. Also, due to the use of the graphics puck held using a spherical grip, it does not extensively test subjects' ability to control wrist and finger movements to perform writing-like motions which are highly relevant to daily living tasks. Using only the spherical grip could increase the risk of incorrectly diagnosing the extent or type of a motor dysfunction, as it is known that the accuracy of actions performed using tools depends on the type of grip used (Hägg and Hallbeck, 2001). In this paper we extend the Drawing Test to test fine motor hand grip as well as overall arm movements. This goal is achieved by having subjects perform the test by means of two different grip patterns: an external precision grip, i.e. the dynamic tripod grip (Wynn-Parry, 1966) for holding a graphics pen, and a spherical grip for holding a puck-type pen holder (MacKenzie and Iberall, 1994; Brunni, 2001) similar in shape to a computer mouse. We applied our test to healthy subjects across a wide age range from 3 years old upwards.

2. Materials and methods

2.1. Subjects

One hundred and eighty-six children and adults (ages 3–70 years, see Table 1) were recruited by means of signs posted in the ETH Zurich and University of Zurich, and from schools and kindergartens in the Zurich area. All subjects (or their parents if they were under 18 years of age) signed an informed consent form. Subjects were included if they had no prior history of motor, mental, or psychological disorders, and had not seriously injured their arms or hands in the previous 6 months. All subjects received a reward in the form of a small chocolate bar for participating in the study.

Table 1
Number of subjects in each age group. All subjects performed the test with the pen holder; a subset of these also performed the test without the pen holder.

Age group (AG)	Age [years]	With pen holder		Without pen holder	
		# subjects	% of total	# subjects	% of total
1	3–6	8	7.3%	18	9.7%
2	7–10	8	7.3%	13	7.0%
3	11–15	44	40.0%	45	24.2%
4	16–20	8	7.3%	12	6.5%
5	21–30	16	14.5%	52	28.0%
6	31–40	8	7.3%	15	8.1%
7	41–50	10	9.1%	15	8.1%
8	51–70	8	7.3%	16	8.6%
Total		110	100%	186	100.0%

2.2. Methods

2.2.1. Handedness questionnaire

Before performing the Drawing Test, subjects completed a questionnaire to determine their handedness based on the Edinburgh Handedness Inventory (Oldfield, 1971). According to this questionnaire, out of 186 subjects, 162 were right-handed and 24 were left-handed. Since some questions in the inventory were not appropriate for children in the youngest age group (3–6 years, self-responding), their handedness was assessed according to which hand was used the most while playing or drawing. The very youngest 3 and 4 years old also reported their abilities verbally using their dominant or non-dominant hand to facilitate the assessment of their handedness.

2.2.2. Measuring device

Subjects were seated in a comfortable chair, with the graphics tablet (TRUST Wireless Scroll Tablet TB-4200, 120 lines per mm) placed in front of them on a desk. The instructor stood next to them, making sure that the pen was held correctly and that the tablet was not moved by the subject. A piece of paper with a vertical 160 mm guide line had been placed on the tablet beforehand, underneath the transparent protective plastic cover of the tablet's work surface (Fig. 1). The length of the line chosen was different from the 200 mm specified in the original Drawing Test (Eder et al., 2005) because of the need to provide a line length that very small children could draw easily.

Subjects were asked to draw from the bottom to the top of the line as quickly and as accurately as possible (Fig. 2). Speed and accuracy were emphasized equally, and all subjects were told to keep the pen on the sheet once drawing had started. The beginning and end time points of each trial were recorded by the experimenter by pressing a key on the computer keyboard. To avoid reaction time effects that would be caused by giving a "go" signal, the experimenter pressed the key to start recording when the subject began moving the pen, and pressed the key to stop recording when the pen stopped moving at the target. We estimate that the experimenter random timing error due to this procedure is approximately 0.1 s for both the start and stop events; i.e. ~0.2 s in total. To help young children who did not understand the task (some did not understand the fact that they could not "see" the lines they were tracing on the tablet), pictures were added to the lines and a story was told by the experimenter. For example, a hedgehog/train was drawn at the bottom of the line, which the child had to run/drive to its nest/station

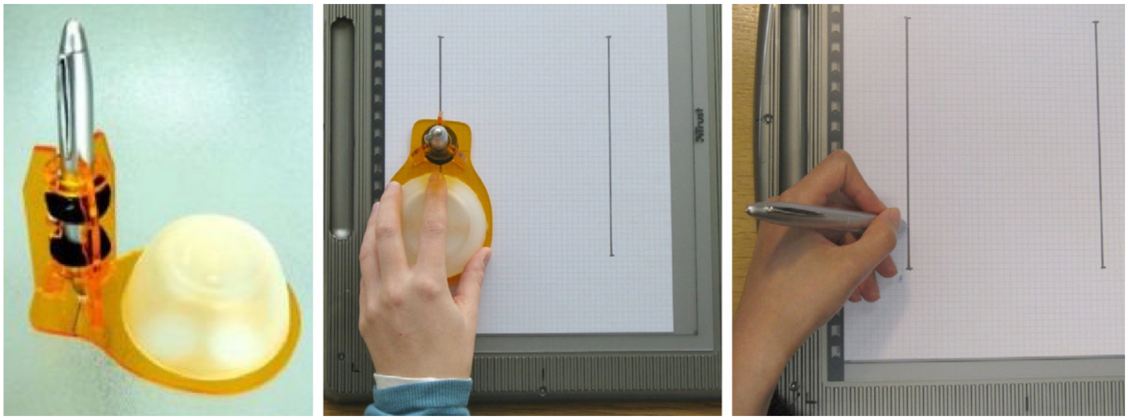

Fig. 1. (Left) Holder for graphics tablet pen with transparent base. (Middle) Pen holder in use on graphics tablet using spherical grip. (Right) Pen held using standard dynamic tripod grip.

drawn at the endpoint. If a child did not understand the task, the measurements were repeated until it was understood.

All subjects were instructed to draw the lines holding the digital pen as if they were writing by means of an external precision grip (MacKenzie and Iberall, 1994), i.e. the dynamic tripod grasp (Wynn-Parry, 1966). This is categorized as a functional grip, in which the pen is held between the tips of the thumb and index finger and rests against the side of the middle finger. Five lines were drawn first using their dominant hand; another five lines were then drawn with the non-dominant hand. Finally, all ten lines were drawn again with the pen inserted into a puck-like pen holder with a smooth base that could slide easily along the graphics tablet surface. The pen holder was grasped using a functional spherical grip, a hand pose used for spherical objects in which fingers are spread and the palm is arched (MacKenzie and Iberall, 1994) (Fig. 1). The pen holder was designed with a transparent base so that users could see the tip of the pen and the line to be followed through the base.

For further details about obtaining the test hardware and software, see our web site at http://rehab.ini.ethz.ch/.

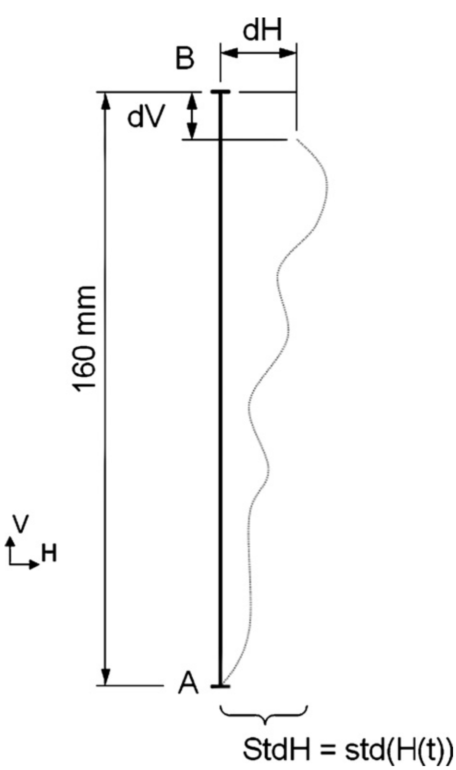

Fig. 2. Scheme of line to be drawn. The subject draws from A to B as straight as possible. For each line, the offset of the endpoint (dH, dV) and the overall horizontal standard deviation of the line StdH are then calculated for assessment.

2.2.3. Statistical analysis

The trajectory of each line was recorded from the graphics tablet as a sequence of points $\{p_0, p_1, \ldots, p_N\} = \{[\mathrm{dH}(t_0), \mathrm{dV}(t_0)], [\mathrm{dH}(t_1), \mathrm{dV}(t_1)], \ldots, [\mathrm{dH}(t_N), \mathrm{dV}(t_N)]\}$ and the following characteristic values were calculated for each line drawn (Fig. 2):

- $T = t_N$: total time taken to draw the line segment.
- $\mathrm{StdH} = \mathrm{std}[\mathrm{dH}(t_0), \mathrm{dH}(t_1), \ldots, \mathrm{dH}(t_N)]$: the standard deviation of line points in horizontal direction, i.e. perpendicular to the guide line. This measurement provides an estimate of the curvature of the drawn line compared to the ideal straight line.
- $(\mathrm{dH}, \mathrm{dV}) = [\mathrm{dH}(t_N), \mathrm{dV}(t_N)]$: the position error of the endpoint for this line.

For each subject and condition (with/without pen holder, dominant/non-dominant hand), the following summary statistics were then calculated:

- Mean_StdH: for each subject and each condition, the overall mean of the horizontal standard deviations for each line. This value measures the overall horizontal variability of the line across all trials for a particular condition.
- Mean_dH, Mean_dV: for each subject and each condition, the mean distance in the horizontal (perpendicular to line) and vertical (along lone) directions between the end of the guide line and the end of the subject's drawn line. These values measure the accuracy of the placement of the endpoint, i.e. the mean position of the endpoint over several trials relative to the target position.
- Std_dH, Std_dV: for each subject and each condition, the standard deviation of distance in the horizontal (perpendicular to line) and vertical (along lone) directions between the end of the guide line and the end of the subject's drawn line. These values measure the precision, i.e. the trial-to-trial variability, of the placement of the endpoint.

The results were then imported into Excel, and statistical calculations were performed using SPSS 15.0 for Windows. Linear mixed models were used for all analyses except where stated in Section 3. The within-subject factors used were the pen holder (used or not used) and the hand with which the lines were drawn (dominant or

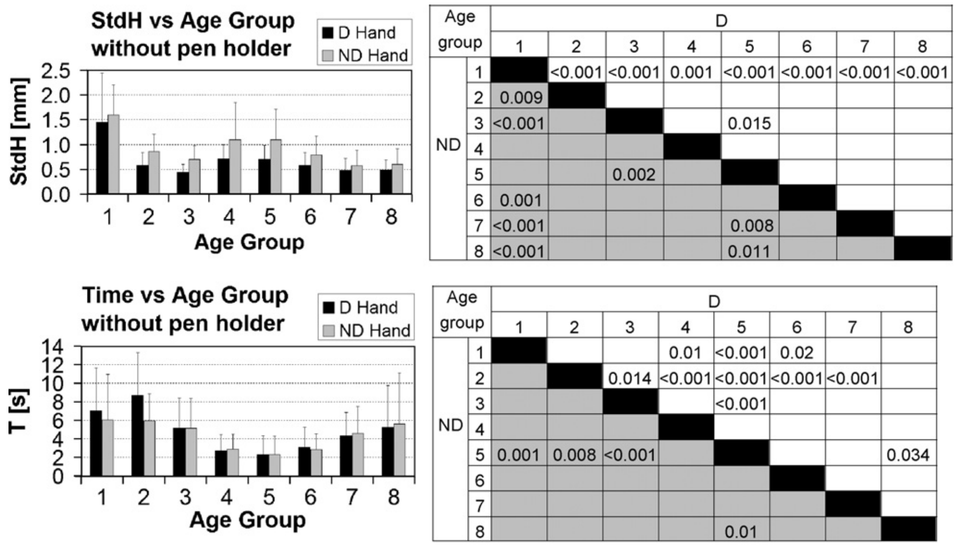

Fig. 3. (Left) Horizontal standard deviation (curvature) of line (StdH, top) and time taken to draw line (*T*, bottom) without pen holder, by age group. Error bars indicate one standard deviation. D = dominant, ND = non-dominant. (Right) Age group pairwise comparisons using linear mixed model for StdH (top) and *T* (bottom). Unshaded = dominant hand, shaded = non-dominant hand. Only significant differences ($p < 0.05$) are shown.

non-dominant). The factor used for between-subject comparisons was the age group (see Table 1). A significance level of 0.05 was taken for reporting.

A summary of the number of subjects and their age groups is shown in Table 1. Because of experimental constraints, some subjects only have data for lines drawn with the pen holder, while some subjects have data for lines drawn both with and without the pen holder.

3. Results

3.1. Dynamic performance: curvature and time

3.1.1. Without pen holder

The mean curvature (mean of StdH, Fig. 3) of subjects' lines, i.e. the deviation compared to the ideal straight line, decreased from early childhood until the age of 15 (age groups 1–3, denoted from here as AG1–3), before increasing again until the age of 30 years (AG4–5). After that age the curvature then decreased again (AG6–8). The youngest children's lines (AG1) had the highest curvature (mean_StdH = 1.45/1.59 mm for dominant/non-dominant hand). The adult peak mean value of StdH was 0.7 mm for the dominant hand and 1.1 mm for the non-dominant hand, occurring in both cases with subjects aged from 16–30 years (AG4–5). For all age groups except AG1, the mean curvature of the lines was significantly lower for the dominant hand than for the non-dominant hand (Table 2).

For StdH in the dominant hand, AG1 was significantly higher than all other age groups. The same was seen in the non-dominant hand except for AG4 and AG5. For both hands the lowest value in AG3 was also significantly different from the adult peak in AG5. In the non-dominant hand, StdH in AG5 was also significantly higher than AG3, AG7 and AG8.

The time (*T*) required for subjects to draw the lines was roughly inverse to the curvature (*T*, Fig. 3). For both hands, it decreased from early childhood until the age of 30 years (AG5) and then increased again with advancing age. Many significant differences between different age groups were found (mostly in the dominant hand), with the largest differences occurring in AG5 which had the shortest times. Furthermore, apart from AG2, there was no significant difference in any group in drawing speed between the dominant and the non-dominant hand (Table 3).

3.1.2. With pen holder

The distribution of StdH obtained using the pen holder was broadly similar in shape to those obtained without the pen holder (Fig. 4). However, the overall values were lower, as might be expected due to the extra support provided by the pen holder.

Table 2
Comparison of dominant and non-dominant hands for mean curvature (StdH) and time (*T*), without pen holder.

Age group	Without pen holder					
	StdH [mm]			Time [s]		
	Dominant	Non-dominant	*p*	Dominant	Non-dominant	*p*
1: 3–6	1.45	1.59	0.198	7.05	6.04	0.085
2: 7–10	0.58	0.86	<0.001***	8.68	5.94	0.009**
3: 11–15	0.44	0.70	<0.001***	5.16	5.17	0.969
4: 16–20	0.71	1.10	0.031*	2.69	2.89	0.398
5: 21–30	0.70	1.10	<0.001***	2.30	2.30	0.944
6: 31–40	0.59	0.79	0.026*	3.12	2.85	0.814
7: 41–50	0.48	0.57	0.046*	4.36	4.62	0.520
8: 51–70	0.48	0.60	0.005**	5.26	5.61	0.332

* Indicate linear mixed model significance levels: 0.05.
** Indicate linear mixed model significance levels: 0.01.
*** Indicate linear mixed model significance levels: 0.001.

Table 3
Comparison of dominant and non-dominant hands for mean curvature (StdH) and time (*T*), with pen holder.

Age group	With pen holder					
	StdH [mm]			Time [s]		
	Dominant	Non-dominant	*p*	Dominant	Non-dominant	*p*
1: 3–6	1.34	1.44	0.606	4.66	3.19	0.043*
2: 7–10	0.82	1.23	0.015*	5.60	4.58	0.025*
3: 11–15	0.57	0.76	<0.001***	5.19	4.76	0.032*
4: 16–20	0.56	0.70	0.144	3.08	2.71	0.251
5: 21–30	0.66	0.86	<0.001***	2.94	2.99	0.737
6: 31–40	0.53	0.72	0.013*	2.66	2.28	0.056
7: 41–50	0.55	0.68	0.093	3.40	3.73	0.037*
8: 51–70	0.43	0.52	0.121	4.85	4.46	0.326

** Indicate linear mixed model significance levels: 0.01.
* Indicate linear mixed model significance levels: 0.05.
*** Indicate linear mixed model significance levels: 0.001.

Nevertheless, children in age groups 1 and 2 reported that the tasks with the pen holder were "tiring" even though they performed better overall. With the pen holder, AG1 and AG2 had the highest values of StdH (1.3 mm and 0.8 mm, respectively, for the dominant hand, 1.4 mm and 1.2 mm for the non-dominant hand).

The age-dependent variations with the pen holder tended to be lower than those found without the pen holder. As for without the pen holder, the youngest age group (AG1) had significantly higher StdH values than all other age groups for the dominant hand. The same was the case for the non-dominant hand except for the comparison with AG2, which was also significantly different to all older age groups except AG5.

The distribution of times with the pen holder followed an approximately similar shape to that obtained without the pen holder, with AG6 being the fastest. However, there were no significant pairwise differences between any of the age groups.

A number of differences in performance with the pen holder were found between the dominant and non-dominant hands, although no age-dependent pattern was discernible (Table 3). There was a significant difference in StdH in AG2, 3, 5 and 6, and a significant difference in T in AG1, 2, 3 and 7.

3.1.3. Dynamic performance with vs. without pen holder

Overall, the line curvature (StdH) with the pen holder was lower for the dominant hand ($p < 0.001$), but no significant difference was found for the non-dominant hand ($p = 0.547$). Older and adolescent children (AG2–AG3) showed a significant or near-significant difference in StdH for both hands, performing better without the pen holder. In contrast, the tendency for most other age groups was to perform slightly (but not significantly) better with the pen holder.

Overall, subjects drew the lines faster with the pen holder using the non-dominant hand ($p = 0.003$). Using the dominant hand, they also tended to be faster with the pen holder without being significantly so ($p = 0.118$). Significant or near-significant age-dependent differences were found in the youngest children (AG1–AG2), who were much faster at drawing with the pen holder (Table 4).

3.2. Endpoint accuracy and precision

The accuracy and precision of the endpoint was measured for each subject as the means and standard deviations of the line end positions in the horizontal and vertical directions, i.e. (Mean_dH, Mean_dV) and (Std_dH, Std_dV). None of the age groups, using either hand with or without the pen holder, showed endpoint errors

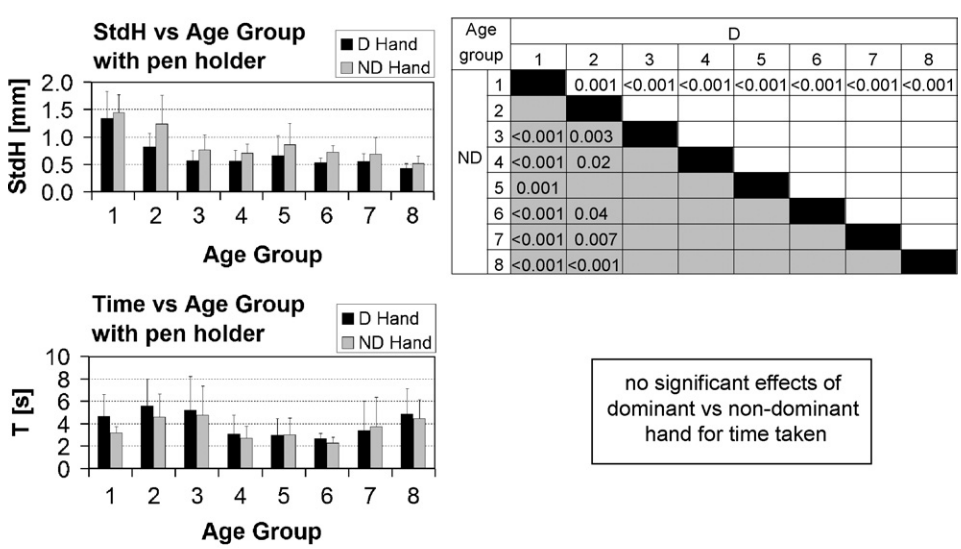

Fig. 4. (Left) Horizontal standard deviation of line (StdH, top) and time taken to draw line (*T*, bottom) with pen holder, by age group. Error bars indicate one standard deviation. D = dominant, ND = non-dominant. (Right) Age group pairwise comparisons using linear mixed model for StdH (top) and *T* (bottom). Unshaded = dominant hand, shaded = non-dominant hand. Only significant differences ($p < 0.05$) are shown.

Table 4
Comparison of performance with and without pen holder (mixed linear model).

Age group	StdH				Time			
	Dominant		Non-dominant		Dominant		Non-dominant	
	Higher	p	Higher	p	Higher	p	Higher	p
1: 3–6	WO	0.091	WO	0.837	WO	0.089	WO	0.021*
2: 7–10	W	0.002**	W	0.006**	WO	0.042*	WO	0.016*
3: 11–15	W	<0.001***	W	0.067	WO	0.905	WO	0.215
4: 16–20	WO	0.219	WO	0.408	W	0.455	WO	0.078
5: 21–30	WO	0.883	WO	0.357	W	0.401	W	0.376
6: 31–40	WO	0.349	WO	0.558	WO	0.837	WO	0.301
7: 41–50	W	0.179	W	0.096	WO	0.555	WO	0.596
8: 51–70	WO	0.466	WO	0.468	WO	0.967	WO	0.676
Overall		<0.001***		0.547		0.118		0.003**

W = value higher with pen holder, WO = value higher without pen holder. Higher values indicate worse performance.
* Indicate significance levels: 0.05.
** Indicate significance levels: 0.01.
*** Indicate significance levels: 0.001.

Table 5
Comparison of accuracy and precision for lines drawn with the pen holder vs. without the pen holder.

AG	Accuracy				Precision			
	Mean_dH		Mean_dV		Std_dH		Std_dV	
	D	ND	D	ND	D	ND	D	ND
1: 3–6	0.635	0.091	0.801	0.433	0.441	0.050* W	0.050* W	0.095
2: 7–10	0.004** W	0.007** W	0.54	0.525	0.314	0.555	0.503	0.055
3: 11–15	0.102	0.014* WO	0.799	<0.001*** WO	0.605	0.586	0.067	0.169
4: 16–20	0.522	0.102	0.701	0.854	0.714	0.512	0.501	0.260
5: 21–30	0.02* WO	0.878	0.194	0.074	0.702	0.591	0.181	0.440
6: 31–40	0.568	0.169	0.35	0.777	0.518	0.224	0.542	0.865
7: 41–50	0.513	0.608	0.741	0.212	0.007** W	0.419	0.643	0.133
8: 51–70	0.082	0.195	0.024* WO	0.043* W	0.008** WO	0.263	0.996	0.043* W
All	0.139	0.454	0.136	0.667	0.539	0.383	0.048* W	0.068* W

W = mean error higher for the "with pen holder" condition; WO = mean error higher for the "without pen holder" condition.
* Indicate linear mixed model significance levels: 0.05.
** Indicate linear mixed model significance levels: 0.01.
*** Indicate linear mixed model significance levels: 0.001.

(Mean_dH or Mean_dV) that were significantly different from 0 (z-test). In other words, on average all subjects were able to accurately position the pen endpoint under all test conditions. However, endpoint accuracy and precision were significantly affected by whether or not a subject used the pen holder (Table 5). Analyzing the table yields the following points:

- When all age groups are taken together, endpoint accuracy is unaffected by the pen holder. Vertical endpoint precision is lower for subjects using the pen holder in either hand, but horizontal endpoint precision is unaffected.
- Endpoint precision is not affected by use of the pen holder except for very young (3–6 years) and older (41–70 years) subjects. The very young children perform worse when using the pen holder, while the older subjects show a range of effects.
- Endpoint accuracy is affected by use of the pen holder in several age groups, with no consistent pattern.

4. Discussion

4.1. An age-independent dynamic performance measure

One of the key problems with assessing hand function is accounting for normal healthy variation due to age effects. A desirable performance measure would remove age effects, allowing direct comparison of patient performance with that of healthy subjects. Such a performance measure can be devised by noting that the time taken to draw the lines (T) was generally inversely correlated with the accuracy of the resulting line (StdH). This speed-accuracy trade-off is a particular case of a well-known phenomenon first formulated in Fitts' Law, which found an inverse logarithmic relationship between the speed and accuracy of human pointing (Fitts, 1954). Fitts' law states that the time taken to draw a line is related to the error of the final position by a logarithmic law. In our case the mean endpoint positions were not significantly different from zero (Section 3.2). However, if we take the overall line accuracy StdH as an error measure then we can create an overall performance index P as follows:

$$\text{Performance}\, P = \frac{1}{T}\ln\left(\frac{1}{\text{StdH}}\right) \quad \text{Units}: \text{s}^{-1}\ln(\text{m}^{-1})$$

We can now define standard performance ranges for healthy subjects (Table 6), and test whether the performance measure is indeed age-independent for both hands, with and without the pen holder (Fig. 5).

Using the performance measure, we can make general statements about how handedness and use of the pen holder affect overall performance in healthy subjects. The data in Table 6 suggests that subjects perform significantly better without the pen holder, when using either the dominant or non-dominant hand. However, there was no performance difference related to handedness when tested under the same drawing condition (with or without the pen holder). This result, also found in another study of

Table 6
Standard Drawing Test age-independent performance measures *P* for healthy subjects.

Standard Performance	Measures	# Subjects	Mean	Std. Dev.
With pen holder	Dominant	110	2.47	1.49
	Non-dominant	110	2.39	1.18
Without pen holder	Dominant	181	3.34	2.90
	Non-dominant	186	3.12	2.56

The following performance measures are significantly different to each other: dominant hand, with pen holder vs. without pen holder ($p = 0.0045$); non-dominant with pen holder vs. dominant without pen holder ($p = 0.0007$); non-dominant hand, with pen holder vs. without pen holder ($p = 0.0059$). All significance values for two-tailed pairwise *t*-test comparisons with Bonferroni correction (6). Brackets with asterisks indicate significant differences: *0.05, **0.01, ***0.001.

children's speed in drawing zig-zag lines (Van Mier, 2006), is useful because it removes handedness as a possibly confounding factor when assessing arm and hand function.

Although the average performance measures were found to be age-independent, the scatter plots in Fig. 5 suggest that the population variability in healthy subjects may change with age. Young adults (21–30 years old) appear to have a larger variation in individual performance than older or younger people, even though the overall average is the same. The source of this higher individual variability in performance is unclear.

Another interesting effect is the tendency for young adults (16–20 and 21–30 years old) to draw their lines faster (lower *T*) but less precisely (higher StdH) than younger children or older adults, even though their overall performance was the same as for others. When holding the pen by hand, the effect was significant for both *T* and StdH, while only the effect on *T* was significant when using the pen holder. Another study comparing pointing in young children with young adults found that manipulating the emphasis of the instructions towards higher speed or accuracy affected the speed but not the accuracy of pointing (Rival et al., 2003). However, in our experiment speed and accuracy were emphasized equally in the instructions for all subjects, so the difference may lie in an age-dependent interpretation of the instructions. An early study in a forced-choice task found a similar age-dependent difference in the speed-accuracy trade-off between young adults (17–30 years) and older adults (31–75 years) (Salthouse, 1979), We suggest that our results may reproduce this earlier finding (involving button pressing) in detailed motor movements (involving line drawing). The underlying developmental and/or social reasons remain unknown.

4.2. Outlook

We have shown that our Extended Drawing Test (EDT), with three modifications from the original test, can be used to quickly assess arm and hand function in healthy subjects from the age of 3 years upwards. The first modification we have proposed is a shortening of the line to be drawn from 200 mm to 160 mm so that very small children can handle the test easily without compromising its usefulness for adults. Secondly, while the original Drawing Test only assesses overall arm control using a computer mouse held in a simple spherical grip, we also added a test component where subjects are forced to use a precision grip, the dynamic tripod grasp, to hold a pen. In this component the same pen is inserted into a specially designed pen holder to allow testing of the spherical grip as well. Together, the EDT allows testing fine motor hand grip as well as overall arm movements. The potential benefit of the small additional testing time is the ability to more precisely diagnose specific arm motor impairments. Thirdly, we have proposed an age-independent performance measure to enable easy assessment of

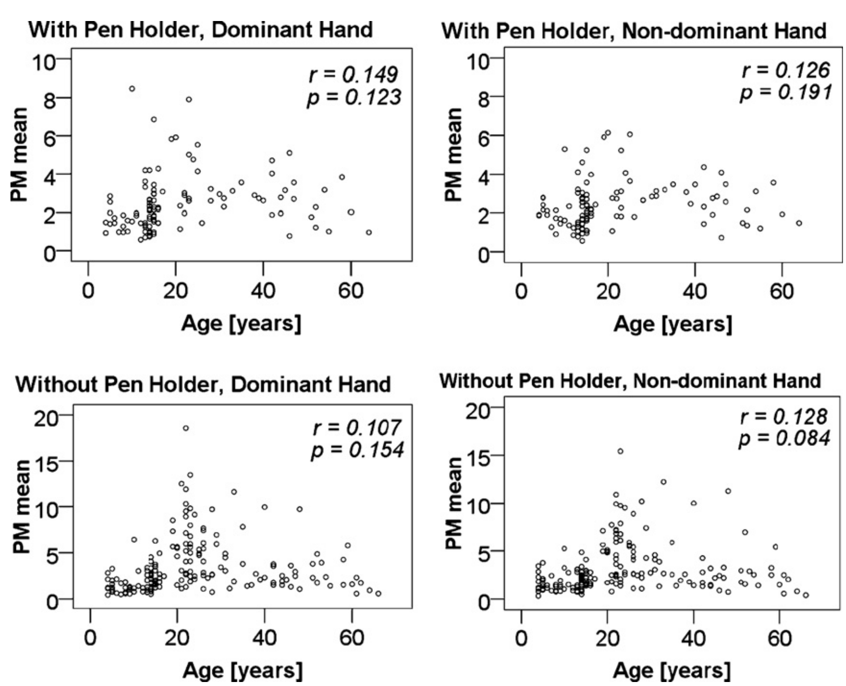

Fig. 5. Scatter plots of mean performance measure (PM) vs. age for each drawing test subject with and without pen holder, for the dominant and non-dominant hands. The Pearson correlation coefficients (*r*) and significance (*p*) are indicated in each plot.

arm function, taking into account handedness and effects due to the use of the pen holder.

The performance measure and healthy performance norms we have introduced with the EDT allows discrimination between different elements of impaired arm and hand function. We suggest that using the EDT on patient populations may reveal performance deficiencies in two main ways. First, patient performance under some or all test conditions may be lower than that of the healthy population. Secondly, patients may perform significantly better or worse in one test condition relative to the others. For example, in healthy subjects it is normal for the performance using either hand without the pen holder to be higher than the performance using the corresponding hand with the pen holder. A patient suffering from hand paresis might show near-normal performance with the pen holder due to intact proximal gross arm function, and the same (or worse) performance without the pen holder due to paralyzed distal finger function. In contrast, existing objective tests such as the Nine Hole Peg Test or the Box and Block Test would not provide differentiation of these cases between proximal and distal motor control. Another way that our performance norms can be used is by noting that performance in healthy subjects is not hand-dependent. Therefore, a significant performance difference in patients between the dominant and non-dominant hand may represent impaired performance in the weaker hand.

Although the EDT is described here as a hand function test, it needs to be emphasized that it does not provide assessment of grasping in terms of dynamically closing and opening the hand to grasp an object. However, the two different grips performed in the EDT can be taken as potential core elements of grasping relating to the real-world tasks of writing, drawing and pointing (including usage of computer mice). Drawing movements using a pen are a frequently exercised part of everyday life and are critical milestones during childhood development. In addition, it is known that performance in existing clinical drawing tests correlate with performance in other clinical tests which do test grasping function, such as the Purdue Pegboard Test (Grosskopf and Kuhtz-Buschbeck, 2005) and the Nine Hole Peg Test (Feys et al., 2007). We suggest that because our EDT tests both overall arm and fine arm-motor control, different parts of the test may be able to correlate with multiple clinical assessments specialized on either overall arm movements or fine motor function. If this turns out to be true then the EDT could be used as an alternative to using a battery of different tests. In addition, since the EDT software records the complete trajectory performed in each trial, it supports the development of future assessments which can be used to re-interpret past trajectory data.

During testing we noticed several problems with evaluating very young children which require special considerations to ensure valid results. Because they had not yet learned to draw properly, 5 of the children aged 3–4 years (out of 18 in the age group) used a prismatic precision grip (4 straight fingers, opposed thumb) when holding the pen, instead of a proper dynamic tripod grip (thumb and index finger form a circle while the pen rests against the side of the third finger). It is not known to what extent these modified grips influenced the results. In addition, it was necessary to explain the instructions in the context of an ad hoc story (e.g. animal returning to house) to ensure that the youngest children carried out the task correctly. Although we believe it is very unlikely that these customized instructions affected the results, future versions of the test should standardize the protocol for very young children to ensure consistent results.

A future enhancement of the EDT could include measuring applied pen pressure; one previous graphonomic study has found that increased variability in patients was accompanied by lower pen pressures (Van Gemmert and Teulings, 2006). Also, we did not investigate variants involving the drawing of horizontal lines or multiple-segment figures such as squares (Popovic et al., 2004). This extension may yield more accurate information about certain motor deficits due to the different movements required to draw horizontal lines, although using multiple-segment lines could possibly introduce confounds related to changes in cortical motor plans during line following. To make the test easier to understand and less strenuous for children, it may also be advisable to conduct the test on a horizontal touch-sensitive screen. With such an arrangement the digital pen can leave behind a line on the screen which is easier for children to understand than a pen that leaves marks at a remote location.

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