Published in final edited form as:

J Forensic Sci. 2014 July ; 59(4): 1020–1024. doi:10.1111/1556-4029.12437.

Kinematics of Signature Writing in Healthy Aging*

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Abstract

Forensic document examiners (FDE) called upon to distinguish a genuine from a forged signature of an elderly person are often required to consider the question of age-related deterioration and whether the available exemplars reliably capture the natural effects of aging of the original writer. An understanding of the statistical relationship between advanced age and handwriting movements can reduce the uncertainty that may exist in an examiner's approach to questioned signatures formed by elderly writers. The primary purpose of this study was to systematically examine age-related changes in signature kinematics in healthy writers. Forty-two healthy subjects between the ages of 60–91 years participated in this study. Signatures were recorded using a digitizing tablet and commercial software was used to examine the temporal and spatial stroke kinematics and pen pressure. Results indicated that vertical stroke duration and dysfluency increased with age, whereas vertical stroke amplitude and velocity decreased with age. Pen pressure decreased with age. We found that a linear model characterized the best-fit relationship between advanced age and handwriting movement parameters for signature formation. Male writers exhibited stronger age effects than female writers, especially for pen pressure and stroke dysfluency. The present study contributes to an understanding of how advanced age alters signature formation in otherwise healthy adults.

Keywords

forensic science; questioned documents; signatures; handwriting; ageing; handwriting kinematics

It is estimated that by the year 2030, 20% of US residents will be age 65 or older, reaching a population of over 88 million people or 21% of the population by 2050 (1). With advanced age there is decline in cognitive and sensorimotor function affecting fine motor control, balance and gait. Routine daily activities become difficult. The decline in motor function stems from multiple factors including alterations in both central and peripheral nervous systems governing neuromotor function (2).

*Supported in part by a grant from National Institute of Aging (AG05131).

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Handwriting is not likely to be spared by this process. A review of the published literature on handwriting kinematics in advanced age revealed a number of findings including slower speed of handwriting movements (3–5), reduced and more uniform pen pressure across strokes (6–7), greater stroke variability (8), increased time of the decelerative phase of movements (8), and greater reliance on visual feedback (8–11) compared with younger writers. The latter findings implicate impaired utilization of the handwriting motor programming as older writers shift from open loop control (i.e. movements that do not depend on feedback for accuracy) to closed loop control (i.e. movements that are altered by visual or proprioceptive feedback). Within a given pen stroke, older writers tend to spend more time in the honing-in or terminal phase of the movement (8) suggesting greater reliance on closed loop control compared with younger writers.

Prior studies on handwriting in aging employed various handwriting tasks such as loops, letters, shopping lists, numbers, and standard or self-generated sentences to examine age-related effects on handwriting movements. Only one study that we are aware of included natural signature writing in the battery of handwriting tasks (7). In this study, subjects between the ages of 60 and 94 years were asked to fill out a check and write their natural signatures; however only a few measures were obtained from these samples including time of contact between pen and paper, movement speed, and pen pressure. While prior research has contributed to a greater understanding of how age can impact handwriting performance on standardized tasks, little is known about signature formation.

Features seen in the handwriting of elderly persons such as slow strokes, dysfluency (tremor), and unnatural pen pressure are also indicative of simulated (forged) signatures. Therefore, advanced age of a writer likely contributes to uncertainty and reduced reliability in the document examiner's judgment of authenticity (9). An understanding of the statistical relationship between advanced age and handwriting movements can reduce the uncertainty in an examiner's approach to questioned signatures formed by elderly writers. The primary purpose of this study was to systematically examine age-related changes in signature kinematics in healthy writers. Secondary aims of the study were to examine whether the best fit characterizing the relationship between age and handwriting movements is linear or non-linear for writers aged 60 years or greater and to examine whether writer gender impacts the strength of these relationships.

Methods

Subjects

Forty-two healthy subjects participated in this study. The 24 male and 18 female subjects ranged in age from 60–91 years with a mean (standard deviation) age of 74.38 (8.36) years. Among the 24 male participants, five were between 60–69 years of age, 13 were between 70–79 years of age and six were over age 80 years. Among the 18 female participants, nine were between 60–69 years of age, four were between 70–79 years of age and five were over age 80 years. Subjects were recruited from a pool of subjects participating in ongoing research at the Shiley-Marcos Alzheimer's Disease Research Center, University of California San Diego. Each subject underwent extensive cognitive, neurological, and medical history evaluations to exclude those with any neuropsychiatric or medical condition

that could impact handwriting performance. Cognition was assessed using the Dementia Rating Scale (DRS)(12) and the Mini-Mental State Exam (MMSE)(13). Parkinsonism was evaluated using Part III of the Unified Parkinson's Disease Rating Scale (UPDRS)(14). Mean scores for the clinical assessments were 139.9 (3.7), 29.3 (0.9), and 0.17 (1.00) for the DRS, MMSE, and UPDRS respectively. All subjects signed institutional review board (IRB) approved informed consent prior to participating.

Handwriting Kinematics

The study utilized quantitative methods to examine the temporal and spatial stroke kinematics and pen pressure associated with the production of natural signatures. Procedures involved the use of a non-inking pen with a Wacom Intuos4 9×12 digitizing tablet (30 cm × 22.5 cm, sampling rate 120 Hz, RMS accuracy 0.01 cm) connected to a desktop computer running MovAlyzeR software (Neuroscript, LLC, Tempe AZ). Subjects were not provided visual feedback during the handwriting tasks. We reasoned that variability in how effectively elderly writers use visual feedback to make on-line corrections (8, 10–11) could bias the results in a nonsystematic manner. Subjects were asked to write their natural signature five times. Each trial was separate by an interval of 3–10 seconds depending on the length of the signature and writing speed of the subject. Data collection began when the pen tip came in contact with the tablet and ended when the pen was lifted for more than 3 seconds. Errors, false starts, or premature termination automatically triggered the software to prompt the examiner to repeat the trial.

Data Reduction—Upon completion of the tasks, kinematic variables and pen pressure were calculated for each vertical and horizontal pen stroke automatically by MovAlyzeR software. The following variables were extracted from each pen stroke: duration of vertical stroke from the onset of vertical movement to peak displacement in msec; absolute amplitude of the vertical stroke from baseline (onset of vertical movement) to peak movement prior to direction change (ascending strokes) or from peak movement to baseline (descending strokes) in cm; instantaneous peak stroke velocity derived from the first derivative of the displacement curve in cm/sec; relative time to peak vertical velocity in %; average normalized jerk derived from the formula $(0.5 \times \sum(\text{jerk}(t)^2) \times \text{duration}^5 / \text{length}^2)$ (15); and pen pressure scaled in arbitrary digital units. Relative time to peak velocity is an index of the proportion of time the writer spends in the decelerative phase of movement for a single stroke. Greater values indicate more time spent in decelerative or terminal phase implying greater reliance on feedback to ensure accuracy. Average normalized jerk is a measure of smoothness of pen movement. Higher scores indicate greater changes in acceleration and consequently less smoothness. Scores for each variable were averaged across strokes and trials and subjected to statistical analyses as dependent variables.

Statistical Analyses

We utilized one-way analyses of variance (ANOVA) for the primary statistical analyses to examine age effects. Subjects were grouped into three age subgroups: 60–69 years, 70–79 years, and 80+ years. The decision to separate subjects in age decades was based on published studies showing that the relationship between age and handwriting movements is likely to be non-linear with the greatest decline in age-related motor function occurring after

age 70 years (4, 6). To test the best fit of the relationship between age and handwriting features, we examined both linear and non-linear (i.e. natural logarithmic) age functions. We expected writer gender to influence the relationships between age and handwriting characteristics. Therefore separate analyses were performed on all data (n=42), males only (n=24) and females only (n=18). All statistical analyses were performed using Statistica software (StatSoft, Inc. version 10, Tulsa, OK)

Results

Table 1 shows the descriptive statistics for the handwriting variables of all three subject groups. The ANOVA results revealed significant effects of age on vertical stroke velocity ($F_{2,39} = 3.95$ $p=0.027$) and pen pressure ($F_{2,39} = 4.65$ $p=0.015$). Post-hoc least square difference tests revealed significant differences between the younger (age 60–69 yrs) and oldest (age >80 years) groups for both stroke velocity ($p=0.009$) and pen pressure ($p=0.004$). There was a trend for the 70–79 year old writers to exhibit lower stroke velocities than the 60–69 year old subjects ($p=0.054$).

Table 2 shows the correlation coefficients for the linear and non-linear models. The observed differences between coefficients derived from the linear relationships were not significantly different from those derived from the log transformed age variable suggesting that the best fit relationship between age and handwriting movement parameters for signatures may be described as linear for writers between the ages of 60 and 91 years.

Figure 1 shows scatterplots of the relationships between age and each of the handwriting parameters. Data from both male and female subjects are included in these scatterplots. We observed that vertical stroke duration increased with age ($r=0.42$), vertical stroke amplitude decreasing with age ($r=-0.42$), vertical stroke velocity decreased with age ($r=-0.43$), movement dysfluency increased with age ($r=0.39$ for average normalized jerk and $r=0.44$ for number of acceleration peaks/stroke), and pen pressure decreased with age ($r=-0.37$). Examination of these relationships for male writers only revealed stronger relationships for each of the above relationships (except pen pressure). A single 91-year old subject was excluded from the analysis for average normalized jerk as he was considered an outlier with an ANJ score of 418.

Among male writers, there was a significant relationship between age and relative time to peak velocity ($r=-0.48$), which increased for male writers over the age of 69 years ($r=-0.61$). This finding is shown in Figure 2. None of the relationships between age and handwriting movement parameters reached statistical significance for female writers. Thus, the main effect of advanced age on handwriting movement appears to be driven by the male writers.

Discussion

The goal of this study was to examine age-related changes in signature kinematics in a group of older healthy writers and to determine whether these changes are linear over a 30-year age range. The effect of gender on the relationship between age and handwriting parameter was of particular interest in this study. Our findings indicated that within the range of 60–91

years of age, there was a linear decline in the size and velocity of pen strokes during natural signature writing. Stroke duration and dysfluency increased linearly over this age range. There was a modest but significant linear decrease in pen pressure. Statistical analyses revealed two important findings. First, the group effects of age on handwriting movement and pressure scores were driven exclusively by differences between the youngest (mean = 65.64 yrs) and oldest (mean = 85.91 yrs) group of writers. Second, data for male writers, especially those over the age of 69 years disclosed significant relationships between age and handwriting movement and pressure scores. The relationships between age and handwriting features for female writers failed to reach statistical significance.

Our findings compare well with two previous studies on handwriting kinematics and pen pressure across the age spectrum. In the first study, Rosenbaum and Werner (7) studied paragraph-writing in 53 healthy writers aged 60–94 years and reported correlation coefficients for age and writing time, speed, and pen pressure of 0.49, –0.35, and –0.33, respectively. The present study of signature writing found correlation coefficients of 0.42, –0.43, and –0.37 for stroke duration, velocity, and pen pressure, respectively. Slight differences between the two studies may be explained by differences in handwriting tasks.

The second study, to utilize quantitative methods to examine effects of advanced age on handwriting kinematics, was by Slavin et al. (8). In that study, young (mean age = 21.6 years) and older (mean age = 73.2 years) adults completed a handwriting task involving continuous cursive letters. They reported a 15% decrease in stroke amplitude, 29% increase in stroke duration, and a 58% increase in the number of acceleration cycles for their no-ink writing condition (similar to present methods) in the older writers compared with younger writers. In the present study, we observed a 70% decrease in stroke amplitude, a 26% increase in stroke duration and a 30% increase in number of acceleration peaks per stroke in our oldest group compared with the youngest group of writers. Differences in the magnitude of the age effect between these studies could be due to differences in the mean ages of the subject groups.

While these studies suggest that the deleterious effects of age on handwriting kinematics are not task-specific, the question remains whether the effects of age are gradual or punctuated with changes occurring at various intervals late in life. Results from three studies (including the present work) suggest that the effects of age on handwriting late in life occur in a progressive fashion. Rodriguez-Aranda (4) studied handwriting speed across a 65-year age span and found a punctuated (or sudden) rather than a gradual pattern with the first increase in writing time occurring after age 60 years, then again after age 80 years. Walton (6) evaluated multiple features from sentences written by healthy subjects between the ages of 39 and 91 years and found that handwriting characteristics remained relatively stable over a 5-year period for writers under the age of 65 years; whereas writers over the age of 70 showed marked changes over the same period of time in such features as the number of pen lifts and pen pressure variability. In the present study of signature formation, we found that while handwriting kinematics for 60–69 year olds did not differ from kinematics for 70–79 year olds, writers over the age of 79 exhibited lower stroke velocities and pen pressure than their younger counterparts. Thus, while the results presented in Table 1 appear to indicate a

gradual decline in handwriting motor skill over a 30-year period, it was not until age 80 that the decline reached statistical significance.

One novel measure of handwriting motor control examined in the present study was the relative time to peak velocity. This measure reflects the degree to which the writer adopts an open or closed loop mode of motor control. Under open loop control the writer executes individual pen strokes without reliance on visual or proprioceptive feedback. Thus, once a pen stroke is initiated it continues on its planned trajectory without correction. Under closed loop control the kinematics of individual pen strokes may be altered or corrected based on visual or proprioceptive feedback. Closed loop or feedback control is necessary when movements require precise distance endpoint for ending the pen stroke or changing direction. In general, movement trajectories may be viewed as consisting of two phases: an initial (open loop) ballistic and a final (closed loop) honing-in component (16–18). These two components may be separated in time by the location of peak velocity. Thus, longer time intervals between the time the pen stroke reached peak velocity to time of peak displacement suggest greater reliance on closed-loop control during which sensory feedback is available. In the present study, we observed a decrease in the relative time to peak velocity for male writers over the age of 69 years suggesting greater reliance on closed loop mode of handwriting control compared with younger male subjects. These findings are consistent with Slavin et al. (8) who reported a 25% increase in the time to peak velocity for older writers. It remains unclear why the shift to more closed loop mode of motor control during natural signature formation that accompanies advanced age in male writers appears to be spared in female writers.

The present study has limitations. It could be argued that the analysis of the relationships between advanced age and handwriting movement parameters for female writers lacked statistical power given the relatively small sample of females in the study, whereas for a larger sample of male writers, these relationships reached statistical significance. Thus while it may be premature to conclude that handwriting movements may not change to a significant degree over a 30-year span among female writers, the deleterious effects of age on handwriting movements for signatures are greater for male than female writers. A second limitation of the present study is our restriction to exclude writers younger than 60 years; while previous studies examined age effects over a wider age range (6,8). The decision to limit enrollment to older writers was based on the potential relevance of our findings to cases most likely encountered by FDEs. The goal of this study was not to replicate or expand on previous findings, but to inform FDEs of relevant features associated with signatures by writers with advanced age to guide decision-making.

In summary, the present study is the first to examine effects of advanced age and gender on signature kinematics. Perhaps one of the more challenging tasks confronting document examiners is determining authorship of signatures written by an individual late in life at a time when control over fine hand movement is waning. Under the Daubert standard (19), FDEs are compelled to employ objective criteria when determining authorship of questioned signatures purportedly written by an elderly writer. These criteria will likely come from prospective empirical research on signatures written by healthy elderly writers.

Acknowledgments

The author wishes to acknowledge Doug Galasko, M.D. and David Salmon, Ph.D. for their leadership in making the ADRC facilities and research participants available to this research and their contribution to the scoring of the clinical assessments.

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FIG. 1.

Scatterplots of the relationships between age and handwriting movement parameters for all subjects. Shown are plots for stroke duration (A, scaled in seconds), stroke amplitude (B, scaled in cm), stroke velocity (C, scaled in cm/sec), average normalized jerk (D, a unitless value), number of acceleration peaks (E, number of peaks per stroke) and pen pressure (F, scaled in digital units) with the linear line of best fit ($\pm$ 95% confidence intervals).

FIG. 2. Scatterplot of the relationship between age and relative time to peak velocity (RTpV, scaled in proportion of stroke extent) for male subjects over the age of 69 years.

TABLE 1

Mean (standard deviation) scores for pen movement stroke parameters for older writers grouped by age and the results from statistical analyses (F-ratio).

	Age 60–69 yrs	Age 70–79 yrs	Age > 79 yrs	F (p)
Stroke Duration	183 (8.9)	199 (9.7)	231 (22.8)	2.96 (<0.10)
Stroke Amplitude	1.7 (0.2)	1.3 (0.1)	1.0 (0.1)	2.88 (<0.10)
Stroke Velocity	12.0 (1.6)	8.8 (0.9)	7.2 (0.7)	3.95 (<0.05)
Relative Time to Peak Velocity	47.8 (0.5)	47.8 (0.4)	46.7 (0.8)	1.01 (>0.10)
Average Normalized Jerk	21.1 (2.2)	24.4 (2.9)	70.6 (35.6)	2.53 (<0.10)
No. Acc. Peaks/Stroke	2.3 (0.1)	2.5 (0.2)	3.0 (0.4)	2.56 (<0.10)
Pen Pressure	696.6 (30.5)	634 (26.1)	560.9 (32.9)	4.65 (<0.02)

TABLE 2

Correlation coefficients for the linear and non-linear relationships between age and pen movement stroke parameter for all subjects (n=42), male only (n=24), and female only (n=18) writers.

		Linear	Log(n)
Stroke Duration	All	0.42 [†]	0.41 [†]
	Males	0.46 [†]	0.45 [†]
	Females	0.36	0.35
Stroke Amplitude	All	-0.42 [†]	-0.44 [†]
	Males	-0.59 [†]	-0.61 [†]
	Females	-0.20	-0.20
Stroke Velocity	All	-0.43 [†]	-0.44 [†]
	Males	-0.60 [‡]	-0.66 [‡]
	Females	-0.19	-0.19
Relative Time to Peak Velocity	All	-0.26	-0.25
	Males	-0.48 *	-0.45 *
	Females	-0.25	0.10
Average Normalized Jerk	All	0.39 *	0.37 *
	Males	0.42 *	0.40
	Females	0.44	0.42
No. Acc. Peaks/Stroke	All	0.44 [†]	0.42
	Males	0.52 [†]	0.50 *
	Females	0.26	0.26
Pen Pressure	All	-0.37 *	-0.36 *
	Males	-0.33	-0.32
	Females	-0.40	-0.40

* p<0.05;

[†] p<0.01;

[‡] p<0.001