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# Signature Dynamics in Alzheimer's Disease

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## Abstract

Forensic document examiners are often called upon to opine on the authenticity of handwritten signatures by individuals with diminished mental capacity. Legal arguments surrounding the decisional capacity of an individual with dementia can be found in many cases involving wills, deeds, trusts, and contracts. The purpose of this study was to provide estimates of feature variability derived from dynamic analyses of signatures written by individuals with dementia of the Alzheimer type (AD) compared with age-comparable healthy individuals. Dynamic features of digitally captured signatures were analyzed to test the hypothesis that AD signature features will show greater variability compared with signatures from age-comparable healthy subjects. The study enrolled 69 AD and 74 age comparable healthy subjects. Results revealed four main findings from AD signatures: 1) that the temporal, spatial and fluency characteristics of signature formation did not differ from signatures of healthy writers; 2) variability in dynamic features over a series of repetitive signatures fell within 10% of the natural variation of healthy subjects; 3) there was a significant association between increased dynamic signature feature variability and increased dementia severity for stylized and mixed signatures only; and 4) despite significant decline in cognitive status over a one-year period, dynamic signature features remained stable. Overall, these results suggest that signature writing is preserved in AD. The association between dementia severity and dynamic feature variability among AD subjects with stylized or mixed signatures warrants further research.

### Keywords

Dementia; Signatures; Signature Variability; Signature Dynamics; Document Examination

## Introduction

Forensic Document Examiners (FDEs) are often tasked with determining if a questioned signature is genuine or non-genuine. Such signatures may appear on documents such as

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wills, deeds, trusts, and contracts and the health of the signatory can be a pertinent factor [1]. In cases of suspected dementia, two questions are usually asked: 1) did the signatory execute the questioned signatures? and 2) did the signatory have the mental capacity to understand what they were signing? Given an adequate number of contemporaneous specimens, the FDE can answer the first questioned to some degree of certainty [2 3 4]. However, uncertainty creeps into this process in cases where the signatory's mental status declines or fluctuates making it difficult for the FDE to estimate the individual's natural variation [5].

Walton [6] cautioned that FDEs must be careful in the examination of writers with neurological diseases. She noted that line quality, tremor, retouching, pen pressure, and speed may be erratic, but this is not necessarily due to simulation, but may result from the effects of normal aging. Her study found that some people in their 90s and even centenarians wrote with normal speed and exhibited little deterioration in their handwriting. Earlier, Behrendt [7] suggested that the FDE should be aware of the writer's medical history and be cognizant of the effects of medication (especially on tremor) on a patient with AD. He warned that contemporaneous standards were a necessity and in late-stage AD, specimens written on the same day as the questioned signature may be necessary to prevent error.

Questionable levels of signature variation in a writer often raises concern of health change, reaction to prescribed medication, or substance use. Of concern to document examiners preparing testimony on signature authorship, the presence of features outside the range of natural variation may be indicative of a simulation. Documents such as wills that bear disputed signatures are frequently submitted to FDEs for examination. Dementia is not an uncommon explanation that is proffered to explain the presence of poor line quality in the testator's signature. However, data are lacking to inform the FDE on the impact of a dementing illness on a writer's natural signature variability. The purpose of this study was to provide estimates of feature variability derived from dynamic analyses of signatures written by individuals with AD compared with age-comparable healthy individuals.

## Materials and Methods

### Participants

Study subjects were recruited from volunteers participating in a large clinical research program at the [removed to protect reviewer blinding]. Sixty-nine subjects meeting DSM-IV criteria for dementia as well as the Alzheimer's Disease and Related Disorders Association (ADRDA) criteria for probable AD [8] and 74 age-comparable healthy control (HC) subjects were included in the study. AD subjects had a mean (standard deviation) age of 75.56 (9.44) years; while HC subjects had a mean age of 74.92 (7.65) years. 60% of the AD and 32% of the HC subjects were male. Subjects had to be in good general health, and with adequate vision, hearing and motor skill to complete the handwriting assessment. Inclusion criteria for healthy control subjects included absence of any neurological, psychiatric, or other medical conditions that could impact performance on the motor or cognitive battery administered by the [removed to protect reviewer blinding]. AD patients meeting consensus criteria for Lewy body dementia or those who were taking neuroleptic medications were excluded. All subjects either signed institutional approved informed consent or, when a subject

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demonstrated questionable decisional capacity, informed consent was obtained through a surrogate prior to participating in this study.

Each subject underwent extensive cognitive, neurological, and medical history evaluations as part of their baseline [removed to protect reviewer blinding] assessment. Cognitive status was assessed using the Mattis Dementia Rating Scale (DRS) [9]. Lower scores on the DRS indicate increasing dementia severity. A diagnosis of dementia is considered when scores on the DRS drop below 124 (out of a possible score of 144). AD subjects had a mean (sd) DRS score of 115.28 (11.84) indicating a moderate degree of dementia severity. It is not uncommon for individuals diagnosed with AD to develop signs of parkinsonism at some time in the course of the disease. As parkinsonism is often a comorbid condition in AD and is known to adversely impact handwriting [10 ,11], we evaluated the presence and severity of clinical parkinsonism using Part III of the Unified Parkinson's Disease Rating Scale (UPDRS) [12]. The UPDRS version used by the National Alzheimer Coordinating Center rates 14 items on a 0–4 point scale and a maximum severity score of 56. Higher scores on the UPDRS indicate increasing severity of parkinsonism. AD subjects had a mean (sd) UPDRS score of 1.22 (3.37) reflecting absent or questionable parkinsonism.

## Signature Sampling

The procedures for measuring signature dynamics involved the use of a non-inking pen and a Wacom UD 9×12 digitizing tablet (30 cm x 22.5 cm, sampling rate 120 Hz, RMS accuracy 0.01 cm) attached to a desktop computer running MovAlyzeR®[1] software. We chose to use a standard non-inking pen in this study to reduce non-motor variability across writers and over time that could develop from inconsistent ink flow or shifting position of writing surface (paper). Subjects were seated at a table and allowed to reposition the tablet to achieve a comfortable writing posture. Subjects were instructed to sign their natural signature as they would to sign a document. They were provided practice to increase familiarity with the inkless stylus and tablet. Subjects repeated their signature five times, each within a recording window of ten seconds. Ten seconds allowed sufficient time to complete the full signature even with initiation delay of a few seconds. The signatures were part of a larger handwriting assessment protocol that included circles, loops and a sentence; however, for the purpose of this report, we present results from the signature component only. Twenty-one of the 69 AD subjects and 35 of the 74 HC subjects were retested one year after the initial assessment using the same procedures. Annual assessments were optional for subjects enrolled in the [removed to protect reviewer blinding] program and many chose not to participate in the longitudinal component. Others were lost to follow-up due to various reasons including institutionalization, refusal to participate in the handwriting assessment, or scheduling conflicts.

Dynamic movement and pressure variables (collectively referred to as dynamic features) were automatically calculated from each vertical and horizontal pen stroke using MovalyzeR® software. Dynamic features included: stroke duration (in seconds), absolute vertical stroke amplitude (in cm), peak vertical stroke velocity (in cm/sec), average

[1]Neuroscript, LLC, Tempe, AZ, USA; https://www.neuroscript.net

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normalized jerk (ANJ)[2], and pen pressure (in tablet units ranging from 0–1023). Means and standard deviations were calculated across all vertical strokes and signature repetitions for each of the variables. A total of 335 signatures from the AD group and 358 from the NC group were examined. Five AD and 6 HC subjects did not complete the full set of five repetitions as instructed.

### Statistical Analyses

Signatures were classified as text-based, mixed, or stylized using published criteria [13] based on consensus agreement by both authors. Signature style was included as covariate in subsequent statistical analyses where appropriate.

Three analyses were performed on the dynamic feature set. First, dynamic signature variables (temporal, spatial, fluency, and pressure) from AD signatures were compared with those from HC signatures to test the hypothesis that signatures written by AD subjects will contain features that differ from signatures of HC writers. Second, tests for group differences in the short-term (over five repetitions) variability were conducted. Coefficients of variability (CV), obtained by dividing the standard deviation across repetitions by the mean score, were subjected to difference tests to compare AD with HC signature variability. To be entered into this analysis subjects needed at least four (out of five) complete signatures. As noted above, five AD and six HC subjects did not meet this requirement and were excluded from this analysis. Larger CVs reflect greater between-signature variability for a given dynamic feature. For this analysis we used non-parametric Mann-Whitney tests as the assumptions of a normal distribution and equal variances were not satisfied to allow parametric difference tests. The third analysis involved testing group differences in the long-term (one year) variability. For this analysis we calculated difference score (1-year follow-up minus baseline) for the dependent variables and applied t-statistics to these difference scores (where appropriate) to examine group differences. For all analyses, an alpha $\leq 0.05$ was set for statistical significance which was subsequently adjusted for multiple comparisons using the Bonferroni correction method of dividing alpha by the number of comparisons. The relationships between severity of dementia and signature dynamic features and their variability were examined using Pearson correlation coefficients.

## Results

The majority of subjects from both groups wrote signatures using text-based style, where every allograph was discernable from the signature. Ten AD (14.5%) and two HC subjects (2.7%) wrote signatures using mixed (8/10 AD) or stylized (2/10 AD and both HC) styles. The difference in proportion of non-text-based signatures between the two groups was statistically significantly ($\chi^2 = 6.46$; p=0.01). For this reason, we report group differences in kinematic features and variability for text-based signatures separately from mixed or stylized signatures.

[2] $\sqrt{(0.5 \times \sum(\text{jerk}(t)^2) \times \text{duration}^5 / \text{length}^2}$

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### Signature dynamics in AD and age-comparable healthy writers

Table 1 shows the descriptive statistics for each of the dynamic features from 59 AD and 72 HC test-based signatures. After adjusting alpha for multiple comparisons using the Bonferroni correction, there were no statistically significant differences between AD and HC on the dynamic signature variables.

### Short-term variability in dynamic features of signatures in AD

Figure 1 shows the mean (with standard error bars) coefficient of variability (CV) calculated for five dynamic variables from repetitive text-based signature samples. AD subjects exhibited significantly greater variability in stroke duration ($Z=3.34$; $p<0.001$), stroke amplitude ($Z=3.04$; $p<0.001$), peak vertical velocity ($Z=3.64$; $p<0.005$), and average normalized jerk ($Z= 3.43$; $p<0.001$) compared with HC subjects for repetitive signatures. Differences in short-term variability for pen pressure ($Z=1.94$; $p > 0.05$) were non-significant. After adjusting alpha to protect against false discovery rate using the Bonferroni correction for multiple comparisons, group differences across repetitive signatures remained statistically significant ($p<0.006$). However, the magnitude of the variability in signature dynamics over repetitive signatures for AD subjects as a group did not exceed 10% of the natural variation measured from healthy writers.

Differences between variability coefficients between repetitive text-based versus non-text-based signatures were examined for AD subjects only. Variability in mean pen pressure for repetitive non-text-based signatures (13.7%) was significantly greater ($z=2.19$; $p<0.05$) than for repetitive text-based signatures (7.5%). No other differences were observed in variability for dynamic features between non-text-based and text-based signatures

Correlational analyses were performed to examine the relationships between clinical state and short-term variability in stroke dynamics for signatures. There were no significant associations between dementia severity and variability in dynamic signature features for text-based writers; however among non-text-based writers ($n=10$), we found an association between lower DRS scores and increased short-term variability in stroke amplitude ($r= -0.70$; $p=0.02$) and peak velocity ($r=-0.65$; $p<0.05$). Figure 2 shows a scatterplot of the relationship between dementia severity (DRS) and variability in stroke amplitude for non-text-based signatures.

### Long-term variability in signature dynamics in AD and age-comparable healthy writers

Table 2 shows the difference scores between baseline and the 1-year follow up assessments for AD and HC subjects. There were no significant differences in change scores for the dynamic signature features between AD and HC subjects based on t-tests despite a mean decrease of 5.9 points on the DRS among AD subjects.

Among the 21 AD and 32 HC subjects two subjects from each group used non-text-based signature styles. While this subset was insufficient to conduct a formal statistical test to examine effects of style on long-term variability in signature dynamics, it is noteworthy that for non-text-based signatures, mean (sd) pen pressure increased by 290.4 (44.6) units over a 1-year period compared to an increase of only 6.7 (93.4) units for text-based signatures.

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## Discussion

Several new findings emerged from the present study. First, dynamic signature features (including stroke duration, amplitude, velocity, smoothness, and pen pressure) for AD subjects did not differ from age-comparable healthy subjects. These findings from a relatively large sample of subjects suggest that the presence of moderate levels of dementia severity associated with AD appeared not to impact signature dynamics. For the FDE, this means that parameters such as stroke height, inferred speed of pen strokes, and pen pressure should not differ substantially from signatures written before the onset of the disease. If the FDE observes substantial differences in speed, stroke height, and pen pressure between questioned and specimen signatures, this may be indicative of simulation rather than effects of AD.

Second, variability in signature dynamics for repetitive samples from AD subjects were significantly more variable than their non-demented counterparts; however, the magnitude of this variability was within 10% of the natural variation of healthy subjects. FDEs recognize the importance of obtaining multiple contemporaneous specimen signatures in order to estimate the natural variation. While many dynamic features of a signature cannot be measured from static traces, some such as stroke height (or size) and pen pressure can be measured with high degrees of accuracy. The results of the present study support Behrendt's [7] cautious recommendation by demonstrating that the range in the natural variation of signature dynamics is slightly greater in the presence of dementia than in the absence of dementia and expand this concern to include individuals with moderate degrees of dementia severity. Furthermore, the relationship between increased dementia severity and increased variability in stroke amplitude and speed for non-text-based signatures suggests that the cognitive impairment(s) in AD may impact the execution of a mixed or stylized signature while sparing text-based signature formation. While we caution against overinterpreting this finding, due to the relatively small sample of mixed and stylized signatures available for this analysis, the finding suggests that when examining the natural variation of signature features in AD, variability will likely be greater in mixed and stylized than text-based signatures, especially in cases with more severe dementia.

These results show that for repetitive signatures, the burden of dementia appears to add approximately 5% to the normal intra-writer variation in temporal and spatial features and 9% to the normal intra-writer variation in fluency. This may be especially important where signatures are signed, for example, on a deed and in a notary log within minutes of each other can appear to have differences in size, speed or pressure. However, it remains unknown whether an experienced document examiner could reliably detect a 10% range in signature stroke features, and it is unlikely that 10% variation on any measurable feature between known and questioned signatures would be enough to suggest a simulation. In these types of cases, contemporary specimen signatures are especially important for an examination.

Third, despite a significant decline in cognitive status over a one-year period, dynamic signature features remained relatively stable in our AD subjects. The present findings suggest that the time frame associated with "contemporaneous" signature specimens can

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span as much as a year without posing a challenge to the FDE undertaking signature comparisons from an individual with dementia.

Two interesting observations emerged from analyses of signature style. First, there were significantly more non-text-based signature writers among the AD sample (14.5%) than the healthy control sample (2.7%). Non-text-based AD signatures had larger stroke amplitudes and higher stroke velocities than text-based signatures. This is consistent with what has been shown in prior studies of signature dynamics in normal healthy writers [13]. In the absence of signatures from before the onset of cognitive changes in individuals with putative dementia, it is difficult to speculate about the diagnostic or forensic implication of this finding. To our knowledge, there have been no empirical studies of writing style preference among older and elderly populations suggesting further study of this is warranted. Secondly, we observed that AD subjects with non-text-based signatures showed increases in mean pen pressure over a period of one year of 322 and 260 units; whereas the mean increase over the same period for text-based signatures was only 6.74 units. The forensic implications of the finding that pen pressure increases over time in stylized but not text-based AD signatures are unclear. Again, this anecdotal finding requires confirmation from future longitudinal studies of a larger group of AD subjects with mixed or stylized signatures.

While prior research on handwriting in dementia focused on lexical and motor disturbances for the purpose of understanding fundamental motor control and disease prognosis in AD [14,15,16,17], the present study focused exclusively on signatures. Our present findings showing normal signature dynamics in AD are at odds with earlier reports of abnormal dynamics for sentences, words, and letters. This discrepancy can be explained by differences in the cognitive demands necessary to execute an over-learnt motor behavior such as a signature compared to spontaneous word or sentence handwriting or copying.

The present study has limitations. First, we recorded only the dynamic aspects of signature writing without an accompanying static paper trace. While FDEs rely almost exclusively on static traces to form opinions of writership, information from studies of dynamic signature features can help guide the evaluative process. Second, for analysis of short-term variability, signatures were repeated five times over a 60-second period. The decision to operationalize short-term variability over this time interval was based on practical concerns and it is possible that dynamic feature variability for signatures would differ when measured over a longer time interval (e.g. days or weeks). Third, we were unable to obtain dynamic signature samples from AD subjects prior to the onset of cognitive decline to strengthen our present conclusion that signatures in moderately severe AD are not impaired. Such a comparison could also shed light on the reliability of the observation that mixed and stylized signatures were more prevalent among AD than HC individuals and whether this increased prevalence is a byproduct of dementia. Because the AD and control subjects were not randomly selected from the population, the results on signature style should be considered preliminary.

## Summary and Conclusions

Previously published empirical research on the impact of dementia on linguistic and motor aspects of handwriting offers little help to the forensic document examiner tasked with

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evaluating signature specimens. This study is one of few and perhaps the largest to address signature writing in individuals with Alzheimer's disease, the most common form of dementia. The study found that signatures written by individuals with AD show normal temporal, spatial, and fluency characteristics when subjected to dynamic analyses. Despite significant decline in cognitive status over a one-year period, signature dynamics remained stable. These results support the conclusion that the cognitive-motor changes that accompany dementia have minimal impact on signature formation.

A primary focus of this study was to quantify feature variability derived from dynamic analyses of signatures written by individuals with AD. While the variability in dynamic features over a series of repetitive signatures ranged from 12.8% (for temporal and spatial features) to 43.2% (for fluency) for AD subjects, these values were within 10% of the natural within-writer variation in signature dynamics for heathy individuals. Increased variability in writers with dementia may be established dogma among FDEs; however, the availability of empirical data characterizing the time-course and magnitude of this variability can strengthen testimony. A finding that signatures are unaffected by the disease for the majority of AD individuals can be very useful to FDEs working cases involving disputed signatures from persons with dementia. It remains unclear if the increased prevalence of stylized and mixed signatures in AD relative to age-comparable healthy controls is a reliable finding. Nonetheless, FDEs should be cognizant of the potential interaction between dementia severity and signature style when examining variability over repeated signatures. When estimating the natural variation of signature features in AD, estimates will likely be greater in mixed and stylized than text-based signatures, especially in cases with more severe dementia.

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## References

1. Woodrow K Fogg v. Paul N. Fogg. No. 13-CA-712. Court of Appeal of Louisiana, Fifth Circuit 142 So.3d 150 (2014)
2. Osborn AS. Questioned Documents (2nd Ed). Nelson-Hall Co. Chicago, IL 1929.
3. Hilton O. A further look at writing standards. The Journal of Criminal Law, Criminology and Police Science, 56(3) (1965) 383–389.
4. Hilton O. (1971). Do we really have adequate signature standards? Journal of the Forensic Science Society, 11(3), 45–49.
5. Hilton O. Influence of serious illness on handwriting identification. Postgraduate Medicine, 19(2) (1956). A-36–48. [PubMed: 13280460]
6. Walton J. Handwriting changes due to aging and Parkinson's syndrome. Forensic Science International, 88 (2009) 197–214.
7. Behrendt J. Alzheimer's disease and its effects on handwriting. Journal of Forensic Sciences, JFSCA, 29 (1) (1984) 87–91

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8. McKhann GM, Knopman DS, Chertkow H, Hyman T, Jack CR, et al., The diagnosis of dementia due to Alzheimer's disease: Recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. Alzheimer's Dement 7 (3) (2011) 263–269. [PubMed: 21514250]
9. Mattis S, DRS: Dementia Rating Scale Professional Manual Psychological Assessment Resources, Inc. Odessa, FL 1981.
10. Caligiuri MP and Mohammed LA, The Neuroscience of Handwriting: Applications for Forensic Sciences CRC Press, Boca Raton, FL 2012
11. Thomas M, Lenka A, Kumar Pal P, Handwriting analysis in Parkinson's disease: Current status and future directions. Mov Disord Clin Pract 4(6) (2017) 806–818. [PubMed: 30363367]
12. Fahn S, and Elton RL, UPDRS Development Committee: Unified Parkinson's Disease Rating Scale. In: Fahn S, Marsden CD, Calne D, Goldstein M, eds Recent Developments in Parkinson's Disease Vol 2 Florham Park, NH: Macmillan, 1987 pp 153–163.
13. Mohammed L, Found B, Rogers D. Frequency of signatures styles in San Diego County. J Am Soc Quest Doc Exam 1 (2008) 9–13.
14. Slavin MJ, Phillips JG, Bradshaw JL, Hall KA Presnell I, Bradshaw JA, Kinematics of handwriting movements in dementia of the Alzheimer's type. Alzheimer's Research, 1 (1995) 123–132.
15. Schröter A, Mergl R, Bürger K, Hampel H, Möller H-J, Hegerl U, Kinematic analysis of handwriting movements in patients with Alzheimer's disease, mild cognitive impairment, depression and healthy subjects. Dementia and Geriatric Cognitive Disorders 15 (2003) 132–142. [PubMed: 12584428]
16. Werner P, Rosenblum S, Bar-On G, Heinik J, Korczyn A, Handwriting process variables discriminating mild Alzheimer's disease and mild cognitive impairment. Journal of Gerontol: B Psychol Sci 61 (2006) 228–236.
17. Yan JH, Rountree S, Massman P, Doody RS, Li H, Alzheimer's Disease and mild cognitive impairment deteriorate fine movement control. Journal of Psychiatric Research, 42 (2008) 1203–1212. [PubMed: 18280503]

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## Highlights

- Dynamic analyses of signatures revealed normal temporal, spatial and fluency features in AD;
- Feature variability over repetitive signatures in AD fell within 10% of the variability of control signatures;
- Variability in stroke amplitude and speed for non-text-based signatures was associated with dementia severity;
- Dynamic aspects of signature formation in AD remained stable over one year.

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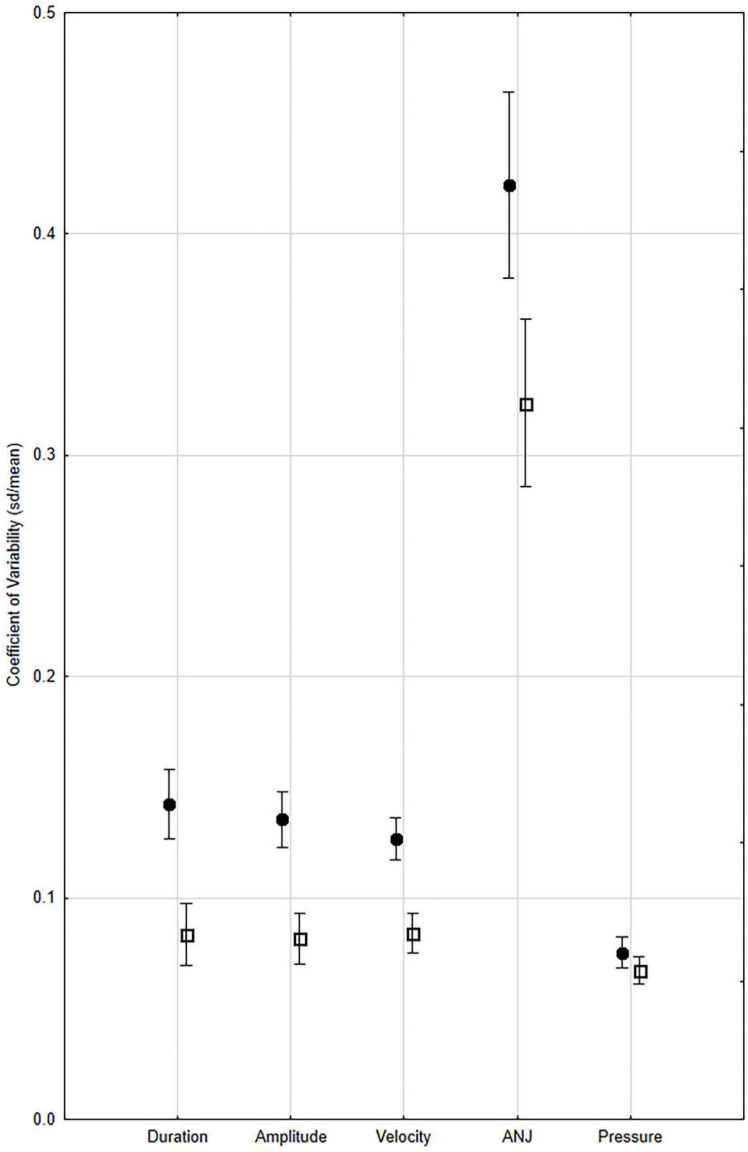


**Figure 1.**

Mean (with standard error bars) coefficients of variability (CV) calculated for five dynamic feature variables associated with repetitive text-based signature · samples for Alzheimer (filled circles) and healthy control (open boxes) subjects.

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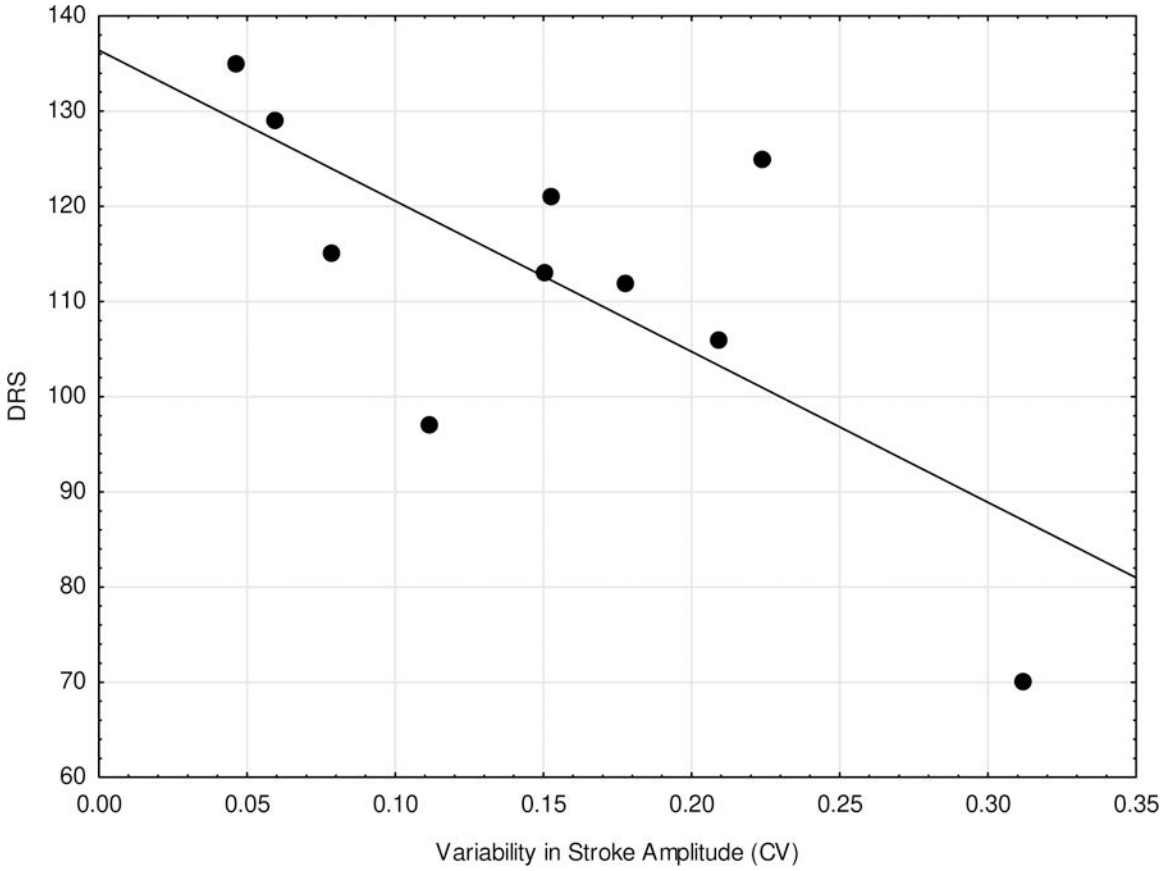


**Figure 2.**

Scatterplot of the relationship between Dementia Rating Scale (DRS) score and variability in stroke amplitude for 10 non-text-based AD signatures.

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**Table 1.**

Mean (with standard deviation) scores for dynamic features associated with text-based signatures in Alzheimer disease (AD) and healthy control (HC) subjects. Variables represent the mean scores across vertical strokes and repetitions and their standard deviations (SD).

| Dynamic Feature | AD (n=59) | HC (n=72) | t-Statistic | p-value* |
|---|---|---|---|---|
| Mean Duration | 0.23 (0.05) | 0.20 (0.05) | 2.75 | 0.007 |
| SD Duration | 0.13 (0.09) | 0.10 (0.08) | 1.92 | ns |
| Mean Amplitude | 1.03 (0.43) | 1.21 (0.55) | 2.01 | 0.05 |
| SD Amplitude | 0.68 (0.35) | 0.78 (0.41) | 1.52 | ns |
| Mean Peak Velocity | 7.14 (3.47) | 8.77 (3.97) | 2.47 | 0.015 |
| SD Peak Velocity | 4.36 (2.29) | 5.02 (2.59) | 1.53 | ns |
| Mean ANJ | 47.14 (65.24) | 32.75 (50.73) | 1.42 | ns |
| SD ANJ | 33.36 (130.02) | 23/44 (102.86) | 0.49 | ns |
| Mean Pen Pressure | 667.92 (124.73) | 649.13 (120.50) | 0.85 | ns |
| SD Pen Pressure | 229.84 (83.68) | 205.21 (83.59) | 1.64 | ns |

*Shown are uncorrected p-values if $p<0.05$; A Bonferroni corrected p-value $\leq 0.005$ is considered statistically significant.

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**Table 2.**

Mean difference scores (with standard deviations) between baseline and 1-year follow up assessments for the signature dynamic features for AD and HC subjects.

| | AD (n=21) | HC (n=32) | t-Statistic | p-value |
|---|---|---|---|---|
| DRS | −5.90 (10.25) | −0.17 (2.89) | −3.12 | 0.002 |
| UPDRS | 2.22 (4.79) | 0.00 (0.00) | 2.56 | 0.013 |
| Stroke Duration | 0.004 (0.051) | 0.005 (0.036) | −0.11 | >0.10 |
| Stroke Amplitude | −0.11 (0.38) | −0.12 (0.44) | 0.096 | >0.10 |
| Peak Vertical Velocity | −0.65 (2.81) | −1.20 (2.75) | 0.72 | >0.10 |
| ANJ | 13.97 (62.12) | 4.44 (46.22) | 0.65 | >0.10 |
| Pen Pressure | 35.11 (124.62) | 25.39 (100.08) | 0.31 | >0.10 |