Characteristics of Handwriting of People With Cerebellar Ataxia: Three-Dimensional Movement Analysis of the Pen Tip, Finger, and Wrist

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Background. There are several functional tests for evaluating manual performance; however, quantitative manual tests for ataxia, especially those for evaluating handwriting, are limited.

Objective. This study aimed to investigate the characteristics of cerebellar ataxia by analyzing handwriting, with a special emphasis on correlation between the movement of the pen tip and the movement of the finger or wrist.

Design. This was an observational study.

Methods. Eleven people who were right-handed and had cerebellar ataxia and 17 people to serve as controls were recruited. The Scale for the Assessment and Rating of Ataxia was used to grade the severity of ataxia. Handwriting movements of both hands were analyzed. The time required for writing a character, the variability of individual handwriting, and the correlation between the movement of the pen tip and the movement of the finger or wrist were evaluated for participants with ataxia and control participants.

Results. The writing time was longer and the velocity profile and shape of the track of movement of the pen tip were more variable in participants with ataxia than in control participants. For participants with ataxia, the direction of movement of the pen tip deviated more from that of the finger or wrist, and the shape of the track of movement of the pen tip differed more from that of the finger or wrist. The severity of upper extremity ataxia measured with the Scale for the Assessment and Rating of Ataxia was mostly correlated with the variability parameters. Furthermore, it was correlated with the directional deviation of the trajectory of movement of the pen tip from that of the finger and with increased dissimilarity of the shapes of the tracks.

Limitations. The results may have been influenced by the scale and parameters used to measure movement.

Conclusions. Ataxic handwriting with increased movement noise is characterized by irregular pen tip movements unconstrained by the finger or wrist. The severity of ataxia is correlated with these unconstrained movements.

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The cerebellum plays a major role in learning fine coordinated movements. Pathological ataxic movements were first investigated in detail in 1917 by Holmes.[1] Cerebellar damage results in intention tremor, dysmetria, and limb movement decomposition. The characteristics of ataxia in handwriting also have been described. Simple letters or characters, such as a figure eight[2] and spirals,[3] are usually chosen for movement analysis. In some studies,[2–6] a digitizer tablet with a stylus pen was used to quantitatively measure handwriting or drawing performance in people with ataxia. Some parameters proposed in these studies revealed increased numbers of errors and oscillations in tracing or drawing by people with ataxia.[4,5] A modest correlation between kinematic parameters and the severity of ataxia was shown.[6] However, the studies did not address the true characteristics of ataxia. Most of the study parameters indicated poorer performance that is seen not only in ataxia but also in other movement disorders (eg, hemiparesis, parkinsonism). Furthermore, the studies did not focus on the relationship between the movement of the pen tip and the movement of the finger or hand.

In this study, we first focused on the variability of handwriting kinematics and the shape of the track of movement of the pen tip. Freeman[7] found that writing time is relatively constant regardless of writing size. This property was later described as the "isochrony" property of adult handwriting. Viviani and Terzuolo[8] measured the velocity of the pen tip during writing and plotted it against time. They found that the shapes of velocity profiles are similar even when a person tries to write faster or larger. This kinematic property of pen tip movement is called "space-time invariance." We further developed this theory to propose the following variability parameters: kinematic variability and variability of the shape of the track of movement of the pen tip.

Secondly, we focused on the movement of the pen tip in relation to the movement of the finger or wrist. Coordinated correlations in movement during handwriting are expected. Harada et al[9] investigated the relationship between pen tip movement and pen holding. They suggested that the ratio of the length of the track of movement of the pen tip to that of the hand represents hand individuality or dexterity. We developed parameters to demonstrate the relationship between pen tip movement and finger or wrist movement with respect to movement direction and velocity and to the shape of the track.

Writing consists of small-amplitude, fast movements. To analyze this fine movement effectively, we used a high-resolution electromagnetic motion tracker to record 3-dimensional (3D) coordinate data at a high sampling frequency. The purpose of this study was to reveal the abilities that are impaired in people with cerebellar ataxia and the factors that are most relevant to grading of the severity of clinical ataxia with the Scale for the Assessment and Rating of Ataxia (SARA).

Method

Participants

Eleven people (4 men and 7 women; mean age=64.5 years, SD=13.7) who were right-handed and had chronic cerebellar ataxia (4 with cerebellar infarction, 1 with cerebellar hemorrhage, 2 with cerebellar tumor, and 4 with spinocerebellar degeneration) were recruited from the stroke unit or the ambulatory rehabilitation clinic of Kyorin University Hospital, Tokyo, Japan, in 2012 and 2013. Seventeen volunteers who were right-handed and healthy (10 men and 7 women; mean age=73.4 years, SD=11.3; P=.07) were recruited in 2013 from older people who lived in the community and gathered periodically for leisure activities. Their age and handedness were matched to those of the 11 people with ataxia. In addition to the 17 volunteers who served as control participants, a volunteer who was healthy (35-year-old man) was included to record handwriting for 10 days during the study period to check the test-retest reproducibility of the writing parameters. All participants were of Japanese heritage. Only people who had cerebellar ataxia and who were able to write a legible character in a 2-cm square frame with both the right hand and the left hand were included. People with apparent dementia, aphasia, or unilateral spatial neglect were excluded by screening with the Mini-Mental State Examination[10] and the Revised Hasegawa Dementia Scale.[11] Informed consent was obtained from all participants.

Clinical Evaluation of Manual Function

Handedness was determined for all participants with the Edinburgh Inventory.[12] Scores on the Edinburgh Inventory range from −100 (completely left-handed) to +100 (completely right-handed), with 0 points indicating ambidexterity. The grip strength of the right and left hands was measured while participants sat in a chair with their elbow joints extended. The SARA[13] was used to evaluate the clinical severity of ataxia. We used only 3 of the 8 SARA items, that is, those pertaining to the upper extremities: finger-chase, finger-to-nose, and fast alternating hand movement tests. Each item was rated on a 5-point scale from 0 (no abnormal movement) to 4 (serious impairment preventing performance of the task). Each of these 3 upper extremity items has been reported to reliably grade ataxia.[13,14]

Sums of the 3 item scores for the right and left hands ranged from 0 to 12. The linearity of each score with the sum was checked with the Spearman rank correlation coefficient to determine whether it was reasonable to use the sum of scores as a single scale.

3D Handwriting Measurement

Handwriting movement was measured with a 3D movement analyzer (Liberty, Polhemus, Colchester, Vermont), which consists of a magnetic field generator, a stylus pen with a position sensor in the pen tip, and 2 small disk-shaped sensors. The disk-shaped sensors were placed at the metacarpal head of the index finger (finger) and the distal end of the radius (wrist). Three-dimensional coordinates for the stylus pen tip and the 2 disk-shaped sensors were recorded at a sampling frequency of 240 Hz. Participants were asked to write the Japanese Hiragana character "*ah*" (Fig. 1A) in free handwriting (their regular handwriting) in frames of 4 different sizes (2.0, 5.0, 7.5, and 15.0 cm) with their right and left hands. This character is a basic Japanese character corresponding to the English letter "*a*." All participants were familiar with this character. They wrote 10 characters in each frame with each hand, for a total of 80 characters. Two practice sessions were completed for each frame size before recording commenced. Furthermore, participants were told "not to hurry" and "do not write carefully." They were given a break to prevent fatigue and were asked not to stabilize their forearms on the table to avoid any reduction in the freedom of motion.

Parameters Representing Handwriting Characteristics

Recorded coordinate data were analyzed with MATLAB general-purpose numerical analysis software (version R2008b, MathWorks, Tokyo, Japan). Time to write a character was averaged for each size and for each hand. The kinematic features of handwriting movement were illustrated as instantaneous velocities of the pen tip plotted against the track length from the initial writing point, expressed as a percentage of the total length (Fig. 1B). Because sampling was done at equal time intervals, the data had to be converted to data at equal length intervals. Spline interpolation was used for this conversion[9] after the length between sampled points was calculated. Mean velocity plots were obtained from the 10 repetitions of writing, and standard deviations were calculated for all plots. Then, the standard deviation was divided by the mean for each plot to compute the "grand mean," which was assumed to represent the variability of the velocity profile for pen tip movement. To avoid confusion with the coefficient of variation (CV), we refer to the grand mean as the "variability parameter" in this article. The distance of the pen tip from the geometric center of its movement track was plotted against the track length to illustrate the shape profile for the movement track (Fig. 1C). The variability of the shape of the track of movement of the pen tip also was represented by the grand mean for distance, similar to the variability parameter for the velocity profile.

Correlations between the movement of the pen tip and the movement of the finger or wrist were examined with respect to movement direction, velocity profile, and the shape of the track of movement of the pen tip as well as that of other sensors. Movement correlation was assumed to be high when the direction of movement of the pen tip was the same as that of the sensors placed on the finger or wrist. Cosines of the angles made by movement vectors of the pen tip and other sensors (Fig. 1D) were plotted against track length (Fig. 1E). Cosine means were used as parameters indicating directional agreement. The coefficient of correlation between the velocity of movement of the pen tip and that of other sensors was used to show similarity between velocity profiles. When the correlation coefficient was high (ie, when the instantaneous velocity of pen tip movement was proportional to that of finger or wrist movement), the movements were assumed to be synchronized or dependent on each other. The coefficient of correlation between the shape of the track of movement of the pen tip and that of the finger or wrist indicated the similarity in the shapes of the writing tracks. When the correlation coefficient was high, the shape of the track of movement of the pen tip resembled that of the finger or wrist.

Data Analysis

The reproducibility of handwriting parameters was determined by analyzing a participant's right-hand writing in the smallest (2-cm) frame; this writing was supposed to be the least reproducible writing (compared with writing in a larger frame). Ten repetitions of writing were recorded on 10 different days. We calculated CVs to ascertain the reproducibility of handwriting parameters for those 10 repetitions and to check the reproducibility of the mean parameters during the 10 trials.

Differences between participants with ataxia and control participants, between right-hand writing and left-hand writing, and among the 4 writing frame sizes were analyzed by 3-way analysis of variance with repeated measures for 2 factors: the hand side and the writing frame size. The estimated marginal means and 95% confidence intervals of the parameters were calculated and tabulated for all 3 factors. Post hoc Bonferroni comparisons were used to show differences between any pairs of factors when a significant interaction among any of the 3 factors was

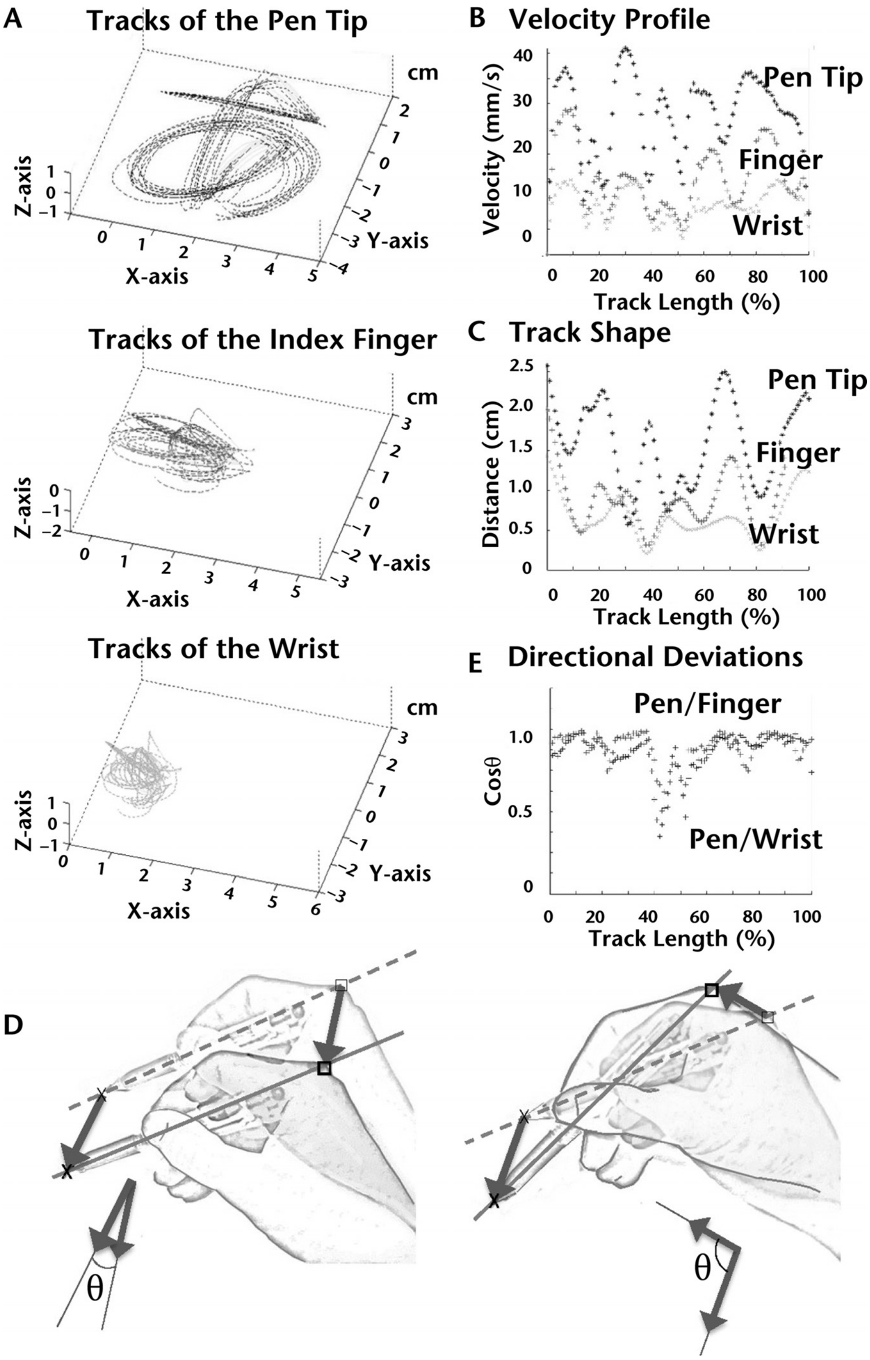

Figure 1.

Writing tracks and writing parameters. (A) Example of "*ah*," a Japanese syllabary character, handwritten by a control participant. Ten tracks of writing movements of the pen tip, metacarpal head of the index finger (finger), and distal end of the radius (wrist) in a 2-cm frame were layered. The index finger and the pen tip drew nearly consistent tracks. (B) Plot of velocity means for 10 writing movements of the pen tip, finger, and wrist against length along the writing tracks, expressed as a percentage. Kinematic features illustrated by the velocity profiles for the pen tip, finger, and wrist were positively correlated. (C) Plot of mean distances of the pen tip, finger base, and wrist from the geometric center of each track against length along the writing tracks as an expression of movement track shape. The shapes of the tracks of movement of the finger and wrist were analogous to that of the pen tip. (D) Definition of angles made by movement vectors of the pen tip and the finger. When the vectors moved in the same direction, the angle θ was close to 0. Movements in different directions produced large positive angles. (E) Plot of cosine means for the angles produced by movements of the pen tip and finger and those produced by the pen tip and wrist against track length. Directional disagreements of movements were observed several times during writing.

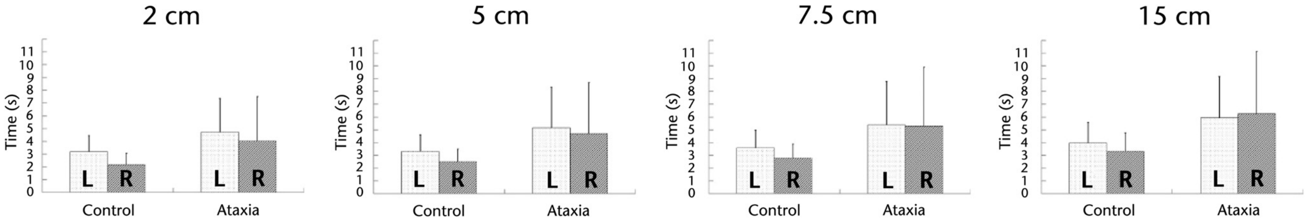

Figure 2.
Time required for writing. Means and standard deviations for writing times are illustrated as bar plots for each writing size in the control group (n=17) and the ataxia group (n=11). The writing time was significantly longer in the ataxia group than in the control group (*P*=.04). The time needed for writing with the right hand was significantly shorter than that with the left hand (*P*=.02). Writing time increased significantly as writing size increased (*P*≤.001). L=left-hand writing, R=right-hand writing.

found by the 3-way analysis of variance. The relationship between the SARA and parameters obtained from the 3D movement analyzer was analyzed with the Spearman rank correlation coefficient. The level of significance was set at 5%. IBM SPSS Statistics for Windows (version 22.0, IBM Corp, Armonk, New York) was used for data analysis.

Role of the Funding Source
This study was supported, in part, by a Grant-in-Aid for Scientific Research (23500615) from the Japan Society for the Promotion of Science. It helped us to purchase the measurement apparatus and software for statistical and numeric analysis and supported our participation in related conferences and English proofreading for reporting the findings of this study.

Results
Functional Evaluation of Upper Extremities
The Edinburgh Inventory handedness scores ranged from 85 to 100 ($\bar{X}$=95.0, SD=5.0) for the ataxia group and 55 to 100 ($\bar{X}$=92.1, SD=11.3) for the control group, indicating that all participants were right-handed. The mean grip strengths of the right and left hands in the ataxia group were 21.3 kg (SD=13.4) and 21.2 kg (SD=15.5), respectively. The mean grip strengths for the control group were 23.1 kg (SD=8.8) for the right hand and 22.0 kg (SD=9.4) for the left hand. The median SARA scores for the ataxia group were 4 (range=0–5, interquartile range=2.0) for the right hand and 3 (range=0–6, interquartile range=2.5) for the left hand. Both hands were equally involved in 8 participants, in 2 participants only the right hand was involved, and in 1 participant only the left hand was involved.

Reproducibility of Handwriting Parameters
The CVs of the time needed to write a character ranged from 2.0% to 8.9% ($\bar{X}$=3.4%, SD=2.0%), and the CV of the mean time for the 10 trials was 3.5%. The CVs of the pen tip velocity variability parameter were 16.5% to 21.4% ($\bar{X}$=18.2%, SD=1.5%), and the CV of the means for the 10 trials was 18.1%. The CVs of the track shape variability parameter were 12.5% to 16.7% ($\bar{X}$=14.0%, SD=1.3%), and the CV of the means for the 10 trials was 14.0%. With respect to correlations between the movement of the pen tip and the movement of the finger or wrist, the CVs of the cosine parameter for the pen tip and finger were 9.9% to 13.9% ($\bar{X}$=12.5%, SD=1.4%), and the CV of the means for the 10 trials was 12.4%; the CVs for the pen tip and wrist were 13.0% to 23.8% ($\bar{X}$=17.8%, SD=3.4%), and the CV of the means for the 10 trials was 17.7%. The CVs of the velocity similarity parameter for the pen tip and finger were 4.5% to 12.9% ($\bar{X}$=8.5%, SD=2.5%), and the CV of the means for the 10 trials was 8.3%; the CVs for the pen tip and wrist were 6.0% to 14.6% ($\bar{X}$=9.8%, SD=3.1%), and the CV of the means for the 10 trials was 9.6%. The CVs of the track shape similarity parameter for the pen tip and finger were 8.8% to 28.5% ($\bar{X}$=15.3%, SD=6.1%), and the CV of the means for the 10 trials was 14.9%; the CVs for the pen tip and wrist were 10.0% to 25.7% ($\bar{X}$=15.6%, SD=5.3%), and the CV of the means for the 10 trials was 15.3%.

Time Needed to Write a Character
The time needed for writing (Fig. 2) was significantly longer in participants with ataxia than in control participants (*P*=.04). Differences in time between right-hand use and left-hand use were significant (*P*=.02). Increases in size-related writing time were significant (*P*≤.001). The estimated marginal means and 95% confidence intervals of writing times are shown in the Table. No significant interaction in writing times for group, hand, or writing size was found.

Variability of Handwriting Movement
Figures 3A and 3B show 10 overlaid writing samples and a velocity profile for the pen tip in the 2-cm frame to demonstrate irregular and inconsistent changes in pen tip velocity in

Table.
Estimated Marginal Means and 95% Confidence Intervals (CI)[a]

Parameter	Group			Side			Size				
	Estimated Marginal Mean (95% CI)		P	Estimated Marginal Mean (95% CI)		P	Estimated Marginal Mean (95% CI)				P
	Control	Ataxia		Right	Left		2 cm	5 cm	7.5 cm	15 cm	
Writing time	3.11 (1.91, 4.32)	5.19 (3.69, 6.69)	.04	3.89 (2.8, 4.97)	4.41 (3.54, 5.29)	.02	3.54 (2.73, 4.34)	3.92 (2.98, 4.86)	4.27 (3.22, 5.31)	4.88 (3.79, 5.96)	≤.001
Kinematic variability	0.25 (0.22, 0.29)	0.35 (0.31, 0.4)	.001[b]	0.3 (0.27, 0.33)	0.31 (0.28, 0.34)	.23[b,c]	0.38 (0.35, 0.42)	0.3 (0.27, 0.34)	0.28 (0.25, 0.31)	0.25 (0.22, 0.27)	≤.001[c]
Track shape variability	0.17 (0.15, 0.19)	0.21 (0.19, 0.24)	.005[d]	0.19 (0.17, 0.2)	0.2 (0.18, 0.21)	.16[c,d]	0.23 (0.21, 0.25)	0.19 (0.18, 0.21)	0.18 (0.16, 0.19)	0.17 (0.15, 0.18)	≤.001[c,d]
Cosine parameter											
Pen tip and finger	0.85 (0.8, 0.9)	0.74 (0.68, 0.81)	.02	0.77 (0.72, 0.81)	0.82 (0.77, 0.88)	.09	0.66 (0.61, 0.71)	0.79 (0.73, 0.84)	0.84 (0.8, 0.88)	0.9 (0.87, 0.93)	≤.001
Pen tip and wrist	0.81 (0.77, 0.85)	0.73 (0.68, 0.77)	.01	0.74 (0.7, 0.78)	0.8 (0.75, 0.84)	.06	0.61 (0.57, 0.65)	0.76 (0.72, 0.8)	0.81 (0.78, 0.85)	0.88 (0.86, 0.91)	≤.001
Kinematic parameter											
Pen tip and finger	0.7 (0.66, 0.73)	0.71 (0.66, 0.75)	.72	0.65 (0.61, 0.69)	0.75 (0.71, 0.79)	.001	0.61 (0.59, 0.64)	0.68 (0.65, 0.72)	0.72 (0.68, 0.76)	0.79 (0.75, 0.82)	≤.001
Pen tip and wrist	0.61 (0.58, 0.65)	0.59 (0.54, 0.63)	.33	0.56 (0.52, 0.59)	0.64 (0.61, 0.68)	≤.001	0.47 (0.43, 0.51)	0.58 (0.54, 0.61)	0.63 (0.6, 0.67)	0.73 (0.69, 0.76)	≤.001
Track shape parameter											
Pen tip and finger	0.72 (0.66, 0.78)	0.62 (0.54, 0.69)	.04	0.62 (0.56, 0.69)	0.71 (0.66, 0.76)	.03	0.53 (0.47, 0.58)	0.64 (0.57, 0.7)	0.7 (0.65, 0.76)	0.8 (0.76, 0.84)	≤.001
Pen tip and wrist	0.68 (0.64, 0.73)	0.58 (0.53, 0.64)	.01[e]	0.63 (0.58, 0.68)	0.63 (0.58, 0.68)	.94	0.5 (0.46, 0.55)	0.61 (0.56, 0.66)	0.66 (0.62, 0.7)	0.76 (0.72, 0.79)	≤.001[e]

[a] Significance, determined with an analysis of variance, was set at a *P* value of ≤.05.
[b] Significant difference for interactions between hand and group.
[c] Significant difference for interactions between hand and writing size.
[d] Significant difference for interactions among hand, group, and writing size.
[e] Significant difference for interactions between group and writing size.

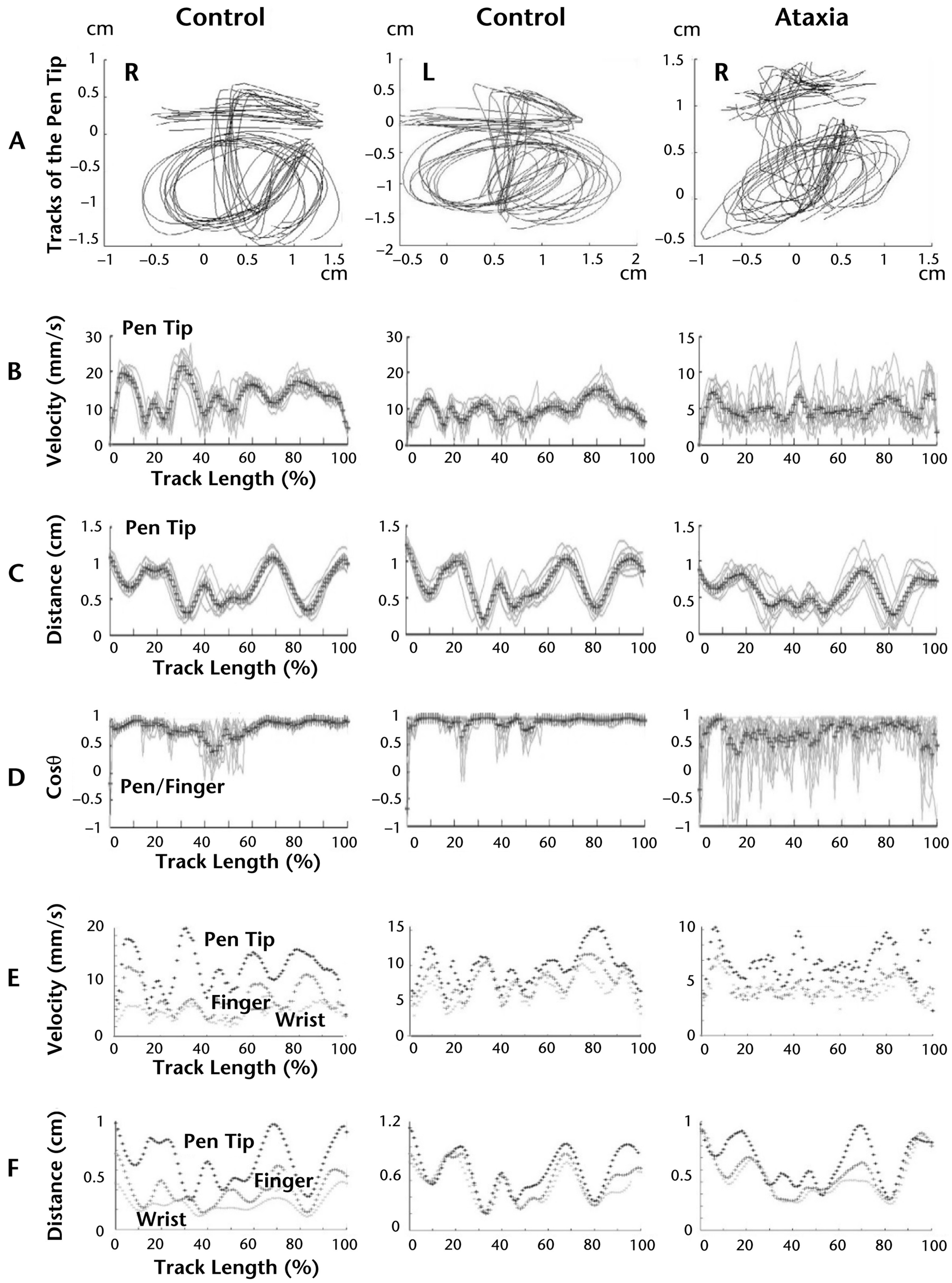

Figure 3.

Examples of writing tracks and profiles of handwriting parameters. (A) Examples of tracks of movement of the pen tip during writing of 10 characters. The tracks varied more for participants with ataxia than for control participants. Tracks made by the right hand seemed more consistent than those made by the left hand. (B) Kinematic profiles of handwriting, shown as plots of the instantaneous velocity of the pen tip against track length, expressed as a percentage, during writing of 10 characters. Kinematic variability was markedly greater in ataxic handwriting. (C) Track shape features for individual handwriting movements, depicted as plots of the distance of the pen tip from the geometric center of each track. Distance deviations were seen frequently in ataxic handwriting. (D) Plots of cosines of angles made by movement vectors of the pen tip and the finger against track length. Directional deviations of the movement of the pen tip from that of the finger were much larger in participants with ataxia. Differences in deviations between writing with the left hand and writing with the right hand were noted in control participants. (E) Kinematic profiles of movements of the pen tip, finger, and wrist, shown as plots of mean velocity against track length. Differences in these profiles were noted in participants with ataxia. (F) Track shape features for movements of the pen tip, finger, and wrist, represented as plots of the mean distance from the geometric center of each track. L=left-hand writing, R=right-hand writing.

a participant with ataxia. As shown in the Table, kinematic variability was significantly larger in the ataxia group than in the control group (P=.001), indicating that changes in handwriting velocity were irregular in participants with ataxia. No significant difference between the right hand and the left hand was found for this variability parameter (P=.23). This parameter became significantly smaller as writing size increased (P≤.001), suggesting lower variability in writing of a larger size. For this variability parameter, interactions between hand and writing size were significant (P=.001), as were those between hand and group (P=.04). Multiple comparisons revealed no right-left differences, except for 2-cm (P=.001) or 7.5-cm (P=.05) frame writing in the control group and 15-cm (P=.04) frame writing in the ataxia group. However, differences between groups in 2-cm (P=.003), 5-cm (P=.002), 7.5-cm (P=.001), and 15-cm (P≤.001) frame writing with the right hand and in 5-cm (P=.003), 7.5-cm (P=.007), and 15-cm (P=.002) frame writing with the left hand were significant.

The profile of the shape of the track of movement of the pen tip in Figure 3C shows the irregularity of the track shape in ataxic handwriting. The variability of writing track shape was significantly larger in the ataxia group than in the control group (P=.005) (Table). Differences between right-hand use and left-hand use were not significant (P=.16), but differences among the 4 writing sizes were significant (P≤.001). For this variability parameter, interactions between hand and writing size were significant (P=.04), and interactions among hand, group, and writing size were marginally significant (P=.05). Multiple comparisons revealed significant right-left differences only in 2-cm (P=.002) frame writing in the control group. Differences between groups in 2-cm (P=.002), 5-cm (P=.007), 7.5-cm (P=.01), and 15-cm (P=.001) frame writing with the right hand and in 5-cm (P=.03) and 7.5-cm (P=.04) frame writing with the left hand were significant.

Relationship Between Movement of the Pen Tip and Movement of the Finger or Wrist

Figure 3D shows the profile for cosines of the angles made by movement vectors of the pen tip and finger during the 10 trials; this profile revealed irregular deviations in the direction of movement of the pen tip from the direction of movement of the finger in ataxic handwriting. The cosine means for angles made by movement vectors of the pen tip and finger (Fig. 1D) in the ataxia group were significantly smaller than those in the control group (P=.02), as were the cosine means for the pen tip and wrist (P=.01) (Table). These results suggest that the index finger and wrist moved in directions different from that of the pen tip more frequently in participants with ataxia than in control participants. The cosine means for the pen tip and finger as well as for the pen tip and wrist did not differ significantly between right-hand use and left-hand use (P=.09 for the pen tip and finger; P=.06 for the pen tip and wrist). Size-related increases in the cosine means were significant for the pen tip and finger (P≤.001) as well as for the pen tip and wrist (P≤.001). For this cosine parameter, interactions among group, hand, and writing size for the pen tip and finger or for the pen tip and wrist were not significant.

Figure 3E shows the velocity profile for the pen tip and finger; in this profile, movements of the pen tip and finger seemed less synchronized in ataxic handwriting. The kinematic correlations between the movement of the pen tip and the movement of the finger or wrist (Table) did not differ in the ataxia and control groups (P=.72 for the pen tip and finger; P=.33 for the pen tip and wrist). However, the correlations were significantly lower for right-hand use than for left-hand use (P=.001 for the pen tip and finger; P≤.001 for the pen tip and wrist). Size-related increases in this parameter for the pen tip and finger (P≤.001) and for the pen tip and wrist (P≤.001) were also significant. No significant interaction was found for this parameter.

We observed that the shape of the track of movement of the pen tip often resembled that of the finger or wrist. Figure 3F shows the profile of the shape of the track of movement of the pen tip and that of the finger; in this profile, less similarity was evident in ataxic handwriting. This shape similarity parameter (Table) in the ataxia group was significantly different from that in the control group (P=.04 for the pen tip and finger; P=.01 for the pen tip and wrist). For this parameter, a significant difference between right-hand use and left-hand use for the pen tip and finger was also found (P=.03). The right-left difference was not significant for the pen tip and wrist (P=.94). However, size-related increases in this parameter were significant for the pen tip and finger (P≤.001) and for the pen tip and wrist (P≤.001). For this shape similarity parameter, interactions between group and writing size were significant for the pen tip and wrist (P=.02). Multiple comparisons of this parameter revealed significant differences between groups only in 2-cm (P=.03) and 7.5-cm (P=.01) frame writing with the right hand and in 2-cm (P=.04) frame writing with the left hand.

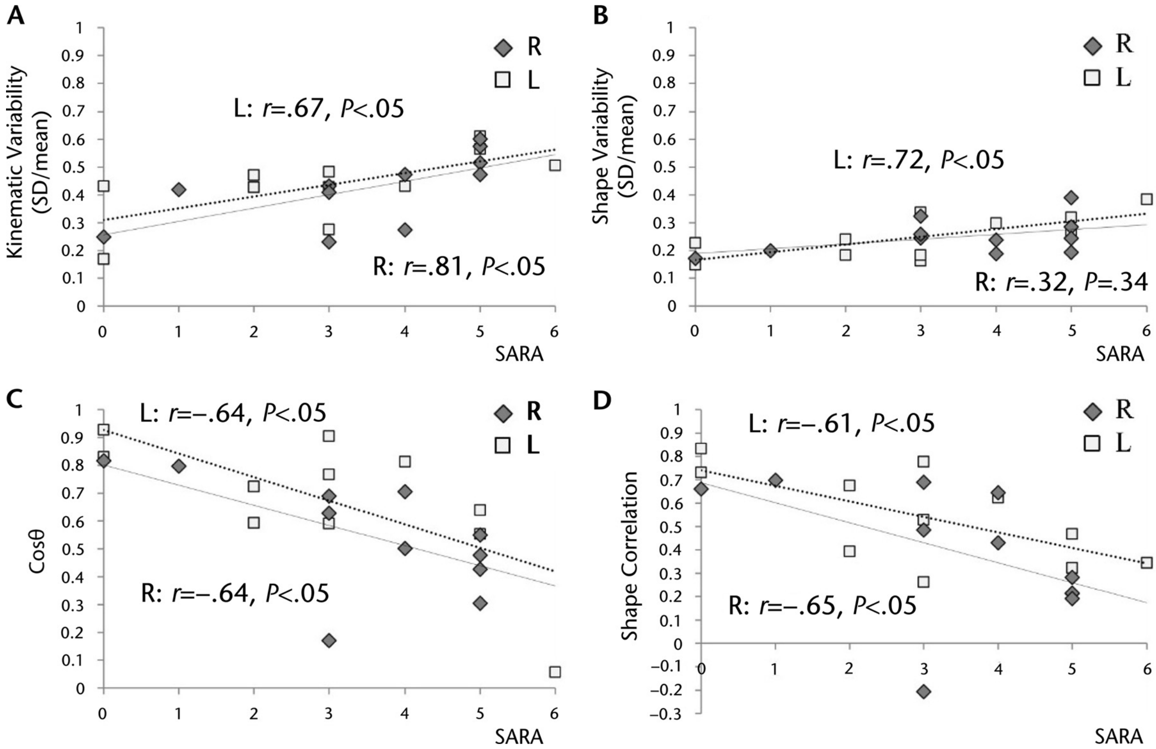

Figure 4.
Severity of upper extremity ataxia and handwriting parameters for 11 participants with ataxia. Plots of the kinematic variability parameter (A), track shape variability parameter (B), cosines of angles made by movement vectors of the pen tip and finger (C), and track shape similarity parameter coefficients of correlation between the pen tip and finger (D) against the sum of the upper extremity Scale for the Assessment and Rating of Ataxia (SARA) scores for 2-cm frame writing. Spearman rank correlation coefficients (*r*) were significant for all but track shape variability with the right hand (B). L=left-hand writing, R=right-hand writing.

Correlations Between Ataxia Severity and Handwriting Movement

The Spearman correlation coefficients for the 3 SARA item scores ranged from .74 (P=.01) to .94 (P≤.001). These results supported our rationale to use the sum of scores as a single scale. The correlation coefficients for the sums of the 3 SARA item scores were calculated for the time needed to write in the 2-cm frame with the right hand (.61, P=.05) and the left hand (.56, P=.07). For the right hand and the left hand, respectively, the correlation coefficients for the kinematic variability parameter (Fig. 4A) were .81 (P=.003) and .67 (P=.03), and those for the track shape variability parameter (Fig. 4B) were .32 (P=.34) and .72 (P=.01).

The coefficients of correlation between the sums of the 3 item scores and the cosine means for angles made by movement vectors of the pen tip and finger were −.64 (P=.04) and −.64 (P=.03) for the right hand and the left hand, respectively (Fig. 4C). For the kinematic correlation parameter, the coefficients of correlation between the pen tip and finger were .15 (P=.66) and −.11 (P=.76) for the right hand and the left hand, respectively. For the track shape similarity parameter, the coefficients of correlation between the pen tip and finger were −.65 (P=.03) and −.61 (P=.04) for the right hand and the left hand, respectively (Fig. 4D).

Discussion

Increased variability of the velocity profile and shape of the track of pen tip movement was observed in the handwriting of participants with ataxia in the present study. The mechanism of this variability was assumed to be localized to the relationship between the movement of the pen tip and the movement of the finger or wrist. Irregularly deviant or uncoordinated movement of the pen tip in relation to movement of the finger or wrist frequently occurred in ataxic handwriting. The severity of ataxia was significantly correlated with deviation of the movement of the pen tip from that of the finger or wrist, as shown by the cosine parameter and by the track shape similarity parameter.

A single trajectory of movement of a pen tip can be performed by an upper limb in several ways for each joint movement. Generally, multijoint movements, such as handwriting, which involve the fingers, the wrist, and sometimes the elbow, enhance pathological movements.[15] Decomposition of multijoint movements into separate segments, a concept first recognized by Holmes,[1] is a hallmark pathology of ataxic handwriting.[15] Most previous attempts to measure cerebellar ataxia severity focused on fluctuation, movement oscillation, or increased time to complete a specific manual task.[4,6,16] However, none of these tests identify ataxia because these abnormalities may reflect reduced performance associated with other motor disorders. The aim of the present study was to identify cerebellar ataxia and major pathological movement components related to ataxia severity.

Parameters Characterizing Ataxic Handwriting

To determine whether it was appropriate to use participant-specific sample means for each parameter, we checked the CVs of each parameter and the reproducibility of the sample means during the 10 trials. The CVs of the parameters were all relatively low, and the CVs of the means calculated from 10 days of recording were also low and indicated reproducibility of the means. However, the use of means might have biased the analysis-of-variance statistics because within-participant variation was neglected. We acknowledge that this reproducibility assessment was limited to one participant and, therefore, that more extensive reproducibility assessment studies are needed.

The handwriting velocity profile originally investigated in detail by Viviani and Terzuolo[8] was shown in the present study by plotting the instantaneous velocity of the pen tip against the track length. Another feature of handwriting that does not vary is the shape of a character written by a particular person, retaining the individual features of writing style.[17,18] We extended the notion of a written character shape to a 3D track of the pen tip and expressed the track shape by plotting the distance from the geometric center of the track against the track length.

To reveal the relationship between the movement of the pen tip and the movement of the finger or wrist, we evaluated 3 parameters. The first was the difference in movement directions, expressed as the cosines of the angles made by movement vectors of the pen tip and finger or wrist (Fig. 1D). A cosine of 1.0 indicated that the pen tip and finger or wrist always moved in the same direction. That is, the movements were completely coupled, and less neuronal control of the movements would have been necessary. A cosine of 0 indicated that the pen tip and the finger or wrist moved independently; thus, coordinated movements might have been performed with more neuronal control, such as with right-hand writing. However, a cosine of 0 also could have indicated that the pen tip moved randomly, unconstrained by the finger or wrist, as an uncoordinated ataxic movement. The kinematic correlation parameter, expressed as the coefficient of correlation in instantaneous velocity between the pen tip and the finger or wrist, was proposed as an indicator of both the synchronicity and the proportionality of their movements. The parameter represented by the shape of the track of movement of the pen tip and finger or wrist, expressed as a correlation coefficient, could indicate similarity in track shapes.

Differences in Writing Between Right Hand and Left Hand

For the most part, neither kinematic variability nor track shape variability of the movement of the pen tip differed between right-hand writing and left-hand writing. It was expected that right-hand writing might be more consistent than left-hand writing. The writing time for the right (dominant) hand was significantly shorter than that for the left hand (P=.02). The higher the speed of writing, the greater the standard deviation of the speed. Thus, the kinematic variability defined by the standard deviation divided by the mean could not reveal a right-left difference. On the other hand, the track shape variability parameter was independent of the speed of writing. The reason for the small difference in the shape variability parameter differed from that for the small difference in the kinematic variability parameter. It is known that the shape of a character written by a particular person does not vary, retaining the individual features of writing style, irrespective of the hand used.[17,18] This property may be the reason for the small right-left difference in shape variability.

With regard to the relationship between the movement of the pen tip and the movement of the finger or wrist, the cosine parameter for the right hand did not differ from that for the left hand. Right-left differences may have been diluted by the results of writing in a larger frame; that is, both the pen tip and the finger or wrist tended to move in the same direction. In contrast to the results for the cosine parameter, a significant right-left difference in the velocity correlation parameter was noted for the pen tip and finger or wrist (P=.001 for the pen tip and finger; $P \leq .001$ for the pen tip and wrist), whereas a difference in the track shape parameter was noted only for the pen tip and finger

($P=.03$). The results for right-left differences may have indicated that pen tip movement by the dominant hand was more consistent and independent of the finger or wrist.

Characteristics of Ataxic Handwriting Movement

Variability of the velocity profile and shape of the track of movement of the pen tip was significantly higher in participants with ataxia ($P=.001$ for the velocity profile; $P=.005$ for the track shape). The direction of movement of the pen tip was significantly less related to the finger or wrist in participants with ataxia ($P=.02$ for the pen tip and finger; $P=.01$ for the pen tip and wrist). Irregular pen tip movement that was not correlated with the finger or wrist in the handwriting of participants with ataxia differed from regular independent movement in the handwriting of the control participants (dominant hand), which was characterized by invariant kinematics and morphology of the track of movement of the pen tip. Contrary to our expectation, the kinematic correlations between the movement of the pen tip and the movement of the finger or wrist did not differ in the ataxia and control groups ($P=.72$ for the pen tip and finger; $P=.33$ for the pen tip and wrist). This finding suggests that irregular movements of the pen tip occur synchronously with those of the finger or wrist in ataxic handwriting.

Correlations With Grading of the Severity of Clinical Ataxia

Reports have shown that the 3 upper extremity SARA item scores are reliable for evaluating ataxia.[13,14] Although the sum of all SARA scores is used to determine the clinical grading of ataxia severity, it is unknown whether the sum of the 3 upper extremity item scores can be used to determine upper extremity ataxia severity. It seemed reasonable to use the sum of the 3 item scores as a single score because we showed linearity of these 3 scores with the sum for the ataxia group. However, the validity of this sum as an indicator of ataxia remains unproven.

Variability of the velocity profile and the track shape changed with writing size. Parameters indicating correlations between the movement of the pen tip and the movement of the finger or wrist with respect to direction, velocity, and track morphology also were related to writing size. In other words, differences in parametric values between the ataxia group and the control group may have been more pronounced with smaller writing size. Thus, the coefficients of correlation between these parameters and the sum of the 3 item scores were calculated for the smallest (2-cm frame) writing size. This 2-cm size most closely mirrors the size of people's daily writing and was therefore assumed to best reflect true handwriting.

The sum of the 3 item scores was modestly correlated with writing time only for writing with the dominant hand. We assumed that ataxia plus clumsiness inherent to the nondominant hand obscured the correlations with time. The sum was correlated with the kinematic variability of movement of the pen tip with both hands (Fig. 4A) and with the pen tip track shape variability with the left hand (Fig. 4B). The lack of correlation between the sum and track shape variability with the right hand might be ascribed to an effort to correct the writing trajectory with the dominant hand so that written characters would be legible when ataxic pen tip movement occurred. Such correction was not easily done with the nondominant hand. An important finding was that upper extremity SARA scores correlated well with directional disagreement of the movement of the pen tip and the movement of the finger or wrist (Fig. 4C). The cosine parameter may have been sensitive to directional deviation of movement of the pen tip with respect to movement of the finger. The upper extremity SARA scores also correlated with track shape dissimilarity, as shown by the correlation coefficients (Fig. 4D). This finding indicates that more ataxia produces more track shape differences between the pen tip and the finger.

Limitations

Our study results would have been different had we used alternate ataxic handwriting parameters or other clinical ataxia grading methods. The use of participant-specific means of parameters obtained from 10 repetitions of writing instead of a single writing would result in bias in the analysis of variance. Furthermore, the use of the sum of 3 SARA item scores as an indicator of upper extremity ataxia severity was not validated in the present study. Participant instructions also may have affected the results. In the present study, participants were asked to write in their regular handwriting and not to write too quickly. If participants had been asked to write as quickly as possible, ignoring legibility, the results would have been different. Further investigations of these factors are needed.

Ataxic handwriting was characterized by increased variability of pen tip kinematics and track shape as well as irregular deviation of the movement of the pen tip with respect to the movement of the finger or wrist. The severity of ataxia was correlated with the deviation in movement direction and the deviation in track shape as well as the variability of pen tip kinematics and the written character shape.

Both authors provided concept/idea/research design. Mr Fujisawa provided writing,

data collection and analysis, and project management. Dr Okajima provided fund procurement and consultation (including review of manuscript before submission).

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