INTRODUCTION

Hemiplegia is characterized by weakness and impaired coordination, which disrupts smooth and separate individual joint movement sequences [1]. Damage to the motor pathway in the brain may result in the abnormal linkage of individual joint movements, which is ascribed to the unintended co-contraction of muscles in the extremities [2]. Clinical grading scales of hemiplegia, such as the Brunnstrom Recovery Scale [3] and the Fugl–Meyer Assessment [4], are structured to emphasize this abnormal movement linkage. Meanwhile, the performance of the hemiplegic extremities, especially that of the hand, is measured quantitatively by standardized manual function tests, such as the Box and Block Test (BBT) and the Nine-Hole Peg Test. Lin et al. [5] reported that both scores correlated well. However, correlations with hemiplegia grade, as measured by the Fugl–Meyer Assessment, were lower, which was likely due to the manual activities of daily living (ADLs). Handwriting may be categorized as a manual ADL [6]. In fact, Platz et al. [7] demonstrated that a dissociation between motor function scores (Fugl–Meyer Assessment and BBT scores) and ADLs were measured by the modified Barthel Index.

Handwriting is a multi-joint movement involving the thumb, fingers, wrist, and, occasionally, the elbow. Each joint moves in relation to the others, and joint tightening has been observed in uncoordinated handwriting movements. Tightening of the finger and wrist joint linkage may reveal similar movement trajectories of the finger and wrist during handwriting. Harada and colleagues [8] focused on the relationship between the movements of the pen tip and holding a pen. They compared movement trajectory sizes between right and left
handwriting. The size of the wrist movement trajectory to the pen tip ratio was smaller for the dominant hand than for the nondominant hand in healthy individuals. This meant that the pen tip movement for nondominant side handwriting was firmly linked to the hand. Furthermore, the pen tip movement for the nondominant side handwriting was dependent on the movement of the proximal hand segment. This linked movement of the distal pen tip with the proximal hand was termed the proximodistal linkage of movement. Conversely, the pen tip for the dominant side handwriting moved independently of the finger and hand movements. This was termed proximodistal separation.

In this study, the speed, kinematics, and morphological consistency of writing were measured as basic parameters of handwriting performance. Ratios of trajectory sizes representing movement linkage or separation, as described above, were analyzed in relation to those performance parameters and the manual function scores in individuals with hemiplegia. We investigated differences in these parameters between the dominant and nondominant hands, between different letter sizes, and between individuals with dominant-hand hemiplegia and controls. We hypothesized that writing with the dominant hand in patients with dominant-hand hemiparesis would retain characteristics of writing with the dominant hand and that this would differ from writing done by the nondominant hand. We assumed that in individuals with dominant-hand hemiplegia, the parameters indicating hemiplegic handwriting performance would not simply correlate with task-specific manual motor function scores. Further, we believed that tightening the linkage of the finger and wrist joints would dominate as a compensatory mechanism in hemiplegic handwriting. This study may facilitate further understanding of writing with a hemiplegic hand, emphasizing the importance of joint linkage strategies that may compensate for hemiplegia.

METHODS

Participants

This was a nonrandomized case-control study. Thirteen right-handed individuals (six males and seven females, mean age = 69.1 yr, and standard deviations (SD) = 12.9 yr) with mild right-handed hemiplegia secondary to first onset of cerebral infarction (frontal cortex: four, corona radiate: one, pons: two, and unknown: four) or hemorrhage (putamen: one and thalamus: one) were recruited from the stroke unit or ambulatory rehabilitation clinic of Kyorin University Hospital. The time from stroke onset to study inclusion ranged from 7 to 40 days (median: 20 days). Fourteen right-handed healthy volunteers (10 males and 4 females, mean age = 71.7 yr, and SD = 11.0 yr) were enrolled as age-matched controls (P = 0.57). Only individuals who could write legible characters in a 2-cm square frame were included. Those with sensory deficits, apparent dementia, aphasia, or unilateral spatial hemineglect were excluded. Past medical histories, affecting central or peripheral nervous systems, such as stroke, cervical myeloradiculopathy, and peripheral neuropathy, were denied. Participants were recruited from senior societies in the local community. This study was approved by the Ethical Board of Faculty of Medicine, Kyorin University. Participants provided informed consent. To statistically analyze the differences, the number of control participants was not fewer than that of the stroke participants.

Clinical evaluation of manual functions

Handedness, the hand used for writing, drawing, and tooth brushing, was determined using the Edinburgh Inventory [9] interview. The Edinburgh score ranges from −100 (completely left-handed) to +100 points (completely right-handed). All individuals with hemiplegia were classified as having mild paresis of stages 4–6, according to the Brunnstrom Recovery Scale. Grip strength and the BBT [10] scores were obtained to show the manual function of both hands. The Smedley Hand Dynamometer® (MIS, Tokyo, Japan) was used for measuring grip strength. In consideration of individual differences in both grip strength and BBT scores, we used the index of the ratio of the right hand to the left hand for these two parameters.

Three-dimensional handwriting analysis

Sitting on a regular wooden dining chair with a wooden desk, participants wrote a Japanese Hiragana character. Handwriting movement was analyzed using a three-dimensional movement analyzer, Liberty® (Polhemus, VT 05446, USA), which consists of a magnetic field generator, a stylus pen with a position sensor in the tip, and two small-block sensors (Fig. 1). The block sensors were placed at the dorsal surface of the index metacarpal head (finger) and the distal end of the radius (wrist). Three-dimensional coordinates of the pen tip and two block sensors were recorded at a sampling frequency of 240 Hz each. Individuals were required to write the Japanese Hiragana character (Fig. 2D) in four differently sized squares (2.0, 5.0, 7.5, and 15.0 cm) in free typeface (their regular typeface) using their right and left hands. This is a basic Japanese character that corresponds to the letter a in the English alphabet. The individuals wrote 10 characters in each frame with each hand, for a total of 80 characters. They were told to write at a comfortable speed and were instructed “not to
hurry and ignore legibility” and “not to intend to write too beautifully.” Recorded coordinate data were analyzed with Matlab® software (Mathworks, Tokyo 107-0052, Japan). Since the analyzer samples data at equal time intervals, the data were converted into intervals of equal length by spline interpolation [8].

Parameters representing handwriting characteristics

The time needed to write a character was averaged for each character’s size and each hand. Kinematic features of handwriting movement were illustrated as the instantaneous speed of the pen tip plotted against the track length from the initial point of writing and were expressed as a percentage of the total length (Fig. 2B). The average speed plots were obtained from 10 writing repetitions, and SDs calculated for the plots were divided by the mean of each plot. The grand mean of all SD/means was assumed to represent the trajectory-shape variability of the pen tip [11].

The linkage of the pen tip to the finger and wrist movement was examined in terms of movement size. The average distance from the geometric center to the movement track represented the size of the movement. This proximodistal linkage was defined by the average distance for the finger and wrist track divided by that of the pen tip [8] (Fig. 2A). When this ratio was near 1 during writing, the holding of the pen was assumed to be tightly fixed to the pen.

Statistical analysis

We used a paired t-test to indicate differences between the right and left hands for grip strength and BBT to ensure that the manual function of the hemiplegic right hand was truly lower than that of the left hand. Three factors, that is, group of the individuals (hemiplegia vs. control), hand used (right vs. left), and frame size of writing (four sizes), were analyzed statistically for differences in writing time, kinematic and track–shape variability, and proximodistal linkage parameters, using a three-way analysis of variance (ANOVA) with repeated measures for two factors (hand side and writing-frame size). Estimated marginal means and 95% confidence intervals of the parameters were calculated. Post hoc Bonferroni comparisons were made to show differences when a significant interaction between any of the three factors was found by the three-way ANOVA. We analyzed the relationship between any pairs of these parameters for the hemiplegic hand using Pearson’s correlation coefficient to find determinants of hemiplegic handwriting proficiency. The level of significance for all analyses was set at 5%. Finally, IBM SPSS Statistics for Windows, version 24.0 (IBM Corp, Armonk, New York) was used for the analysis.

RESULTS

Functional evaluation of the hemiplegic hand

All participants were right-handed. The Edinburgh handedness scores were 70–100 (mean = 94.6 and SD = 8.4) and 55–100 (mean = 92.1 and SD = 12.2) for the hemiplegic and control groups, respectively. The mean and SD of the grip–strength ratio of the right to left hand were 0.80 (SD = 0.21) for the hemiplegic group and 1.07 (SD = 0.11) for the control group. The mean and SD of the BBT ratio of the right to left hand were 0.82 (SD =
Fig. 2. Writing tracks and correlations of writing parameters

A: An example of the Japanese syllabic character handwritten by a control individual. Ten tracks of writing movements with the pen tip, metacarpal head of the index finger, and radial end of the wrist in a 2-cm square are layered. The tracks of the index finger base, pen tip, and wrist were of a similar shape. Average distances from the pen tip, finger, and wrist to the geometric center of their tracks are shown by \( p \), \( f \), and \( w \), respectively.

B: Pen tip speed is plotted against length along the writing tracks expressed as a percentage. Ten trials are layered, and the average plots are illustrated as small crosses. These plots indicate the kinematic features of the pen tip movement. The kinematic variability was defined by the coefficient of variation in the difference in speed from the mean.

C: Distances of the pen tip from the geometric center of the track are plotted against the length along the writing tracks. Ten trials of writing are layered, and the average plots are illustrated as small crosses. These plots indicate the morphology of the pen tip track. This morphological variability was defined by the coefficient of variation of difference from the averaged distance.

D: The Japanese Hiragana character ‘ah’.

D: The Japanese Hiragana character adopted for this study.
0.17) for the hemiplegic group and 1.05 (SD = 0.10) for the control group. Both the grip strength and BBT were significantly lower in the right hand than in the left hand in the hemiplegic group (paired t-test, $p < 0.001$).

**Time needed to write a character (Table 1)**

The time needed for writing did not differ between the hemiplegic and control groups (ANOVA, $F(1, 25) = 1.79, p = 0.193$). Writing time was significantly greater for the left than for the right hand ($F(1, 25) = 8.90, p = 0.006$) and for larger-sized letters ($F(3, 75) = 53.18, p < 0.001$). A significant interaction was found between the group and side of the hand used ($F(1, 25) = 6.96, p = 0.014$) between which a multiple comparison showed that it took more time in the hemiplegic group for right-handed writing in the 2-cm (Bonferroni test, $p = 0.045$) and 5-cm ($p = 0.048$) frames.

**Handwriting variability (Table 1)**

The kinematic variability (Fig. 2B), as defined by the coefficient variation of the pen tip speed, did not differ between the hemiplegic and control groups ($F(1, 25) = 2.28, ANOVA, p = 0.144$) or between right-handed and left-handed writing ($F(1, 25) = 2.20, p = 0.151$). However, it decreased significantly when the frame size for writing increased ($F(3, 75) = 150.31, p < 0.001$).

In addition, the track–shape variability (Fig. 2C) did not differ between the groups ($F(1, 25) = 4.18, ANOVA, p = 0.52$) or between right and left hand writing ($F(1, 25) = 0.98, p = 0.331$). It was significantly less for larger-sized writing ($F(3, 75) = 76.56, p < 0.001$). A significant interaction was found between the group and the hand side ($F(1, 25) = 4.65, p = 0.041$) and between the size and the hand side ($F(1, 25) = 3.21, p = 0.028$).

Multiple comparisons indicated that group differences in shape variability were significant for right-handed writing in the 2-cm (Bonferroni test, $p = 0.011$) and 7.5-cm ($p = 0.014$) frames and were insignificant for right-handed writing in the 5-cm frame ($p = 0.083$) and 15-cm frame ($p = 0.072$). There was a significant difference between the right and left hands only in the 2-cm frame in the control group ($p = 0.011$).

Between-size differences in track–shape variability were significant for the 2/7.5-cm (Bonferroni test, $p = 0.002$) and 2/15-cm ($p < 0.001$) size pairs in right-handed writing in the control group and for the 2/5-cm ($p < 0.001$), 2/7.5-cm ($p < 0.001$), 2/15-cm ($p < 0.001$), and 5/15-cm ($p = 0.016$) size pairs in left-handed writing in the control group. Differences were also significant for the 2/5-cm ($p < 0.001$), 2/7.5-cm ($p < 0.001$), 2/15-cm ($p < 0.001$), and 5/15-cm ($p = 0.02$) pairs in right-handed writing in the hemiplegic group. In left-handed writing in the hemiplegic group, differences were significant for the 2/5-cm ($p < 0.001$), 2/7.5-cm ($p < 0.001$), 2/15-cm ($p < 0.001$), 5/7.5-cm ($p = 0.03$), and 5/15-cm ($p < 0.001$) size pairs. In general, track–shape variability tended to increase in right-handed writing in the hemiplegic group as well as in smaller-sized writing in both the hemiplegic and control groups.

**Proximodistal linkage of handwriting movements (Table 1)**

The proximodistal linkage (Fig. 2A), which was defined as the ratio of movement track diameter of the finger to the pen tip (finger–pen ratio), was significant for the group (ANOVA, $F(1, 25) = 6.05, p = 0.021$), side of handwriting ($F(1, 25) = 14.80, p = 0.001$), and frame size ($F(3, 75) = 9.41, p = 0.001$). Those defined as the wrist–pen ratio were significant and/or marginally significant for the group ($F(1, 25) = 4.21, p = 0.051$), side of handwriting ($F(1, 25) = 17.4, p < 0.001$, and frame size ($F(3, 75) = 10.28, p = 0.001$). Interactions in the finger–pen ratio were found for the factors of the group and side of handwriting ($F(1, 25) = 6.89, p = 0.015$), side of handwriting and frame size ($F(3, 75) = 1.40, p = 0.001$), and for all three included factors ($F(3, 75) = 1.40, p = 0.066$). Interaction in the wrist–pen ratio was found for the side of handwriting and frame size ($F(3, 75) = 5.43, p = 0.002$) and for all three factors ($F(3, 75) = 5.80, p = 0.001$).

Multiple comparisons of the finger–pen ratio revealed significant group differences for all four frame sizes (Bonferroni test, 2-cm: $p = 0.004$, 5-cm: $p = 0.001$, 7.5-cm: $p = 0.009$, and 15-cm: $p = 0.009$) in right-handed writing. Right–left differences were also significant for all four sizes of right-handed writing in the control group (2-cm: $p < 0.001$, 5-cm: $p < 0.001$, 7.5-cm: $p = 0.007$, and 15-cm: $p = 0.015$). Size-related differences were significant for all right-handed writing size pairs in the control group (2/7.5-cm: $p = 0.003$, 2/15-cm: $p < 0.001$, 5/7.5-cm: $p = 0.002$, 5/15-cm: $p < 0.001$, and 7.5/15-cm: $p < 0.001$), apart from the 2/5-cm pair. It was significant only for the 7.5/15-cm pair of left-handed writing in the control group ($p = 0.001$). Size-related differences in the hemiplegic group were not found for any pair of sizes in either right-handed or left-handed writing.

Group differences in the wrist–pen ratio were found for the 2-cm (Bonferroni test, $p = 0.015$) and 5-cm (Bonferroni test, $p = 0.011$) frames of right-handed writing. Right–left differences were significant for all four sizes in the control group (2-cm: $p < 0.001$, 5-cm: $p < 0.001$, 7.5-cm: $p = 0.014$, and 15-cm: $p = 0.012$) and for the 7.5-cm frame in the hemiplegic group ($p = 0.02$). Between-size differences in right-handed writing were
Table 1  Estimated Marginal Means and 95% Confidence Intervals (CI)*

| Parameters             | Estimated marginal mean | Estimated marginal mean | Estimated marginal mean |
|------------------------|-------------------------|-------------------------|-------------------------|
|                        | (95% CI)                | df | F  | P  | (95% CI)                | df | F  | P  | (95% CI)                | df | F  | P  |
| **Group**              |                         |    |    |    |                         |    |    |    |                         |    |    |    |
| Control                | 3.21                    | 1  | 1.79 | .19  | 3.38                    | 1  | 8.9  | .006  | 3.10                    | 3  | 15.3  | < .001 |
| Hemiplegia             | (2.35, 4.07)            |    |    |    | (2.75, 4.02)            |    |    |    | (2.55, 3.65)            |    |    |    |
| **Side**               |                         |    |    |    |                         |    |    |    |                         |    |    |    |
| Rt                     | 3.38                    | 1  | 4.02 | .19  | 3.45                    | 1  | 4.02 | .19  | 3.73                    | 1  | 4.02 | .19  |
| Lt                     | (2.75, 4.02)            |    |    |    | (3.20, 4.50)            |    |    |    | (3.06, 4.39)            |    |    |    |
| **Size**               |                         |    |    |    |                         |    |    |    |                         |    |    |    |
| 2cm                    | 3.10                    | 1  | 1.79 | .19  | 3.10                    | 1  | 1.79 | .19  | 3.73                    | 1  | 1.79 | .19  |
| 5cm                    | (2.55, 3.65)            |    |    |    | (2.83, 4.08)            |    |    |    | (3.06, 4.39)            |    |    |    |
| 7.5cm                  | 3.45                    | 1  | 1.79 | .19  | 3.45                    | 1  | 1.79 | .19  | 3.73                    | 1  | 1.79 | .19  |
| 15cm                   | (3.06, 4.39)            |    |    |    | (3.06, 4.39)            |    |    |    | (3.06, 4.39)            |    |    |    |

Kinematic variability

| (SD/mean)              |                         |    |    |    |                         |    |    |    |                         |    |    |    |
|                        | 0.25                    | 1  | 2.28 | .14  | 0.27                    | 1  | 2.28 | .14  | 0.35                    | 1  | 2.28 | .14  |
|                        | (0.22, 0.29)            |    |    |    | (0.24, 0.30)            |    |    |    | (0.25, 0.31)            |    |    |    |

Track shape variability

| (SD/mean)              |                         |    |    |    |                         |    |    |    |                         |    |    |    |
|                        | 0.17                    | 1  | 4.18 | .052  | 0.18                    | 1  | .98  | .33  | 0.23                    | 1  | .98  | .33  |
|                        | (0.16, 0.19)            |    |    |    | (0.17, 0.19)            |    |    |    | (0.21, 0.24)            |    |    |    |
|                        | (0.18, 0.21)            |    |    |    | (0.18, 0.20)            |    |    |    | (0.17, 0.20)            |    |    |    |

Movement size ratio

| Finger/pen-tip         |                         |    |    |    |                         |    |    |    |                         |    |    |    |
| (ratio)                | 0.78                    | 1  | 6.05 | .021  | 0.78                    | 1  | 6.05 | .021  | 0.79                    | 1  | 6.05 | .021  |
|                        | (0.75, 0.82)            |    |    |    | (0.75, 0.81)            |    |    |    | (0.76, 0.83)            |    |    |    |
|                        | (0.81, 0.88)            |    |    |    | (0.81, 0.87)            |    |    |    | (0.77, 0.83)            |    |    |    |

| Wrist/pen-tip          |                         |    |    |    |                         |    |    |    |                         |    |    |    |
| (ratio)                | 0.73                    | 1  | 4.21 | .051  | 0.73                    | 1  | 4.21 | .051  | 0.73                    | 1  | 4.21 | .051  |
|                        | (0.69, 0.77)            |    |    |    | (0.68, 0.76)            |    |    |    | (0.70, 0.77)            |    |    |    |
|                        | (0.74, 0.82)            |    |    |    | (0.76, 0.82)            |    |    |    | (0.72, 0.77)            |    |    |    |

\* Significance, determined with an analysis of variance, was set at a \( P \) value of <.05.

\( ^b \) Significant difference for interactions between side and group.

\( ^c \) Significant difference for interactions between side and writing size.

\( ^d \) Significant difference for interactions among side, group, and writing size.
significant for all size pairs in the control group (2/7.5-cm: $p = 0.001$, 2/15-cm: $p = 0.001$, 5/7.5-cm: $p < 0.001$, 5/15-cm: $p < 0.001$, and 7.5/15 cm: $p = 0.002$) except for the 2/5-cm pair, similar to the finger–pen ratio, and was significant for the 7.5/15-cm pair in the hemiplegic group ($p = 0.03$). However, no size-related differences were found in left-handed writing, in either the control or hemiplegic groups.

In general, the proximodistal linkage was high, causing tightly linked movement of the pen tip with the finger and wrist in left-handed writing in the control group and both right-handed and left-handed writing in the hemiplegic group. In contrast, it was low for right-handed writing in the smaller frames in the control group, indicating a separation of the pen tip movement from the finger and wrist movement.

**Characteristic determinants of writing by the hemiplegic hand**

The ratio of hemiplegic right-handed grip strength to left-handed grip strength marginally correlated with the same BBT score ratio ($r = 0.553, p = 0.05$). The grip–strength ratio of the hemiplegic hand correlated with track–shape variability for right-handed writing in the 2-cm ($r = -0.712, p = 0.006$), 5-cm ($r = -0.727, p = 0.005$), and 7.5-cm size frame ($r = -0.642, p = 0.018$). However, the BBT ratio did not correlate with writing time, kinematic variability, or proximodistal linkage parameters.

As shown in Fig. 3, the Pearson’s correlation coef-
Coefficients of both finger–pen and wrist–pen ratios showing proximodistal linkage for the hemiplegic right hand were significant for the writing time ($r = 0.61–0.90$, $P = 0.03–< 0.001$) and kinematic variability for all four sizes ($r = 0.63–0.88$, $p = 0.06–< 0.001$; Fig. 4).

Other correlations were significant between writing time and kinematic variability ($r = 0.859$ for the 2-cm frame, $r = 0.914$ for the 5-cm frame, $r = 0.939$ for the 7.5-cm frame, $r = 0.897$ for the 15-cm frame, and $p < .001$) and between kinematic variability and trajectory-shape variability ($r = 0.563$ for the 2-cm frame, $p = 0.045$; $r = 0.688$ for the 7.5-cm frame, $p = 0.009$; and $r = 0.792$ for the 15-cm frame, $p = 0.001$).

**DISCUSSION**

*Handwriting and the manual function of the hemiplegic hand*

Speed and accuracy, or writing time and consistency of writing trajectory, are assumed to be major indicators of movement performance, but they may represent a trade-off [12] as accuracy decreases with increasing speed. However, regarding writing, the movement of handwriting becomes automatic and consistent after years of practice [13]. Freeman [14] found that writing time is relatively constant regardless of writing size, that is, the isochrony property of adult handwriting, in contrast to the immature handwriting of children where writing time changes in proportion to the size of writing,
and is ascribed to a constant pen tip movement speed. Wright [15] investigated this property by the sophisticated methods. Viviani & Terzuolo [16] measured instantaneous pen tip speed during writing and plotted it against time. They found that this speed profile maintained a similar shape even with faster or larger writing. This kinematic property of pen tip movement, or handwriting rhythm, is called space–time invariance. In other words, smaller kinematic variability is evidence of more mature handwriting. Morphological invariance of writing [15, 17] is another writing characteristic that is individually acquired. To date, no reports focus on changes in these invariance properties caused by stroke hemiplegia.

Only grip strength showed a moderate correlation with morphological variability. In other words, only weakness affected the morphological consistency of writing. However, other parameters, such as writing time, kinematic variability, and proximodistal movement linkage, were irrelevant to either grip strength or BBT. There is no reason that BBT and/or grip strength would be correlated with handwriting parameters since BBT assesses the proximal rather than the distal movement of the upper extremity, and grip strength simply represents the strength of the distal musculature. This study only included individuals with hemiplegia who could write legible characters. Therefore, hemiplegia was mild and less varied in terms of severity. In principle, handwriting is categorized as an activity involving various factors, such as individual customs and aesthetic consciousness. Therefore, it was expected that the parameters in the present study would not be strongly related to the manual or proximal arm function as measured by grip strength or BBT, respectively.

We introduced parameters quantifying kinematic and morphological variability of writing, on the basis of the studies of Viviani and Terzuolo [16] and Castiello and Stelmach [17] respectively, both of which graded the clinical severity of ataxia [11]. In the present investigation, significant differences in both measures of variability were found for some of the frame sizes between the hemiplegic hand and the healthy dominant hand and between the dominant and nondominant hand in the control group. In addition, a larger variability in these parameters was ascribed to less controllability of the hemiplegic hand and the nondominant hand.

Increased proximodistal linkage in hemiplegic handwriting

Handwriting involves multiple joint systems that include the fingers and wrist. A single character or letter can be written using numerous joint movement patterns. However, each joint moves smoothly in a coordinated manner, resulting in writing with similar kinematics and morphology. Lacquaniti [18] demonstrated that the wrist and elbow became increasingly involved in dominant handwriting with increasing writing size. In contrast, the wrist and elbow, rather than the thumb and fingers, are mainly used in nondominant handwriting irrespective of writing size. Meulenbroek et al. [19] reported such linkage between pen tip movements and finger or wrist movements in circle-drawing. However, circle-drawing may differ from handwriting in its mechanisms of movement control. Circle-drawing is done principally through the visual feedback information of drawn lines, whereas handwriting is accomplished without correction based on feed-forward control acquired after the daily activity of writing during childhood.

The relationship in movement size between the pen tip and finger/wrist was the major focus of the present investigation and elucidated the proximodistal linkage of movements as first proposed by Harada et al. [8]. Contrary to their expectation, they could not indicate a significant increase in the proximodistal movement linkage of the hemiplegic handwriting. Only in hemiplegic cases with position sense impairment did the pen tip move in linkage with the finger and hand for dominant side handwriting. However, two issues may prevent us from drawing conclusions from their study. The first was the inclusion of the patients with position sense impairment, which might have obscured minor differences in handwriting between the patients with dominant-hand hemiplegia and the controls. Position sense impairment caused ataxia, which would cause a large variability of handwriting kinematics and morphology [11]. The other problem was the exclusion of small-sized writing. Harada et al. [8] did not include small-sized writing for statistical analysis, which would require a separation in the distal movements. Our study revealed that writing size was a major determinant of writing time, variability, and proximodistal linkage parameters.

Factors affecting proximodistal movement linkage

In hemiplegic handwriting, both writing time and kinematic variability significantly increased, regardless of writing size, as the trajectory–size ratio of the finger or wrist to that of the pen tip approached 1 (Figs. 3 and 4). In other words, proximodistal linkage in hemiplegia correlated with longer handwriting time and larger kinematic variation. Writing time correlated positively with kinematic variability regardless of writing size, indicating that a trade-off rule was not necessarily applicable to the relationship between writing size and kinematic variability. In addition, kinematic variability correlated positively, in part, with morphological variability. However, the morphological variability did not correlate with writing time. This suggests stronger morphological
invariance than time and kinematic invariance in writing with the hemiplegic hand.

Proximodistal linkage is not always pathological, as has been seen in individuals with severe hemiplegia. Osu et al. [20] investigated the targeted reaching movement in healthy volunteers and demonstrated that the flexor and extensor muscles of the arm co-contracted so that freedom of motion could be lessened for easier control and higher performance of the intended movement. It is important to maintain the same shape of the writing, irrespective of hemiplegia, as characters should be written legibly. Individuals with dominant-hand hemiplegia may tighten joint linkage of the upper extremity and slow their writing speed, resulting in the disruption of kinematic invariance of the pen tip movement. This is most likely done in an attempt to yield consistent writing shapes.

Conclusion
Handwriting may be categorized as an ADL. Individuals with stroke hemiplegia of the dominant hand re-acquire writing while adapting to hemiplegia. Legibility is seemingly more important than writing speed, as writing could result in nonsense without being legible. In this study, individuals with hemiplegia could write legibly by slowing their writing speed, which might cause greater kinematic and/or shape variability, and by tightening the finger and wrist joints as if they were moving as a solid block. This helped them control the hemiplegic hand by reducing the degree of freedom of motion. The results of this study may be helpful in understanding the fine manual movement of individuals with hemiplegia. A reduction in the degree of freedom of motion by tightening the joint linkage was important in accomplishing dexterous movement with the hemiplegic hand.

The conclusions of this study were obtained from a limited number of participants. With a larger sample size, we could have produced greater statistical data. The instructions given to the participants for the experiment were important as the writing performance by the hemiplegic hand might depend on the instructions. In this study, participants were instructed to write at their own speed, neither too quickly nor too slowly. If they had been asked to write as fast as possible, ignoring legibility, different results would have been obtained. Further studies are needed to address these issues.

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