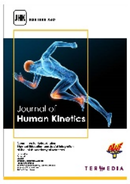

Journal of Human Kinetics volume xx/xxxx, x–x DOI: 10.5114/jhk/215533 x
Section I – Kinesiology

Neuromuscular Control Strategies in Dominant and Non-Dominant Handwriting

by
Bowen Liu [1], Ryogo Takahashi [1,2], Naotsugu Kaneko [1], Inhyeok Jeong [3],
Mayu Dohata [1], Kimitaka Nakazawa [1,]*

The present study aimed to investigate how hand use and the eye state affected handwriting performance. Twelve right-handed students (6 females and 6 males, aged 27.2 ± 2.4 years) completed handwriting tasks with both dominant and non-dominant hands under eyes-open and eyes-closed conditions. Handwriting tracing dynamics, handwriting quality, and legibility were measured, while electromyography signals were recorded bilaterally from the upper limb muscles. A two-way ANOVA revealed no significant interaction effects of hand use and the eye state on handwriting tracing dynamics or muscle activity. However, significant interaction effects were found for the number of intersection points ($p = 0.034$, $\eta p^2 = 0.129$) and the legibility score ($p = 0.004$, $\eta p^2 = 0.205$). Post hoc tests indicated greater handwriting accuracy degradation in the non-dominant hand under eyes-closed conditions, with significant differences in the number of intersection points ($p = 0.016$, $d = 0.350$) and the legibility score ($p < 0.001$, $d = -0.130$). To further explore relative differences between eyes-open and eyes-closed conditions, the ratio of change was calculated for each handwriting feature. The results showed a significantly greater change in the number of intersection points ($p = 0.027$, $r = 0.639$) and the legibility score ($p = 0.012$, $r = -0.723$) for the non-dominant hand compared with the dominant hand. These findings highlight distinct neural mechanisms underlying handwriting control, suggesting greater reliance of the non-dominant hand on visual feedback for handwriting accuracy. This study advances our understanding of motor skill learning and the acquisition of fine motor skills.

***Keywords**: electromyography; hand; feedback*

Introduction

Handwriting, as a fundamental communication tool, involves intricate cognitive, psychomotor, and biophysical processes. It engages several senses that induce visual and somatosensory feedback and synergistically recruits multiple upper limb muscles in executing fine motor movements crucial for fluent and high-quality writing.

Visual feedback provides real-time spatial information, such as writing location and direction, contributing to the letter form and spatial arrangement in complex writing. Researchers have controlled visual feedback by manipulating eye states (i.e., closing the eyes eliminates visual feedback) (Imai et al., 2025; Lopez and Vaivre-Douret, 2021). Previous studies have found that the lack of visual feedback makes it difficult for writers to accurately control word spacing and punctuation placement (Danna and Velay, 2015), and that perturbating the visual environment degrades spatial-motor stability (Mortazavi Najafabadi et al., 2025). Furthermore, visual feedback aids in error correction, maintaining the accurate association of elements, and ensuring legibility (Smyth and Silvers, 1987). Performance in visually guided motor tasks varies across different participant's groups (Popowczak and Zwierko, 2025). For example, individuals with visual impairment exhibit slower and less legible writing compared to their peers (Grewal et al.,

---

[1] *Department of Life Sciences, University of Tokyo, Tokyo, Japan.*
[2] *Japan Society for the Promotion of Science (JSPS), Tokyo, Japan.*
[3] *Research Center for Brain Communication, Kochi University of Technology, Kochi, Japan.*
* Correspondence: nakazawa@idaten.c.u-tokyo.ac.jp

2014). In addition to visual feedback, somatosensory feedback also plays an important role in handwriting, especially in the absence of visual feedback, operating through two key concepts: proprioception and kinesthesia (Guilbert et al., 2019; Stelmach et al., 1984). Proprioception primarily involves awareness and effort in movement (Hepp-Reymond et al., 2009; Teasdale et al., 1993), contributing to spatial arrangement (Ebied et al., 2004; van Doorn and Keuss, 1992). In skilled writers, the absence of proprioception leads to significant changes in the stroke count and writing speed (Marie et al., 2009). Conversely, kinesthesia involves the perception of movement (Kishore, 2021), which directly impacts word legibility (Harris and Livesey, 1992; Hong et al., 2016). Higher kinesthesia is associated with improved word legibility, with no significant correlation with proprioception (Hong et al., 2016). In summary, the impairment or absence of visual and somatosensory feedback affects handwriting speed and legibility of the dominant hand. However, it remains unclear whether these feedback-induced changes also occur in the non-dominant hand and whether the effects of visual and somatosensory feedback differ between the two hands. Given the reduced familiarity and precision associated with non-dominant hand movements, it is hypothesized that the non-dominant hand may exhibit more pronounced disruptions in handwriting performance in the absence of visual or somatosensory feedback.

As an acquired skill, both left-handed and right-handed individuals can be trained to write with their non-dominant hand (Klöppel et al., 2007; Sandve et al., 2019). Typically, proficient writers exhibit lower variability in proximal compared to distal muscles, suggesting that proximal muscles play a stabilizing role in dominant handwriting (Gerth, 2023; Ishak et al., 2014; Naider and Katz, 2007). However, when using their non-dominant hand, distal joint activity decreases while proximal joint activity increases (Kim, 2021). This variation in muscle activity highlights differences in control strategies between the dominant and non-dominant hands (Liang et al., 2021), highlighting how sensorimotor integration adapts to the use of the non-dominant hand. Exploring these questions will deepen our understanding of the neural mechanisms and cognitive processes involved in writing behavior (Stelmach, 1984).

Therefore, this study aimed to explore the effects of the eye state (eyes open with visual feedback vs. eyes closed relying on somatosensory feedback) and hand use (dominant vs. non-dominant) on handwriting features. Handwriting with the dominant hand, as a fine motor skill, is highly trained and represents an already acquired motor skill. Moreover, in the absence of visual feedback, the dominant hand is more adept at dynamic trajectory control compared to the non-dominant hand, as proposed by the dynamic dominance hypothesis (Goble et al., 2006; Sainburg, 2005). Based on these previous studies, we hypothesized that the removal of visual feedback (eyes-closed condition) would have a more pronounced impact on the handwriting trajectory control of the non-dominant hand compared to the dominant hand.

Methods

Participants

Twelve right-handed healthy individuals (6 females and 6 males, aged 27.2 ± 2.4 years) with no history of neuromuscular disorders participated in this study. The participants were graduate students recruited from the university. The sample size was estimated using G*Power (v3.1.9.4), with the effect size set to 0.4, power set to 0.8, and one group of subjects undergoing four repeated measurements. The number of subjects required was at least 12. All participants had been taught English since the elementary school and acquired proficiency in written English. Right-handedness was defined by having a laterality quotient of 50 or higher on the Edinburgh Handedness Inventory (Oldfield, 1971). According to the Declaration of Helsinki, we obtained written informed consent for participation in the study from each participant. The study was approved by the ethics committee of the University of Tokyo, Tokyo, Japan (approval number: 754-8; approval date: 23 August 2024).

Data Collection

Handwriting

Handwriting features were recorded using a graphic tablet (13.3-inch, 60-Hz refresh rate, 1920 × 1080 screen resolution; Wacom One 13, Wacom, Japan), along with a standard pen supporting 4096 levels of pressure sensitivity. Participants performed the handwriting task with their forearms comfortably placed on the tablet (Figure 1A). The task was designed using the Eye and Pen software (v.3rd, University of Poitiers, France) (Alamargot et al., 2006). Details of the task are provided in the *Handwriting task* section. These handwriting features were recorded at a sampling frequency of 200 Hz.

Muscle Activity

Electromyography (EMG) signals were amplified and synchronously recorded using wireless EMG sensors (Pico EMG, Cometa Srl, Italy) from 12 muscles of the bilateral upper limbs and the shoulder (six per side): the abductor pollicis brevis (APB), first dorsal interosseous (FDI), extensor carpi radialis (ECR), flexor carpi ulnaris (FCU), anterior deltoid muscle (ADM), and upper trapezius (UT) muscles at a frequency of 2000 Hz (Figure 1A). For each muscle, two Ag/AgCl (Vitrode F-150S, Nihon Kohden, Japan) surface electrodes were placed at a 24-mm inter-electrode distance on the center of the muscle belly in the direction of the muscle fibers (Hermens et al., 2000).

Procedure

The present study employed the handwriting task used in previous research, which considered limb control of pen movements in various directions (Chartrel and Vinter, 2006). The task contained five letters (a, o, l, m, p) and three pseudowords (lamopa, molopa, palomo), each composed of five letters (Figure 1C). The font required for the task was Segoe Script. The selected letters assessed the capability to move the pen in distinct directions, with "m" emphasizing horizontal writing, "l" and "p" focusing on vertical writing, and "a" and "o" targeting aperture. The pseudowords, constructed from the specified letters, served as more integrated tests, facilitating the examination of writing movements in all directions during the composition of a single pseudoword.

Before the formal task, each participant was required to sit comfortably in front of a table and to practice the handwriting task on the graphic tablet using their dominant hand. There was no time limit for the practice, and participants were required to use the same grip posture and write the words fluently in a single stroke with their eyes open. The practice trials were terminated when there was no hesitation or pause in the task process, and each letter was easily recognized with our visual confirmation.

In the formal experiment, participants were required to complete the handwriting task randomized to four conditions: writing with (1) the dominant hand (right hand) and eyes open (DO), (2) the dominant hand and eyes closed (DC), (3) the non-dominant hand (left hand) and eyes open (NO), and (4) the non-dominant hand and eyes closed (NC). They wrote each of the five isolated letters and three words with a single stroke, repeating them randomly eight times (64 trials in total). Finally, a 3-s isometric maximum voluntary contraction (MVC) for each tested muscle was recorded.

Data Analysis

Handwriting Tracing Dynamics

The recording software of writing trajectories allowed us to calculate writing tracing dynamics (reflecting the efficiency of writing) automatically (Figure 1D). Handwriting tracing dynamics indicators included duration (in s) of each task trial, length (in cm) representing total handwriting in each trial, and speed (in cm/s) calculated as the handwriting length divided by duration. Pen pressure was normalized by dividing raw values by the highest recorded value for each hand, determined as the maximum value observed across both eyes-open and eyes-closed conditions. The normalized values were expressed as a percentage of the respective hand's maximum, enabling comparisons across conditions while accounting for individual differences.

Handwriting Quality and Legibility

The handwriting trajectory for each trial was exported as an image and analyzed using ImageJ (v.1.54h, Wayne Rasband, USA) software. Three indicators were calculated (Figure 1E): (1) area (in square centimeters), determined by selecting the highest, lowest, leftmost, and rightmost points of the trajectory in each image and calculating the enclosed area in square centimeters; (2) tilt angle (in degree), automatically measured as the angle between a straight line drawn beneath a long word and the horizontal axis; (3) and intersection points, representing the total number of points where handwriting strokes intersected or overlapped in each image.

A legibility score was assigned by identifying letters in pseudowords, with each correctly identified letter earning one point, for a maximum possible score of 6 points per trial. Scoring was conducted by two independent raters who did not participate in the handwriting task. They performed the scoring on two separate occasions, with a one-week interval between each session. Participants' names were omitted during the process.

In addition, the scoring method was also assessed by intra-rater and inter-rater reliability. Intra-rater reliability was determined by comparing the first and second scores of each rater, while inter-rater reliability was determined using the first score of both raters. They were evaluated using the intraclass correlation coefficient (ICC) for average measures in a two-way random effect model with consistency for the legibility score, calculated using SPSS (v.20, IBM, USA). For the interpretation of the ICC, values between 0.75 and 0.9 and greater than 0.90 indicated good and excellent reliability, respectively (Koo and Li, 2016).

Muscle Activity

Pre-processing of EMG signals was performed using MATLAB (R2023a, MathWorks, USA). First, only the segments where the pen tip was in contact with the tablet were identified and included in the analysis. Next, a bandpass filter within the range of 10–500 Hz and a notch filter at 50 Hz were applied to the EMG data. Then, the pre-processed EMG data were full-wave rectified, and low-pass filtered (Butterworth filter, 7th order) at 6 Hz to obtain the envelope curve. Subsequently, enveloped EMG was normalized by MVC values. Finally, the root mean square (RMS) of the normalized EMG was calculated using the following equation:

$$\text{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

where N represented the total number of sample points, and denoted the value of the sample point.

Statistical Analysis

Statistical analysis assessed the relationship between the dependent variables including handwriting tracing dynamics, handwriting quality, legibility, and muscle activity, and the main independent variables, namely hand use and the eye state. Statistical analysis was performed using RStudio (v. 1.4, Posit, USA), SPSS (v.22, IBM, USA).

For comparisons between conditions, first, the normality of the data was examined using the Shapiro-Wilk test. Since the dependent variables significantly deviated from the normal distribution, the data were transformed using the Aligned Rank Transformation (ART) method in RStudio, utilizing the ARTool package, to meet the normality assumption for ANOVA. Subsequently, two-way repeated measures ANOVA was conducted in RStudio, with hand use (the dominant hand and the non-dominant hand) and the eye state (eyes-open and eyes-closed) as within-subject factors for each variable. When a significant interaction effect was observed, a post hoc contrast test was conducted. Furthermore, p-values were adjusted using the Bonferroni-Holm method, and the significance level was set at $p < 0.05$. Effect sizes for the main effect and the interaction effect were reported as partial eta squared ($\eta_p{}^2$) and Cohen's d (d), respectively.

In addition, while the ANOVA results identified significant effects in each hand, they did not quantify the relative impact of visual feedback on the handwriting features of the two hands. To address this, the ratio of change was introduced as a complementary analysis to assess the relative change between the eyes-open and eyes-closed conditions across hands. Given that baseline differences between hands were expected under the eyes-open condition, this analysis refined the ANOVA results by offering a clearer quantification of visual feedback's influence on handwriting features. The formula for the ratio of change was as follows:

$$\text{Ratio of change} = \frac{(Eyes\ closed\ value - Eyes\ open\ value)}{Eyes\ open\ value} \times 100\%$$

To compare the ratio of changes in the dependent variables between the two hands, the Wilcoxon signed rank test was performed in SPSS, with effect sizes denoted by r. For correlation analysis, the Spearman correlation coefficient (Spearman's ρ) was applied to the rate of change data, with an interest in the correlation between muscle activity and handwriting tracing dynamics, as well as between muscle activity and handwriting quality and legibility. SPSS was chosen for this analysis due to its efficiency in handling non-parametric correlation tests. The p-values were corrected with the False Discovery Rate (FDR) method, and the significance level for correlation analysis was set at $p < 0.05$.

Results

Analysis of Handwriting Tracing Dynamics

Figure 2 shows the examples of one participant's handwriting tasks under four conditions. Table 1 presents the mean ± standard deviation (SD) values for all measured variables across all experimental conditions. Table 2 summarizes the statistical results of the measured variables, with Figure 3 illustrating each condition. A significant main effect of hand use was found, with the non-dominant hand showing longer handwriting duration (non-dominant hand: 3.62 ± 0.11 s, dominant hand: 2.32 ± 0.63 s, Figure 3A), greater length (non-dominant hand: 16.66 ± 4.97 cm, dominant hand: 11.44 ± 2.05 cm, Figure 3B), and lower pen pressure (non-dominant hand: 60.91 ± 14.93%, dominant hand: 71.27 ± 13.35%, Figure 3D). Similarly, a significant main effect of the eye state was observed, with eyes closed leading to shorter handwriting duration (eyes-closed: 2.68 ± 0.97 s, eyes-open: 3.26 ± 1.21 s, Figure 3A), longer length (eyes-closed: 15.01 ± 4.98 cm, eyes-open: 13.09 ± 4.04 cm, Figure 3B), and faster speed (eyes-closed: 6.33 ± 2.13 cm/s, eyes-open: 4.86 ± 1.43 cm/s, Figure 3C). Notably, no significant interaction effect between hand use and the eye state was found across all dynamics indicators (all, $p > 0.05$), suggesting that the impact of hand use and the eye state on handwriting tracing dynamics were largely independent.

Analysis of Handwriting Quality and Legibility

First, ICC analysis confirmed sufficient reliability in handwriting quality and the legibility score (inter-rater reliability, ICC = 0.848; intra-rater reliability, ICC = 0.965). A significant interaction effect between hand use and the eye state was observed for the number of intersection points (Figure 3G) and the legibility score (Figure 3H). Post hoc tests showed that the non-dominant hand was associated with a greater number of intersection points ($t = 3.10$, $p = 0.016$, $d = 0.350$) and a lower legibility score ($t = -3.10$, $p < 0.001$, $d = -0.130$), especially under the eyes-closed condition. These findings suggest that the non-dominant hand produced less precise handwriting compared to the dominant hand, with visual feedback playing a crucial role in mitigating these deficits. No significant interaction effect was found for the handwriting area (Figure 3E) or the tilt angle (Figure 3F). A significant main effect of hand use was found for the handwriting area, which was larger when handwriting with the non-dominant hand (non-dominant hand: 10.74 ± 5.38 cm^2, dominant hand: 5.44 ± 1.95 cm^2, Figure 3E). Similarly, a significant main effect of the eye state was found for the area and the tilt angle. Under the eyes-closed conditions, the handwriting area was larger compared to the eyes-open condition (eyes-closed: 8.87 ± 3.92 cm^2, eyes-open: 7.31 ± 3.42 cm^2, Figure 3E), and tilt angles were also greater (eyes-closed: 5.53 ± 1.92°, eyes-open: 2.59 ± 1.76°, Figure 3F). These results highlight the importance of both hand use and visual feedback in handwriting quality and legibility.

Analysis of Muscle Activity

A significant main effect of hand use was identified in the FDI, ECR, FCU, and ADM muscles. Specifically, the non-dominant hand exhibited lower RMS values in the FDI (non-dominant hand: 4.53 ± 3.06%MVC, dominant hand: 7.59 ± 6.79%MVC, Figure 3J), ECR (non-dominant hand: 11.13 ± 5.43%MVC, dominant hand: 12.71 ± 4.85%MVC, Figure 3K), and FCU muscles (non-dominant hand: 3.40 ± 2.04%MVC, dominant hand: 5.68 ± 2.70%MVC, Figure 3L) compared to the dominant hand, but higher RMS values in the ADM muscle (non-dominant hand: 8.45 ± 5.33%MVC, dominant hand: 3.89 ± 2.22%MVC, Figure 3M). These results suggest that the non-dominant hand showed lower activation in hand and forearm muscles (FDI, ECR, and FCU), but compensated with greater activation in the ADM muscle, possibly reflecting different motor strategies during handwriting. No significant interaction effect between hand use and the eye state was observed (all, $p > 0.05$), suggesting that visual feedback did not significantly modulate muscle activity depending on hand use.

Analysis of the Ratio of Change

Table 3 and Figure 4 present the ratio of change in each variable between the eyes-open and eyes-closed conditions for the dominant and non-dominant hands. The Wilcoxon signed-rank test revealed that the non-dominant hand exhibited a higher ratio of change in handwriting speed (non-dominant hand: 44.67 ± 36.60%, dominant hand: 20.77 ± 24.13%, Figure 4C), pen pressure (non-dominant hand: 25.09 ± 22.70%, dominant hand: 5.30 ± 11.36%, Figure 4D), intersection points (non-dominant hand: 41.53 ± 33.17%, dominant hand: 13.76 ± 18.10%, Figure 4G), and the legibility score (non-dominant hand: 15.11 ± 22.23%, dominant hand: −2.62 ± 4.06%, Figure 4H), compared to the dominant hand. Specifically, the non-dominant hand showed a greater increase in speed, pen pressure, and intersection points, while the legibility score decreased more compared to the dominant hand. These findings suggest that the non-dominant hand required greater effort and encountered more difficulty in maintaining legibility, particularly in the absence of visual feedback. No significant differences were found in the ratios of change for the remaining variables between the hands (all, $p > 0.05$), suggesting comparable adjustments in both hands under eyes-open and eyes-closed conditions.

Correlation analysis of the ratio of change in handwriting features between the eyes-open and eyes-closed conditions showed no significant correlation between muscle activity and the handwriting tracing dynamics (all, $p > 0.05$), nor between muscle activity and handwriting quality or legibility (all, $p > 0.05$). This suggests that changes in muscle activity did not directly impact handwriting performance across conditions.

Discussion

This study examined how the eye state and hand use influenced handwriting performance under different conditions (DO, DC, NO, NC). For handwriting tracing dynamics (duration, length, speed, pen pressure), we observed significant main effects of hand use and the eye state, but no significant interaction effect (Figure 3A–D). Using the non-dominant hand increased duration and length, and decreased speed and pen pressure, while closing the eyes decreased duration but increased length, speed, and pen pressure. For handwriting quality and legibility, a significant interaction effect was found for intersection points (Figure 3G) and the legibility score (Figure 3H), but not for the area (Figure 3E) or the tilt angle (Figure 3F).

Table 1. Summary of the mean values (mean ± SD) of the measured variables under each condition.

	Dominant hand, eyes open (DO)	Dominant hand, eyes closed (DC)	Non-dominant hand, eyes open (NO)	Non-dominant hand, eyes closed (NC)
Handwriting tracing dynamics				
Duration (s)	2.51 ± 0.67	2.13 ± 0.54	4.01 ± 1.17	3.23 ± 1.00
Length (cm)	11.0 ± 1.86	11.9 ± 2.20	15.2 ± 4.59	18.1 ± 5.09
Speed (cm/s)	5.24 ± 1.01	6.35 ± 1.87	4.49 ± 1.72	6.30 ± 2.45
Pen pressure (%)	69.81 ± 13.64	72.73 ± 13.48	55.53 ± 16.23	66.30 ± 11.80
Handwriting quality and legibility				
Area (cm^2)	5.14 ± 1.97	5.73 ± 1.93	9.47 ± 4.86	12.0 ± 5.90
Tilt angle (degree)	2.68 ± 2.25	5.57 ± 2.36	2.50 ± 1.18	5.49 ± 1.47
Intersection points (count)	7.71 ± 1.99	8.84 ± 3.17	9.45 ± 3.17	13.4 ± 5.48
Legibility score (score)	5.79 ± 0.28	5.64 ± 0.36	4.97 ± 1.20	4.19 ± 1.47
Muscle activity				
APB (%MVC)	14.30 ± 10.12	13.79 ± 11.81	11.41 ± 8.52	9.53 ± 7.39
FDI (%MVC)	8.02 ± 7.10	7.16 ± 6.74	4.92 ± 3.13	4.14 ± 3.08
ECR (%MVC)	12.98 ± 4.58	12.45 ± 5.29	11.14 ± 5.41	11.12 ± 5.70
FCU (%MVC)	5.89 ± 2.95	5.47 ± 2.54	3.42 ± 2.17	3.38 ± 2.00
ADM (%MVC)	3.70 ± 2.21	4.09 ± 2.31	7.18 ± 3.30	9.73 ± 6.72
UT (%MVC)	15.96 ± 12.90	16.54 ± 16.61	19.04 ± 12.87	18.33 ± 11.74

Table 2. Summary of the two-way ART-ANOVA (hand use × eye state) of the measured variables.

	Hand use main effect			Eye state main effect			Hand use × eye state interaction		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Handwriting tracing dynamics									
Duration (s)	61.9	< 0.001***	0.652	13.2	< 0.001***	0.286	1.62	0.212	0.047
Length (cm)	114	< 0.001***	0.776	18.1	< 0.001***	0.354	3.49	0.071	0.096
Speed (cm/s)	4.04	0.053	0.109	15.8	< 0.001***	0.324	0.958	0.335	0.028
Pen pressure (%)	10.78	0.002**	0.246	3.08	0.089	0.085	1.406	0.244	0.041
Handwriting quality and legibility									
Area (cm^2)	106	< 0.001***	0.763	9.42	0.004**	0.222	1.62	0.212	0.047
Tilt angle (degree)	0.082	0.777	0.002	46.1	< 0.001***	0.583	0.168	0.685	0.005
Intersection points (count)	13.9	< 0.001***	0.297	10.1	0.003**	0.234	4.90	0.034 *	0.129
Legibility score (score)	63.5	< 0.001***	0.658	17.5	< 0.001***	0.346	8.51	0.004**	0.205
Muscle activity									
APB (%MVC)	2.69	0.111	0.075	1.66	0.206	0.048	0.034	0.855	0.001
FDI (%MVC)	8.87	0.006**	0.212	0.609	0.441	0.018	0.013	0.909	< 0.001
ECR (%MVC)	6.27	0.017 *	0.160	0.458	0.503	0.014	0.610	0.440	0.018
FCU (%MVC)	22.9	< 0.001***	0.409	0.069	0.795	0.002	0.148	0.703	0.004
ADM (%MVC)	35.4	< 0.001***	0.518	1.95	0.172	0.056	0.604	0.443	0.018
UT (%MVC)	3.81	0.059	0.104	0.020	0.889	0.001	< 0.001	1.000	< 0.001

$* p < 0.05$, $** p < 0.01$, $*** p < 0.001$

Table 3. Summary of mean values (mean ± SD) and the Wilcoxon Signed Rank test of the measured variables.

	Descriptive statistics for the ratio of change (%)		Test statistics		
	Dominant hand	Non-dominant hand	Statistic (*Z*)	*p*	Effect size (*r*)
Handwriting tracing dynamics					
Duration (s)	−13.2 ± 0.15	−18.6 ± 0.12	−1.11	0.266	−0.321
Length (cm)	8.74 ± 0.14	21.7 ± 0.23	1.27	0.204	0.367
Speed (cm/s)	20.8 ± 0.24	44.5 ± 0.37	2.03	0.042*	0.586
Pen pressure (%)	5.30 ± 0.11	25.1 ± 0.23	2.71	0.007**	0.781
Handwriting quality and legibility					
Area (cm^2)	13.6 ± 0.25	34.2 ± 0.51	0.955	0.339	0.276
Tilt angle (degree)	189 ± 1.84	145 ± 0.91	−0.800	0.424	−0.231
Intersection points (count)	13.8 ± 0.18	41.5 ± 0.33	2.21	0.027*	0.639
Legibility score (score)	−2.62 ± 0.04	−15.1 ± 0.15	−2.51	0.012*	−0.723
Muscle activity					
APB (%MVC)	−10.2 ± 0.21	−13.4 ± 0.23	−0.800	0.424	−0.231
FDI (%MVC)	−5.72 ± 0.30	−13.4 ± 0.30	−1.03	0.301	−0.298
ECR (%MVC)	−5.57 ± 0.13	−1.13 ± 0.16	0.569	0.570	0.164
FCU (%MVC)	−4.87 ± 0.21	0.25 ± 0.21	−0.628	0.527	−0.308
ADM (%MVC)	12.2 ± 0.42	30.1 ± 0.39	1.03	0.301	0.295
UT (%MVC)	−1.50 ± 0.30	−4.27 ± 0.21	−0.265	0.791	−0.077

$* p < 0.05$, $** p < 0.01$

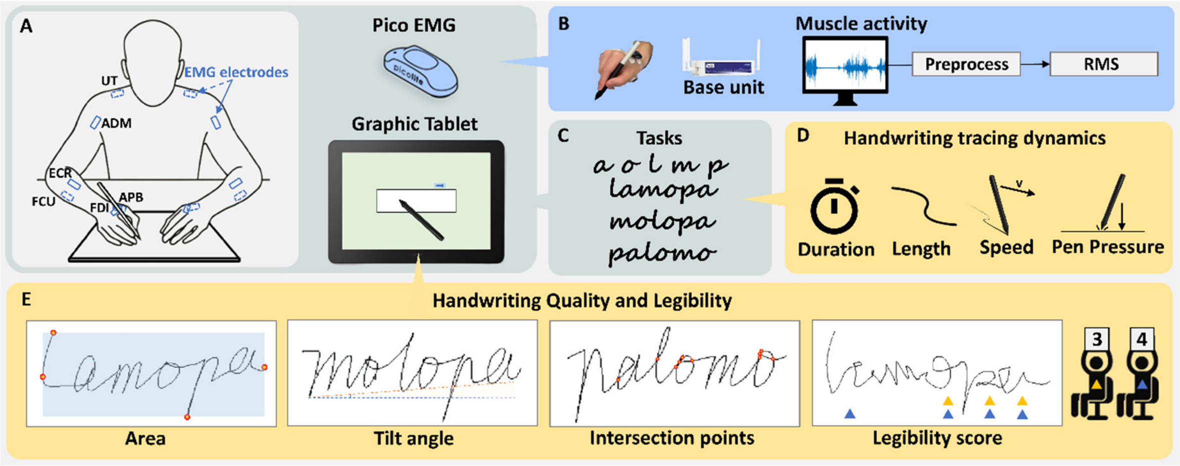

Figure 1. Instruments and handwriting features.

Panel A shows the experimental instruments, the Pico EMG, and the graphic tablet (UT: upper trapezius muscle; ADM: anterior deltoid muscle; ECR: extensor carpi radialis muscle; FCU: flexor carpi ulnaris muscle; FDI: first dorsal interosseous muscle; APB: abductor pollicis brevis). Panel B briefly demonstrates that the EMG signals during handwriting were received by the Base unit and transmitted to the computer; they were subsequently pre-processed and finally calculated to obtain the RMS amplitude. Panel C contains the five letters (a, o, l, m, p) and the three pseudowords (lamopa, molopa, palomo) composed of these letters. Panel D presents four metrics for handwriting tracing dynamics. These metrics were automatically calculated by the Eye and Pen software. Panel E presents four metrics of handwriting quality and legibility, and how each metric was calculated or evaluated.

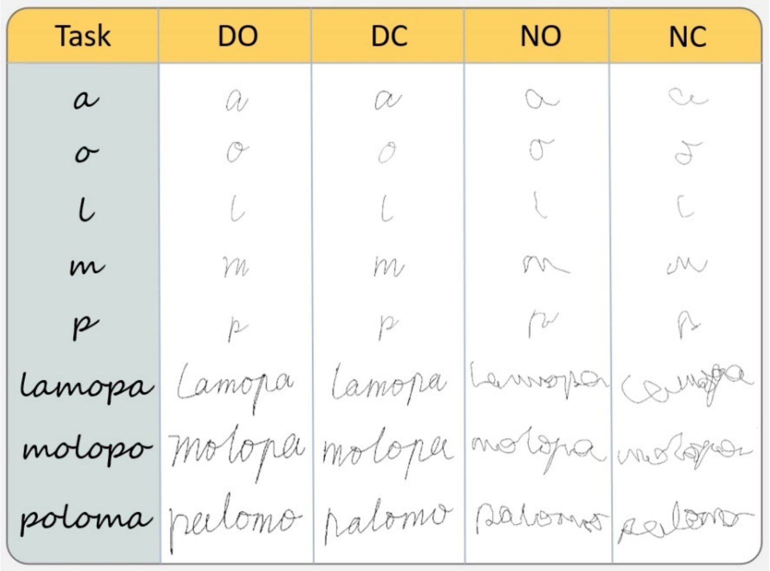

Figure 2. Handwriting examples.

DO: dominant hand with eyes open; DC: dominant hand with eyes closed; NO: non-dominant hand with eyes open; NC: non-dominant hand with eyes closed

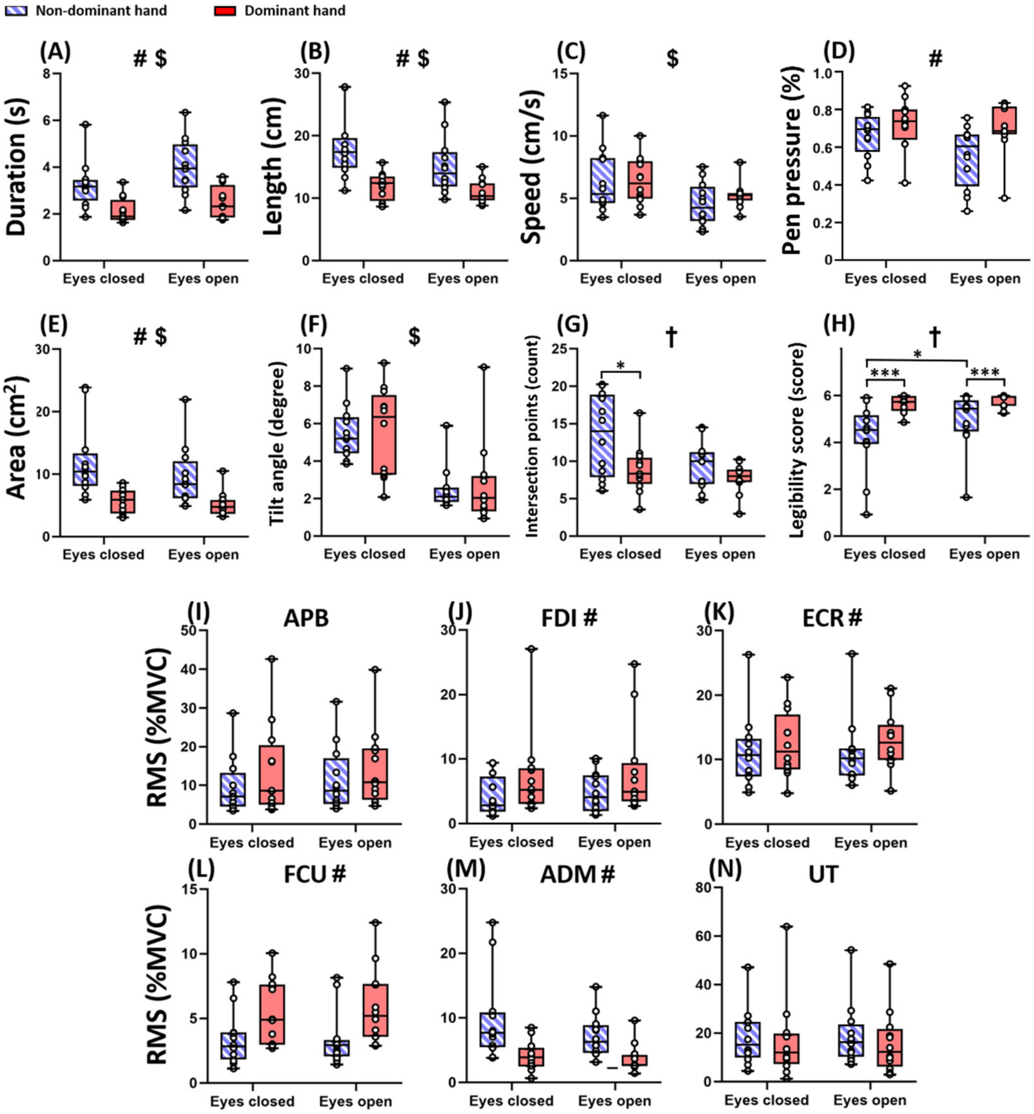

Figure 3. Group data for each variable.

*The lines in the box plots indicate median values, and the ends of the boxes represent the 25th and 75th percentiles; hollow circles represent individual participants' data points. † Significant hand use × eye state interactions; # significant main effect of hand use; $ significant main effect of the eye state; significant post hoc comparisons * ($p < 0.05$) and *** ($p < 0.001$) for significant hand use × eye state interactions. RMS: root mean square; APB: abductor pollicis brevis; FDI: first dorsal interosseous muscle; ECR: extensor carpi radialis muscle; FCU: flexor carpi ulnaris muscle; ADM: anterior deltoid muscle; UT: upper trapezius muscle*

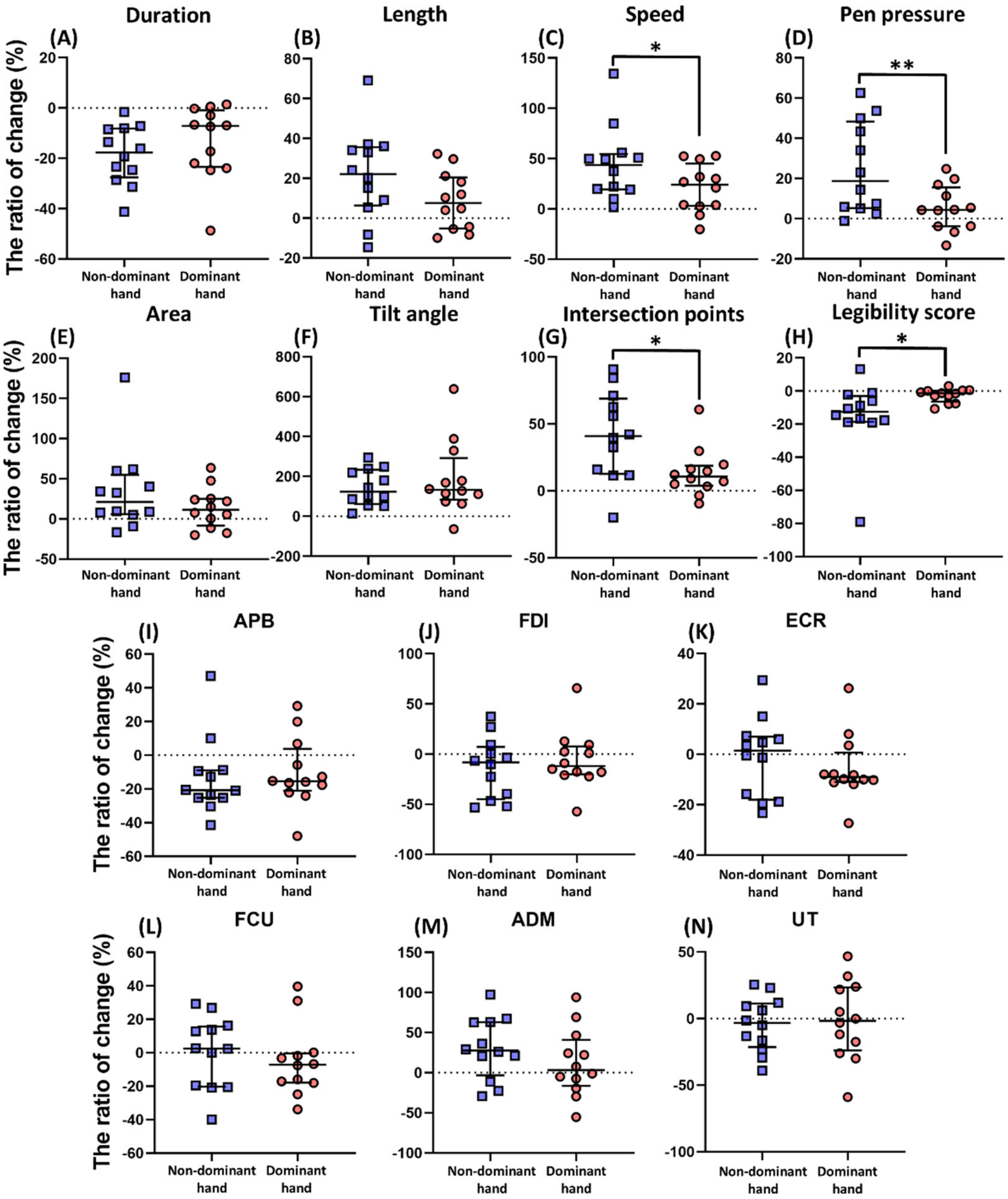

Figure 4. Wilcoxon signed-rank test for the ratio of change of all variables.

*The filled plots display individual data in the dominant hands, and the filled squares display individual data in non-dominant hands. The lines in the box plots indicate median values, and the ends of the boxes represent the 25th and 75th percentiles. * p < 0.05, ** p < 0.01. APB: abductor pollicis brevis; FDI: first dorsal interosseous muscle; ECR: extensor carpi radialis muscle; FCU: flexor carpi ulnaris muscle; ADM: anterior deltoid muscle; UT: upper trapezius muscle*

The EMG results showed that hand use significantly affected muscle activity for FDI, ECR, FCU, and ADM muscles (Figure 3J–M). FDI, ECR, and FCU muscle activity decreased in the non-dominant hand, while ADM muscle activity increased. Additionally, we examined the relative differences in the ratio of change of handwriting features and muscle coordination patterns between the two hands by comparing the eyes-open and eyes-closed conditions. The non-dominant hand exhibited significantly greater changes in writing speed (Figure 4C), pen pressure (Figure 4D), intersection points (Figure 4G), and the legibility score (Figure 4H) between the eyes-open and eyes-closed conditions, suggesting a stronger dependence on visual feedback. No significant correlation between handwriting features and muscle activity was found, suggesting that handwriting control involves more than a simple linear correlation.

Hand Use and the Eye State Independently Affect Handwriting Tracing Dynamics

Contrary to our hypothesis, the eye state and hand use did not interact significantly in affecting handwriting tracing dynamics (all, $p > 0.05$) (Table 2). The absence of interaction effects can be attributed to several factors. First, dominant hand movements are highly automated and require minimal visual feedback due to precise motor control (Marquardt et al., 1999). Second, the non-dominant hand performs poorly regardless of the eye state, indicating that the lack of visual feedback does not worsen its already suboptimal performance. Third, the simplicity of our handwriting task means it relied more on somatosensory feedback, reducing the impact of visual input on tracing dynamics.

Our results revealed significant main effects of hand use and the eye state on handwriting dynamics (Table 2 and Figure 3A–D). Consistently with prior research (Sandve et al., 2019; van Doorn and Keuss, 1993), handwriting length was longer with non-dominant hands or with eyes closed, supporting the dynamic-dominance hypothesis of motor lateralization which posits that the dominant hand is more proficient in producing a smooth hand-path (Przybyla et al., 2012). The lower pen pressure observed with the non-dominant hand likely reflects greater reliance on pen dexterity to compensate for reduced precise control. A prior study has reported that grip and pinch strength negatively correlate with fine motor skills (Duman and Subaşı, 2020), suggesting that fine motor performance may depend more on motor coordination than strength. Therefore, the observed differences in tracing dynamics between hands may reflect distinct muscle control strategies between hands rather than differences in muscle strength.

Visual feedback minimizes trajectory deviations by providing continuous spatial guidance, allowing precise adjustments to maintain a horizontal writing trajectory (Marquardt et al., 1996). In the absence of visual feedback, participants relied solely on proprioceptive feedback, leading to an increased handwriting tilt angle, a larger area, and longer trajectory length, while handwriting duration decreased. Notably, handwriting speed increased with eyes closed, which contrasts with previous studies reporting no significant effect of visual feedback on speed (Poletti et al., 2016). This discrepancy may stem from differences in task complexity, as the letter combinations in this study may have required more complex motor control than those used in earlier research (sustained writing l), potentially prompting a trade-off between accuracy and efficiency, where participants prioritize speed over precision. Overall, these findings suggest that hand use and the eye state exert independent effects on handwriting dynamics, underscoring the crucial role of visual feedback in optimizing motor control.

Non-Dominant Hands Are More Disrupted by the Absence of Visual Feedback

Consistently with our partial hypothesis, the ratio of change analysis (i.e., relative change from eyes-open to eyes-closed conditions) revealed that the non-dominant hand exhibited significant changes in handwriting speed (Figure 4C), pen pressure (Figure 4D), intersection points (Figure 4G), and the legibility score (Figure 4H), when visual feedback was removed. This underscores the non-dominant hand's strong reliance on visual feedback for tracing dynamics and legibility. In contrast, the dominant hand, supported by the dominant hemisphere's motor integration skills, relies more on internal cues like somatosensory feedback. The non-dominant hemisphere, with its greater reliance on visuospatial processing, experiences greater disruption when visual feedback is unavailable (Shalabi, 2020).

Intersection points objectively measure handwriting clarity by reflecting stroke separation, whereas the legibility score provides a subjective evaluation of information completeness. Although not directly correlated, both measures reflect handwriting accuracy and highlight the combined influence of visual and proprioceptive feedback on motor control. The non-dominant hand exhibits lower motor proficiency, which increases susceptibility to trajectory errors (Jones et al., 2020). Without visual feedback, proprioceptive input alone cannot ensure precise motor control (Przybyla et al., 2012), resulting in more intersection points. This finding underscores the role of visual feedback in fine motor control, particularly for spatial accuracy when writing with the non-dominant hand.

However, contrary to expectations, no significant differences in the change of ratios of muscle activity were found between the bilateral arms when visual feedback was removed. This may be because handwriting is a highly coordinated motor activity, and the central nervous system prioritizes overall motor coherence (Babadi et al., 2021). As a result, this coordination may remain stable between bilateral arms even without visual feedback. In addition, muscle activity alone may not fully reflect subtle neuromuscular adjustments (Cherifi et al., 2023), as these are likely regulated at the neural level, where motor patterns are maintained without major shifts in muscle activity.

Furthermore, no significant correlation was found between changes in handwriting features and muscle activity, which is consistent with previous research suggesting no significant relationship between muscle activity and handwriting quality (Naider and Katz, 2007). Several factors may account for this finding. First, handwriting relies on the coordinated activation of multiple muscles rather than the isolated activity of individual muscles (Stelmach et al., 1984). Notably, fine motor control relies on both extrinsic and intrinsic muscles of the hand (e.g., the lumbricals and interossei) (Long et al., 1970). However, intrinsic muscles are difficult to assess effectively by surface EMG. Additionally, agonist-antagonist coactivation, which is essential for movement stability, may further obscure direct correlations between handwriting features and muscle activity (De Luca and Mambrito, 1987). Another potential factor is the temporal resolution of this study, which was based on the handwriting process of an entire word lasting several seconds. This temporal scale may not be optimal for capturing fine-grained dynamic changes in muscle activation. Finally, the relationship between muscle activity and behavior is likely transmitted in a non-linear manner, which makes the correlation less straightforward to capture (Wang, 2023).

Non-Dominant Handwriting Relies More on Proximal Muscles

No significant interaction effect on muscle activity was found (all, $p > 0.05$) (Table 2 and Figure 3), suggesting that somatosensory feedback compensates for the absence of visual feedback in maintaining consistent muscle activation across the eye state (van Doorn and Keuss, 1992). The simplicity of the writing task may minimize the need for visual feedback, leading to more stable muscle activation patterns (Smyth and Silvers, 1987). However, a significant main effect of hand use was observed, with greater ADM activity during non-dominant handwriting (Table 2 and Figure 3). This suggests compensatory reliance on more easily controlled proximal joints (e.g., the shoulder) to offset the inherently limited fine motor control of distal joints, such as the wrist and fingers. This observation aligns with studies showing that novice writers predominantly activate proximal muscles to control hand movements, reflecting a less developed motor control system (Ishak et al., 2014; Sabrina and Julia, 2023). Despite the increased involvement of proximal muscles, this compensatory strategy was insufficient for precise handwriting control, as it increased energy expenditure and motor variability, ultimately reducing fine motor precision (Kim, 2021). These findings underscore that the non-dominant hand adopts a distinct muscle control strategy, emphasizing proximal stabilization to compensate for its deficits in fine motor control, but this approach does not fully overcome its limitations in handwriting performance.

Limitations

This study provides an initial exploration of motor control mechanisms in handwriting, focusing on hand use and the eye state, but has three limitations. First, only right-handed individuals were recruited, limiting generalizability. Future studies should include left-handed individuals to better understand brain lateralization in motor control. Second, the use of the ratio of change introduces potential limitations, including sensitivity to small baseline values that may disproportionately amplify changes, and inherent reliance on proportionality assumptions that might not fully capture non-linear handwriting changes. Finally, surface EMG primarily records activity from extrinsic muscles, making it less effective in assessing the role of intrinsic hand muscles involved in fine motor control. Future studies could incorporate ultrasound imaging, which can capture morphological changes and help understand the involvement of intrinsic muscles in the fine control of the hand.

Conclusions

This study demonstrates that handwriting with the non-dominant hand is significantly more disrupted by the absence of visual feedback compared to the dominant hand, particularly in terms of speed, pen pressure, and spatial accuracy. While the dominant hand benefits from internal somatosensory feedback and can better maintain handwriting performance without visual input, the non-dominant hand is more dependent on visual feedback. Interestingly, despite significant differences in handwriting ability between the two hands, changes in muscle activity were not significantly different, suggesting that writing behavior does not depend solely on the magnitude of changes in muscle activity, but rather on complex nonlinear muscle coordination. These findings underscore a fundamental difference between the neural control mechanism of the dominant and non-dominant hands, contributing to a deeper understanding of motor skill acquisition and the role of sensory feedback in fine motor skills.

Author Contributions: Conceptualization: B.L. and K.N.; methodology: B.L., R.T. and K.N.; software: B.L.; validation: B.L.; formal analysis: B.L., R.T. and I.J.; investigation: B.L., R.T. and M.D.; resources: K.N.; data curation: B.L.; writing—original draft preparation: B.L.; writing—review & editing: B.L., R.T., N.K., I.J., M.D. and K.N.; visualization: B.L.; supervision: K.N.; project administration: K.N.; funding acquisition: N.K. All authors have read and agreed to the published version of the manuscript.

ORCID iD:

Bowen Liu: https://orcid.org/0000-0003-2139-3950

Ryogo Takahashi: https://orcid.org/0009-0005-5835-6880

Naotsugu Kaneko: https://orcid.org/0000-0002-1587-9287

Inhyeok Jeong: https://orcid.org/0000-0002-1343-7442

Mayu Dohata: https://orcid.org/0009-0008-7026-4032

Kimitaka Nakazawa: https://orcid.org/0000-0001-5483-8659

Funding Information: This work was supported by the Nakatomi Foundation to N.K., a Grant-in-Aid for Japan Society for the Promotion of Science (JSPS) WAKATE to N.K. (#50969285), JST PRESTO program to N.K. (#JPMJPR24I5), and JST-MOONSHOT program to K.N. (#JPMJMS2012–2-2–2).

Institutional Review Board Statement: This study was conducted following the principles of the Declaration of Helsinki and approved by the ethics committee of the University of Tokyo, Tokyo, Japan (approval number: 754-8; approval date: 23 August 2024).

Informed Consent: Informed consent was obtained from all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Received: 10 October 2024

Accepted: 12 December 2025

References

Alamargot, D., Chesnet, D., Dansac, C., & Ros, C. (2006). Eye and pen: A new device for studying reading during writing. *Behavior Research Methods*, *38*(2), 287–299. https://doi.org/10.3758/bf03192780

Babadi, S., Vahdat, S., & Milner, T. E. (2021). Neural substrates of muscle co-contraction during dynamic motor adaptation. *Journal of Neuroscience*, *41*(26), 5667–5676. https://doi.org/10.1523/jneurosci.2924-19.2021

Chartrel, E., & Vinter, A. (2006). The role of visual information in the production of cursive letters in children and adults. *L'Année Psychologique*, *106*(1), 45–66. https://doi.org/10.4074/S0003503306001047

Cherifi, D., Salah, I., Chihaoui, T., Moudoud, M., Boubchir, L., & Nait-Ali, A. (2023). Automated diagnosis of neuromuscular disorders using EMG signals. In *2023 5th International Conference on Bio-engineering for Smart Technologies (BioSMART)* (pp. 1–5). IEEE. https://doi.org/10.1109/BioSMART58455.2023.10162039

Danna, J., & Velay, J. L. (2015). Basic and supplementary sensory feedback in handwriting. *Frontiers in Psychology*, *6*(169), 1–11. https://doi.org/10.3389/fpsyg.2015.00169

De Luca, C. J., & Mambrito, B. (1987). Voluntary control of motor units in human antagonist muscles: Coactivation and reciprocal activation. *Journal of Neurophysiology*, *58*(3), 525–542. https://doi.org/10.1152/jn.1987.58.3.525

Duman, Ç., & Subaşı, F. (2020). Effects of pinch, grip and upper extremity muscle strength on fine motor skills. In F. E. Aslan (Ed.), *Scientific researches in health sciences* (pp. 11–21). Peter Lang. https://www.peterlang.com/document/1111075

Ebied, A. M., Kemp, G. J., & Frostick, S. P. (2004). The role of cutaneous sensation in the motor function of the hand. *Journal of Orthopaedic Research*, *22*(4), 862–866. https://doi.org/10.1016/j.orthres.2003.12.005

Gerth, S., & Festman, J. (2023). Muscle activity during handwriting on a tablet: An electromyographic analysis of the writing process in children and adults. *Children*, *10*(4), 1–17. https://doi.org/10.3390/children10040748

Goble, D. J., Lewis, C. A., & Brown, S. H. (2006). Upper limb asymmetries in the utilization of proprioceptive feedback. *Experimental Brain Research*, *168*(1–2), 307–311. https://doi.org/10.1007/s00221-005-0280-y

Grewal, R., Vig, D., & Saini, S. (2014). Role of visual perception in improving quality of handwriting. *Indian Journal of Health and Wellbeing*, *5*(5), 591–595. https://www.i-scholar.in/index.php/ijhw/article/view/53112

Guilbert, J., Alamargot, D., & Morin, M. F. (2019). Handwriting on a tablet screen: Role of visual and proprioceptive feedback in the control of movement by children and adults. *Human Movement Science*, *65*, 30–41. https://doi.org/10.1016/j.humov.2018.09.001

Harris, S. J., & Livesey, D. J. (1992). Improving handwriting through kinaesthetic sensitivity practice. *Australian Occupational Therapy Journal*, *39*(1), 23–27. https://doi.org/10.1111/j.1440-1630.1992.tb01731.x

Hepp-Reymond, M. C., Chakarov, V., Schulte-Mönting, J., Huethe, F., & Kristeva, R. (2009). Role of proprioception and vision in handwriting. *Brain Research Bulletin*, *79*(6), 365–370. https://doi.org/10.1016/j.brainresbull.2009.05.013

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, *10*(5), 361–374. https://doi.org/10.1016/s1050-6411(00)00027-4

Hong, S. Y., Jung, N. H., & Kim, K. M. (2016). The correlation between proprioception and handwriting legibility in children. *Journal of Physical Therapy Science*, *28*(10), 2849–2851. https://doi.org/10.1589/jpts.28.2849

Imai, S., Harato, K., Morishige, Y., Nagura, T., Matsumoto, H., & Hase, K. (2025). Effects of visual occlusion on lower extremity biomechanics during a low-intensity single-leg landing. *Journal of Human Kinetics*, *97*, 51–63. https://doi.org/10.5114/jhk/190681

Ishak, N. A., Khalid, P. I., Mahmood, N. H., & Harun, M. (2014). Study of muscle signal variability based on wrist and thumb movements during handwriting activity. In *2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES)* (pp. 817–820). IEEE. https://doi.org/10.1109/IECBES.2014.7047623

Jones, B. D., van Gemmert, A. W. A., & Dalecki, M. (2020). Does hand-dominance matter in non-standard visuomotor transformations? *Journal of Motor Behavior*, *53*(5), 622–631. https://doi.org/10.1080/00222895.2020.1817840

Kim, T.-H. (2021). Comparison of dominant and nondominant handwriting with the signal of a three-axial accelerometer. *International Journal of Internet, Broadcasting and Communication*, *13*(2), 260–266. https://doi.org/10.7236/IJIBC.2021.13.2.260

Kishore, M. (2021). Proprioception and kinesthesia: The sixth sense organ. *Advances in Health and Exercise*, *1*(1), 12–17. https://www.turkishkinesiology.com/index.php/ahe/article/view/3

Klöppel, S., Vongerichten, A., van Eimeren, T., Frackowiak, R. S., & Siebner, H. R. (2007). Can left-handedness be switched? Insights from an early switch of handwriting. *Journal of Neuroscience*, *27*(29), 7847–7853. https://doi.org/10.1523/JNEUROSCI.1299-07.2007

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Liang, D., Yarossi, M., Jacobs-Skolik, S. L., Furmanek, M. P., Brooks, D., Erdogmus, D., & Tunik, E. (2021). Synergistic activation patterns of hand muscles in left-and right-hand dominant individuals. *Journal of Human Kinetics*, *76*, 89–100. https://doi.org/10.2478/hukin-2021-0002

Long, C., II, Conrad, P. W., Hall, E. A., & Furler, S. L. (1970). Intrinsic-extrinsic muscle control of the hand in power grip and precision handling. An electromyographic study. *Journal of Bone and Joint Surgery*, *52*(5), 853–867. https://doi.org/10.2106/00004623-197052050-00001

Lopez, C., & Vaivre-Douret, L. (2021). Influence of visual control on the quality of graphic gesture in children with handwriting disorders. *Scientific Reports*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-02969-7

Marquardt, C., Gentz, W., & Mai, N. (1999). Visual control of automated handwriting movements. *Experimental Brain Research*, *128*(1–2), 224–228. https://doi.org/10.1007/s002210050841

Marquardt, C., Gentz, W., & Mai, N. (1996). On the role of vision in skilled handwriting. In M. L. Simner, C. G. Leedham, & A. J. W. M. Thomassen (Eds.), *Handwriting and Drawing Research: Basic and Applied Issues* (pp. 87–97). IOS Press. https://www.researchgate.net/publication/334326599

Mortazavi Najafabadi, S., Najafi Ashtiani, M., Zagrodny, B., & Grzelczyk, D. (2025). Examining the impact of visual perturbation caused by virtual reality on postural stability. *Journal of Human Kinetics*, *99*, 43–54. https://doi.org/10.5114/jhk/197097

Naider-Steinhart, S., & Katz-Leurer, M. (2007). Analysis of proximal and distal muscle activity during handwriting tasks. *American Journal of Occupational Therapy*, *61*(4), 392–398. https://doi.org/10.5014/ajot.61.4.392

Oldfield R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–112. https://doi.org/10.1016/0028-3932(71)90067-4

Poletti, C., Sleimen-Malkoun, R., Lemaire, P., & Temprado, J. J. (2016). Sensori-motor strategic variations and sequential effects in young and older adults performing a Fitts' task. *Acta Psychologica*, *163*, 1–9. https://doi.org/10.1016/j.actpsy.2015.10.003

Popowczak, M., & Zwierko, T. (2025). Effects of oculomotor scanning on agility performance: gender and a type of team sport comparison. *Journal of Human Kinetics*, *99*, 263–274. https://doi.org/10.5114/jhk/196002

Przybyla, A., Good, D. C., & Sainburg, R. L. (2012). Dynamic dominance varies with handedness: Reduced interlimb asymmetries in left-handers. *Experimental Brain Research*, *216*(3), 419–431. https://doi.org/10.1007/s00221-011-2946-y

Sainburg, R. L. (2005). Handedness: differential specializations for control of trajectory and position. *Exercise and Sport Sciences Reviews*, *33*(4), 206–213. https://doi.org/10.1097/00003677-200510000-00010

Sandve, H., Lorås, H., & Pedersen, A. V. (2019). Is it possible to change handedness after only a short period of practice? Effects of 15 days of intensive practice on left-hand writing in strong right-handers. *Laterality*, *24*(4), 432–449. https://doi.org/10.1080/1357650X.2018.1534856

Shalabi, K. (2020). Neuroscience of motor learning in adults with non-dominant hand. *Journal of Critical Reviews*, *7*(6), 27–30. https://doi.org/10.31838/jcr.07.06.07

Smyth M., & Silvers, G (1987). Functions of vision in the control of handwriting. *Acta Psychologica*, *65*(1), 47–64. https://doi.org/10.1016/0001-6918(87)90046-1

Stelmach, G. E., Mullins, P. A., & Teulings, H. L. (1984). Motor programming and temporal patterns in handwriting. *Annals of the New York Academy of Sciences*, *423*(1), 144–157. https://doi.org/10.1111/j.1749-6632.1984.tb23425.x

Teasdale, N., Forget, R., Bard, C., Paillard, J., Fleury, M., & Lamarre, Y. (1993). The role of proprioceptive information for the production of isometric forces and for handwriting tasks. *Acta Psychologica*, *82*(1–3), 179–191. https://doi.org/10.1016/0001-6918(93)90011-f

van Doorn, R. R., & Keuss, P. J. (1992). The role of vision in the temporal and spatial control of handwriting. *Acta Psychologica*, *81*(3), 269–286. https://doi.org/10.1016/0001-6918(92)90021-5

van Doorn, R. R., & Keuss, P. J. (1993). Does the production of letter strokes in handwriting benefit from vision? *Acta Psychologica*, *82*(1–3), 275–290. https://doi.org/10.1016/0001-6918(93)90016-k

Wang, X., Luo, Z., Zhang, M., Zhao, W., Xie, S., Wong, S. F., Hu, H., & Li, L. (2023). The interaction between changes of muscle activation and cortical network dynamics during isometric elbow contraction: A sEMG and fNIRS study. *Frontiers in Bioengineering and Biotechnology, 11,* 1–15. https://doi.org/10.3389/fbioe.2023.1176054