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Original Article

Quantitative evaluation of handwriting: factors that affect pen operating skills

Sho Horie, OTR, MS[1, 2)*], Katsuyuki Shibata, OTR, PhD[3)]

[1)] *Section of Rehabilitation, Kanazawa University Hospital: 13-1 Takara-machi, Kanazawa-shi, Ishikawa 920-8641, Japan*
[2)] *Division of Health Science, Graduate School of Medical Science, Kanazawa University, Japan*
[3)] *Faculty of Health Sciences, Institute of Medical, Pharmaceutical and Health Sciences, Kanazawa University, Japan*

Abstract. [Purpose] The purpose of this study was to present control data on writing pressure, the amount of weight on the upper limb, joint angle, and the area of overlap from the sample in graphic tracing tasks, and to extract factors that affect pen-operating skills. [Participants and Methods] The participants included 35 healthy volunteers who performed 1-inch graphic tracing and writing. The measurements were recorded under two conditions as follows: strong and weak writing pressure tasks, and fast and careful writing speed tasks. [Results] In the writing pressure task, increase in pen pressure was accompanied by increase in hand pressure; however, the forearm pressure did not change. In the writing speed task, no significant difference in pressure was observed, except for a slight difference in writing pressure. The degree of variation in pen pressure and areas of overlap were greater in the fast task than in the careful task. Two multiple regression models revealed the contributing factors to pen-operating skills, both showing that the degree of variation in pen pressure was significantly involved. [Conclusion] The multiple regression analysis results showed that pen-operating skills can likely be evaluated, where the degree of variation in writing pressure is an index for deciding the effect of treatment intervention.
Key words: Handwriting, Writing pressure, Multiple regression analysis

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INTRODUCTION

Writing activity for individuals with disability and children is an important activity, even for daily activities in terms of entering school and the work-force. Diseases that decrease writing performance include central nervous system disorders and peripheral nerve disorders. As such, quantitative evaluation to show the writing performance of a patient and efficacy of rehabilitative intervention is important. Previous studies used indices such as writing pressure[1–3)], upper limb joint angle[4–6)], and writing speed[7–9)] for the quantitative evaluation of writing performance. Of these, writing pressure has been measured in many studies. However, studies on weight of the hands and forearm supported by the desk surface are occasionally seen. Moreover, an increase in writing speed has been reported to be associated with an increase in writing pressure[2)]. In addition, writing speed and accuracy are not compatible[9)]. Reports that compared the instructions to which participants give priority when writing, namely instructions on writing pressure, speed, and accuracy, are also few.

Evaluation of practical writing performance involves a subjective observation-based evaluation by a therapist. Meanwhile, there is a report where an objective evaluation involved loading of a traced image created by tracing writing onto a computer, and then the area of overlap with the sample, pen displacement etc., were evaluated quantitatively[10)]. In the current study, we objectively evaluated pen operating skills, and analyzed the factors involved in the accuracy of pen operating skills in tracing

*Corresponding author. Sho Horie (E-mail: horiemon@med.kanazawa-u.ac.jp)

writing by multiple regression analysis.

The objective of this study was to perform a graphic tracing task under learning conditions with differing writing pressures and writing speeds. This was performed to 1) extract control data such as writing pressure, the amount of weight of the upper limb, and joint angle of young healthy volunteers, and 2) to extract the factors of the relative merits of pen operating skills that affect areas of overlap (accuracy).

PARTICIPANTS AND METHODS

The participants included 35 young adult volunteers consisting of 5 men and 30 women, with a mean age of 21.3 ± 1.7 years. All participants were right handed. The exclusion criteria consisted of a physical disorder in motion of the dominant hand of the upper limb that was measured, and individuals with a history of orthopedic surgery or disease. A written explanation of the study objective and methods was given to the participants and the study was performed after obtaining their signed written informed consent.

The writing pressure measurement devices (DKH Inc.) included 4 sites, namely, the writing pressure pen (A), writing pressure plate (B), hand pressure plate (C), and forearm pressure plate (D) (Fig. 1).

A dual axis digital angle protractor (Biometrics Inc.) was placed at the dorsal side of the wrist joint, and dorsal side of the proximal interphalangeal (PIP) joint to measure 2 axes of the palmar flexion and dorsiflexion and radial and ulnar flexion of the wrist joint, and one axis of the index finger PIP joint flexion. Writing pressure and angle data sampling were measured at 1,000 Hz.

The posture for the experiment was sitting in a chair, and the positions of the plates (B, C, and D)) were decided in advance. Eighteen participants were requested to trace the position of the writing limb on the desk surface to determine the mean value of the position of each plate (Fig. 1).

The tracing task consisted of a combination of straight and curved lines. A diagram where an equilateral triangle was inserted in a circle 25 mm in diameter was used (Fig. 1). For writing speed, each diagram was divided into 3 compartments, and tracing was performed at the pace of a metronome in each compartment.

The instructions given to the participants were the four conditions of the two tasks outlined below. (1) The writing pressure task consisted of a ‘strong’ task (write while pressing as hard as possible) and a ‘weak’ task (‘write while pressing as light as possible) (2 sec in each compartment). (2) The writing speed task consisted of a ‘fast’ task (write at the pace of the fast metronome) (1 sec in each compartment) and a ‘careful’ task (write at the pace of the slow metronome) (3 sec in each compartment). The tasks were performed three times, and the measurements were also recorded three times.

The items measured were pen pressure (A), writing surface pressure (B), hand pressure (C), and forearm pressure (D). Mean pressure during the performance of each task was calculated. In addition, the degree of variation in pen pressure and writing surface pressure were determined using the calculation method of Shindo et al.[11] (the absolute value of the difference of the actual measured value (Pi) of each writing pressure, $\Delta Pi=|Pi+1 - Pi|$). For writing time, the number of data per time was standardized. For accuracy of pen operation, the area of overlap from a sample diagram was determined. Regarding the calculation of the area of overlap, the line drawing was loaded onto a computer via scanning (resolution of 300 dpi), and the area (in pixels) of overlap was calculated from the sample diagram.

The Student’s t-test was used to compare mean values of the parameters of each task. To extract the factors involved in pen operating skills, a multiple regression analysis was performed with the area of overlap as the objective variable and the various measurement items as the explanatory variables. The variables affecting the area of overlap were investigated. A step-wise method was used to select the variables, and a threshold value for increase or decrease in the variables was $p=0.2$. The statistical software used was JMP version 10.0.2 (SAS Institute Japan).

This study was performed after obtaining the approval from the Medical Ethics Committee of Kanazawa University (approval number: 569).

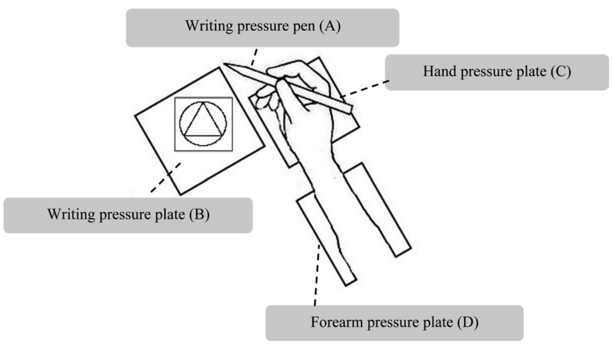

Fig. 1. Experimental environment.

RESULTS

Mean measurement values in the writing pressure and writing speed tasks are presented in Table 1. In the 'strong' task for writing pressure, pen pressure, writing surface pressure, and hand pressure were significantly higher than the values in the 'weak' task ($p<0.01$). On the other hand, forearm pressure showed no significant difference. The degree of variation in pen pressure and writing surface pressure in the 'strong' task were significantly higher ($p<0.01$). Writing speed was adjusted using a metronome; however, significant differences were observed in the 'strong' and 'weak' tasks ($p<0.01$). Wrist joint angle increased significantly in the 'strong' task with palmar dorsoflex and radial and ulnar flexion ($p<0.01$). The area of overlap in the tracing task was significantly smaller in the 'strong' task compared to in the 'weak' task ($p<0.05$).

In the writing speed task, pen pressure and writing surface pressure increased significantly in the 'fast' task compared to the 'careful' task ($p<0.05$). Meanwhile, hand area pressure and forearm area pressure showed no change. The degree of variation in pen pressure and writing surface pressure were significantly higher in the 'fast' task ($p<0.01$). The area of overlap was significantly smaller in the 'careful' task compared to the 'fast' task ($p<0.01$).

The factors involved in the accuracy of pen operation were extracted by multiple regression analyses using two models, 'strong' and 'careful' ($p<0.01$. Table 2). In the 'strong' model, the extracted factors, namely, degree of variation in pen pressure and level of writing speed, were significantly involved in pen operability ($p<0.01$). On the other hand, the factor extracted using the 'careful' model, namely, the degree of variation in pen pressure, was significantly involved in pen operability ($p<0.01$).

Table 1. Mean measurement values in the writing pressure and writing speed tasks

	Writing pressure task		Writing speed task	
Measurement index	Strong	Weak	Fast	Careful
Pressure				
Pen pressure (g)	433 ± 92	83 ± 33**	222 ± 74	200 ± 63*
Writing surface pressure (g)	506 ± 114	83 ± 40**	248 ± 87	223 ± 76*
Hand pressure (g)	787 ± 259	350 ± 150**	432 ± 179	451 ± 176
Forearm pressure (g)	1,881 ± 730	1,888 ± 726	1,747 ± 639	1,815 ± 761
Degree of variation				
Pen pressure (ΔPi)	5,050 ± 830	4,060 ± 330**	5,040 ± 740	4,170 ± 450**
Writing surface pressure (ΔPi)	10,760 ± 3,100	9,220 ± 700**	10,690 ± 1,420	9,460 ± 1,200**
Writing speed (mm/s)	11.49 ± 0.31	11.70 ± 0.32**	21.85 ± 1.16	7.78 ± 0.12**
Range of motion				
Palmar flexion and dorsiflexion (degrees)	9.2 ± 2.5	7.7 ± 2.2**	8.1 ± 2.3	8.1 ± 2.5
Radial and ulnar flexion (degrees)	12.6 ± 3.3	11.0 ± 2.3**	11.3 ± 2.8	11.4 ± 2.8
Index finger PIP flexion (degrees)	19.0 ± 7.0	18.4 ± 6.0	18.7 ± 6.9	19.7 ± 6.2
Area of overlap (pixels)	435 ± 601	650 ± 712*	1,177 ± 1,202	229 ± 353**

n=35 (for each condition); PIP: proximal interphalangeal.
*p<0.05, **p<0.01.

Table 2. The factors involved in the accuracy of pen operation were extracted by multiple regression analyses (n=35)

Model	Variable	Unstandardized coefficients		Standardized Coefficients	p-value	Adjusted R^2
		B	SE	β		
'Strong' model	Degree of variation in pen pressure	448.38	152.86	0.62	0.0064**	0.28
	Writing speed	1,003.05	291.25	0.52	0.0017**	
	Range of index finger PIP flexion	23.75	13.13	0.28	0.0805	
	Pen pressure	−2,341.34	1,342.13	−0.36	0.0913	
'Careful' model	Degree of variation in pen pressure	366.30	114.22	0.47	0.0031**	0.28
	Writing speed	872.20	446.76	0.29	0.0600	
	Range of palmar flexion and dorsiflexion	−33.75	20.72	−0.24	0.1133	

PIP: proximal interphalangeal.
**p<0.01.

DISCUSSION

Writing pressure determined by a pen stylus was reported in previous studies to be approximately 1.4–1.5 N when writing at a normal speed[1, 2]. In this study, where 'strong' (4.25–4.96 N), 'weak' (0.81 N), and normal writing pressures were compared, the 'strong' pressure showed a weight of 3–3.5 times higher to normal while 'weak' showed approximately 1/2 lower to normal. In the 'strong' hand pressure task, both writing pressure and hand pressure increased collaboratively. Although, forearm pressure maintained at a constant pressure regardless of an increase or decrease in writing pressure. Thus, looking at the pressure ratio on the desk surface, in the 'strong' task, the writing surface and hand area ratios were high, while in the 'weak' task, the forearm ratio was high. Large-sized writing accompanies proximal joint motions of the shoulder and elbow[12], while in the small-sized writing, coordinated movement of the distal muscles of the upper limb including finger and wrist joints is important. Therefore, to increase stability, the distal part of the upper limb tends to be immobile, and operations are performed by motions more distal to the wrist joint[13]. In the small 1-inch size task in this study, forearm pressure remained constant regardless of writing pressure, suggesting that the role of the immobilized forearm was elucidated. The degree of variation[11], expressing the roughness of writing, was high in the 'strong' task. Shindo et al.[11] stated that the larger the up and down waveform of writing pressure, the larger the degree of variation. However, they postulated a case where maximum writing pressure of the comparative object was equivalent, while in the writing pressure task of this study, maximum writing pressure varied notably, which likely caused a difference in the degree of variation. Previous studies on the correlation between pen movement and angle of displacement of the fingers state that the finger joints are used mainly for backward and forward strokes, while the wrist joint is used mainly for left and right strokes. However, coupling of the motion of the finger and wrist joints is necessary to make slanted strokes[4, 5]. In this study, the palmar flexion and dorsiflexion of the wrist joint was 7.7–9.2° and the radial and ulnar flexion was 11.0–12.6°, whereas the index finger PIP joint was 18.4–19.7°, which was close to the sum value of the palmar flexion and dorsiflexion and radial and ulnar flexion. The geometrical diagram used in this study required more complex vertical and horizontal motions compared to triangular horizontal lines. Therefore, the mutual motions of the index finger PIP and wrist joint angle displayed in the tracing task were adjusted to the direction of the tracing. In the 'strong' task that demanded a strong writing pressure, palmar flexion and dorsiflexion and radial and ulnar flexion became significantly large values because to output a stronger tripod grip, the hand needs to approach the mild dorsiflexion position of the wrist joint, which is the functional limb position of the wrist joint, and a mild ulnar flexion position[14]. This is a superior strategy where strong writing pressure can be applied. In addition, the area of overlap in the 'weak' task was significantly large but was small in the 'strong' task. Kao et al. stated that when the level of difficulty of a task became complicated, writing pressure increased[15]. In the 'strong' task of this study, the area of overlap was small compared to that of the 'weak' task, and was therefore, applicable to the level of difficulty of strong writing pressure tasks. As such, pen accuracy increased. In other words, this showed that a trade-off between writing pressure and pen operation accuracy was not established.

Previous studies have reported that writing pressure in a normal writing speed is 1.4–1.5 N, and that increases in writing speed cause that value to reach 1.7 N[1, 2]. Writing pressure in the writing speed task was close to the significantly high value in the 'fast' task. Meanwhile, the pressure ratio on the desk surface was almost the same in both conditions. The pressure ratio of the upper limb was shown to cause hardly any pressure change due to writing speed. With pens that display the roughness of writing, the degree of variation of the writing surface and area of overlap were significantly larger in the 'fast' task. Berwick et al.[9] reported that writing speed and accuracy are incompatible. In other words, in the writing speed task, writing speed and accuracy of pen operation affect the 'trade-off' correlation, which was notably reflected in the degree of variation in pen pressure and area of overlap. On the other hand, the standard difference was also larger, indicating that individual differences were also large. Thus, even when writing speed is high, there are cases where the area of overlap can be suppressed, and as such, an investigation of multiple factors including writing pressure and joint angle is necessary.

Two regression models were selected, namely, 'strong' and 'careful' for factors involved in pen operability (area of overlap) by multiple regression analysis. In the 'strong' model, degree of variation in pen pressure and writing speed factors were shown to be involved in pen operability; while in the 'careful' model, only the degree of variation in pen pressure was shown to be involved. The degree of variation in writing pressure was significantly affected by pen operating skills, and it became evident that it is an important factor in the evaluation of writing. In the 'strong' model, writing speed became a significant variable; however, in this study, despite control over the writing speed, minute changes were shown to affect the area of overlap.

Based on the above findings, regarding instructions when evaluating writing, when 'strong' is the writing condition in the writing pressure task, and 'careful' is the writing speed task according to the treatment target, pen operating skills can likely be evaluated where the degree of variation in writing pressure is an index for deciding the effect of treatment intervention. In addition, further investigation is necessary to determine the development of training methods in the future.

This study has some limitations. First, measurements were only recorded by healthy volunteers. Second, the age group of the participants was restricted. Third, the size and type (only graphical) of the tasks were limited, and last, factors that likely affected handwriting, such as electromyograms, and pen grip pressure, were not included.

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