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The effect of task complexity on handwriting kinetics

L'effet de la complexité des tâches sur la cinétique de l'écriture

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Key words: Children; Fine motor; Occupational therapy; Schools; Task performance.

Mots clés : Écoles; Enfants; Ergothérapie; Exécution des tâches; Motricité fine.

Abstract

Background. Knowledge regarding the relationship between writing kinetics and the difference among writing tasks is limited. **Purpose.** This study examined the differences in handwriting performance when doing tasks with different levels of challenge from both temporal and kinetic perspectives among children in four different age groups. **Method.** The cross-sectional design introduced a force-acquisition pen to detect differences of pen grip and writing kinetics among 170 school-age children doing writing tasks at different difficulty levels. Data were obtained on the force information of the digits and pen tip and the kinetic parameters to examine the coordination-and-control mechanism between the digits and pen. Statistical analyzes were carried out to indicate the differences in writing performance among groups and tasks. **Findings.** Statistical differences in the pen-grip forces, force fluctuation, and force ratio between grip and pen-tip forces were found when performing different writing tasks and among different age groups. **Implications.** The study provides an alternative method to explore how writing performance among school-age children can vary according to the difficulty of the writing tasks.

Abrégé

Description. Les connaissances concernant la relation entre la cinétique de l'écriture et la différence entre les tâches d'écriture sont limitées. **But.** Cette étude examinait les différences entre les performances à l'écrit d'enfants de quatre groupes d'âges différents, lors de l'exécution de tâches ayant différents degrés de difficulté, d'un point de vue temporel et cinétique. **Méthodologie.** Ce devis transversal comprenait un stylo muni d'un système permettant de recueillir des données sur la force, afin de détecter les différences entre les forces de préhension et la cinétique d'écriture de 170 enfants d'âge scolaire pendant qu'ils effectuaient des tâches d'écriture ayant différents degrés de difficultés. Des données ont été obtenues sur la force exercée par les doigts sur le barillet et la force exercée sur la pointe du stylo et sur les paramètres de la cinétique, en vue d'examiner le mécanisme de coordination et de contrôle entre les doigts et le stylo. Des analyses statistiques ont été effectuées pour indiquer les différences entre les différents groupes et tâches, en ce qui concerne la performance à l'écrit. **Résultats.** Des différences statistiques ont été constatées entre les forces de préhension exercées sur le stylo, la fluctuation des forces et le rapport entre la force de préhension et les forces exercées sur la pointe du stylo lors de l'exécution de différentes tâches d'écriture et dans les différents groupes d'âges. **Conséquences.** L'étude propose une méthode différente pour explorer comment la performance à l'écrit des enfants d'âge scolaire peut varier en fonction du degré de difficulté des tâches d'écriture.

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Approximately 31% to 60% of children's daily academic activities are related to fine-motor performance, and 85% of these are related to handwriting or drawing tasks (McHale & Cermak, 1992). Moreover, handwriting is an essential ability that children need to acquire and learn to perform well at school. Handwriting is a precise but complicated activity, and its common performance components include hand and upper-limb kinesthesia, motor planning, eye–hand coordination, visuomotor integration, and in-hand manipulation skills (Cornhill & Case-Smith, 1996). When one or some of these components are not well coordinated, it may lead to writing problems, such as poor legibility, improper writing speed, an inability to achieve the writing-task requirements, or incorrect ergonomic performance, and thus adversely affect children's academic performance and self-esteem (Schneck & Amundson, 2010).

Thanks to advancements of technology, the measurement of writing performance is focusing on not only the writing products but also the writing movement itself in recent decades. Therapists can use computer-based tools, such as digital tablets and kinetic pens, to approach handwriting problems by revealing information such as pen speed and grip force (Baur, Furholzer, Jasper, Marquardt, & Hermsdorfer, 2009; Baur, Furholzer, Marquardt, & Hermsdorfer, 2009; Falk, Tam, Schwellnus, & Chau, 2010). Moreover, some studies analyzed more specific movement from the information of each digit to understand the role of different fingers while writing or drawing (Ghali, Thalanki Anantha, Chan, & Chau, 2013; Kuo et al., 2014; Shim et al., 2010). However, comprehensive data related to gripping kinetics of school-age children are still limited. Therefore, in the present study, a custom force-acquisition pen (FAP) system was used to measure the pen grip and writing kinetics of school-age children. In addition, writing movement would be influenced by not only personal ability but also the corresponding tasks. To understand the influence of task complexity, in this paper, we present the size effect on simple circle drawing and traditional Chinese characters writing.

Literature Review

Handwriting is a developmental process that begins from early scribbling around 2 years old to mature writing ability in the higher grades of primary school. The maturity of one's writing capability corresponds with the development of the perceptual-motor skills, such as fine-motor functions, motor planning, visual-motor integration, visual perception, kinesthesia, sensory modalities, and cognitive functions. Consequently, writing tasks with different challenges (e.g., style, speed, or size) are generally used with children at the appropriate developmental level as part of their handwriting/drawing practice or homework.

With preschool children or handwriting beginners, teachers and occupational therapists tend to choose large letters (or characters) and strokes to teach handwriting. Onose (1989) suggested that copying practice with the characters changing in size (from large to normal) is an effective way for older students in kindergarten to learn handwriting skills. Previous studies have made comparisons of writing accuracy in relation to different-sized spaces between the guiding lines among different-grade students. For example, Waggoner, Lanunziata, Hill, and Cooper (1981) investigated the handwriting accuracy of kindergarten and first-grade students by using paper with different-sized spaces between the guiding lines and found that larger spaces induced greater handwriting accuracy for suburban students but not for urban ones. Trap-Porter, Gladden, Hill, and Cooper (1983) reported similar findings for second- and third-grade students. When learning to write English, children write on paper with specific widths between each guiding line, and thus the size available for a letter might vary from 1.1 cm to 3.4 cm. In contrast, children learn to write Chinese or Kanji characters in a square box. In Japan, elementary school students practise writing Kanji in different sizes of boxes, from 2.5 cm × 2.5 cm to 2 cm × 2 cm (PadinHouse, 2019). In Taiwan, students from the senior grade of kindergarten learn to write simple characters in a large box (5 cm × 5 cm). Based on the principles of the 9-year curriculum (Ministry of Education, 2001), Taiwanese students are asked to keep learning new words by practising handwriting in normal boxes (2 cm × 2 cm) and small boxes (1.5 cm × 1.5 cm) through Grades 1 and 2. They are also asked to write smaller characters (1 cm × 1 cm) through Grades 3 and 4. However, the new words they are requested to learn are decided not by the complexity of the characters but by the frequency with which they are used. As such, students often need to confine very complicated characters in small boxes, and when they are in the early stage of schooling, this might be very challenging for their handwriting skills. Yen (2002) thus suggested that it is necessary to enlarge the handwriting boxes used in elementary schools. Although prior works have indicated the positive effect of enlarging characters on the resulting handwriting products, research on the relationship between character size and handwriting skills among children of different ages is still limited.

For dealing with children's handwriting problems, occupational therapists usually focus on the control of handwriting movement. Due to the advances in computer technology, therapists and researchers could use objective evaluations, such as a graphic tablet, to reveal handwriting kinematics (Chang, Yu, & Shie, 2009; Li-Tsang et al., 2011; Rosenblum & Livneh-Zirinski, 2008). While graphic tablets provide valuable information regarding writing kinematics, they still cannot quantitatively describe how the fingers engage in driving the pen during writing performance. Writing kinetics include pen-grip force and pen-tip force (Herrick & Otto, 1961). The amount of force output by digits would be directly influenced by the motor-control ability and the demands of task. While one grips a pen and applies force on the utensil, appropriate sensory feedback is relied upon to output a fluent movement to write (Danna & Velay, 2015). Naider-Steinhart and Katz-Leurer (2007) analyzed the handwriting performance of third- and fourth-grade children and found faster speed of writing is associated with less force variability from the thumb. Falk et al. (2010) collected the grip-force data with writing from 35 first- and second-grade students and found that those who demonstrated poor handwriting quality showed lower grip-force variability. Schwellnus et al. (2013) investigated writing kinetics from 74 fourth-grade students and found a greater amount of force applied on the pen barrel when the thumb was adducted and crossed over the index finger. That is, the roles of the fingers and hand when controlling a pen might be crucial factors that affect handwriting performance.

To date, only a few studies have applied a custom device to measure the digit forces or grip-force distribution to better understand the mechanism of the grip force of the fingers when performing writing tasks (Falk, Tam, Schellnus, & Chau, 2011; Herrick & Otto, 1961; Hooke, Park, & Shim, 2008; Hsu et al., 2013). To obtain more information with regard to the relationship between the hand-control mechanism on the pen and the resulting performance under different levels of writing challenge, this study attempts to investigate the differences in pen-grip and writing kinetics among school-age children carrying out writing tasks with different kinds of challenges using a custom FAP system (Hsu et al., 2013). The specific question examined in this study is whether the kinetic performance of the fingers and pen is significantly different among children in different age groups when doing writing tasks with different character sizes and shapes. The hypotheses of the present study were as follows: (a) Age and character size would affect pen-grip kinetics. (b) The pen-grip kinetics would be different between traditional Chinese writing and simple circle drawing.

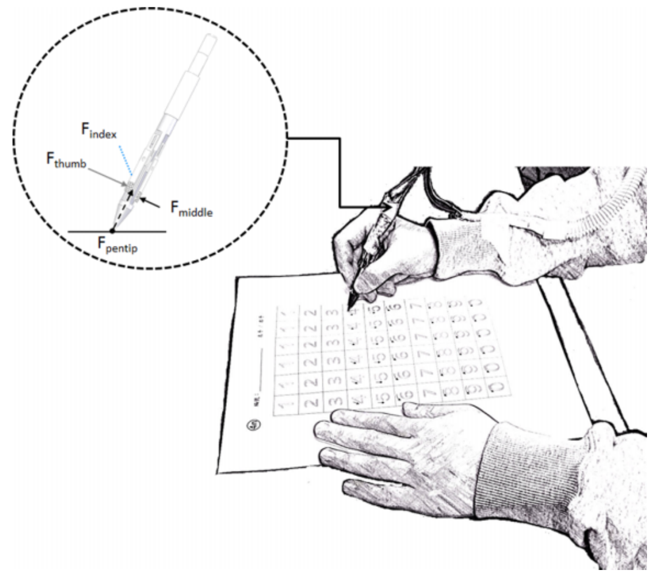

Figure 1. The setting of the force-acquisition system and the writing tasks and design of the force-acquisition pen.

Method

Study Design

This study used a cross-sectional design to observe differences in handwriting performance when doing tasks with different levels of challenge from both temporal and kinetic perspectives among children in four age groups. The children were evaluated with the Bruininks-Oseretsky Test of Motor Proficiency (2nd ed.; BOT-2; Bruininks & Bruininks, 2005) subtests and handwriting tasks using the FAP system to screen fine-motor skills and quantify the writing kinetics, respectively. One certified occupational therapist conducted all the above-mentioned assessments, and the sequence of testing was randomized to minimize potential performance bias.

Participants

One hundred and eighty-one children (age range: 5 to 12 years old) from kindergartens and public elementary schools in the suburban regions of southern Taiwan were recruited from September 2011 to June 2012. The participants and their guardians who agreed to join in this study were asked to sign a consent form, which was approved by the institutional review board at National Cheng Kung University Hospital. If the participants had documented developmental disabilities, neurological deficits, or severe muscular or orthopedic problems of their upper extremities, they were excluded from the study. In addition, the data from children whose standard scores on any of the three subtests (Fine Motor Precision, Fine Motor Integration, and Manual Dexterity) of the BOT-2 were determined to be "below average" or "well below average" were not analyzed. The final data of 170 participants were analyzed for this study, which involved 38 children from the senior grade in kindergarten (13 boys and 25 girls; mean age of 6.11 $\pm$ 0.31 years), 36 from second grade (18 boys and 18 girls; mean age of 7.97 $\pm$ 0.57 years), 32 from fourth grade (14 boys and 18 girls; mean age of 9.93 $\pm$ 0.29 years), and 64 from sixth grade (30 boys and 34 girls; mean age of 11.72 $\pm$ 0.32 years). A Student's *t*-test analysis had been conducted to confirm whether there was a sex influence due to the imbalanced sex ratio of the kindergarten group. Generally, no significant difference was found in demographic data, fine-motor performance, or handwriting performance.

Materials and Measures

The handwriting kinetics was collected using the FAP system (see Figure 1). This custom system was developed in the shape of a standard ballpoint pen and contains three thin-beam force sensors and one button-shape transducer (TBS-5 and SLB-50, Transducer Techniques, Temecula, CA, USA) to simultaneously detect the forces between the digits (thumb, index and middle fingers) and pen barrel as well as the contact force between the pen tip and writing surface (Hsu et al., 2013). The barrel is made of aluminum, with a weight of 30 g. The FAP is 12 cm in length, and the diameter of the pen barrel is 1.1 cm. The analog force data were converted and collected using the instruNet network device (iNet-100, GW Instruments, Charlestown, MA, USA) connected to a laptop computer. The sampling rate for assessing the force data was 70 Hz. The raw force data were filtered using a Butterworth low-pass filter with a cutoff frequency of 3 Hz.

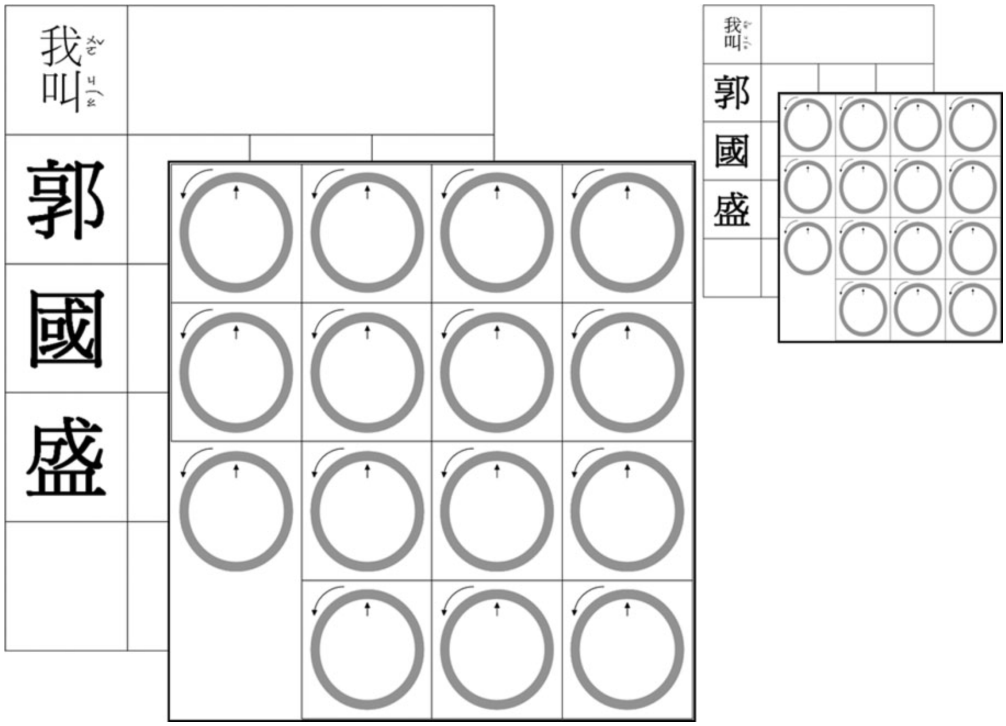

Figure 2. The required handwriting task on A4-size sheets of paper.

Writing Tasks and Procedures

The participants were asked to write and trace the designed writing tasks with different levels of challenge on an A4 sheets of paper (see Figure 2) using the FAP. The two tasks were of different levels of difficulty, with tracing a circle and writing the requested traditional Chinese characters as the simple and difficult tasks, respectively. As kindergarten children might not have been taught to write the Chinese characters yet, only those participants studying in elementary school (Grades 2, 4, and 6) were asked to write the Chinese characters for further comparison. The other challenge level investigated in this study was the size of the circle or the Chinese characters, written in two different prescribed squares with sizes of 5 cm $\times$ 5 cm and 1.5 cm $\times$ 1.5 cm for the *large* and *small* writing requests, respectively. The sequence of each stroke of the Chinese characters was set in a particular order, as was the direction of the circles, with visual guidance given on the writing sheet. The order of items in the writing tasks was randomly assigned. Before the writing tests, each participant was asked to sit in front of a height-adjustable desk with both arms resting on it, with 90-degree knee flexion and both feet resting comfortably on the floor. Each participant had enough time to be familiar with the use of the FAP using a mature pen-grip pattern (Tseng, 1998), known as the tripod grasp, although most could do this without any practice. During the writing test, the participants were allowed to write at their natural pace without any timing restraint. There was a total of three trials of each writing task under the different levels of challenge. The children could have a 1-min rest interval between trials.

Parameters of Handwriting Performance

This study examined four kinetic parameters and one temporal parameter, namely, average force (AF), coefficient of variation of force (CVF), number of force fluctuations per second (NFFPS), force ratio (FR), and task time (TT), to describe the children's handwriting performance. The AF indicates the mean instant force for one trial and has been used in previous studies (Chang & Yu, 2010; Falk et al., 2010; Kushki, Schwellnus, Ilyas, & Chau, 2011; Schwellnus et al., 2013). Four AFs were obtained from each trial, one each for the thumb, index finger, middle finger, and pen tip. The AF from the pen tip was calculated when the pen was touching the paper. The CVF is the ratio of the standard deviation of instant force over the AF in one trial (Falk et al., 2010). A higher CVF indicates more dynamic force output or force fluctuation from the digits or pen tip. The NFFPS is defined as the total number of peaks of force throughout the total writing time in one trial, and three NFFPSs were obtained, one for each of the three digits that were examined. The greater the NFFPS, the more adjustments in force exertion were made during writing. The NFFPS thus indicates the frequency with which the forces applied by the digits changed during a writing task. When the NFFPS increases, then this means that the frequency of pressing the pen barrel from the three digits also increases. A higher NFFPS might not represent better or worse coordination of force control but shows only a type of force control pattern. The FR is defined as the instant force of the pen tip divided by the instant total force of the three digits. The FR was calculated only when the pen was touching the paper. A previous study has used this factor to better

Table 1
Effects of Character Size, Task Complexity, and Age on the Average Force (AF)

		Chinese character			Circle			
Location of force	Size	Grade 2	Grade 4	Grade 6	Kindergarten	Grade 2	Grade 4	Grade 6
$AF_{thumb}^{a,c,d}$	Large	2.46 (1.24)^{k}	2.86 (1.22)^{k}	2.60 (1.00)^{k}	2.22 (0.88)	2.37 (0.95)	2.90 (1.05)	2.88 (1.09)^{e,f,g,h}
	Small	2.98 (1.22)^{k}	3.31 (1.22)^{k}	3.14 (1.16)^{k}	2.63 (0.91)	2.73 (1.20)	3.65 (1.31)	3.13 (1.21)
$AF_{index}^{a,d}$	Large	1.74 (0.71)^{k}	1.67 (0.60)^{k}	1.74 (0.64)^{k}	1.48 (0.69)	1.66 (0.56)	1.63 (0.64)	1.93 (0.77)^{f}
	Small	1.95 (0.73)^{k}	1.84 (0.69)^{k}	1.91 (0.70)^{k}	1.57 (0.57)	1.73 (0.64)	1.93 (0.85)	1.98 (0.72)
$AF_{middle}^{a,b,c,d}$	Large	1.11 (0.69)^{j}	1.54 (0.81)^{k}	1.71 (0.74)^{g,h,k}	0.83 (0.53)	0.81 (0.42)	1.25 (0.65)	1.58 (0.86)^{e,f,g,h}
	Small	1.63 (0.93)^{k}	2.12 (0.84)^{j}	2.22 (1.04)^{j}	1.04 (0.59)	1.30 (0.73)	1.70 (0.74)	1.81 (1.03)
$AF_{pen\ tip}^{a,b,c,d}$	Large	0.9 (0.31)^{j}	0.99 (0.40)^{j}	0.72 (0.24)^{g,i,j}	1.14 (0.41)	1.15 (0.36)	1.41 (0.44)	1.26 (0.40)^{e,g,i}
	Small	0.63 (0.18)^{j}	0.75 (0.23)^{j}	0.54 (0.23)^{j}	1.04 (0.34)	1.03 (0.31)	1.37 (0.43)	1.16 (0.43)

Note. Value definition: mean (SD).
[a]Indicates a significant main effect of size with Chinese character task ($p < .05$ under two-way ANOVA). [b]Indicates a significant main effect of age with Chinese character task ($p < .05$ under two-way ANOVA). [c]Indicates a significant main effect of size with circle task ($p < .05$ under two-way ANOVA). [d]Indicates a significant main effect of age with circle task ($p < .05$ under two-way ANOVA). [e]Indicates a statistical difference between kindergarten group and Grade 4 group ($p < .05$ under Bonferroni post hoc test). [f]Indicates a statistical difference between kindergarten group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [g]Indicates a statistical difference between Grade 2 group and Grade 4 group ($p < .05$ under Bonferroni post hoc test). [h]Indicates a statistical difference different between Grade 2 group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [i]Indicates a statistical difference between Grade 4 group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [j]Indicates a statistical difference between Chinese character and circle tasks ($p < .05$). [k]Indicates no statistical difference between Chinese character and circle tasks.

understand the patterns of force applied during pen grip among children with no handwriting problems and those with spastic hemiplegic cerebral palsy (Chau, Ji, Tam, & Schwellnus, 2006). It also shows a type of force control pattern when gripping a pen and can be used to obtain the ratio of force applied to the desk and pen barrel. The TT was defined as the total time from the first pen-touching on the paper to last pen-lifting from the paper in one trial, which was set by the force data measured from the pen tip. The initiation time was defined as the first time point when the instant force value was 0.1 N higher than baseline, which was the average instant force of the initial 0.5 s. The termination time was defined as the last time point when the instant force value was 0.1 N higher than baseline. The parameters were quantified using custom MATLAB programs (MathWorks Ltd., Natick, MA, USA). All the data for the parameters were averaged (over three trials) for further statistical analyzes.

Data Analysis

Statistical analyzes were performed using SPSS 17.0. Descriptive statistics were used to calculate the means and standard deviations of the demographic data regarding the recruited children among different age groups. The experimental data were analyzed using a two-way ANOVA with one between-factor test (group: kindergarten vs. second grade vs. fourth grade vs. sixth grade) and one within-factor test (character size: large vs. small), while a Bonferroni post hoc test was used to understand the differences of the kinetic and temporal parameters under different writing tasks for the various groups of children. Student's t test was also used to analyze the differences between traditional Chinese characters and simple circle drawing. The level of significance was set at $p < .05$.

Results

Effects of Character Size, Task Complexity, and Age on the AF

Table 1 shows the results regarding the effects of character size, task complexity, and age on the AF. There was no interaction effect between the factors of character size and age when analyzing the AF via the two-way ANOVA. When investigating the effect of character size on the AF, most of the AFs of digits were larger in the writing of smaller characters (1.04 ∼ 3.65) than for the larger ones (0.81 ∼ 2.90). In contrast, the AFs of the pen tip were greater when writing the larger characters (0.72 ∼ 1.41) compared to the smaller ones (0.54 ∼ 1.37). Although the results did not show any statistical significance between age groups when using the Bonferroni test, the higher-grade students (Grades 4 and 6) had higher AFs of the digits (1.25 ∼ 3.65) than the lower grades (0.81 ∼ 2.98) when writing both Chinese characters and circles, except the AF_{thumb} and AF_{index} when writing the former. No significant differences were found between Chinese characters and circles on most of the AFs, except for the AF_{middle} and $AF_{pen\ tip}$. In particular, the AFs of the pen tip were significantly larger when writing the circles.

Effects of Character Size, Task Complexity, and Age on the CVF

There was also no interaction effect of the CVF between the factors of character size and age. Table 2 shows that the CVFs of the digits were significantly greater when writing the larger Chinese characters (0.35 ∼ 0.47) than the smaller ones (0.24 ∼ 0.35). However, while no significant differences were found for the CVF_{thumb} and CVF_{index} when tracing the large and small circles, there was a significant difference for the CVF_{middle}.

Table 2
Effects of Character Size, Task Complexity, and Age on the Coefficient of Variation of Force (CVF)

		Chinese character			Circle			
Location of force	Size	Grade 2	Grade 4	Grade 6	Kindergarten	Grade 2	Grade 4	Grade 6
CVF$_{thumb}$[a.c,d]	Large	0.43 (0.09)[l]	0.38 (0.09)[k]	0.37 (0.10)[h,i,k]	0.42 (0.09)	0.38 (0.10)	0.32 (0.08)	0.33 (0.08)[f,g,h,i]
	Small	0.30 (0.08)[k]	0.27 (0.06)[k]	0.25 (0.07)[k]	0.41 (0.08)	0.42 (0.11)	0.34 (0.07)	0.36 (0.08)
CVF$_{index}$[a,d]	Large	0.40 (0.88)[k]	0.37 (0.09)[k]	0.35 (0.07)[i,k]	0.40 (0.10)	0.34 (0.08)	0.30 (0.08)	0.29 (0.06)[e,f,g,i]
	Small	0.26 (0.08)[k]	0.26 (0.07)[k]	0.23 (0.07)[k]	0.36 (0.07)	0.32 (0.09)	0.30 (0.07)	0.29 (0.06)
CVF$_{middle}$[a,b,c,d]	Large	0.47 (0.20)[l]	0.35 (0.11)[l]	0.36 (0.12)[h,i,l]	0.59 (0.22)	0.56 (0.28)	0.40 (0.13)	0.38 (0.14)[f,g,h,i]
	Small	0.35 (0.21)[k]	0.25 (0.07)[k]	0.24 (0.08)[k]	0.49 (0.15)	0.49 (0.19)	0.39 (0.12)	0.40 (0.11)
CVF$_{pen\ tip}$[a,b,c,d]	Large	0.54 (0.05)[k]	0.54 (0.06)[k]	0.54 (0.07)[k]	0.30 (0.07)	0.28 (0.08)	0.23 (0.03)	0.25 (0.04)[f,g,h,j]
	Small	0.52 (0.06)[k]	0.53 (0.07)[k]	0.51 (0.07)[k]	0.33 (0.07)	0.31 (0.06)	0.27 (0.03)	0.29 (0.05)

Note. Value definition: mean (SD).
[a]Indicates a significant main effect of size with Chinese character task ($p < .05$ under two-way ANOVA). [b]Indicates a significant main effect of age with Chinese character task ($p < .05$ under two-way ANOVA). [c]Indicates a significant main effect of size with circle task ($p < .05$ under two-way ANOVA). [d]Indicates a significant main effect of age with circle task ($p < .05$ under two-way ANOVA). [e]Indicates a statistical difference between kindergarten group and Grade 2 group ($p < 0.05$ under Bonferroni post hoc test). [f]Indicates a statistical difference between kindergarten group and Grade 4 group ($p < .05$ under Bonferroni post hoc test). [g]Indicates a statistical difference between kindergarten group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [h]Indicates a statistical difference between Grade 2 group and Grade 4 group ($p < .05$ under Bonferroni post hoc test). [i]Indicates a statistical difference between Grade 2 group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [j]Indicates a statistical difference between Grade 4 group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [k]Indicates a statistical difference different between Chinese character and circle tasks ($p < .05$). [l]Indicates no statistical difference between Chinese character and circle tasks.

Table 3
Effects of Character Size, Task Complexity, and Age on the Number of Force Fluctuations per Second (NFFPS)

		Chinese character			Circle			
Location of force	Size	Grade 2	Grade 4	Grade 6	Kindergarten	Grade 2	Grade 4	Grade 6
NFFPS$_{thumb}$[a,c,d]	Large	1.92 (0.34)[l]	2.00 (0.33)[l]	2.22 (0.42)[f,g,l]	1.23 (0.22)	1.33 (0.39)	1.28 (0.26)	1.28 (0.35)
	Small	2.26 (0.27)[l]	2.47 (0.36)[l]	2.70 (0.37)[l]	1.12 (0.25)	1.08 (0.26)	1.03 (0.21)	1.10 (0.27)
NFFPS$_{index}$[a,d]	Large	1.92 (0.32)[l]	2.05 (0.34)[l]	2.26 (0.45)[e,f,g,l]	1.50 (0.47)	1.51 (0.30)[h]	1.72 (0.45)[h]	1.74 (0.53) [h,i]
	Small	2.24 (0.30)[l]	2.55 (0.41)[l]	2.74 (0.41)[l]	1.38 (0.41)	1.26 (0.33)	1.28 (0.27)	1.31 (0.39)[j]
NFFPS$_{middle}$[a,b,c,d]	Large	2.16 (0.33)[l]	2.29 (0.32)[m]	2.34 (0.32)[e,f,l]	1.62 (0.58)[h]	1.83 (0.65)[h]	2.29 (1.03)[h]	1.69 (0.81)[h,k]
	Small	2.39 (0.28)[l]	2.56 (0.30)[l]	2.65 (0.34)[l]	1.30 (0.26)	1.27 (0.47)	1.40 (0.37)	1.21 (0.32)[j]

Note. Interaction effects of size and age were found in NFFPS of index and middle fingers while tracing circle. The simple main effects were then analyzed with *t* test (for size) and one-way ANOVA (for age). Value definition: mean (SD).
[a]Indicates a significant main effect of size with Chinese character task ($p < .05$ under two-way ANOVA). [b]Indicates a significant main effect of age with Chinese character task ($p < .05$ under two-way ANOVA). [c]Indicates a significant main effect of size with circle task ($p < .05$ under two-way ANOVA). [d]Indicates a significant main effect of age with circle task ($p < .05$ under two-way ANOVA). [e]Indicates a statistical difference different between Grade 2 group and Grade 4 group ($p < .05$ under Bonferroni post hoc test). [f]Indicates a statistical difference between Grade 2 group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [g]Indicates a statistical difference between Grade 4 group and Grade 6 group ($p < .05$ under Bonferroni post hoc test). [h]Indicates a statistical difference between large and small size. [i]Indicates a statistical difference between four age groups with one-way ANOVA test, and no statistical difference was found with Bonferroni post hoc test. [j]Indicates no statistical difference was found with one-way ANOVA test. [k]Indicates a statistical difference among four age groups with one-way ANOVA test, a statistical difference between kindergarten group and Grade 4 group, and a statistical difference between Grade 4 group and Grade 6 group ($p < .01$ under Bonferroni post hoc test). [l]Indicates a statistical difference between Chinese character and circle tasks ($p < .05$). [m]Indicates no statistical difference between Chinese character and circle tasks.

Significant differences in CVF among different age groups were found when writing both Chinese characters and circles. The children with lower grades had greater CVFs (0.26 ~ 0.59) of the digits than the children with higher grades (0.23 ~ 0.38). Significant differences were found between Chinese character and circles on most of the CVFs, except for the CVF$_{thumb}$ and CVF$_{middle}$. In particular, the CVFs of the pen tip were significantly larger when writing the traditional Chinese characters.

Effects of Character Size, Task Complexity, and Age on the NFFPS

No interaction effects of the NFFPS between the factors of character size and age were found, as shown in Table 3. The NFFPSs of each digit were significantly greater when writing the smaller Chinese characters (2.24 ~ 2.74) than the larger ones (1.92 ~ 2.34). There were also significant differences of the NFFPSs among different age groups (Table 3). The children with higher grades had greater NFFPSs of the digits

Table 4
Effects of Character Size, Task Complexity, and Age on the Force Ratio (FR)

	Chinese character*			Circle*			
Size	Grade 2	Grade 4	Grade 6	Kindergarten	Grade 2	Grade 4	Grade 6
Large	0.18 (0.09)[c]	0.16 (0.06)[c]	0.12 (0.05)[a,c]	0.26 (0.10)	0.25 (0.09)	0.26 (0.07)	0.21 (0.07)[b]
Small	0.10 (0.04)[c]	0.11 (0.04)[c]	0.08 (0.03)[c]	0.20 (0.06)	0.19 (0.07)	0.20 (0.06)	0.17 (0.05)

Note. Asterisk denotes significant main effects of size and age ($p < .001$ under two-way ANOVA). Value definition: mean (SD).
[a]Indicates FR of Grade 6 group was significantly lower than FR of Grade 2 and Grade 4 ($p < .01$ under Bonferroni post hoc test). [b]Indicates FR of Grade 6 group was significantly lower than FR of kindergarten, Grade 2, and Grade 4 ($p < .05$ under Bonferroni post hoc test). [c]Indicates a statistical difference between Chinese character and circle tasks ($p < .05$).

Table 5
Effects of Character Size, Task Complexity, and Age on the Task Time (TT; in seconds)

	Chinese character*			Circle*			
Size	Grade 2	Grade 4	Grade 6	Kindergarten	Grade 2	Grade 4	Grade 6
Large	20.76 (5.80)[d]	20.26 (6.66)[d]	16.56 (5.25)[a,c]	22.40 (7.17)	21.40 (7.35)	21.79 (5.88)	19.01 (5.77)[b]
Small	15.65 (3.44)[c]	14.45 (4.54)[d]	11.58 (3.41)[d]	16.10 (5.46)	12.64 (4.45)	13.82 (4.69)	11.08 (4.34)

Note. Asterisk denotes significant main effects of size and age ($p < .001$ under two-way ANOVA). Value definition: mean (SD).
[a]Indicates TT of Grade 6 group was significantly lower than TT of Grade 2 and Grade 4 ($p < .001$ under Bonferroni post hoc test). [b]Indicates TT of Grade 6 group was significantly lower than TT of kindergarten and Grade 4 ($p < .01$ under Bonferroni post hoc test). [c]Indicates a statistical difference between Chinese character and circle tasks ($p < .05$). [d]Indicates no statistical difference between Chinese character and circle tasks.

(2.00 ∼ 2.74) than the children with lower grades (1.92 ∼ 2.39).

The statistical results of the NFFPS while tracing the circle indicated that the size of circle had a significant influence on the $NFFPS_{thumb}$. The $NFFPS_{thumb}$ when tracing a larger circle (1.23 ∼ 1.33) was significantly higher than when tracing the smaller circle (1.03 ∼ 1.12). In addition, there were interaction effects regarding both the character size and age on the $NFFPS_{index}$ and $NFFPS_{middle}$. The $NFFPS_{index}$ was found to have statistical differences among different age groups when tracing the larger circle, based on the one-way ANONA analysis. However, no significant difference was found between the paired comparisons in the post hoc test. Similarly, the $NFFPS_{middle}$ was found to have statistical differences among different age groups when tracing the larger circle. The $NFFPS_{middle}$ of the Grade 4 children (1.40 ∼ 2.29) was significantly larger than that for the kindergarten (1.30 ∼ 1.62) and Grade 6 (1.21 ∼ 1.69) children, as found in the post hoc comparison. The $NFFPS_{index}$ when tracing a larger circle (1.51 ∼ 1.74) was significantly greater than when tracing a smaller circle (1.26 ∼ 1.31) for the children in Grades 2, 4, and 6. Similarly, the $NFFPS_{middle}$ when tracing the larger circle (1.62 ∼ 2.29) was significantly greater than when tracing the smaller circle (1.21 ∼ 1.40) for all the children. For the effect of task complexity, except for the $NFFPS_{middle}$ of the fourth-grade children when drawing large Chinese characters and circles, most of the NFFPSs were significantly larger while writing Chinese characters as compared with circles.

Effects of Character Size, Task Complexity, and Age on the FR

Both the factors of character size and age had statistical influence on the FR when performing the Chinese character writing and circle tracing, but no interaction effect between the factors was found with regard to this (Table 4). The FRs were significantly greater when writing the larger Chinese characters (0.12 ∼ 0.18) than the smaller ones (0.08 ∼ 0.11), and the same was true for the circles. There were also significant differences in the FRs among different age groups when writing on both Chinese characters and circles, as seen in the post hoc test ($FR_{kindergarten} > FR_{6th}$; $FR_{2nd} > FR_{6th}$; $FR_{4th} > FR_{6th}$). The FRs were significantly greater when drawing circles as compared with when writing Chinese characters.

Effects of Character Size, Task Complexity, and Age on the TT

Both the factors of character size and age had statistical influence on the TT when performing both Chinese character writing and circle tracing, but no interaction effect was found (see Table 5). The TTs were significantly greater when writing the larger characters (16.56 ∼ 22.40 s) than the smaller ones (11.08 ∼ 16.01 s). The TTs for completing the Chinese characters in Grades 2 and 4 were significantly longer (14.45 ∼ 20.76 s) than seen with Grade 6 (11.58 ∼ 16.56 s). Similarly, the TTs for tracing the circles for the kindergarten and Grades 2 and 4 children (12.64 ∼ 22.40 s) were significantly longer than those for the children in Grade 6 (11.08 ∼ 19.01 s). For the effect of task complexity, no significant differences were found in most of the TTs when writing Chinese characters as compared with circles, except for the TTs for the larger characters and circles for the Grade 6 children and the smaller characters and circles for the Grade 2 children.

Discussion

When children have handwriting problems, their parents or teachers may consult occupational therapists, who often use standardized assessments to find out the severity of handwriting difficulties or determine specific writing problems (Case-Smith, 2002; Chu, 1997). Although tools such as the Tseng Handwriting Problem Checklist (Tseng, 1993), Chinese Handwriting Evaluation Questionnaire (Chang & Yu, 2005), Minnesota Handwriting Test (Reisman, 1993), Children's Handwriting Evaluation Scale (Phelps, Stempel, & Speck, 1985), and Evaluation Tool of Children's Handwriting (Diekema, Deitz, & Amundson, 1998) have been widely used to assist in identifying certain handwriting problems, such as those related to legibility, writing speed, and grip patterns, the motor performance of the hand or the gripping relationship between the digits and pen still cannot be detected using these. Occupational therapists or parents usually give advice such as "Relax the fingers to hold the pen," "Hold the pen steadily," or "Use less downward force," to guide children while performing writing tasks. However, the exact amount of the grip or pen-tip force that should be exerted remains an enigma for children, parents, and therapists. That is, it is not possible to describe the correct action for each digit when holding a pen to write or draw. An examination of the mechanisms of grip force when handwriting requires tools that can measure the forces of the digits and pen, and these have been reported in only few studies (Chau et al., 2006; Herrick & Otto, 1961; Hooke et al., 2008).

There are still only a few comprehensive databases regarding the maturation or developmental process of school-age children's handwriting performance, and more data are needed for further clinical and research applications. Some recent studies have begun paying more attention to these issues from kinematic or dynamic perspectives (Accardo, Genna, & Borean, 2013; Falk et al., 2011; Lin, Luo, Wu, Shen, & Sun, 2015; Rueckriegel et al., 2008). Specifically, computerized tablet systems are now widely used as research tools to quantify various writing characteristics, such as the spatial/temporal relations of the strokes, writing speed, pen-tip position, and pen-tip pressure, of handwriting performance. In most of the factors examined in these studies, the typically developing children improved their written performance or products with age. However, the actual motor-control strategies of the hands on the pen are still not well known, due to the lack of the information with regard to the manipulative patterns of the digits on the pen. The results of this study showed that the FAP had the capability to measure the force exerted by each digit on the pen barrel and the pen-tip force acting on the writing surface. Although the AF results did not show significant differences among different age groups, the AFs of the digits in the higher-grade (Grades 4 and 6) children were generally greater than the forces seen in the younger (kindergarten and Grade 2) children. Not surprisingly, the AFs did not show significant differences among the groups, because the AF is a more generic factor that indicates the average pen-grip force throughout the writing task. However, the role of each finger regarding its force exertion could be obtained via the AF factor. Through the results presented in this work, we can see that the thumb is the principal digit that exerts force on the pen barrel to counterbalance the forces exerted by the index and middle fingers.

The larger CVFs in the lower grades indicated more unstable grip-force outputs or force fluctuations from the digits and pen tip. In other words, the students in the higher grades might have the capability to apply the optimal grip force on the pen with smaller ranges of fluctuation, and this might contribute to their greater writing efficiency. In addition, the children in the higher grades had greater NFFPSs of the digits than those in the lower grades, especially when doing more complicated tasks, such as writing Chinese characters. More specifically, these findings indicated that the older children tended to use lower grip-force variability patterns but make more frequent adjustments than the younger children when performing a writing task. The results also indicate that lower grip-force variability and the optimal adjustment of the forces applied by the digits, as based on the focal writing task, may be a strategy to achieve more efficient adjustment of the pen grip and related forces among the older students. Tseng (1998) found that the rate of using the lateral tripod grip is higher in the population of Taiwanese children as compared with American children. That study proposed that such a stable way to manipulate a pen might be more appropriate for writing Chinese characters, which are characterized by discrete strokes. The CVF and NFFPS results in our study provided details of the mechanism of gripping the pen and support Tseng's results. Although the grip-force variability might be low, the frequent adjustments of force output from the digits might achieve a more efficient pattern to write Chinese characters. Moreover, the significant differences found in tasks with different levels of complexity indicate that writing Chinese characters does need more frequent adjustments than tracing circles.

The FR was used to represent the relationship between the pen-grip forces by the digits and the products output by the pen tip (Chau et al., 2006; Kuo et al., 2014). The FR results of this study were consistent with previous findings (Chau et al., 2006) that showed that more proficient writers, as older children, might apply forces to the barrel to control the pen, rather than applying downward force to the paper through the pen tip. The TT is an indicator that is used in several handwriting studies to show the writing efficiency or level of maturation, because it is likely to be an outcome generated from the above-mentioned kinematic or kinetic parameters. This study also has similar findings, showing that the Grade 6 children needed significantly less time to complete the task compared to the younger participants. We believe that the lower CVF and FR and higher NFFPS of the older children might have contributed to this more efficient writing pattern.

There are few works with a biomechanical perspective that focus on the relations between writing complexity or the degree of task challenge and children's writing capabilities. The AF results in this study showed that larger pen-grip forces were found when writing smaller characters. In contrast, smaller pen-tip forces were detected in the same condition. When writing a large character, either a Chinese character or circle (5cm $\times$ 5 cm), more wrist and forearm movements might join in the writing performances, and thus the precise control of the digit forces might be disturbed, resulting in greater $AF_{pen\ tip}$ and CVF of three digits. This difference shows that the children used an efficient method, such as eliminating changes in force exertion and increasing the writing speed, when writing the smaller characters by using a more static pattern to grip the pen.

Greater NFFPSs indicate more adjustments in force exertion during handwriting. If the NFFPSs increase when writing smaller Chinese characters, then this means that the frequency of pressing the pen barrel from the three digits also increases, due to the complexity of the characters. However, conflicting results were found when tracing the large and small circles in comparison with the writing of Chinese characters. This difference might be because most of the children needed to use more proximal joints of the hand, such as the metacarpophalangeal joint or wrist joint, while tracing a large circle, which might result in more force fluctuations of the fingertip acting on the pen barrel. The findings of this study showed that the FRs were influenced by the character size. A larger FR indicates greater downward force pressing on the writing surface when writing large characters or tracing large circles. For children who have problems making ink darker on paper, using larger characters to write may make it easier for them to apply the appropriate amount of downward force.

The task complexity also contributed to the different FR results. When doing more complicated writing tasks, such as writing traditional Chinese characters, more grip forces were exerted by the digits to the pen barrel compared to the downward pressing forces through the pen tip. The AFs from the pen tip during circle tracing were larger than the forces found when writing Chinese. As there are no consistent results for the AFs from the three digits, the reason for the larger AFs from the pen tip when tracing a circle remains unclear, and thus this finding requires more in-depth research to investigate the control mechanism of the digits in this condition. Furthermore, writing and drawing are essentially different systems from perspectives on motor development (Adi-Japha & Freeman, 2001) and brain activation (Harrington, Farias, Davis, & Buonocore, 2007). In our study, although writing Chinese characters looks like drawing a picture due to the complex composition of strokes, the execution of free writing and that of graph tracing are still distinct, which should be noticed.

This study provides objective values with regard to pen-grip kinetics, as obtained via the FAP system. Parameters such as the AF, CVF, NFFPS, FR, and TT were used to represent the handwriting kinetics and so reveal any differences in performance among different-age children doing different kinds of writing tasks from dynamic and biomechanical perspectives. The results show that tasks with different levels of complexity might have their own requirements with regard to the writing skills and capabilities needed by children of different ages.

Study Limitations and Future Research

Although this study provides useful kinetic information about writing performance, it has the following limitations. First, this study collected only data on writing kinetics, although the collection of kinematic parameters during writing tasks is also needed to obtain a comprehensive picture of handwriting performance. Future research should thus combine kinetic and kinematic experiments. Second, the challenges or conditions of the writing tasks used in this study might be too simple to illustrate all the writing conditions or show the differences among the age groups of children who took part in this work. Third, due to technical constraints, the FAP system is capable only of detecting the normal forces applied by each digit to the pen barrel, and that applied by the pen tip to the writing surface, as well as the tripod grip, for writing performance. In addition, although the FAP was constructed as a standard pen, real pens come in a variety of shapes, sizes, and weights, and this issue should be considered in future research. Finally, this study focused only on the writing performance of normally developing children, and future works could examine children with writing difficulties and to extend the writing tasks in the writing pattern of the English alphabet, as the results might be more interesting for clinicians, teachers, and parents. However, the evidential database established by this study can be used in future works investigating the handwriting performance of children, and this is a significant contribution of this study.

Conclusion

This study developed a system to reveal force information while doing different writing tasks. The findings from the study suggest that using larger characters to write may help children who have problems making ink darker on paper to apply the appropriate amount of downward force. Furthermore, for older children, the efficient gripping pattern for the Chinese writing system may be with characteristics such as less variation, more frequent adjustments of force, and more force on the pen barrel than toward the paper. Much remains to be done, then, but this study has still provided objective data for practitioners to intervene in children's handwriting.

Key Messages

- A force-acquisition pen system is suitable for revealing the force data for occupational therapists to approach children's gripping-force problems.
- Children applied more force toward paper than to the pen barrel while writing larger characters.
- While writing, older children chose to use a gripping pattern with characteristics such as less variation, more

frequent adjustments of force, and more force to the pen barrel than to the paper.

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