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Are the shapes and sizes of pen barrel the factors to influence handwriting kinetics?

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ABSTRACT

Handwriting plays a vital role in children's learning. Choosing the correct writing tools, particularly in terms of pen shape and size, remains challenging. The influence of pen design on handwriting performance, particularly hand kinetics, is not fully understood. This study investigated how different pen shapes and sizes affect handwriting kinetics and performance in children and adults. Using a custom Force Acquisition Pen (FAP) system, the average force (AF), coefficient of variation of force (CVF), and force ratio (FR) were measured in 12 children (9.19 ± 0.97 years) and 18 adults (26.29 ± 3.21 years). Participants completed tracing tasks rather than free copying using circular and triangular pens with altered grip diameters (13, 17, and 21 mm), simulating the effect of different pen barrel thicknesses to standardize stroke paths and ensure consistency across trials. The findings revealed that, at smaller grip diameters (13 mm and 17 mm), triangular pens elicited lower FR values than circular pens in children. Adults showed more stable force control with a lower CVF across grip sizes. These results offer valuable guidance in selecting appropriate writing tools for children.

1. Introduction

Handwriting is a crucial part of children's daily learning, both at school and home (Tseng and Cermak, 1993). Handwriting is a complex activity that is influenced by kinesthetic perception, visual perception, fine motor skills, and motor planning (Cornhill and Case-Smith, 1996). Studies have shown that approximately 85 % of the fine motor activities in school-aged children involve handwriting or drawing (McHale and Cermak, 1992). Achieving appropriate handwriting performance naturally requires careful consideration of the pen used for writing. Therefore, parents and teachers often face challenges when selecting the most suitable handwriting tool from a variety of designs.

The ergonomic analysis of handwriting focuses on the design and construction of writing instruments and how their interaction with users influences the efficiency of writing tasks (Kao, 1979). In pediatric occupational therapy, sensorimotor-based handwriting interventions often incorporate a variety of nontraditional writing tools—including felt-tip pens, weighted pens, triangular grips, and wide-barreled pencils—to promote fine motor control and engagement (Schneck, 2019). Although studies such as Oehler et al. (2000) found no significant differences in handwriting performance between different pencil shapes and sizes among kindergartners, such tools are widely recommended for their benefits in promoting proprioceptive feedback and stabilizing grasp. Previous studies have demonstrated that the design of a pen, including its shape and center of gravity, is associated with user satisfaction (Goonetilleke et al., 2009; Kim et al., 2020; Wu and Luo, 2006).

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Kim et al. (2020) examined 16 commercially available ballpoint pens, with four adults assessing the influence of physical and emotional factors related to pen design on user satisfaction. The study found that to enhance user satisfaction, the pen design should feature a heavier (up to 11.6 g), longer (up to 174 mm), and thicker grip body (up to 11.05 mm) with a non-slip grip, along with a finer pen tip (as thin as 0.38 mm). Additionally, the center of gravity is positioned closer to the pen tip, specifically around 70 mm from the tip, was more favorably rated. Wu and Luo (2006) recruited 16 adult participants to evaluate 12 different touch pens of varying sizes and lengths. The study designed four pen diameters (5.5 mm, 8 mm, 11 mm, and 15 mm) and three lengths (80 mm, 110 mm, and 140 mm) to investigate participants' preferences, writing duration, and error rates. The results indicated that a pen diameter of 8 mm and a length of 100 mm (or longer) are most suitable for the majority of touch pen devices. Goonetilleke et al. (2009) conducted two experiments to examine pen preferences and writing accuracy among university students and Chinese participants. The first experiment engaged 27 university students in evaluating nine different shapes and sizes of ballpoint pens, including circular, elliptical, and hexagonal designs, with diameters of 20 mm, 15 mm, and 8 mm. Participants exhibited a preference for larger-sized pens; however, their writing accuracy diminished when utilizing these larger pens. The second experiment involved 20 Chinese participants who evaluated 36 pens featuring six shapes (circular, hexagonal, octagonal, triangular, elliptical, and square) and three diameters (small, medium, large), including both lightweight and heavier options. Participants in the second experiment demonstrated a preference for pens featuring circular barrels.

These three studies focus on pen design for adult users. However, due to variations in limb length, muscle strength, and motor performance between children and adults, the design of tools used in daily life also differs. Numerous previous studies have addressed product design specifically for children, such as eyeglasses (Zhang et al., 2023), bicycles (Grainger et al., 2017), chopsticks (Yokubo et al., 2021), computer input devices (Blackstone et al., 2008), and twist bottle caps (Wilson and Bix, 2021) for children's use.

In terms of pen design for children, previous studies have examined different pen designs (Lee et al., 2017; Wu et al., 2018). Lee et al. (2017) developed a digital drawing pen and interface specifically designed for children aged 4–7 years. They recruited 16 children within this age range to assess their subjective user satisfaction and operational performance. Wu et al. (2018) also developed a digital drawing pen specifically for children, recruiting 14 participants aged 7–10 years. The pen offers multiple operational modes, including pressing buttons on the shaft or rotating the pen body to switch between different functions.

For parents of school-aged children, satisfaction with the pen's usability is not the only consideration; the child's actual handwriting performance during use is also of great importance. Research on the impact of pen design on children's writing performance has yielded mixed results. Wiles (1943) found a minimal effect of pen diameter (7.4 mm, 8.6 mm, and 9.8 mm) on physical strain in first graders. Similarly, Carlson and Cunningham (1990) observed no significant impact of pencil diameter (7.5 mm and 10 mm) on preschoolers' writing performance. Oehler et al. (2000) found no significant differences in writing quality or grip among kindergarteners with different pencil shapes and sizes. Sinclair and Szabo (2015) reported no effect of pen size on preschoolers' handwriting legibility or grip, although preferences varied between age groups. Goonetilleke et al. (2009) observed that pen choice is largely subjective, with round pens being favored, although larger pens reduce writing accuracy. While these studies have focused on the effects of pen diameter and shape on handwriting performance and grip preferences, fewer have explored how pen design influences muscle activation and force distribution during writing.

Ferriell et al. (2000) examined the impact of three pen grips (no grip, triangular grip, and pear-shaped grip) on hand muscle kinetics using electromyography and found that triangular grips benefitted individuals with weak intrinsic muscles, whereas pear-shaped grips facilitated a dynamic tripod grasp. The force exerted by the fingers is controlled by sensorimotor capabilities and task demands (Danna and Velay, 2015). Few studies have explored digit forces during writing tasks using custom force detection devices (Falk et al., 2011; Herrick and Otto, 1961; Hooke et al., 2008; Hsu et al., 2013), with Ferriell et al. being the only one focusing on pen design's effects on handwriting kinetics (Ferriell et al., 2000).

Movement control changes with development and maturity, prompting studies to explore the differences in writing performance between adults and children. Greer and Lockman (1998) found no significant differences in pen-grip patterns between five-year-olds and adults (Greer and Lockman, 1998). Harris and Rarick (1959) noted that both college students and fourth graders exhibited similar writing patterns; as writing speed increased, legibility decreased and force exertion became more variable (Harris and Rarick, 1959). These studies suggested no clear differences in pen grip or writing responses between adults and children, which seems counterintuitive to the natural development of motor control. This inconsistency may have stemmed from the use of different evaluation methods.

This study addresses whether different pen shapes and sizes affect handwriting kinetics in adults and children rather than focusing on satisfaction, speed, legibility, or grip form. As pen selection is crucial for developing children's writing skills, we aimed to analyze the influence of pen design on writing mechanics and hand kinetics. The current study builds on earlier ergonomics research on pen and stylus design. Wu and Luo (2006) highlighted the influence of stylus dimensions on task efficiency in touch-based interfaces, whereas Goonetilleke et al. (2009) and Kim et al. (2020) emphasized user preference and writing accuracy with different pen shapes and weights. Our findings regarding force control and stability offer a biomechanical complement to these user-centered studies, extending the literature into pediatric and developmental contexts. Utilizing digital measurement tools, we assessed participants' handwriting and proposed two hypotheses: (1) pen shape and size affect handwriting kinetics, and (2) adults and children differ in their responses to these designs.

2. Methods

2.1. Study ethics

Participants and their guardians who agreed to participate in this study were requested to sign a consent form approved by the Institutional Review Board of National Cheng Kung University Hospital (protocol no. A-ER-103385).

2.2. Study design

This cross-sectional study investigated the handwriting performance from kinetic and temporal perspectives in both children and adults using pens of various shapes and sizes. A custom Force Acquisition Pen (FAP) system (Hsu et al., 2013) featuring different barrel designs was used to measure writing kinetics to ensure that all participants completed the handwriting tasks under consistent conditions.

2.3. Participants

Twelve children, who were originally intended to represent the age range from the final year of kindergarten through elementary school, were recruited through convenience sampling; all child participants were between 8 and 12 years old. The child group included six boys and six girls. In addition, 18 adults without any history of neuromuscular or orthopedic conditions affecting the upper extremities or hands were recruited for this study. The adult group included eight men and 10 women. The average age of the adult participants was 26.29 years (SD = 3.21), whereas that of the children was 9.19 years (SD = 0.97). In addition to demographic characteristics, hand span was measured for all participants by instructing them to fully abduct their fingers and measuring the distance from the tip of the thumb to the tip of the little finger. The average hand span was 20.1 cm (SD = 1.05) for adults and 17.51 cm (SD = 1.08) for children. All participants were right-handed, except for one child participant who used their left hand for writing.

2.4. *Instruments*

The handwriting kinetics were measured using the custom FAP system. The FAP resembled a standard ballpoint pen and was equipped with three thin-beam force sensors (TBS-5, Transducer Techniques, Temecula LLC, CA, USA) to measure the forces applied by the thumb, index, and middle fingers, and a button-shaped transducer (SLB-50) to detect the pen-tip force. The positions of the sensors were adjustable and the pen weighed approximately 30 g. The pen body was approximately 12 cm in total length, with the center of mass located approximately 55 mm from the pen tip. Although the FAP was heavier and thicker than typical writing instruments due to the integration of electronic components and internal supports, every effort was made to reduce its weight and diameter. The pen design was informed by a range of commercial writing tools and assistive products such as children's markers and adult fountain pens like the Montblanc 149 (32 g, 14.7 cm long, with a grip diameter of approximately 13.7 mm). Shape and size variations were limited to the gripping area based on ergonomic features commonly found in commercially available pencil grippers.

Three barrel sizes—large (21 mm), medium (17 mm), and small (13 mm)—were developed, each in both circular and triangular cross-sections (Fig. 1a and b). For the circular pens, size was defined by the outer diameter; for the triangular pens, size was defined by the diameter of the inscribed circle. This approach ensured that the grip diameter was equivalent across both shapes of the same nominal size, allowing for a consistent comparison of shape effects. To ensure stable data transmission while minimizing the influence of cable drag during handwriting, the data cable was secured to the participant's hand or forearm using kinesiology tape. The attachment site (either on the dorsum of the hand or on the volar forearm near the wrist) was adjusted according to each participant's comfort and the tension dynamics of the cable. The analog force data were converted to digital signals using an instruNet network device (iNet-100, GW Instruments, Inc., MA, USA) connected to a notebook and sampled at 70 Hz. A Butterworth low-pass filter with a 3 Hz cutoff was applied to the raw data. The FAP system demonstrated strong validity and acceptable reliability. Each of the four load cells was calibrated individually using a regression-based procedure against standard weights as the gold standard. The regression analysis results showed that the R^2 values for all load cells (TBS-5 and SLB-25) were greater than 0.999 ($p < 0.001$), confirming the high accuracy and linearity of force detection. For validity tests, we used the standard weight as the gold standard to verify the validity of four load cells. For test-retest reliability, intraclass correlation coefficients (ICCs) were computed based on the average force (AF) values obtained from six FAP units during the circle tracing task, with a test interval of three days. For adult participants, ICCs ranged from 0.794 to 0.936 ($p < 0.001$), with an average ICC of 0.891. For child participants, ICCs ranged from 0.693 to 0.932 ($p < 0.001$), with an average ICC of 0.841. These results support the reliability and consistency of the FAP system across repeated measurements and age groups.

2.5. *Writing task sheet*

The participants used the FAP to trace the designed figures on A4 paper (Fig. 2). The figures consisted of circles printed inside squares of three different sizes: large (50 mm × 50 mm), medium (20 mm × 20 mm), and small (15 mm × 15 mm). This study did not examine the differences in circle size. The participants were instructed to trace each circle in one continuous stroke, maintain a counterclockwise direction, and ensure that the start and end points overlapped to complete a successful trial. Each trial involved tracing the same circle four times. For each circle size, the participants traced four consecutive circles, and this process was repeated three times per size. The average parameters

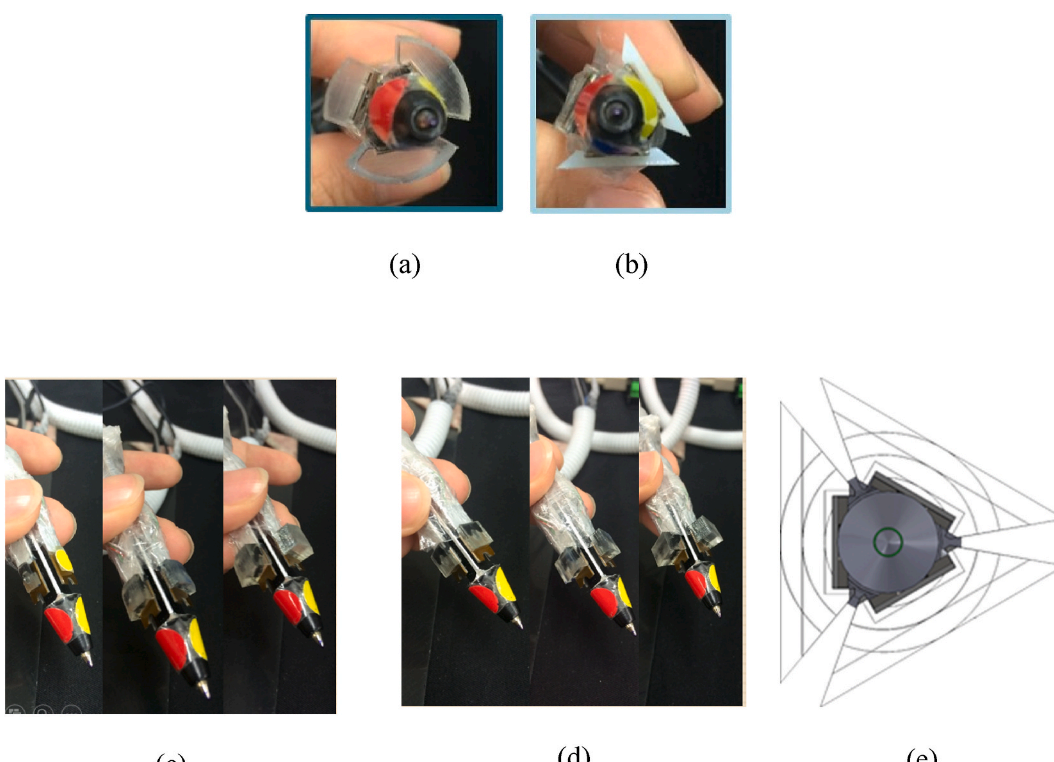

Fig. 1. The Force Acquisition Pen used in this study.

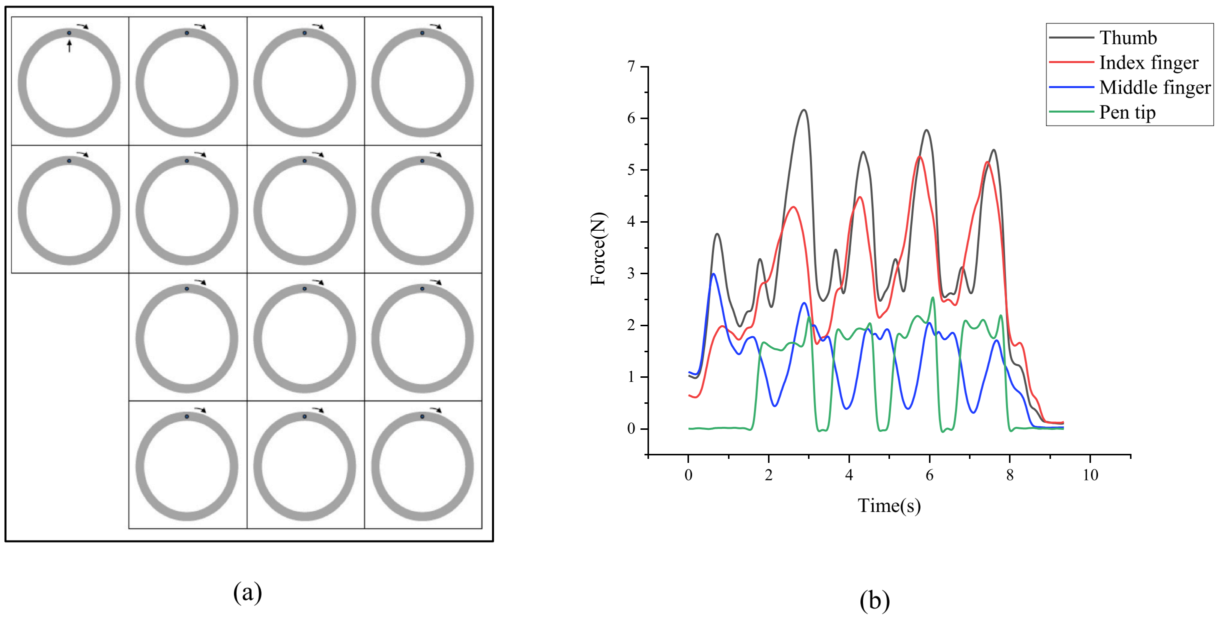

Fig. 2. Examples of an A4 writing task sheet and force data.

across the trials were then calculated.

A tracing task was used rather than a free copying task to reduce variability in movement trajectories and improve comparability across participants. In free copying, each participant may produce characters of different shapes, sizes, and stroke sequences, making it difficult to analyze handwriting forces under consistent conditions. Tracing ensures that all participants follow the same predefined path, allowing for more controlled and reliable measurement of handwriting kinetics. Additionally, circles were chosen as the tracing shape because they involve continuous directional changes throughout the stroke, covering all angular orientations in a single movement. This provides a comprehensive assessment of fine motor control and force modulation across multiple directions. Unlike alphabetic or logographic characters, circles are culturally neutral and avoid the confounding effects of language-specific stroke patterns. This design ensures that the tracing task is universally applicable and not biased by differences in script or writing conventions.

2.6. Parameters of handwriting performances

This study utilized three kinetic parameters and one temporal factor to describe handwriting performance: average force (AF), coefficient of variation of force (CVF), force ratio (FR), and task time (TT). AF represents the mean instantaneous force for each trial, with separate AF values calculated for the thumb, index finger, middle finger, and pen tip. The AF of the pen-tip was measured while it was in contact with the paper. The CVF is the ratio of the standard deviation of the instantaneous force to the AF, with a lower CVF indicating a more consistent force output from the digits or pen tip. FR is the ratio of the instantaneous force of the pen tip to the total instantaneous force from the three digits, and was calculated only when the pen tip touched the paper. TT is the total duration from the initial pen contact to the final lift-off in a trial, based on force data from the pen tip. Customized MATLAB (MathWorks Ltd., Natick, MA, USA) was used to quantify these parameters, which were averaged over three trials for the statistical analysis.

2.7. Experimental protocol

Before starting the writing tasks, each participant was instructed to sit on a table with both arms resting on it, knees bent at 90°, and feet flat on the floor. Each participant's habitual grip pattern was observed. Most participants naturally used a traditional tripod or lateral tripod grasp. A few participants initially used a quadrupod grasp, but all participants were able to adjust to the required tripod grasp after one brief practice task (such as writing their names).

The participants were then taught to use a consistent grip pattern—a tripod grasp—to hold the FAP. They were instructed to use their thumb and index finger pads to touch the sensors marked with blue and red stickers, respectively, while the distal radial side of the middle finger touched the unmarked button. Each digit was assigned to a specific sensor. During the familiarization phase, participants practiced using the FAP and tracing figures before formal assessments. The practice period typically lasted less than 30 s and was adjusted based on the participant's comfort and readiness. They were asked to write at their natural pace and accurately trace the figures. The order of writing tasks for the three circle sizes and pen shapes was randomized.

To assess test-retest reliability, each participant was invited to repeat the same writing procedure after an interval of three days. The second session was conducted using the same protocol and pen configurations, and the resulting data were used for ICC computation.

2.8. Statistical analysis

The sample size was determined using G*Power, with an effect size of 0.6 and a power of 0.8. A one-way analysis of variance (ANOVA) was conducted with three groups, requiring a total of 30 participants, with at least 10 participants per group. One-way repeated-measures ANOVA was used to evaluate the effects of the three sizes. Post hoc comparisons were performed using Bonferroni's method. Paired t-tests were conducted to assess differences between pen shapes (circular and triangular), whereas independent t-tests were used to compare the adult and child groups. The significance level was set at $p < 0.05$. In addition, a post hoc power analysis was conducted using G*Power to evaluate whether the sample size of 12 participants was adequate to detect differences between pen shapes using a one-tailed paired *t*-test. Assuming a large effect size ($d = 0.8$), a significance level of $\alpha = 0.05$, and a power set at 0.7 due to practical constraints in participant recruitment, the calculated statistical power was approximately 0.78. Although this power is slightly below the conventional threshold of 0.80, it is considered acceptable for an exploratory study.

3. Results

3.1. Effect of size difference on handwriting kinetics

Table 1 presents the mean values and standard deviations of each parameter. Statistical comparisons of the effect of pen size on AF, CVF, and FR, based on one-way repeated-measures ANOVA, are summarized in Table 2 for both the adult and child groups.

3.1.1. Effect of size difference on AF

3.1.1.1. Size effect on AF for adults. The results of the repeated-measures one-way ANOVA, presented in Table 2, indicate significant differences in the AF for the thumb (AF_{thumb}), index finger (AF_{index}), and middle finger (AF_{middle}) with circular-shaped FAP. According to the Bonferroni post-hoc test, AF_{thumb} and AF_{middle} were higher with $FAP_{Circular\text{-}13mm}$ and $FAP_{Circular\text{-}17mm}$ compared with $FAP_{Circular\text{-}21mm}$.

Significant differences were also observed between AF_{thumb} and AF_{middle} with triangular-shaped FAP. The Bonferroni post hoc test revealed that AF_{thumb} was lower with $FAP_{Triangular\text{-}13mm}$ and $FAP_{Triangular\text{-}17mm}$ than with $FAP_{Triangular\text{-}21mm}$. Additionally, AF_{middle} was lower with $FAP_{Triangular\text{-}13mm}$ than with $FAP_{Triangular\text{-}21mm}$.

3.1.1.2. Size effect on AF for children. The repeated-measures one-way ANOVA results indicated significant differences in AF_{thumb} and AF_{middle} with circular-shaped FAP (Table 2). The Bonferroni post hoc test revealed that AF_{middle} was greater with $FAP_{Circular\text{-}13mm}$ than with $FAP_{Circular\text{-}21mm}$. No significant differences were found in AF_{thumb}, AF_{index}, AF_{middle}, or $AF_{pen\text{-}tip}$ with triangular FAP of different sizes.

3.1.2. Effect of size difference on CVF

3.1.2.1. Size effect on CVF for adults. The repeated-measures one-way ANOVA results indicated significant differences in CVF_{thumb}, CVF_{index}, and $CVF_{pen\text{-}tip}$ with the circular-shaped FAP. The Bonferroni post hoc test revealed that CVF_{thumb} was higher with $FAP_{Circular\text{-}17mm}$ than with $FAP_{Circular\text{-}21mm}$. The CVF_{index} was greater for $FAP_{Circular\text{-}17mm}$ than for $FAP_{Circular\text{-}13mm}$. Additionally, the $CVF_{pen\text{-}tip}$ was higher with $FAP_{Circular\text{-}17mm}$ than with $FAP_{Circular\text{-}13mm}$, and also greater with $FAP_{Circular\text{-}21mm}$ than with $FAP_{Circular\text{-}13mm}$.

Significant differences were also observed in CVF_{thumb} with the triangular-shaped FAP. The Bonferroni post-hoc test showed that the CVF_{thumb} was higher with $FAP_{Triangular\text{-}13mm}$ than with both $FAP_{Triangular\text{-}17mm}$ and $FAP_{Triangular\text{-}21mm}$.

3.1.2.2. Size effect on CVF for children. No significant differences were observed among the various sizes of CVFs with circular or triangular-shaped FAPs.

3.1.3. Effect of size difference on FR

3.1.3.1. Size effect on FR for adults. The repeated-measures one-way ANOVA results indicated significant differences in the FR among different sizes with the circular-shaped FAP. The Bonferroni post-hoc test revealed that FR was higher with $FAP_{Circular\text{-}17mm}$ than with $FAP_{Circular\text{-}21mm}$. No significant differences in FR were observed among the triangular-shaped FAPs.

3.1.3.2. Size effect on FR for children. Repeated-measures one-way ANOVA revealed significant differences in FR among different sizes with circular-shaped FAP. The Bonferroni post-hoc test indicated that the FR was lower with $FAP_{Circular\text{-}21mm}$ than with both $FAP_{Circular\text{-}13mm}$ and $FAP_{Circular\text{-}17mm}$. No significant differences in FR were observed among the triangular-shaped FAPs.

3.2. Effect of shape difference on handwriting kinetics

The statistical comparisons of pen shape (circular vs. triangular) were assessed using paired t-tests, with significant outcomes presented in Table 3. Corresponding mean values and standard deviations that support these comparisons are reported in Table 1. The following sections describe the effects of shape on AF, CVF, and FR for both the adult and child groups.

3.2.1. Effect of shape difference on AF

3.2.1.1. Shape effect on AF for adults. The paired *t*-test results showed no significant differences between pen shapes in the AF_{thumb} and $AF_{pen\text{-}tip}$. However, the AF_{index} was significantly lower when using the $FAP_{Circular\text{-}13mm}$ than when using the $FAP_{Triangular\text{-}13mm}$. Additionally, the AF_{index} and AF_{middle} were significantly lower for $FAP_{Circular\text{-}17mm}$ than for $FAP_{Triangular\text{-}17mm}$.

3.2.1.2. Shape effect on AF for children. The paired *t*-test results showed no significant differences between pen shapes in the AF_{thumb} and $AF_{pen\text{-}tip}$. However, AF_{middle} was significantly lower when using the $FAP_{Circular\text{-}13mm}$ than when using the $FAP_{Triangular\text{-}13mm}$, and similarly, AF_{middle} was significantly smaller with $FAP_{Circular\text{-}17mm}$ than with $FAP_{Triangular\text{-}17mm}$. Additionally, AF_{index} was significantly lower with $FAP_{Circular\text{-}21mm}$ than with $FAP_{Triangular\text{-}21mm}$.

3.2.2. Effect of shape difference on CVF

3.2.2.1. Shape effect on CVF for adults. The paired *t*-test results indicated a significant difference in $CVF_{pen\text{-}tip}$ between the pen shapes. $CVF_{pen\text{-}tip}$ was significantly lower when using $FAP_{Circular\text{-}13mm}$, $FAP_{Circular\text{-}17mm}$, and $FAP_{Circular\text{-}21mm}$ than when using $FAP_{Triangular\text{-}13mm}$, $FAP_{Triangular\text{-}17mm}$, and $FAP_{Triangular\text{-}21mm}$.

3.2.2.2. Shape effect on CVF for children. Paired *t*-test results showed no significant differences between pen shapes in the CVF.

3.2.3. Effect of shape difference on FR

3.2.3.1. Shape effect on FR for adults. The paired *t*-test results revealed a significant difference in FR between shapes. FR was significantly higher when using $FAP_{Circular\text{-}17mm}$ than when using $FAP_{Triangular\text{-}17mm}$.

3.2.3.2. Shape effect on FR for children. The paired *t*-test results indicated a significant difference in FR between the shapes. FR was significantly higher when using $FAP_{Circular\text{-}13mm}$ and $FAP_{Circular\text{-}17mm}$ than when using $FAP_{Triangular\text{-}13mm}$ and $FAP_{Triangular\text{-}17mm}$.

3.3. Comparison of handwriting performance between adults and children

Detailed results comparing AF, CVF, FR, and TT between adults and children, analyzed using independent t-tests, are presented in Table 3.

3.3.1. Difference in AF between adults and children

Independent *t*-test results indicated no significant difference in AF between children and adults.

3.3.2. Difference in CVF between adults and children

The independent *t*-test results showed a significant difference in the CVF for the thumb, index finger, and middle finger between children and adults, with children displaying significantly higher CVF values. However, no significant difference was found in the CVF for the pen tip between the two groups.

Table 1
Difference in AF, CVF, FR, and TT between adults and children.

Parameter		AF			CVF			FR[a]			TT[a]		
Source	Size	Adult	Children	*p*	Adult	Children	*p*	Adult	Children	*p*	Adult	Children	*p*
Circular													
Thumb	13	3.15 ± 1.09	3.05 ± 1.66	0.76	0.32 ± 0.06	0.38 ± 0.10	0.00	0.24 ± 0.08	0.29 ± 0.09	0.01	12.57 ± 5.00	14.70 ± 5.12	0.05
	17	3.20 ± 0.93	2.98 ± 1.23	0.36	0.33 ± 0.07	0.41 ± 0.09	0.00	0.25 ± 0.09	0.28 ± 0.09	0.20	11.64 ± 4.15	12.81 ± 4.69	0.22
	21	3.72 ± 1.09	3.64 ± 1.95	0.83	0.30 ± 0.07	0.39 ± 0.11	0.00	0.22 ± 0.07	0.22 ± 0.05	0.81	10.84 ± 3.69	13.64 ± 5.14	0.01
Index	13	2.20 ± 0.74	2.36 ± 1.22	0.47	0.31 ± 0.08	0.40 ± 0.11	0.00						
	17	2.26 ± 0.64	2.41 ± 0.83	0.34	0.34 ± 0.08	0.40 ± 0.08	0.00						
	21	2.42 ± 0.68	2.52 ± 1.27	0.67	0.33 ± 0.09	0.40 ± 0.09	0.00						
Middle	13	1.27 ± 0.69	1.04 ± 0.77	0.14	0.31 ± 0.10	0.46 ± 0.18	0.00						
	17	1.09 ± 0.50	1.04 ± 0.69	0.72	0.33 ± 0.11	0.50 ± 0.16	0.00						
	21	1.48 ± 0.67	1.39 ± 0.92	0.61	0.30 ± 0.13	0.44 ± 0.20	0.00						
Pen-tip	13	1.59 ± 0.67	1.71 ± 0.67	0.42	0.29 ± 0.06	0.30 ± 0.05	0.38						
	17	1.63 ± 0.64	1.71 ± 0.73	0.59	0.30 ± 0.05	0.31 ± 0.05	0.56						
	21	1.60 ± 0.66	1.66 ± 0.94	0.72	0.31 ± 0.05	0.32 ± 0.06	0.34						
Triangular													
Thumb	13	3.18 ± 0.94	2.96 ± 1.22	0.33	0.33 ± 0.06	0.41 ± 0.11	0.00	0.23 ± 0.07	0.24 ± 0.08	0.68	10.84 ± 3.95	16.05 ± 6.79	0.00
	17	3.28 ± 0.98	3.06 ± 1.10	0.30	0.31 ± 0.06	0.41 ± 0.09	0.00	0.23 ± 0.07	0.22 ± 0.07	0.57	11.14 ± 4.36	15.33 ± 6.84	0.00
	21	3.54 ± 1.13	3.25 ± 1.68	0.32	0.31 ± 0.07	0.39 ± 0.07	0.00	0.22 ± 0.08	0.22 ± 0.05	0.91	10.78 ± 4.59	13.90 ± 5.34	0.00
Index	13	2.55 ± 0.76	2.49 ± 0.99	0.74	0.33 ± 0.07	0.39 ± 0.09	0.00						
	17	2.52 ± 0.79	2.69 ± 0.95	0.36	0.33 ± 0.08	0.37 ± 0.08	0.02						
	21	2.58 ± 0.87	2.88 ± 1.32	0.23	0.33 ± 0.08	0.39 ± 0.07	0.00						
Middle	13	1.23 ± 0.37	1.51 ± 0.86	0.07	0.33 ± 0.11	0.44 ± 0.17	0.00						
	17	1.39 ± 0.60	1.56 ± 0.84	0.31	0.31 ± 0.11	0.44 ± 0.12	0.00						
	21	1.42 ± 0.51	1.54 ± 0.78	0.42	0.32 ± 0.11	0.46 ± 0.11	0.00						
Pen-tip	13	1.61 ± 0.65	1.55 ± 0.48	0.59	0.31 ± 0.05	0.31 ± 0.08	0.59						
	17	1.61 ± 0.69	1.56 ± 0.73	0.77	0.32 ± 0.06	0.30 ± 0.05	0.25						
	21	1.63 ± 0.78	1.69 ± 1.03	0.76	0.32 ± 0.07	0.30 ± 0.04	0.17						

Note. AF: average force (unit: N), CVF: coefficient of variation of force, FR: force ratio, TT: task time (unit: s). The adult group consisted of 18 participants, and the children group consisted of 12 participants.

[a] For FR and TT, they are not separated by different sources of forces.

Table 2
Results of the one-way repeated ANOVA for the effect of size on AF, CVF, and FR.

Source of force	AF		CVF		FR	
	Adult	Children	Adult	Children	Adult	Children
Circular shape						
Thumb	21 > 13,17	–	17 > 21	n.s.		
Index	–	n.s.	17 > 13	n.s.		
Middle	21 > 13,17	21 > 13	n.s.	n.s.		
Pen-tip	n.s.	n.s.	17,21 > 13	n.s.		
All together					17 > 21	13,17 > 21
Triangular shape						
Thumb	21 > 13,17	n.s.	13 > 17,21	n.s.		
Index	n.s.	n.s.	n.s.	n.s.		
Middle	21 > 13	n.s.	n.s.	n.s.		
Pen-tip	n.s.	n.s.	n.s.	n.s.		
All together					n.s.	n.s.

Note: Bonferroni was used for post-hoc test. AF: average force (unit: N), CVF: coefficient of variation of force, FR: force ratio. L: large, 21 mm; M: medium,17 mm; S: small,13 mm.
" n.s." indicates no significant difference found in the main test. "-" indicates that a significant difference was found in the main test, but no significant difference was found in the post-hoc test.

3.3.3. *Difference in FR between adults and children*

The independent *t*-test results indicated that the FR was significantly larger in children than in adults when using $FAP_{Circular\text{-}13mm}$.

3.3.4. *Difference in TT between adults and children*

The independent *t*-test results revealed that the TT was significantly longer in children than in adults when using $FAP_{Circular\text{-}13mm}$, $FAP_{Circular\text{-}21mm}$, $FAP_{Triangular\text{-}13mm}$, $FAP_{Triangular\text{-}17mm}$, and $FAP_{Triangular\text{-}21mm}$.

4. Discussion

The market offers a wide range of pencils and grips for children's handwriting in various shapes and sizes. Opinions on the effectiveness of different writing instruments are mixed, making it challenging for students and parents to select the most suitable pen. This study aims to elucidate the mechanics of handwriting to offer teachers and therapists valuable insights into the use of various writing tools. In addition, it seeks to provide information on handwriting mechanics across different age groups. To better understand these differences and provide data-driven guidance for tool selection, we analyzed the biomechanics of handwriting using validated kinetic tools.

Prior ergonomic studies on pen and stylus design (Goonetilleke et al., 2009; Kim et al., 2020; Wu and Luo, 2006) have focused mainly on user preferences, satisfaction, and perceived comfort. For instance, Wu and Luo (2006) found that intermediate stylus diameters (around 8 mm) and longer lengths improved user task performance, while Goonetilleke et al. (2009) and Kim et al. (2020) explored how pen shape, grip texture, and balance affected perceived writing quality and comfort. In contrast, the current study provides real-time biomechanical data (AF, CVF, FR) and developmental insights by comparing children and adults. This builds upon prior work using the FAP, which has been validated in earlier studies. Lin et al. (2017) used the FAP to explore the relationship between handwriting forces and fine motor performance in children, while Lin et al. (2019) examined how task complexity (e.g., circle tracing vs. Chinese character writing) influenced handwriting force profiles. Both studies demonstrated the FAP's sensitivity in capturing kinetic differences across developmental stages and writing tasks. The present study extends this framework by applying the FAP to systematically compare how pen shape and size affect grip dynamics across age groups. By integrating kinetic metrics with ergonomic principles, our findings advance understanding in both motor control science and handwriting tool design. To further explore these insights, we analyzed group-specific effects starting with the adult participants.

In the adult group, the effect of pen size was not significant across all parameters. Regarding the size effect on the AFs, the mean values indicate that the AFs tend to be larger when using a larger $FAP_{Circular}$. However, the difference was minimal, within less than one standard deviation. This suggests that the use of a larger FAP does not significantly influence the average force applied by the digits in adults. The results were not significant for the size effect on CVFs. A trend was observed where the CVF in the three digits was higher with $FAP_{Circular\text{-}17mm}$, with *p*-values ranging from 0.01 to 0.16. No such trend was observed for $FAP_{Triangular}$. Therefore, in adults, using the $FAP_{Circular\text{-}17mm}$ may result in a less stable force application. For the size effect on FR, significance was found only for $FAP_{Circular}$ and not for $FAP_{Triangular}$. FR was larger with $FAP_{Circular\text{-}17mm}$ in adults.

The reason this specific size and shape affected this group requires further investigation. Overall, we can conclude that for adults, the size of the FAP may not influence the amount of force applied but may affect the stability and distribution of the force. Specifically, adults may generate less stable force from the fingers and apply less force on the pen barrel than on the pen tip when using $FAP_{Circular\text{-}17mm}$ compared with other sizes of $FAP_{Circular}$. In the research conducted by Wu and Luo (2006), it was observed that pens with diameters of up to 15 mm,

Table 3
Results of pair *t*-test of shape on AF, CVF, and FR.

Size	Source	AF		CVF		FR	
	of force	Adult	Children	Adult	Children	Adult	Children
13	Thumb	n.s.	n.s.	n.s.	n.s.		
	Index	T > C	n.s.	n.s.	n.s.		
	Middle	n.s.	T > C	n.s.	n.s.		
	Pen-tip	n.s.	n.s.	T > C	n.s.		
	All together					n.s.	C > T
17	Thumb	n.s.	n.s.	n.s.	n.s.		
	Index	T > C	n.s.	n.s.	n.s.		
	Middle	T > C	T > C	n.s.	n.s.		
	Pen-tip	n.s.	n.s.	T > C	n.s.		
	All together					C > T	C > T
21	Thumb	n.s.	n.s.	n.s.	n.s.		
	Index	n.s.	T > C	n.s.	n.s.		
	Middle	n.s.	n.s.	n.s.	n.s.		
	Pen-tip	n.s.	n.s.	T > C	n.s.		
	All together					n.s.	n.s.

Note. AF: average force (unit: N), CVF: coefficient of variation of force, FR: force ratio. T: Triangular shape; C: Circular shape; " n.s." indicates no significant difference was found in the test.

characterized by a circular design, resulted in reduced completion times and fewer errors during drawing tasks. In contrast, our study revealed that the application of force with pens measuring 13 mm and 21 mm in diameter exhibited greater stability compared to those with a 17 mm diameter. The findings from these two studies are not congruent, which may be explained by variations in the type of writing instrument employed (ballpoint pen versus touch pen) and the specific characteristics of the writing tasks involved.

For the children group, the size effect was not significant across all parameters. Similar to the adult group, the size of the FAP did not influence the AF applied by the digits. Regarding the size effect on the CVFs, no significant differences were found, indicating that for children, using a larger FAP did not affect force stability. For the size effect on FR, significance was observed only for $FAP_{Circular}$ and not for $FAP_{Triangular}$. The children group exhibited a smaller FR when using $FAP_{Circular\text{-}21mm}$ compared to other sizes. A lower FR indicates that when children manipulate the pen, they tend to apply more force to the barrel rather than pressing downward on the pen tip, which darkens the ink on the paper. Moreover, when comparing FR values across age groups with different sizes of $FAP_{Circular}$, the $FAP_{Circular\text{-}21mm}$ consistently yielded lower FR in both children and adults. This pattern indicates that when using a substantially thicker pen, such as the 21 mm barrel, which differs considerably from typical writing tools, participants may need to exert additional effort to stabilize the pen through the barrel grip. In other words, to produce comparable ink output, users appear to compensate by increasing grip force, particularly when the pen's diameter deviates markedly from what they are accustomed to.

The mean AF values from the three digits showed that with a larger $FAP_{Circular}$, the overall AFs increased. However, the mean AF values from the pen tip showed no noticeable changes across sizes. This implies that using a smaller barrel size in the $FAP_{Circular}$ is associated with a higher FR, allowing children to grip the pen with less force. For children with muscle weakness, using a larger pen, such as the FAP_{21mm} in this study, may be challenging because it requires greater force application.

In the adult group, the shape differences were not consistently significant across all parameters. Regarding the shape effect on the AFs, no significant differences were found in any instance, and no clear trend emerged from the mean AF values. Regarding the shape effect on CVFs, only $CVF_{pen\text{-}tip}$ showed a significant difference, with $CVF_{Triangular}$ being larger than $CVF_{Circular}$ across all FAP sizes. This suggests that when using $FAP_{Circular}$, the force applied to the pen tip is more consistent with the writing surface. However, no significant trends were observed in CVF_{thumb}, CVF_{index}, or CVF_{middle}. From an anatomical perspective, using a triangular-shaped pen passively separates the three digits, increasing the thumb-index web angle. A larger thumb-index web angle can increase pen-tip mobility, leading to greater force variability. In contrast, $FAP_{Circular}$ allows for more stable force generation at the pen tip. The relationship between the $CVF_{pen\text{-}tip}$ and the thumb-index web angle remains unclear and requires further investigation. Regarding the shape effect on the FRs, significant differences were found only with FAP_{17mm}. Specifically, FR was significantly larger with $FAP_{Circular\text{-}17mm}$ than with $FAP_{Triangular\text{-}17mm}$. This indicates that when adults use $FAP_{Triangular\text{-}17mm}$, they apply less force to the pen barrel compared with $FAP_{Circular\text{-}17mm}$, even when the force at the pen tip remains the same.

For the children group, the shape differences were not consistently significant. Regarding the shape effect on the AFs, no significant differences were found, and no clear trend emerged from the mean AF values. In our study, neither size nor shape had a measurable effect on the AF, suggesting that the average force alone may not be sensitive enough to detect changes caused by pen type. Recent studies have shifted away from relying solely on average force to assessing handwriting performance (Bartov et al., 2024; Hochhauser et al., 2021; Kushki et al., 2011; Lin et al., 2022), focusing more on movement control. For instance, Hochhauser et al. (2021) examined not only the average pressure in children's handwriting, but also the ratio between grip and tip force, as well as force variability. Regarding the shape effect on the CVFs, no significant differences were observed in children. Regarding the FRs, significant differences were only observed for FAP_{13mm} and FAP_{17mm}. FR was significantly larger when $FAP_{Circular\text{-}13mm}$ and $FAP_{Circular\text{-}17mm}$ were used than when their triangular counterparts were used. This means that when children use $FAP_{Triangular\text{-}13mm}$ or $FAP_{Triangular\text{-}17mm}$, they apply less force to the pen barrel than when using $FAP_{Circular}$ of the same size, even when the pen tip force remains the same. Ferriell et al. (2000) found that individuals using triangular pens tend to generate less intrinsic muscle activity, suggesting that these tools may reduce muscular effort during handwriting and improve motor efficiency. However, their study did not report the specific dimensions of the pencil grippers used, and their participants were adults aged 18 to 35. These findings are not entirely consistent with our results. In our study, we found that when children used 13 mm and 17 mm pens, they exerted greater relative force with their three fingers on triangular barrels compared to circular ones in order to produce ink with comparable darkness.

Expanding upon this research, van Galen et al. (1993) revealed that individuals with poor writing skills demonstrate significantly elevated levels of neuromotor noise compared to their proficient counterparts. Their theoretical framework posits that this heightened noise arises from ineffective regulation of limb stiffness, which is generally managed through the concurrent co-contraction of agonist and antagonist muscles when high accuracy is required. For children who experience handwriting difficulties, reducing muscular effort through more ergonomic tools, such as circular pens, may potentially lessen the demands on fine motor control and attenuate the influence of neuromotor noise on handwriting performance, though further empirical validation is warranted.

When comparing children and adults, no significant differences were found in the AFs, indicating that the two groups applied a similar average force. This finding aligns with that of Guilbert et al. (2019), who found no differences in pen pressure between first graders, fifth graders, and adults when writing letters or pseudowords. However, CVF_{thumb}, CVF_{index}, and CVF_{middle} were larger in children than in adults, although no significant differences were observed in the $CVF_{pen\text{-}tip}$. Because tracing is a relatively simple motor-cognitive task for both groups, this suggests that the pen-tip force, as the final output of movement control, may not reveal differences between children and adults. However, when examining the forces applied by the fingers to the pen barrel, in which the fingers acted as the source of movement and force control, clear differences emerged between the groups. This finding aligns with previous research by Lin et al. (2017), which examined pen-grip kinetics among children aged 5 to 12 during digit-tracing tasks. Their results indicated that younger children exhibited a greater coefficient of variation in grip force (CVF) compared to older children, suggesting that grip force variability decreases with age. Notably, the current study similarly found that adults demonstrated lower CVF than children, reinforcing the interpretation that more mature individuals apply force in a more consistent manner during handwriting tasks. Lin et al. further proposed that older children adopt a writing strategy characterized by reduced variability in grip force and more frequent micro-adjustments, likely to optimize precision during tracing. This pattern suggests that minimizing grip force variability may reflect a refined motor control strategy aimed at achieving greater efficiency and stability in pen handling.

For FRs, a significant difference was found only with $FAP_{Circular\text{-}13mm}$. When using the $FAP_{Circular\text{-}13mm}$, adults applied more force to the pen barrel than children, even though the pen-tip force remained the same. This finding is in line with previous research (Chau et al., 2006; Lin et al., 2017), which noted that more proficient writers or older individuals may be more likely to modulate grip force on the barrel rather than increase downward pressure on the writing surface. These patterns may reflect differences in force control strategies associated with age or writing experience. However, no significant differences were found for the other five pens. The variations in pen shape and size across these pens appeared to have a greater impact on the Force Ratio (FR) than differences in writing maturity or age. These findings suggest that modifying the shape and size of writing tools may have a more immediate and observable influence on handwriting force control than developmental factors alone. This potentially underscores the practical importance of selecting ergonomically appropriate pens, particularly for students who may experience challenges with grip strength or force modulation during writing tasks.

Regarding the task times (TTs), adults wrote significantly faster than children, except when using $FAP_{Circular\text{-}17mm}$. The mean task time showed a general trend in which adults wrote faster than children at their natural writing speed. This result is consistent with findings from prior studies (Lin et al., 2017; Tseng and Hsueh, 1997), which have demonstrated that handwriting speed increases with age.

This study analyzed handwriting kinetics by examining various parameters to explore differences in pen design, as well as differences in writing performance between adults and children. Notably, differences were observed in the CVFs of the digits, indicating that even in less challenging tasks, motor control strategies can be highlighted by specific parameters. Importantly, the effect of pen design on children was a key focus of this study. Our results showed that, in terms of pen size, using 13 mm and 17 mm pens allowed children to apply less force to the pen barrel while maintaining a consistent force at the pen tip compared to using the 21 mm $FAP_{Circular}$. This phenomenon was not observed when the children used the $FAP_{Triangular}$. Additionally, the analysis of pen shape revealed that when children used $FAP_{Triangular\text{-}13mm}$ and $FAP_{Triangular\text{-}17mm}$, they applied more force to the pen barrel than when using $FAP_{Circular\text{-}13mm}$ and $FAP_{Circular\text{-}17mm}$, while maintaining a consistent force at the pen tip. These findings suggest that selecting pens with smaller grip diameters (specifically 13 mm and 17 mm), particularly those with a circular shape, may help children achieve more efficient force distribution during handwriting. From a clinical or educational perspective, such tools could support children who struggle with grip stability or fatigue by reducing unnecessary force on the pen barrel while maintaining effective control at the pen tip.

As noted in Section 2.4, the pen barrel sizes used in this study (13 mm, 17 mm, and 21 mm) were selected to reflect the dimensions of assistive writing tools and pencil grips commonly applied in pediatric occupational therapy. The variation in diameter was confined to the gripping area and was not intended to simulate standard classroom pencils. Rather, the aim was to approximate the real-world characteristics of therapeutic tools currently used by children with fine motor challenges or weak grip strength. This design choice supports the clinical relevance of our findings and highlights their potential application in school-based or rehabilitative settings.

This study has several limitations. One key limitation involves the modest sample size and use of convenience sampling, which may limit the generalizability of the findings. Future studies should aim to recruit larger and more demographically diverse samples to validate these preliminary results. Second, the smallest pen used in this study had a diameter of 13 mm, whereas a standard pencil commonly used by first-grade students typically has a diameter of 7 mm and weighs less than 10 g. Although larger and heavier pencils and pens are available, future studies should consider the use of smaller and lighter pencils. Third, the tasks in this study were designed to capture participants' natural writing patterns. Future studies could introduce time constraints or increase the number of characters to better assess differences across various pen designs and conditions. Fourth, the tasks were not free-writing exercises; therefore, further research is required to explore how different pen designs affect writing in more complex tasks. Fifth, the center of gravity and weight of the pens were acknowledged but not explored in depth. For adults in certain professions, such as engineering, the pen's center of gravity might influence their choice of writing instruments. Additionally, children with sensory issues may benefit from weighted pens because therapists often recommend them to improve proprioception and handwriting performance. Therefore, future studies should investigate the effects of pen weight and the center of gravity on writing mechanics.

Sixth, the requirement to align each finger precisely with the FAP sensor zones may have affected the naturalness of participants' handwriting. While most participants adjusted to the tripod grasp easily, the imposed grip pattern could have introduced variability in force production, particularly for those unaccustomed to this grip. This methodological constraint, while necessary for data consistency, represents a limitation in terms of ecological validity. Seventh, while hand span was recorded as an indirect measure of hand size, finger strength was not assessed. This is a limitation, as finger strength influences handwriting force and control. Imrhan and Loo (1989) showed that pinch strength varies by digit and age, with children consistently showing lower values than adults. Future studies should include direct measures of finger strength to better interpret handwriting kinetics across age groups. Additionally, although different circle sizes were included in the writing task to introduce variation, the study did not systematically analyze how figure size interacts with pen shape and size. Future research may benefit from incorporating tasks involving both circular and linear writing trajectories, as these may differ in the required finger rotation and movement stability, particularly across different pen designs.

5. Conclusions

Based on these results, we suggest that using a circular pen with a diameter of 13 or 17 mm (relatively smaller within our custom pen designs) may benefit children who lack sufficient grip strength, even though these sizes remain thicker than most standard children's writing tools. These smaller circular barrels allowed children to exert less force on the barrel while maintaining consistent pen tip pressure, suggesting improved grip efficiency. Furthermore, among pens of the same diameter, the circular shape required less grip force than the triangular counterpart. Despite the limitations, these findings offer valuable insights into how pen design influences force control. This information may assist clinicians, parents, and educators in selecting writing tools that better support children's motor performance and comfort during handwriting tasks.

CRediT authorship contribution statement

Li-Chieh Kuo: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Chung-Hung Tsai:** Resources, Project administration, Methodology, Data curation. **Chieh-Hsiang Hsu:** Software, Resources, Data curation. **Cheng-Feng Lin:** Methodology, Formal analysis. **Hsiu-Yun Hsu:** Resources, Methodology, Formal analysis, Data curation. **Chin-Wei Liu:** Resources, Methodology, Data curation. **Yu-Chen Lin:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of authorship

All authors were fully involved in the study and preparation of the manuscript and the corresponding author has full access to data and has the right to publish such data. CHT, YCL and LCK carried out the study design. CHT, YCL, CHH, HYH and CWL were the main contributors with regard to data collection and clinical assessments. YCL, CFL, HYH and LCK participated in the data interpretation, analysis and interpretations. All the authors read and approved the contents and format of the final manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT/

WORDVICE.AI/Grammarly in order to proofread. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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