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On the development of a computer-based handwriting assessment tool to objectively quantify handwriting proficiency in children

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ARTICLE INFO

Article history:
Received 2 February 2010
Received in revised form
3 December 2010
Accepted 10 December 2010

Keywords:
Handwriting
MHA
Grip force
Digitizing tablet

ABSTRACT

Standardized writing assessments such as the Minnesota Handwriting Assessment (MHA) can inform interventions for handwriting difficulties, which are prevalent among school-aged children. However, these tests usually involve the laborious task of subjectively rating the legibility of the written product, precluding their practical use in some clinical and educational settings. This study describes a portable computer-based handwriting assessment tool to objectively measure MHA quality scores and to detect handwriting difficulties in children. Several measures are proposed based on spatial, temporal, and grip force measurements obtained from a custom-built handwriting instrument. Thirty-five first and second grade students participated in the study, nine of whom exhibited handwriting difficulties. Students performed the MHA test and were subjectively scored based on speed and handwriting quality using five primitives: *legibility*, *form*, *alignment*, *size*, and *space*. Several spatial parameters are shown to correlate significantly ($p < 0.001$) with subjective scores obtained for alignment, size, space, and form. Grip force and temporal measures, in turn, serve as useful indicators of handwriting legibility and speed, respectively. Using only size and space parameters, promising discrimination between proficient and non-proficient handwriting can be achieved.

1. Introduction

Handwriting, defined here as manuscript writing consisting only of individual printed letters, is an important life skill. Handwriting has been recognized by the child and youth edition of the International Classification of Functioning, Disability and Health (ICF) as a necessary skill for learning and applying knowledge [1]. It is known that difficulties in handwriting can lead to delay in the development of written language [2–4], diminished emotional well-being and social functioning [5,6] as well as reduced self-confidence and personal relationships [7]. To prevent the adverse effect of handwriting difficulties on child development, early referral for therapy is recommended [8], preferably during the second half of senior kindergarten [9].

The most commonly reported difficulties with handwriting are slow speed and reduced quality [10–12]. Teachers indicate, however, that readability of the written product is of primary concern [13]. Numerous handwriting assessments are available today [14] and serve as diagnostic tools to determine whether or not the student is writing at rates and quality

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doi:10.1016/j.cmpb.2010.12.010

levels that are comparable to their peers. Despite scoring criteria being available to guide therapists, existing handwriting quality assessment tests are laborious [15] and depend on subjective judgment of the written product [14].

In light of the significant economic and human resource invested in remediation and the risk of delaying child development through inappropriate intervention, clinicians acknowledge the need to better comprehend the underlying processes of handwriting for intervention planning [16]. As a consequence, there is growing interest in *quantitative determinants* of proficient handwriting. As attested by recent research, computerized instrumentation can play a key role in developing such metrics [15,17–21].

To date, computerized instrumentation has consisted mostly of digitizing tablets connected to a personal computer and have focused on measuring kinematics (e.g., position, angle, velocity, and acceleration of the pen), temporal parameters, and the downward (normal) force exerted by the pen on the writing surface. Only a few studies have measured grip forces, i.e., the forces exerted radially on the barrel of the writing utensil, for assessment of handwriting function [17,22,23]. Earlier work showed that grip force patterns differed between children and adults [22], while more recent work has suggested that grip strength can be used to distinguish able-bodied children with no known handwriting difficulties from children with spatic hemiplegic cerebral palsy and fine motor difficulties [17,23]. To the best of our knowledge, no published study has looked at grip force patterns to quantify handwriting difficulties in able-bodied children.

In this paper, a custom handwriting instrumentation system is described, built from off-the-shelf hardware that simultaneously measures grip forces, normal forces, *x*–*y* positions on the tablet, and timing information. We derived several *objective* parameters from these measures that may serve as correlates of the *subjective* Minnesota Handwriting Assessment (MHA) [24,25] rate score and handwriting quality primitives consisting of *legibility*, *form*, *alignment*, *size*, and *space*. The overarching goal of this study is to investigate the correlation between the proposed biomechanical parameters and subjective handwriting rate and quality scores. A secondary goal is to gauge the potential of discriminating between proficient and non-proficient handwriting on the basis of the proposed quantitative measures. Ultimately, it is hoped that computer-based analysis of written productivity, including automated analysis of grip force patterns, will allow for fast, reliable and objective assessment of handwriting proficiency in children.

2. Methods

2.1. *Participants*

Participants included 16 first-grade students and 19 second-grade students (ages 84.9 ± 7.3 months) recruited from a local community school. Participants were identified as proficient or non-proficient writers using the Minnesota Handwriting Assessment test described in Section 2.3. Using this test, nine students were deemed non-proficient, four of which were first graders. The study was approved by the research ethics boards of the hospital and participating elementary school. All participants freely consented to the study.

2.2. *Instruments*

A Wacom 9 in. × 12 in. Intuos3 digital tablet and an instrumented wireless pen were used in this study. A custom graphite nib for the Wacom pen was developed to better approximate the feel of a pencil and to provide the students with the conventional pen-to-paper experience they are accustomed to in their educational environment. The pen was further instrumented with a TekScan model 9811 pressure sensor array on its barrel (4 elements in azimuth by 8 elements along the axis of pen). The sensors measured the force applied radially to the barrel by the user's hand, i.e., the grip force. The total weight of the instrumented pen was 19.7 g with a diameter of 16.9 mm. This is somewhat heavier and thicker than a newly sharpened Dixon D308 primary school pencil (weight = 11.1 g, diameter = 10.3 mm) but physically similar to a child-sized Crayola marker (weight = 12.6 g, diameter = 14.9 mm) and to previously-reported instrumented pens (e.g., the one described in [17]).

Custom electronics were developed to multiplex the sensor signals for transmission over a thin, light, compliant cable to a National Instruments data acquisition card, as depicted in Fig. 1(a). Custom software was developed to record time stamps, x and y positions, and vertical pressures from the Wacon tablet at a sample rate of 75 Hz. Grip force at each of the 32 sensors on the pen barrel was also recorded by a custom software at a sample rate of 20 Hz. Both the tablet and grip sensor data acquisition programs were time-synchronized. Children's hand movements were also recorded on video in order to detect any events that may have caused prolonged pauses during the writing task.

2.3. *Minnesota Handwriting Assessment*

The Minnesota Handwriting Assessment (MHA) test requires students to copy words from a printed stimulus sheet either in manuscript or D'Nealian style print. The words are from the sentence "the quick brown fox jumped over lazy dogs", which are short in length and contain all letters of the alphabet. The words are presented in mixed order to reduce the memory advantage of better readers [25]; word order is displayed in Fig. 1(b). In this study, the manuscript version of the MHA was used.

The MHA is used due to its validity [14,26], as well as its short administration time of 2.5 min. The test subjectively quantifies five quality aspects of students' handwriting – *legibility*, *form*, *alignment*, *size*, and *space* – as well as a *rate* score. Alignment, size, and space are judged on the basis of ruler measurement; legibility and form, on the other hand, require subjective judgement. At the beginning of the rating process, a total of 34 points are given to each category (one point per letter). During rating, the total number of errors in each category are subtracted from this total. The rate score is determined based on the number of letters completed in the 2.5 min. The scores are then used to classify students as "performing like peers", "perform-

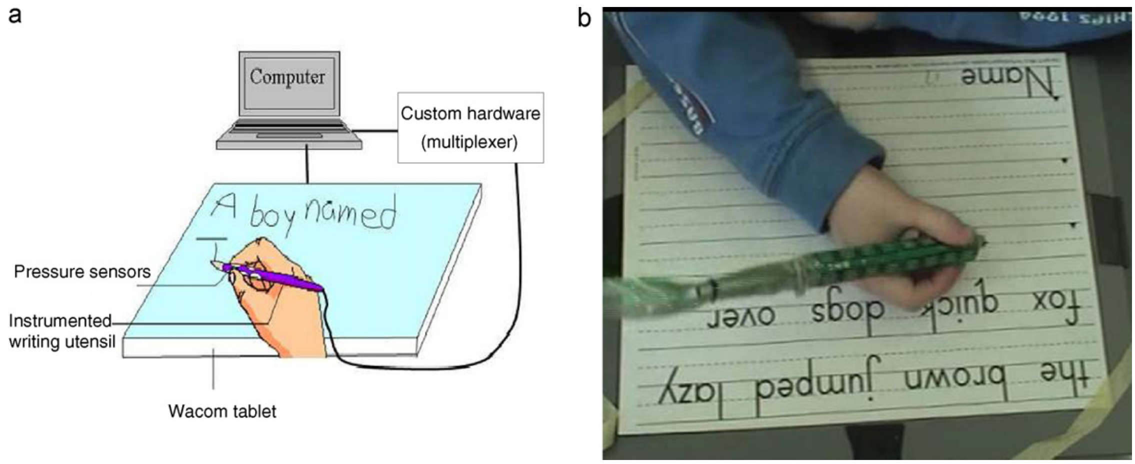

Fig. 1 – Custom-built handwriting instrumentation: (a) block diagram and (b) actual setup of the Wacom tablet with the Minnesota Handwriting Assessment test sheet.

ing somewhat below their peers," or "performing well below their peers".

2.4. *Experimental procedure*

All therapists involved in the study were required to complete the training protocol specified by the MHA before the test was administered. The Wacom tablet was placed on a desk or table at a comfortable height for the child and MHA test sheets were fastened with tape to the top of the tablet, as depicted in Fig. 1(b). Participants were given 2.5 min to copy all the words in the page and were instructed to copy letters with the same size as the example and to attempt to use good handwriting. Scoring was performed by two experienced raters and interrater reliability correlations ranged from 0.91 (legibility) to 0.98 (space). It was observed that the scores obtained with the instrumented pen were in line with those reported in the literature for average 1st and 2nd graders (e.g., [24–26]) using a conventional pencil, suggesting minimal effect of writing implement.

2.5. *Tablet data analysis*

To automate the scoring process, several parameters are computed from spatial metrics obtained from the tablet data. First, individual characters are detected and a bounding box is placed around the letter, as depicted in Fig. 2. The "centre of mass" (CM) of the letter enclosed by the bounding box is computed using Mathwork's Matlab® function *regionprops* and is represented with the symbol "×" in the figure. The width and height of bounding boxes are computed for two classes of letters: tall/descending (e.g., t,q,y) and small (e.g., x,o,r) letters. These parameters are represented as W_t and H_t, or W_s and H_s, respectively, in Fig. 2(a). Distances d between letters are quantified by the horizontal distance between two neighbouring CMs. Distances between words D, in turn, are quantified by the horizontal distance between the last letter in a word and the first letter of the next word. Lastly, the angles θ between two neighbouring CMs in a word are computed in degrees. Using these metrics, various geometric and spatial parameters are computed and used as correlates of four of the five MHA quality primitives, as detailed in the subsections to follow.

2.5.1. *Form*

Form is a quality primitive that describes letter quality, particularly capturing instances of exaggerated small letters (e.g., letter 's' in Fig. 2(b)) and compressed tall/descending letters (e.g., letter 'k' in Fig. 2(b)). Using the widths and heights of the detected bounding boxes, we propose to use three correlates of letter form, namely, the average small and tall letter aspect ratios ($\overline{AR}_s$ and $\overline{AR}_t$ respectively), and the ratio of small-to-tall letter aspect ratios (STAR). The three measures are given by

$$\overline{AR}_s = \frac{1}{21}\sum_{i=1}^{21}\frac{W_{s,i}}{H_{s,i}}, \tag{1}$$

$$\overline{AR}_t = \frac{1}{13}\sum_{i=1}^{13}\frac{W_{t,i}}{H_{t,i}}, \tag{2}$$

$$\text{STAR} = \frac{\overline{AR}_s}{\overline{AR}_t} \tag{3}$$

where the values "21" and "13" in the denominators (and upper summation limits) in the first two equations correspond to the total number of small and tall letters, respectively. The STAR measure should ideally be close to 2, as both letter types should have equal widths but tall letters should have double the height of small letters (since students were supposed to write within the reference lines depicted by Fig. 1(b)). Significant deviations from this threshold indicate that the child is not consistent with their form. For the purpose of this study, both ascending (e.g., 't') and descending ('g') letters are considered to be tall letters.

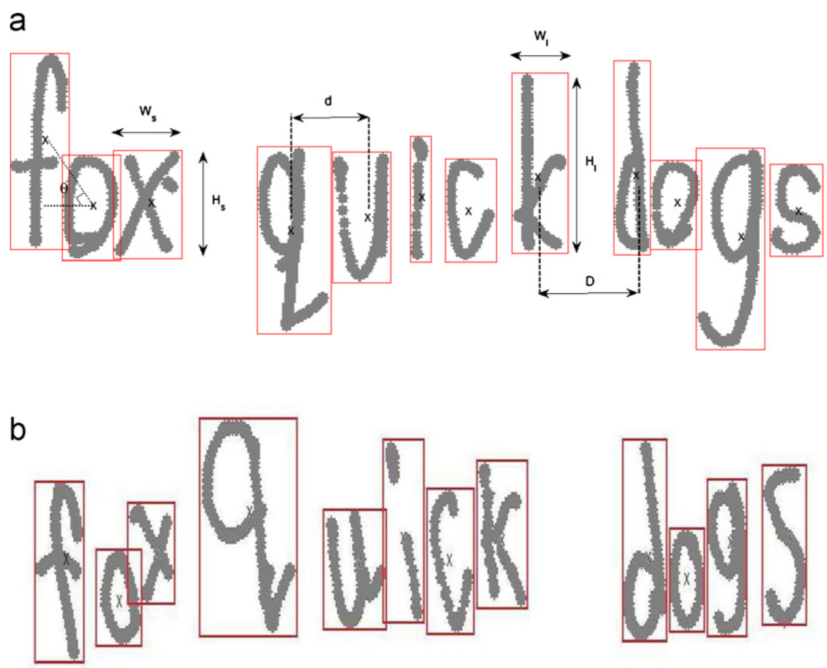

Fig. 2 – Automatic segmentation for letter detection for (a) proficient and (b) non-proficient writer. The "×" symbol represents the "centre of mass" of the letter surrounded by the bounding box.

2.5.2. *Alignment*

The alignment quality primitive identifies letters placed far above or below the reference lines available in the MHA score sheets (see Fig. 1(b) and the word 'fox' in Fig. 2(b)). Using the angles computed between successive CMs, we propose to use i) average angle between successive CMs within a word ($\bar{\theta}$), averaged over all eight words (i.e, a total of 26 angles) and ii) standard deviation of the angles (σ_A) as correlates of alignment. Parameters are computed as:

$$\bar{\theta} = \frac{1}{26}\sum_{i=1}^{26}\theta_i \tag{4}$$

$$\sigma_A = \sqrt{\frac{1}{25}\sum_{i=1}^{26}(\theta_i - \bar{\theta})}. \tag{5}$$

2.5.3. *Size*

The size quality primitive measures the distances of the letters to the mid, upper (for ascenders), and lower reference lines (for descenders) available in the MHA score sheets. Using the detected bounding boxes, we propose to use i) coefficient of variation (CV_H) of both tall and small letter heights $\mathcal{H} = \{H_s, H_t\}$ and ii) tall-to-small letter height ratio (TSHR) as quantitative determinants of size. Parameters are computed as follows:

$$CV_H = \frac{\sqrt{\frac{1}{33}\sum_{i=1}^{34}(\mathcal{H}_i - \overline{\mathcal{H}})}}{\overline{\mathcal{H}}} \times 100\%, \tag{6}$$

$$\text{TSHR} = \frac{\overline{H}_t}{\overline{H}_s}, \tag{7}$$

where

$$\overline{H}_s = \frac{1}{21}\sum_{i=1}^{21}H_{s,i},$$

$$\overline{H}_t = \frac{1}{13}\sum_{i=1}^{13}H_{t,i}, \text{ and}$$

$$\overline{\mathcal{H}} = \frac{1}{34}\sum_{i=1}^{34}\mathcal{H}_i,$$

where again, the values "21" and "13" in the denominators and upper summation limits correspond to the total number of small and tall letters, respectively, and "34" is the total number of letters.

2.5.4. *Space*

The space quality primitive identifies excessive or insufficient spaces between successive letters and/or words (e.g., excessive space between 'quick dogs' in Fig. 2(b)). Using inter-letter and inter-word distances computed from the tablet data, we propose to use i) the average normalized inter-letter distance (NILD) and ii) the average normalized inter-word distance (NIWD) as estimators of the space primitive. These parameters are given by:

$$\text{NILD} = \frac{\frac{1}{26}\sum_{i=1}^{26}d_i}{\text{STAR}}, \tag{8}$$

$$\mathrm{NIWD} = \frac{\frac{1}{6}\sum_{i=1}^{6} D_i}{\mathrm{STAR}}, \tag{9}$$

where the values "26" and "6" correspond to the number of spaces between letters and between words, respectively.

2.6. *Grip force analysis*

Grip force is defined here as the force magnitudes applied to all 32 grip sensors on the pen and summed to result in an overall grip force measure $F(t)$, given in Newtons, for time instance t. While the instrumented acquisition system provided discrete-time data, we use continuous-time notation for convenience. Grip force measurements from each of the 32 grip sensors on the pen were calibrated using vendor data. It is hypothesized that metrics derived from temporal grip force patterns can provide correlates of quality primitives *form* and *legibility* as biomechanical processes likely play a significant factor in poor handwriting (e.g., increased stiffness) [27]. Past research with children with cerebral palsy has already demonstrated that several grip force parameters may serve as indicators of non-proficient printing [17].

In order to observe the variability of the grip forces over time, the root-mean-square (F_{rms}) value of the overall grip force temporal series was computed for consecutive T-second segments, i.e.,

$$F_{rms}(n) = \sqrt{\frac{1}{T}\int_{(l-1)T}^{lT} F(t)^2 dt}. \tag{10}$$

Here, T is empirically set to 2 s, thus 75 F_{rms} segments were available in the 2.5 min data recording session. In particular, we computed the standard deviation (σ_{rms}) of the F_{rms} temporal series, given by:

$$\sigma_{rms} = \sqrt{\frac{1}{74}\sum_{n=1}^{75}(F_{rms}(n) - \bar{F}_{rms})}, \tag{11}$$

where

$$\bar{F}_{rms} = \frac{1}{75}\sum_{n=1}^{75} F_{rms}(n).$$

2.7. *Temporal analysis*

Vertical pressures and timing recorded by the digitizing tablet are used to compute average per-stroke durations ($\overline{TS}$) and the standard deviation of per-stroke durations (σ_T). Each stroke duration TS_i is computed as the time duration where vertical pressures were detected by the instrumentation (i.e., "on-paper" times). Motivated by previous studies [15,18,19], total in-air time (IA) is also computed and explored as a potential correlate of the MHA rate score. To account for unexpected pauses (e.g., child scratching arm), videos were analyzed whenever in-air duration exceeded 2 s. The temporal parameters are computed as:

$$\overline{TS} = \frac{1}{N_s}\sum_{i=1}^{N_s} TS_i,$$

$$\sigma_T = \sqrt{\frac{1}{N_s - 1}\sum_{i=1}^{N_s}(TS_i - \overline{TS})},$$

$$IA = \sum_{i=1}^{N_{ia}} IA_i,$$

where N_s and N_{ia} are the total number of strokes and in-air periods, respectively.

2.8. *Automated discrimination of proficient handwriting*

According to MHA guidelines, students whose scores were in the lower 25th percentile of the grade-level samples were considered to be performing "below their peers," thus suggesting non-proficient writing [24]. Using this classification strategy, nine of the 35 participants were considered to be non-proficient writers, four of which were in grade one and five in grade two. Careful analysis of each individual MHA quality primitive suggests that for both grades *legibility*, *size*, and *space* are the three most influential factors in characterizing non-proficient writing, as shown in Fig. 3(a). Primitives *size* and *space*, however, exhibit the most discrimination power, as illustrated by Fig. 3(b). As a consequence, we investigate the use of size- and space-dependent parameters CV_H, TSHR, NILD, and NIWD for automated discrimination of proficient handwriting.

3. Results

Pearson correlation coefficients were computed between all proposed measures and the MHA rate and five subjective quality scores. Tables 1–3 report significant correlations ($p < 0.001$) for all participants, as well as for participants separated by grade and by handwriting proficiency, respectively. The average small and average tall letter aspect ratios, as well as the in-air time parameter are omitted from the tables as they resulted in insignificant correlations with MHA rate and quality scores. For correlations separated by grade and writing proficiency (Tables 2 and 3, respectively), Fisher's z-test with a 90% confidence level is used to explore if differences in correlations are statistically significant. When separated by grade, parameters with correlations that differ significantly ($p < 0.1$, identified by an asterisk in the table) are related to letter size and spacing. Moreover, when separated by writing proficiency, significant differences in correlations are observed only for parameters related to alignment. For second graders and for non-proficient writers, the computation of correlation coefficients for the temporal measures was not possible (indicated by the term "NaN," not a number, in the table) as all students obtained the same full rate score.

For automated discrimination of proficient handwriting, it is observed that proposed parameters σ_{rms}, NILD,

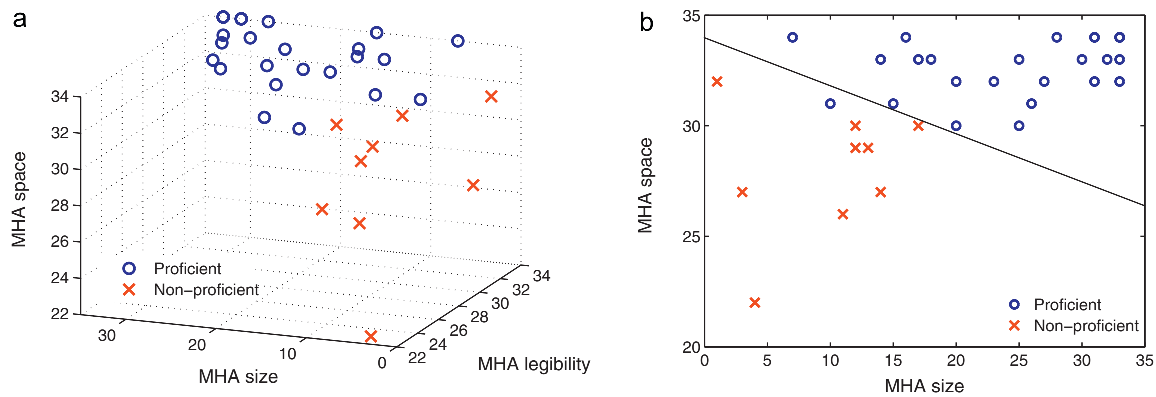

Fig. 3 – Scatter plot of MHA quality primitives: (a) *legibility*, *size*, and *space* and (b) *size* versus *space*. Symbols "o" and "×" correspond to proficient and non-proficient writers, respectively. Note that some proficient writers obtained equal space and size MHA scores, thus overlap in the plots. The solid line represents the best line that separates the two classes of writers.

Table 1 – Correlations obtained between the proposed measures and the MHA rate score and the five handwriting quality primitives for all 35 participants.

Analysis	Proposed measure	Overall, $n = 35$					
		Rate	Leg.	Form	Align	Size	Space
Temporal	$\overline{TS}$	−0.66					
	σ_T	−0.67					
Grip force	σ_{rms}		0.73	0.68			
Tablet	STAR			−0.83			
	$\bar{\theta}$				−0.81		
	σ_A				−0.89		
	CV_H					0.77	
	TSHR					0.88	
	NILD						−0.87
	NIWD						−0.74

Table 2 – Correlations obtained between the proposed measures and the MHA rate score and the five handwriting quality primitives separated by student grade. The term "NaN" indicates that computation of the correlation coefficient was not possible since all students obtained the same subjective score. An asterisk indicates that differences in correlation coefficients between 1st and 2nd graders were statistically significant ($p < 0.1$) at a 90% confidence level using Fisher's z-test.

Analysis	Proposed measure	1st Grade, n=16						2nd Grade, n=19					
		Rate	Leg.	Form	Align	Size	Space	Rate	Leg.	Form	Align	Size	Space
	$\overline{TS}$	−0.66						NaN					
Temporal	σ_T	−0.74						NaN					
Grip force	σ_{rms}		0.74	0.70					0.70	0.65			
Tablet	STAR			−0.87						−0.80			
	$\bar{\theta}$				−0.81						−0.76		
	σ_A				−0.92						−0.83		
	CV_H					0.89*						0.73*	
	TSHR					0.92						0.90	
	NILD						−0.92*						−0.80*
	NIWD						−0.87						−0.74

and TSHR are most influential, as illustrated by Fig. 4(a). Size- and space-dependent parameters NILD and TSHR, in turn, are shown to convey the most discriminatory power and, as depicted by Fig. 4(b), can correctly identify all non-proficient writers with a simple linear classification strategy based on linear discriminant analysis [28].

4. Discussion

4.1. *Beyond screening: identification of specific issues with rate and quality*

Literature has supported the use of digitized tools to conduct or assist with handwriting assessments [15,17–21]. Most

Table 3 – Correlations obtained between the proposed measures and the MHA rate score and the five handwriting quality primitives separated by writing proficiency. The term "NaN" indicates that computation of the correlation coefficient was not possible since all students obtained the same subjective score. An asterisk indicates that differences in correlation coefficients between (non-) proficient writers were statistically significant ($p < 0.1$) at a 90% confidence level using Fisher's z-test.

Analysis	Proposed measure	Proficient, n=26						Proficient, n=9					
		Rate	Leg.	Form	Align	Size	Space	Rate	Leg.	Form	Align	Size	Space
	$\overline{TS}$	−0.70						NaN					
Temporal	σ_T	−0.72						NaN					
Grip force	σ_{rms}	−0.72	0.68	0.46					0.66	0.59			
Tablet	STAR			−0.85						−0.74			
	$\bar{\theta}$				−0.65*						−0.88*		
	σ_A				−0.81						−0.90		
	CV_H					0.63						0.73	
	TSHR					0.79						0.78	
	NILD						−0.72						−0.83
	NIWD						−0.64						−0.29

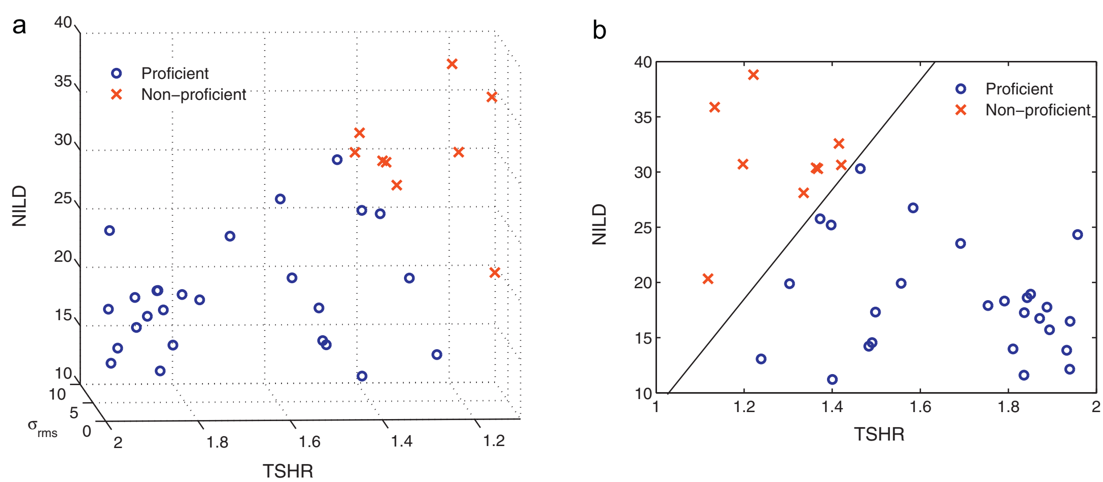

Fig. 4 – Scatter plot of (a) σ_{rms}, TSHR, and NILD and (b) NILD versus TSHR. Symbols "o" and "×" correspond to proficient and non-proficient writers, respectively. The solid line represents the best line that separates the two classes.

digitized tools, however, have only focused on screening for non-proficient writing, and have not identified the specific difficulties in written productivity which contribute to poor handwriting, such as poor letter form. This study has taken a first step towards the automatic identification of specific handwriting difficulties. In particular, significant correlations between quantitative parameters and expert ratings of rate and quality (legibility, form, alignment, size and spacing) have been uncovered. These findings suggest that it may be possible to comprehensively assess handwriting rate and quality objectively, using an instrumented writing utensil and digitizing tablet. For example, by measuring grip force during a handwriting task, it may be possible to infer legibility, given the high correlation between these two variables ($r = 0.73$, $p < 10^{-6}$). Likewise, the standard deviation of the angle between the centre of mass of consecutive words would assist at pinpointing alignment issues, as these two variables are also strongly anti-correlated ($r = -0.89$, $p < 10^{-13}$). The standard deviation of stroke durations would provide information about handwriting rate ($r = -0.67$, $p < 10^{-5}$), while small-to-tall letter aspect ratios would reveal issues of letter form ($r = -0.83$, $p < 10^{-9}$). Finally, tall-to-small letter height ratios may identify size discrepancies ($r = 0.88$, $p < 10^{-12}$), whereas normalized inter-letter distances would uncover irregular spacing ($r = -0.87$, $p < 10^{-12}$).

Taken together, these strong correlations suggest that in the future, handwriting rate and quality might be quickly and objectively assessed from a short writing sample using an instrumented utensil and digitizing tablet. These objective assessments could complement clinical acumen and subjective ratings. In fact, treatment decisions may be better informed with the addition of biomechanical quantities which evaluate specific aspects of writing quality. Conventional handwriting assessments like the MHA often require specialized test materials and trained raters, therefore demanding non-trivial commitments of time and human resources – a luxury often not available in most school settings. The findings reported herein support the development of an economical and objective computerized handwriting assessment that retains the critical and targeted information about rate and quality.

4.2. Grade- and function-dependent correlates of rate and quality

Comparing grades one and two, significant differences were found in the correlations between subjective scores and quantitative parameters relating to size and space (i.e., coefficient of variation of letter heights and average normalized inter-letter distances). It is observed, however, that the correlations in question are all high ($|r| > 0.73$) and are consistent in direction between grades. This finding suggests that while the patterns of correlation are similar across grades, the letter height and inter-letter distance parameters are more strongly associated with size and space quality primitives, respectively, for younger writers. Given that handwriting is a relatively new skill at the ages under consideration, it is not surprising that there may be a developmental profile to certain quantitative measures, due in part to progressive motor maturation, as argued in [29]. In turn, this suggests that grade-level or age-specific assessments may be necessary, as also argued in [24].

Comparing proficient and non-proficient writing, the only significant difference in correlation was observed between subjective scores and the average within-word angles; for non-proficient writing, a stronger anti-correlation was observed. As the written letters depart further from the reference lines, the angle between successive centres of mass within a word increases, but more so in non-proficient writing. This finding suggests that while the direction of correlation is consistent across proficient and non-proficient writing, certain quantitative parameters may be more sensitive in detecting specific quality deficits, a finding also argued in [30].

4.3. The need for grip force measurement

An additional important finding of this study is the fact that tablet information alone is shown to provide insufficient information for objective measurement of the legibility quality primitive, as all spatial- and temporal-related measures resulted in insignificant correlations with subjective scores. To this end, grip force analysis, made possible by the custom-built instrumentation described in Section 2.2, is required. The proposed grip force measure – standard deviation of grip force root-mean-square values – describes the child's grip strategy and its dynamics over time. Significant positive correlations attained with MHA legibility scores suggest that more dynamic grasps (higher σ_{rms}) are related to improved legibility. Such quantitative finding is in line with clinical acumen [31] and warrants further investigation.

4.4. Automated discrimination between proficient and non-proficient writing

Interestingly, in-air time, a parameter previously proposed as being acutely discriminatory between proficient and non-proficient Hebrew writing [19,32], exhibited no significant correlations with MHA rate scores ($p = 0.53$). Hebrew writing consists of disjoint letters mostly formed in a counter-clockwise direction, written from right to left, with vowels formed by adding dots or lines below or above letters [33]. Since the amount of dots and crosses used in the MHA were significantly lower from the dots and crosses used in [19,32], we suspect these differences may have lead to the discrepant in-air time results between the present English and previous Hebrew writing studies.

On the other hand, average stroke duration exhibited significant differences (*t*-test, $p = 0.03$) between proficient and non-proficient writing, with the latter requiring more time per-stroke. This finding resonates with clinical observation that children with handwriting difficulties often write slower and corroborate literature reports of the same (e.g., [34]). Parameters relating to letter size and space conveyed the most discriminatory information between proficient and non-proficient writing. As emphasized by Fig. 4, non-proficient writing is categorized mostly by large inter-letter distances and the inability to discriminate between small and tall/descending letter sizes. Similar findings have been reported previously where spatial inaccuracies were shown to significantly contribute to poor handwriting in children [35–37].

4.5. Limitations

The results presented herein are based on a single administration of the MHA on a digitizing tablet. The repeatability of the quantitative parameters would need to be investigated before they could serve as an adjunct to conventional subjective assessments. The correlation findings described herein are based exclusively on the critical grades during which handwriting quality rapidly develops [38,39], but the broader developmental profiles of the identified parameters deserve further investigation by way of a larger cross-sectional study. The reported discrimination between proficient and non-proficient writing is based largely on the graphical demarcation of a two-dimensional feature space using a simple linear classifier at present. The systematic identification of key diagnostic parameters would necessitate more rigorous quantification of the discriminatory power of different combinations of quantitative parameters.

5. Conclusion

We have described and validated an innovative computer-based handwriting assessment tool to objectively quantify handwriting proficiency in children. Ten parameters are proposed based on spatial metrics computed from an x–y digitizing tablet and from grip force patterns measured from a custom-built pen instrumented with 32 force sensors. The proposed parameters are statistically associated with the five handwriting quality primitives available in the Minnesota Handwriting Assessment test as well as writing speed. As a consequence, automatic identification of specific difficulties in written productivity may be made possible with the use of digitized handwriting tools, thus overcoming the need for time-consuming, resource-intensive subjective assessments. Moreover, the proposed parameter obtained from grip force measurements suggests that writers who possess a more static grip force pattern attain lower legibility scores. Lastly, the proposed parameters relating to letter size and spacing demonstrate potential for discriminating between proficient and non-proficient handwriting in children.

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