Grip Force Variability and Its Effects on Children's Handwriting Legibility, Form, and Strokes

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A comprehensive understanding of the underlying biomechanical processes during handwriting is needed to accurately guide clinical interventions. To date, quantitative measurement of such biomechanical processes has largely excluded measurements of the forces exerted radially on the barrel of the writing utensil (grip forces) and how they vary over time during a handwriting task. An instrumented writing utensil was deployed for a direct measurement of kinematic and temporal information during a writing task, as well as forces exerted on the writing surface and on the barrel of the pen. The writing utensil was used by a cohort of 35 students (19 males), 16 in first grade and 19 in second grade, as they performed the Minnesota Handwriting Assessment (MHA) test. Quantitative grip force variability measures were computed and tested as correlates of handwriting legibility, form, and strokes. Grip force variability was shown to correlate strongly with handwriting quality, in particular for students classified by the MHA as nonproficient writers. More specifically, static grip force patterns were shown to result in poor handwriting quality and in greater variation in handwriting stroke durations. Grip force variability throughout the writing task was shown to be significantly lower for nonproficient writers (t-test, $p<0.01$) while the number of strokes and per-stroke durations were shown to be higher ($p<0.03$). The results suggest that grip force dynamics play a key role in determining handwriting quality and stroke characteristics. In particular, students with writing difficulties exhibited more static grip force patterns, lower legibility and form scores, as well as increased variation in stroke durations. These findings shed light on the underlying processes of handwriting and grip force modulation and may help to improve intervention planning.
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1 Introduction

Handwriting is a complex skill requiring integration of cognitive, perceptual, sensory, and motor abilities [1], including high levels of coordination and high-precision force regulation [2]. Proficient handwriting typically involves coordinated control of the arm, wrist, and small movements of the fingers, particularly the flexion-extension of the finger joints and abduction-adduction of the wrist joint [3]. As a consequence, underdeveloped fine motor skills and proprioception-kinesthesia are leading causes of handwriting difficulties among young children [4–7], negatively impacting letter size and placement [1,4], handwriting fluency [1], pencil grasp, and the forces exerted on the writing utensil (i.e., grip force) [1,6,8,9]. Ultimately, difficulties with handwriting may affect a child's academic success, development of written language, and social-emotional well-being [10,11]. As a consequence, reliable assessments are needed to identify children with handwriting difficulties so that interventions can be provided in a timely and effective manner.

Grip form and its effects on handwriting legibility, speed, and endurance have been extensively studied in the past [9,12–16]. Earlier work reported in Refs. [5,12] has suggested that grip form is strongly related to writing difficulty, and nonproficient writers showed more immature static grips relative to proficient writers who used more dynamic tripodlike grasps. Other studies, however, have produced conflicting results [13–15] and have suggested that grip form bears negligible consequence on handwriting legibility and speed. All such studies, however, have been subjective and have focused on classifying grip forms based on the analysis of videos of children's hands during handwriting. Poor proprioceptive-kinesthetic awareness, however, may influence not only pencil grip but also the force applied to the writing utensil [1], a factor difficult to quantify subjectively. Additionally, the ability to change grip patterns during writing has been noted to be an important factor in handwriting fluency [9]. "Quantitative" studies that relate grip force variability and handwriting performance are lacking in the literature.

With the use of computer instrumentation for handwriting assessment on the rise [9,17–19], direct measurement of the biomechanical processes involved in handwriting has become possible. For example, instrumentation has been used to measure kinetic (e.g., point pressure on writing surface) and temporal (e.g., pen-paper contact time and pen-lift time) information and their effects on the final written product [9,17]. More recently, pressure sensor arrays have also been instrumented to the barrel of the writing utensil, thus allowing for accurate measurement of grip forces during a handwriting task [18–20]. The work described in Ref. [18], for example, showed that the grip force could be used to distinguish able-bodied children with no known handwriting difficulties from children with spastic hemiplegic cerebral palsy and fine motor difficulties. More recently, fractal properties of grip forces measured during a 2 min pediatric handwriting assessment performed by proficient writers were shown to be poor indicators of handwriting quality [20], suggesting that proficient handwriting may not be associated with the repetitiveness of grip force patterns, but more so, on their variability over time, as suggested in Ref. [21].

In this paper, we take the first steps toward "quantitatively" characterizing the effects of grip force variability on handwriting

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legibility, form, and stroke production. For example, clinical acumen suggests that more dynamic grasps are related to better legibility, but this has not been demonstrated empirically. Ultimately, it is hoped that with automated analysis of grip force patterns, fast and reliable objective assessment of handwriting proficiency in children will be possible.

2 Method

2.1 Participants. A convenience sample of 35 students (19 males) was recruited from a local public elementary school, 16 of which were in first grade and 19 were in second grade. The mean participant age for first graders was 6 years and 7 months (standard deviation(SD)=5 months), and for second graders, it was 7 years and 6 months (SD=4 months). All students, with the exception of one first grader, were right-handed. The study was approved by the research ethics boards of the hospital and the participating school board, and all participants freely consented to the study.

2.2 Assessment. Participants were identified as proficient or nonproficient writers based on the scores obtained with the MHA test [22,23], which quantifies five quality aspects of students' handwriting, namely, legibility, form, alignment, size, and space, as well as writing speed. Students copied words from the sentence, "The quick brown fox jumped over lazy dogs," where the words were presented in scrambled order across two lines in order to reduce the memory advantage of better readers [22]. Initially, a total of 34 points were given to each quality category (one point per letter). During the scoring process, the total number of errors in each category was subtracted from this total. Lastly, per-category quality scores were summed to obtain an overall score; lower scores indicated poorer handwriting quality. Individuals that attained overall scores in the lower fifth percentile of their grade distribution were classified as "nonproficient" writers or students "performing well below their peers" [23]. Based on such criteria and on subjective scores obtained from two expert raters (inter-rater reliability of 0.93), nine students were deemed nonproficient, four of which were first graders. Gender distribution was balanced across the two groups with 57% and 45% male participants in the proficient and nonproficient groups, respectively.

2.3 Instrumentation. The instrumentation used in this study consisted of a Wacom 9×12 in.^{2} Intuos3 digital tablet (Wacom Co., Ltd., Vancouver, Canada) and a custom-built wireless pen [18]. To better approximate the feel of a pencil and to provide the students with the familiar pencil-to-paper experience, a custom graphite nib was developed for the wireless writing utensil. The pen was instrumented with a TekScan model 9811 pressure sensor array (TekScan Inc., Boston, MA) on its barrel—four elements in azimuth by eight elements along the axis of the pen—to allow for measurement of grip forces. The total weight of the instrumented pen was 19.7 g, and the diameter of the pen was 16.9 mm. Although our instrumented pen is somewhat heavier and thicker than a Dixon D308 primary school pencil (weight=11.1 g, diameter =10.3 mm), it is 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 Ref. [18]).

2.4 Procedure. 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. The participants were given 2.5 min to copy all the words in the test sheet and were instructed to copy letters with the same size as the example given and to attempt to use good handwriting [23]. Time stamps, x- and y-axes positions, and vertical pressures exerted on the Wacom tablet were recorded by a custom-written software at a sample rate of 75 Hz. Grip force measurements at each of the 32 sensors on the pen barrel were also recorded in synchronicity with the tablet data. Videos were recorded of hand movements in order to retrospectively detect any events that may have caused prolonged pauses during the writing task, such as scratching of an arm.

2.5 Data and Statistical Analysis. Grip force measurements from each of the 32 grip sensors on the pen were calibrated using vendor data and summed to result in an overall grip force measure $F(t)$ given in Newtons for time instance t. Note that while discrete-time data were available, we use continuous-time notation below for convenience. Since we were interested in observing the variability of the grip forces over time and to understand its effects on handwriting legibility, the root-mean-square (F_{rms}) value of the overall grip force temporal series was computed for consecutive T-second segments, i.e.,

$$F_{\text{rms}}(n) = \sqrt{\frac{1}{T}\int_{(l-1)*T}^{l*T} F(t)^2 dt}, \quad l = 1, \ldots, 75 \tag{1}$$

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 considered three parameters: the mean (μ_{rms}), the standard deviation (σ_{rms}), and the coefficient of variation (ζ_{rms}) of the 75 computed F_{rms} segments. The parameters are given, respectively, by

$$\mu_{\text{rms}} = \frac{1}{75}\sum_{l=1}^{75} F_{\text{rms}}(l) \tag{2}$$

$$\sigma_{\text{rms}} = \sqrt{\frac{1}{74}\sum_{l=1}^{75} [F_{\text{rms}}(l) - \mu_{\text{rms}}]^2} \tag{3}$$

$$\zeta_{\text{rms}} = \frac{\sigma_{\text{rms}}}{\mu_{\text{rms}}} \tag{4}$$

Furthermore, we investigated the effects of grip force variability on handwriting strokes. Vertical pressures $p_v(t)$ and timing information were recorded by the digitizing tablet and were used to compute stroke durations, here defined as the length of time that contiguous segments with $p_v \neq 0$ (i.e., "on-paper" times) were detected by the instrumentation. Similar to the parameters computed for grip forces, the total number of strokes $\mathcal{S}$, the average per-stroke duration μ_S, and the standard deviation of all stroke durations σ_S were computed.

A two-sided t-test ($\alpha=0.05$) was used to examine differences between the two groups of writers, both in terms of grip forces and writing fluency. Moreover, Pearson correlations r between the grip force and MHA legibility and form scores were examined, as well as correlations between fluency and grip force related parameters. To examine if the computed correlations differed significantly between proficient (r_{prof}) and nonproficient (r_{nprof}) writers, a Fisher's z-test ($\alpha=0.05$) was used [24]. First, a Fisher transformation was applied to the two correlations, i.e.,

$$r' = 0.5 \ln\left|\frac{1+r}{1-r}\right| \tag{5}$$

The z-statistic was then computed between the two transformed correlations using

$$z = \frac{r'_{\text{prof}} - r'_{\text{nprof}}}{\sqrt{\dfrac{1}{n_{\text{prof}}-3} + \dfrac{1}{n_{\text{nprof}}-3}}} \tag{6}$$

where $n_{\text{prof}}=26$ and $n_{\text{nprof}}=9$ are the numbers of samples used to compute the correlations.

Similarly, a t-test ($\alpha=0.05$) was performed to investigate if the slopes from least-squares regression analyses (between proposed parameters and MHA scores or between proposed fluency and grip force parameters) were significantly different between the

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Table 1 Correlations obtained between the three quantitative rms-based grip force parameters and the Minnesota Handwriting Assessment scores for handwriting quality primitives "legibility" and "form" for all 35 participants and for participants separated by writing proficiency. An asterisk indicates correlations significantly different from proficient writers ($p<0.05$) and an "†" indicates correlation coefficient significantly different from zero ($p<0.05$).

	Overall, $n=35$		Proficient, $n=26$		Nonproficient, $n=9$	
Grip force parameter	Legibility	Form	Legibility	Form	Legibility	Form
μ_{rms}	$0.56^{\dagger}$	$0.51^{\dagger}$	0.45	0.29	0.47	0.40
σ_{rms}	$0.73^{\dagger}$	$0.68^{\dagger}$	0.68	0.46	0.66	0.59
ζ_{rms}	$0.80^{\dagger}$	$0.77^{\dagger}$	0.75	0.52	0.92^{*}	0.93^{*}

two groups. The test statistic was computed as follows:

$$t = \frac{a_{\mathrm{prof}} - a_{\mathrm{nprof}}}{\sqrt{s^2_{a_{\mathrm{prof}}} + s^2_{a_{\mathrm{nprof}}}}} \tag{7}$$

with $n-$four degrees of freedom ($n=35$), where a_x denotes the slope obtained for proficient (x=prof) or nonproficient (x=nprof) writers and "s_{a_x}" denotes the standard error of the slope obtained for the respective group.

3 Results

Table 1 reports correlations significantly different from zero ($p<0.05$) between rms-based grip force measures and MHA legibility and form scores for all participants, as well as for participants separated by handwriting proficiency. Correlations between stroke-related parameters and MHA scores are not reported as they were not significantly different from zero ($p>0.05$). As observed in the table, significant differences in correlations between the two groups were only observed for the ζ_{rms} parameter for both legibility and form quality primitives.

Figure 1 depicts the MHA legibility score (subplot a) and the MHA form score (subplot b) versus ζ_{rms} for proficient and nonproficient writers, respectively. Moreover, the dashed and solid lines represent the least-squares linear fit for nonproficient and proficient writers; R^2 statistics and p-values are also reported for each regression line. The results indicate that for students with handwriting difficulties, legibility and form scores increase linearly with ζ_{rms}, suggesting that more dynamic grip forces are needed (higher ζ_{rms}) for improved handwriting legibility. While the linear relationship was shown for both groups, higher R^2 was obtained for the nonproficient group, suggesting that for nonproficient writers, handwriting legibility and form are more sensitive to changes in ζ_{rms}. Additionally, for proficient writers, higher ζ_{rms} values were observed (see results in Table 2) and lower correlations with expert ratings were obtained (see Table 1).

Table 2 further reports the per-group statistics as well as significance t-test results for the proposed grip force rms and stroke-related measures for children in both groups. It can be observed that students classified as nonproficient writers obtained significantly lower rms-based measures relative to their peers. Nonproficient writers also produced more strokes (higher $\mathcal{S}$) and took more time per-stroke (higher μ_S) relative to their peers.

To further explore the effects of grip force variability on handwriting strokes, stroke-related parameters were analyzed as a function of ζ_{rms} for both groups. Figure 2 depicts the relationships observed for stroke parameters μ_S and σ_S. In the plots, the dashed and solid lines represent the least-squares linear fit for nonproficient and proficient writers, respectively; R^2 statistics and p-values are also reported for each regression line. For both groups, a negative slope was observed between μ_S and ζ_{rms}, indi-

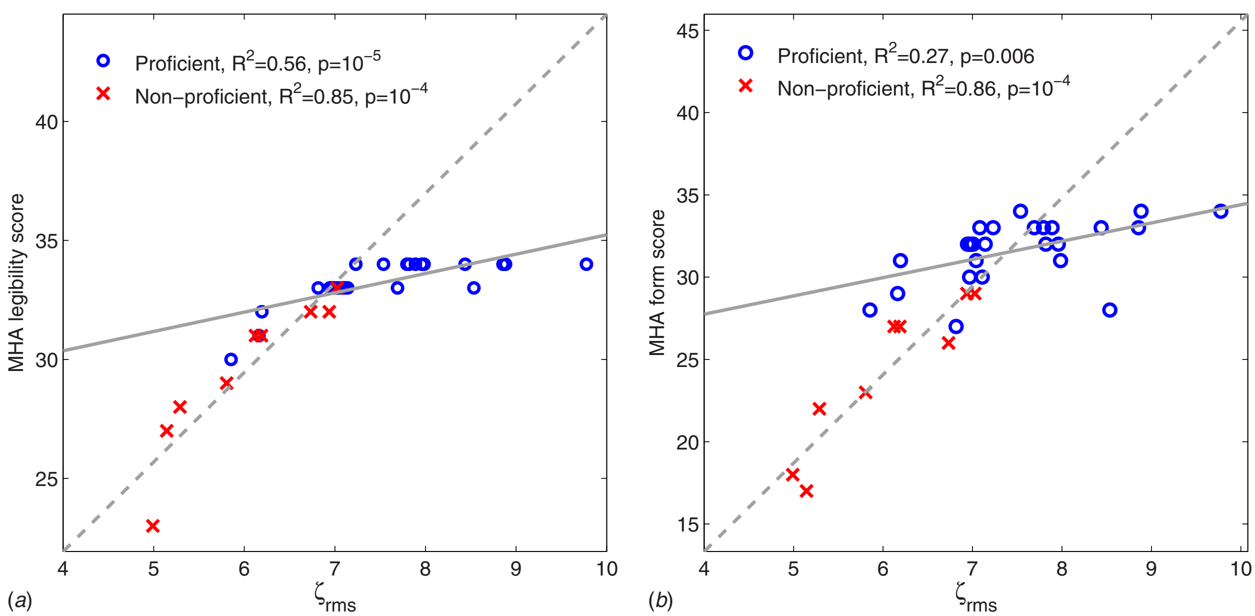

Fig. 1 Plots of Minnesota Handwriting Assessment scores for (*a*) legibility and (*b*) form versus ζ_{rms} for proficient and nonproficient writers. Dashed and solid curves represent linear fits for nonproficient and proficient writers, respectively. The R^2 statistics and p-values are also reported for each regression line.

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Table 2 Significance t-test between groups for all grip rms- and stroke-related parameters. Table reports mean, SD, and p-values. All measures with the exception of σ_S have differences between groups that are statistically significant ($p<0.05$).

		Proficient, $n=26$	Nonproficient, $n=9$	
Parameter modality	Quantitative parameter (units)	Mean (SD)	Mean (SD)	p
Grip rms	μ_{rms} (N)	22.95 (4.25)	18.4 (5.10)	0.01
	σ_{rms} (N)	1.75 (0.40)	1.15 (0.45)	0.0006
	ζ_{rms} (%)	7.49 (0.91)	6.03 (0.77)	0.0001
Stroke	$\mathcal{S}$	72.03 (13.69)	85.78 (16.91)	0.02
	μ_S (s)	0.94 (0.38)	1.22 (0.25)	0.03
	σ_S (s)	0.52 (0.14)	0.48 (0.12)	0.49

cating that more static grip patterns (lower ζ_{rms}) resulted in longer stroke durations. Significant differences between the two lines, however, were not observed between the two groups ($p>0.05$). Variation in stroke durations (σ_S), in turn, was shown to attain a significantly higher R^2 for nonproficient writers ($p<0.05$) with proficient writers obtaining an R^2 close to zero (suggesting no correlation). These findings suggest that for nonproficient writers, lower grip force variability is strongly associated with a larger variation in per-stroke durations.

4 Discussion

4.1 Grip Force Variability and Handwriting Legibility. This study has provided evidence of a relationship between grip force variability and handwriting legibility. When correlations between grip force related parameters and MHA legibility and form scores were calculated separately for proficient and nonproficient writers, significant differences were observed for the proposed coefficient of variation parameter—a measure indicative of the child's grip strategy and its dynamics over time. This finding suggests that while the patterns of correlation were similar across the two groups, grip force dynamics were more strongly associated with handwriting quality for nonproficient writers. As illustrated in Fig. 1, an increase in grip force dynamics (represented by an increase in ζ_{rms}) was shown to be strongly correlated with handwriting legibility and form ($r=0.92$, $p<0.0001$ and $r=0.93$, $p<0.0001$, respectively). Such results suggest that for nonproficient writers, static grips (indicated by low ζ_{rms}) are indicative of poorer handwriting quality while more dynamic grip forces (higher ζ_{rms}) reflect improved quality, corroborating findings observed subjectively by Refs. [5,7,12].

For proficient writers, in turn, the correlations observed between handwriting quality and ζ_{rms} were significantly lower for legibility ($r=0.75$, $p<0.001$) and for form ($r=0.52$, $p<0.01$), indicating that further changes in grip force variability (or dynamics) may only lead to incremental improvements in handwriting quality. The differences observed in the correlations between groups may be due to different mechanisms that underlie handwriting quality for the two groups of writers, as argued in Ref. [25]. Lastly, if both groups are analyzed together, it can be observed from Fig. 1 that grip force dynamics is related to handwriting quality in a nonlinear manner, a relationship also mentioned in Ref. [5] for a drawing task. The quantitative measures developed here have the potential to be used as determinants of functional printing and guidance for intervention. Knowledge about the bio-

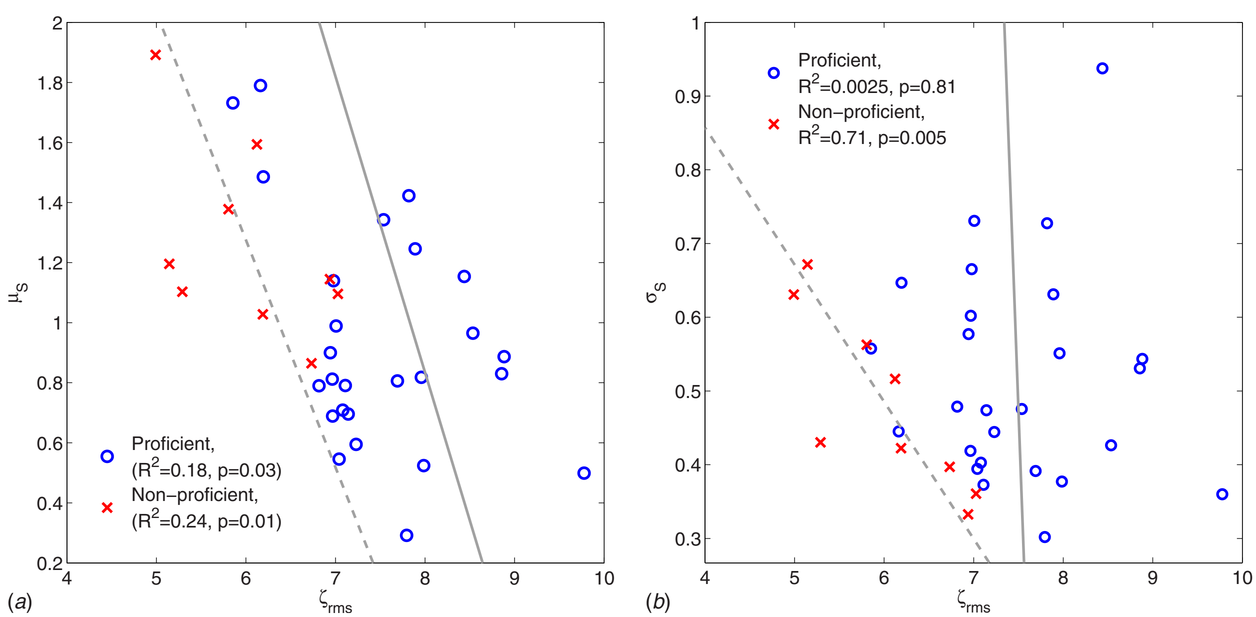

Fig. 2 Plots of (a) average per-stroke duration (μ_S) and (b) standard deviation of all stroke durations (σ_S) versus grip force coefficient of variation (ζ_{rms}) for proficient and nonproficient writers. Dashed and solid curves represent linear fits for nonproficient and proficient writers, respectively. The R^2 statistics and p-values are also reported for each regression line.

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mechanical processes underlying handwriting difficulties may lead to more precise evaluations and treatment programs.

4.2 Differentiating Between Proficient and Nonproficient Writers. Results reported in Table 2 suggest that significantly lower mean, standard deviation, and coefficient of variation of grip force rms temporal series were obtained for nonproficient writers relative to their peers. Lower grip forces and grip force spread (relative to able-bodied children with no known handwriting difficulties) have been reported previously for children with spastic hemiplegic cerebral palsy [18] and are likely indicative of fine motor control difficulties. Such a hypothesis is further corroborated by a recent study that showed a strong relationship between grip forces and motor impairment for patients with writer's cramp [26].

In terms of handwriting strokes, nonproficient writers produced a significantly larger number of strokes with higher per-stroke durations relative to their peers, echoing the findings reported by Refs. [27,17], respectively. The standard deviation of per-stroke durations did not show significant differences between the two groups. Unfortunately, the lack of research available on per-stroke variability limits the comparison with previous work.

4.3 Grip Force Variability and Handwriting Strokes. As discussed in Ref. [1], the two most crucial factors in handwriting performance are legibility and fluency. Previous studies have investigated the effects of pencil grip on writing speed [13,15] and have found that pencil grip and stroke are not highly correlated. The mean per-stroke duration versus ζ_{rms} plot shown in Fig. 2(*a*) corroborates such findings for both groups of writers. The plots for variation in stroke durations shown in Fig. 2(*b*), however, suggest that significant differences in correlation between the two groups exist. It is observed that for nonproficient writers, more static grip force patterns (lower ζ_{rms}) are related to larger variations in stroke durations (higher σ_S). Larger variations in stroke durations may be due to excessive pauses [9], impaired sensory awareness that can cause increased fatigue and limitations in the automaticity of handwriting [1] or the inherent variability of the motor system [28,29].

5 Conclusion

A computer-based handwriting assessment tool was used to quantitatively measure the forces exerted on the writing instrument during a handwriting task. For students with writing difficulties, parameters that quantify grip force dynamics during the handwriting task were shown to be highly correlated with two quality primitives, legibility and form, and with variation in stroke durations. In summary, nonproficient writers who possess a more static grip force pattern tend to attain lower legibility and form scores as well as increased variation in stroke durations.

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