
Relationships Among Biomechanical Ergonomic Factors, Handwriting Product Quality, Handwriting Efficiency, and Computerized Handwriting Process Measures in Children With and Without Handwriting Difficulties

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OBJECTIVES. Handwriting is a work activity for children, hence it may be evaluated based on ergonomic factors. This study investigated whether nonproficient handwriters could be distinguished by biomechanical ergonomic factors during handwriting, as well as by measures of handwriting efficiency. Furthermore, the relationships among ergonomic factors, handwriting quality, efficiency, and measures of the handwriting process were examined.

METHODS. Fifty proficient and 50 nonproficient third-grade handwriters performed a handwriting task on an electronic tablet. Biomechanical ergonomic factors, measures of handwriting quality, and efficiency were rated using the Hebrew Handwriting Evaluation. Handwriting process measures were obtained from a computerized system.

RESULTS. Biomechanical ergonomic factors and handwriting efficiency measures significantly differentiated between the study groups. Significant correlations were found among ergonomic factors and handwriting quality, efficiency, and process measures.

CONCLUSION. Nonproficient handwriting is a work activity that is often characterized by inferior biomechanical ergonomics, handwriting quality, efficiency, and significantly different handwriting process measures. Results provide insights that can assist in planning intervention.

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Work is a term that refers to activities that involve purpose and effort (Pheasant, 1991) and are related to various roles that persons undertake during different stages of their life (Jacobs & Bettencourt, 1995). Functionally effective work performance is that which produces a quality product through an efficient process (Eklund, 1997). With respect to children, academic school activities can be considered as a major domain of their occupational work performance (Parush, Levanon-Erez, & Weintraub, 1998). This concept has largely been overlooked in the past (Larsen, 2004), yet it has found support in the discovery by various researchers that early elementary schoolchildren clearly described the school tasks they do as work and not play (Cunningham & Weigel, 1992; King, 1982; Wing, 1995). For example, in Wing's study (1995) early-elementary schoolchildren stated that they considered reading and writing to be work, and more specifically, they categorized handwriting as the *ultimate* work activity. Since 30% to 60% of children's school day is spent in the performance of fine motor tasks, consisting primarily of handwriting (McHale & Cermak, 1992), and given its consideration as a work related activity, it is appropriate to consider children's performance of handwriting in terms of its quality and efficiency.

Those children who do not succeed in developing proficient handwriting are defined by some authors as "poor handwriters" and by others as "dysgraphic" (Marr & Cermak, 2001). Hamstra-Bletz and Blote (1993) defined "dysgraphia" as a disturbance or difficulty in the production of written language that has to do with the mechanics of writing. The difficulty is manifested in the inadequate performance

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of handwriting among children who are of at least average intelligence level and who have not been identified as having any obvious neurological or perceptual-motor problems. It is reported that the prevalence of handwriting difficulties among school-age children varies between 10%–34% (Rubin & Henderson, 1982; Smits-Engelsman, Niemeijer, & Van Galen, 2001; Smits-Engelsman, Van Galen, & Michels, 1995).

Over the years, many methods have been developed for the evaluation of handwriting performance. Most are based on analyzing the quality or legibility of the handwritten product, however, a number of assessments have attempted to examine the overall efficiency of performance by measuring handwriting speed as well (e.g., Hamstra-Beltz & Blote, 1993; Kaminsky & Powers, 1981; Maeland & Karlsdottir, 1991; Rubin & Henderson, 1982; Sovik, Arntzen, & Thygsen, 1987). (For a comprehensive review of handwriting assessments see Rosenblum, Weiss, and Parush, 2003.) However, because handwriting is an important component of the child's "work" at school, consideration of ergonomic factors that contribute to handwriting efficiency and productivity would also seem appropriate (Parush et al., 1998).

Ergonomics is a body of knowledge that focuses on the study of work performance with an emphasis on human safety and productivity (Jacobs & Bettencourt, 1995). Ergonomic factors are those that relate to design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable, and effective human use (Chapanis, 1991). In fact, clinicians and researchers have noted that biomechanical ergonomic factors related to body position and pencil use are characteristic of nonproficient handwriters (Parush et al., 1998). Furthermore, these factors can be easily observed by teachers in the classroom or by clinicians in the therapy setting. Therefore, it is surprising that no consideration is given to ergonomic factors in most handwriting evaluations despite the fact that these could add important information about the child and his or her relationship with handwriting tasks, tools, and with the environment.

Currently, inadequate research exists regarding the relationships among ergonomic factors and handwriting performance. The studies that exist have examined the relationship among handwriting and biomechanical ergonomic factors such as body posture (Blote, Zielstra, & Zoetewey, 1987; Sassoon, Nimmo-Smith, & Wing, 1986) and pencil grip (Blote et al.; Sassoon et al.; Ziviani & Elkins, 1986).

Body posture is generally considered to have an important influence on the efficiency of the writing process and product (Yeats, 1997). Clinicians have observed that trunk instability due to low muscle tone among children prevents

them from making necessary postural adjustments while focusing on activities that require fine motor skills such as handwriting (Amundson, 1992). Thus, clinicians have included instruction regarding sitting position as a part of a handwriting instructional curriculum (Graham & Weintraub, 1996). However, studies that investigated body posture among children as they wrote found that much variation exists in their writing posture both within and among them, and that only 50%–60% of the children sit in the recommended upright position (Blote et al., 1987; Sassoon et al., 1986). Moreover, only a weak correlation was found between sitting position and the quality of children's handwriting.

Another biomechanical ergonomic factor that has been considered by clinicians to be related to handwriting performance is pencil grip (Ziviani, 1983). Nevertheless, the results of several studies have indicated that pencil grip varies among children and adults and that the dynamic tripod grip is not the only common functional option (Blote et al., 1987; Herrick & Otto, 1961; Sassoon et al., 1986; Schneck & Henderson, 1990; Ziviani & Elkins, 1986). Furthermore, the research findings related to the relationship between pencil grip and handwriting legibility are not consistent. For example, some researchers have found that the quality of children's written products and their pencil grip are only weakly correlated (Ziviani & Elkins). In addition, most researchers have not found pencil grip to significantly affect handwriting legibility (Ziviani & Elkins), handwriting speed (Parush et al., 1998; Sassoon et al., 1986; Sovik et al., 1982; Ziviani & Elkins), or writing accuracy among children (Sovik, Arntzen, & Teulings, 1982). Yet, Schneck (1991) found that students with handwriting difficulties demonstrated less mature grips than their peers.

However, these studies have had methodological limitations that warrant further research into a possible relationship between pencil grip and handwriting performance. First, in most studies the task chosen was to write a single sentence, and as a result, the effect of fatigue experienced during the performance of extended writing tasks on pencil grip was not considered. In addition, the determination of pencil grip was made based on a single momentary observation and not throughout the task performance, although Blote et al. (1987) reported that some children changed their grip while writing.

In a study performed by Parush and colleagues (1998), researchers compared good and poor handwriters during a paragraph writing task with respect to a number of ergonomic factors that included two other measures related to the dynamic aspects of pencil grip. The first of these, pencil positioning, was defined as whether a child can or cannot automatically and easily establish an appropriate

pencil grip in preparation for a writing task. The second variable, consistency of pencil grip, was used to score whether and how often a child's grip changed during the performance of a paragraph writing task. Findings from their study revealed significant differences between the study groups in pencil positioning but not in consistency of pencil grip. Yet, as was previously mentioned, Blote and colleagues (1987) reportedly observed that some children do tend to change their writing grip during task performance. Unfortunately, no objective substantiation of this observation was made in their study. Thus, it appears that despite anecdotal observations with respect to both pencil positioning and the consistency with which children hold a writing tool, very little research has been performed to establish their clinical significance.

Thus, the overall picture obtained from the literature is that despite clinicians' belief that biomechanical factors such as those described above should be considered with respect to handwriting performance, research has not adequately determined that these factors can be used to identify poor handwriters. Moreover, studies have shown that these factors vary among children. It is possible that the evidence to support the answers to these questions requires more comprehensive and controlled methodological practices relating to the measurement, criteria, and tasks used (Yakimishyn & Magill, 2002).

As mentioned previously, efficiency is another important issue related to work and ergonomics. To be efficient, effective handwriting performance should be considered not only with respect to the overall handwriting speed, but also with respect to the fluency of handwriting production. In fact, clinical observations have indicated that not only do proficient and nonproficient writers differ with respect to handwriting speed, handwriting product quality, and ergonomic factors, but also that nonproficient handwriters tend to pause during handwriting performance (Benbow, 1995; Kaminsky & Powers, 1981). Because most handwriting product evaluations do not measure fluency, the tendency of poor handwriters to pause while writing was revealed through research that included a computerized data collection system. This system includes a digitizer, that is, an electronic tablet on which the handwriting is performed in tandem with a special pen and computer, to allow for the recording of data that can be used to determine the spatial and temporal features of handwriting in real time (Schoemaker, Shellekens, Kalverboer, & Kooistra, 1994; Schoemaker & Smits-Engelsman, 1997; Smits-Engelsman, Van Galen, & Portier, 1994; Sovik et al., 1987; Wann & Jones, 1986).

The results of these studies seem to indicate that pauses or breaks in writing fluency may have a particular sig-

nificance in the evaluation of children's handwriting difficulties (Rosenblum, Parush, & Weiss, 2003b). Furthermore, although these computerized studies have provided valuable information regarding the relative duration of pauses between writing strokes of proficient versus nonproficient handwriters, it would seem that the efficiency of handwriting function could also be related to the number of breaks children take when performing prolonged writing tasks such as in writing words, sentences, and paragraphs, and the quantity of writing that they produce between successive breaks.

In a previous study, a computerized system that included a digitizer electronic tablet and Penmanship Objective Evaluation Tool (POET) software (Rosenblum, Parush, & Weiss, 2003a) was used to collect data on objective measures of time and space during the handwriting process. Furthermore, an analysis of the relationship between computerized spatial and temporal measures of the handwriting process and the quality of the handwritten product indicated that a more comprehensive understanding and superior evaluation of developmental dysgraphia would combine the assessment of both these aspects of handwriting performance (Rosenblum, Weiss, & Parush, 2004).

The current study was performed to examine whether proficient and nonproficient writers differ with respect to biomechanical ergonomic factors and measures of handwriting efficiency. Furthermore, the study was also designed to examine the relationships among biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and computerized spatial and temporal handwriting process measures. It was hoped that the information gained by this study could lead to better insight into phenomena associated with poor handwriting performance, and provide a more sensitive and accurate method of distinguishing between proficient and nonproficient handwriters (Rosenblum et al., 2003a, 2003b).

To this end, the Hebrew Handwriting Evaluation (HHE) (Erez & Parush, 1999) was used to collect data regarding biomechanical ergonomic factors, handwriting product quality, and handwriting efficiency among the study's participants. The HHE, a valid and reliable assessment of Hebrew handwriting, provides structured criteria for rating biomechanical ergonomic factors related to handwriting, and detailed specific criteria for the analysis of handwriting product quality. The HHE also includes measures of handwriting efficiency, operationalized as the number of letters and words a child is observed to produce during a single handwriting sequence, as well as the number of breaks taken by a child during handwriting production. Finally, in addition to the administration of the HHE, the computerized system described previously was used to

collect data from proficient and nonproficient handwriters on objective measures of time and space during the handwriting process.

In this way, the current research addressed the following questions: (1) How do nonproficient and proficient handwriters differ with respect to biomechanical ergonomic factors and/or measures of handwriting efficiency? (2) How does a relationship exist among biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and/or temporal and spatial handwriting process measures?

Methods

Study Design

This study used a cross-sectional design in which the handwriting performance of children with nonproficient handwriting and children with proficient handwriting (matched to the first group by age, sex, and classroom) were compared with respect to biomechanical ergonomic factors and handwriting efficiency. The relationships among measures of biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and computerized spatial and temporal handwriting process measures were then investigated through correlational analysis.

Participants

One hundred study participants were recruited from eight regular public schools located in four different types of municipalities in northern Israel (large town, small town, kibbutz, and community settlement). All participants were born in Israel, used the Hebrew language as their primary means of verbal and written communication, and all pupils used their right hand only when handwriting. The participants were composed of two study groups: 50 third-grade nonproficient handwriters, 8.6 years of age \pm 3 months and 50 third-grade proficient handwriters, 8.7 years of age \pm 4 months. Third-grade pupils were selected as the target population as a result of research that indicates that by the time a child reaches this grade handwriting has become efficient, organized, and readily available as a tool to facilitate the development of ideas (Berninger, Mizokawa, & Bragg, 1991; Levine, 1993). Thus, children of this age whose handwriting lacks these qualities may be demonstrating a sign of a developmental problem.

The handwriting proficiency status of all 100 participants in this study was established with the aid of the standardized and validated Teachers' Questionnaire for Handwriting Proficiency (TQHP) (Rosenblum, Jessel, Adijapha, Parush, & Weiss, 1997) completed by their classroom teachers. The questionnaire was constructed from criteria selected from the literature and handwriting

assessments including handwriting legibility, speed, fatigue, and complaints of pain or discomfort while writing (Alston, 1983; Cornhill & Case-Smith, 1996; Rubin & Henderson, 1982). The TQHP was validated for content through a table of specifications by 10 occupational therapy clinicians and researchers who were experienced in the assessment and treatment of handwriting difficulties. Interrater reliability for the TQHP was determined to be high ($r = .89, p < .001$) (Rosenblum, Parush, Epsztein, & Weiss, 2003). The teachers were asked to use the questionnaire to evaluate the handwriting of each student in comparison to what they would expect handwriting legibility and speed for children of that age and background. Seventy percent of the nonproficient handwriters identified were boys, a gender bias that has been reported in the literature for children in England (Rubin & Henderson, 1982) and the Netherlands (Smits-Engelsman et al., 1995).

The proficient handwriters were matched to nonproficient handwriters on the basis of gender, age, school, and grade. For each child in the nonproficient handwriting group, a matched control participant was chosen from his or her classroom peers and was therefore taught by the same classroom teacher. There were no statistically significant differences between the two groups with respect to age or gender ratio (30% girls vs. 70% boys in both groups).

Children with documented developmental delay, neurological deficits, or physical impairment were excluded from the study. Permission to carry out this study was granted by the Ministry of Education and signed parental agreement was obtained for each participant.

Instruments

The Hebrew Handwriting Evaluation (HHE) (Erez & Parush, 1999). The HHE was used to collect data from the proficient and nonproficient handwriters regarding the following three types of outcome variables: (1) biomechanical ergonomic factors, (2) handwriting product quality measures, and (3) handwriting efficiency measures, through their performance of a paragraph copying task. The evaluation provides normative data for second and third graders. During test development, reliability and validity were established and reported in the test manual (Erez & Parush). Internal consistency was high ($\alpha = .81$) and interrater reliability ranged from $r = .75$ to $.79$.

Construct validity of the HHE has been established by demonstrating statistical significant differences between the performance of children with proficient and poor handwriting ($t = 2.34; p = .027$) (Devash, Levi, Traub, & Shapiro, 1995) and across school grades (second and third) ($p < .013$ to $p < .001$) (Erez & Parush, 1999). No significant differences were found for gender.

The paragraph copying task contains all the letters in the Hebrew alphabet, and included 30 words and 107 letters (Erez & Parush, 1999). The standardized text from the HHE (Erez & Parush) was also chosen in the current study as the paragraph copying task to be analyzed by the digitizer, to enhance the fidelity between subjective (HHE) and the objective (digitizer) approaches.

HHE Outcome Measures:

1. HHE measures of biomechanical ergonomic factors—These are observed according to the standardized HHE protocol (Erez & Parush, 1999) and include the following variables: body posture, pencil grip, pencil positioning, and consistency of pencil grip. All the ergonomic factors except for pencil grip are scored according to predetermined criteria on a 4-point scale, with 1 representing the best performance, and 4 the worst performance.
 - a. Body posture is given a score of 1 if the child sits in an upright position with the head flexed no greater than 30°. A score of 4 is given if the child's head rests on his or her hand or on the table while the other hand writes.
 - b. Pencil grip is evaluated according to the Schneck and Henderson Pencil Grip Rating Scale (Schneck & Henderson, 1990). The scale includes 10 possible pencil grips, arranged according to a developmental sequence. In order to enable recording grips that are not included in the Schneck Rating, an option of "other" was added.
 - c. Pencil positioning is scored as 1 if the pencil is picked up automatically with one hand, and as 4 if the pencil is picked up by the nonwriting hand and then repositioned in his or her writing hand.
 - d. Consistency of pencil grip is scored as 1 if the child's grip does not change while writing, whereas if the grip changes more than twice while writing the text a score of 4 is given.
2. HHE outcome measures of handwriting product quality—These include "global legibility," scored on a 4-point Likert scale, from the most legible (1) to the least legible (4), which refers to the overall clarity of the handwriting product.

In addition, the analytic measurement of legibility used in the HHE examined the following three component variables:

 - a. Letters erased and/or overwritten—the number of letters that were erased and/or written over.
 - b. Unrecognizable letters—the total number of letters that could not be recognized due to the quality of letter closure, rounding of letters, or letter reversals.

- c. Spatial arrangement of the written text, as determined according to detailed and precise criteria, using a caliper that is calibrated to the millimeter. Specifically, these criteria included vertical alignment of letters (including the extensions of letters above and below the lines), the spacing of words and letters (whether too wide or overlapping), and letter size. The minimum score for spatial arrangement is 9, and the maximum is 24.
3. HHE measures of handwriting efficiency include the following two variables:
 - a. Handwriting fluency is scored as 1 if the child writes without pausing and 4 if the child stops five or more times.
 - b. Number of letters or words produced per writing sequence is scored 1 when the child writes two to three consecutive words without stopping and 4 if only one letter is written between writing breaks.

For all of the outcome measures of the HHE, a low score indicates better performance and a high score indicates poorer performance.

Digitizing Tablet and Online Data Collection and Analysis Software was used to measure spatial and temporal measures of the handwriting process. A suite of online, computerized handwriting evaluations (POET) (Rosenblum et al., 2003a)¹ developed by the researchers via MATLAB² software toolkits was used to administer the stimuli and to collect and analyze the data. The evaluation was developed in response to the absence of a quantitative objective handwriting tool for Hebrew language. All writing tasks were performed on A4-size lined paper affixed to the surface of a WACOM³ (404 X 306 X 10 mm) x-y digitizing tablet using a wireless electronic pen with pressure-sensitive tip (Model GP-110). The digitizing tablet system provides raw data as to pen displacement, pressure, and pen tip angle, sampled at 150 Hz via a 650 MHz Pentium III laptop computer. The computerized system enables the collection of spatial, temporal, and pressure data while the child is writing.

Computerized outcome measures included temporal and spatial measures of handwriting kinematics that allowed for the operationalization of handwriting process information. The temporal measures included:

- a. Total time—time taken to write the entire paragraph.
- b. On paper time—the amount of time during the paragraph writing that the pen was in contact with the paper.

¹POET: <http://research.haifa.ac.il/~rosens>

²MATLAB: <http://www.mathworks.com/products/matlab>

³WACOM: <http://www.wacom.com>

- c. In air time—the amount of time during the paragraph writing that the pen was not in contact with the paper.
- The spatial measures included:
- a. Total length—The total path length of all the characters written in the paragraph.
 - b. On paper length—the length of the excursion of the pen during which the pen was in contact with the paper throughout the paragraph writing.
 - c. In air length—the length of the excursion of the pen during which it was not in contact with the paper throughout the paragraph writing.

Procedure

All participants completed the experimental procedure under similar environmental conditions in a quiet classroom in their school. Each subject was tested individually during the morning hours by the same evaluator, who was blinded as to group assignment. In an effort to achieve writing samples that would resemble those typically made by the subjects, all environmental factors were kept as similar as possible to writing conditions that the child would normally experience. Thus, the subject was seated on a standard school chair and in front of a school desk, appropriate to his or her height. Each child was tested during one 45-minute session carried out at his or her school.

The paragraph copying task was presented visually on the computer screen in Hebrew 20-point size font type Gutman Yad-Brush. Biomechanical ergonomic factors and measures of functional handwriting efficiency were observed and documented as the child performed the paragraph copying task on normal writing paper with printed lineature, which was affixed to the digitizing tablet. Each subject was instructed in the same fashion about what he or she would be required to do. The testing for this part of the study took approximately 15 minutes; the subjects had previously engaged in other handwriting tasks (see Rosenblum, Parush, and Weiss [2001] for a full description) for an additional 25 minutes.

The handwriting product quality was then evaluated by an independent research assistant who was blinded as to group assignment, based on the standardized HHE criteria (e.g., global legibility, letters erased or overwritten, unrecognizable letters, and spatial arrangement).

Data Analysis

To examine whether the nonproficient and proficient handwriting groups differed with respect to biomechanical ergonomic factor and handwriting efficiency scores, frequencies and Mann-Whitney analyses were performed. To investigate what relationships exist among the biomechanical

ergonomic factor scores, handwriting product quality scores, handwriting efficiency measure scores, and the computerized temporal and spatial handwriting process measures with respect to all the participants, Spearman correlational analyses were performed. Data were analyzed using the SPSS for Windows analysis program.

Results

The first variables to be analyzed were the biomechanical ergonomic measures, obtained via the HHE. Mann-Whitney analysis applied to these four variables (i.e., body posture, pencil grip, pencil positioning, and consistency of pencil grip) and yielded statistically significant differences between the children with proficient and the nonproficient handwriting for the paragraph copying task (see Table 1). The results of this analysis indicated that children with proficient handwriting received significantly lower scores (i.e., performed better) in all four biomechanical ergonomic variables than did the children with nonproficient handwriting for the paragraph copying task.

Next, Mann-Whitney analyses were performed to compare handwriting efficiency of the study groups. With respect to handwriting fluency, findings indicated that significant differences exist between proficient ($M = 1.12$, $SD = .47$) and nonproficient ($M = 2.98$, $SD = .86$) handwriters ($Z = 8.38$, $p = .001$). Similarly, with respect to the measure of the number of letters or words produced per writing sequence, Mann-Whitney analysis also revealed significant differences ($Z = 7.51$, $p < .001$) between proficient writers ($M = 1.10$, $SD = .36$) and nonproficient writers ($M = 2.64$, $SD = 1.00$).

In order to address the second research question, Spearman correlational analyses were performed, and these results can be found in Table 2. With respect to the relationships among the biomechanical ergonomic factors and handwriting product quality measures of the HHE, significant correlations, ranging from $r = .29$ to $r = .50$ ($p < .01$), were found between three of the biomechanical ergonomic factors (i.e., body positioning, pencil positioning, and

Table 1. Comparison of Biomechanical Ergonomic Factor Measures Between Proficient and Nonproficient Handwriters (Mann-Whitney Analysis)

Biomechanical ergonomic factors	Proficient <i>n</i> = 50		Nonproficient <i>n</i> = 50		<i>Z</i>	<i>p</i>
	Mean	<i>SD</i>	Mean	<i>SD</i>		
Body positioning	1.04	0.20	2.14	0.53	8.55	.00
Pencil grip	1.42	1.01	2.54	1.48	4.93	.00
Pencil positioning	1.00	0.00	1.84	0.51	7.88	.00
Consistency of pencil grip	1.12	0.33	2.34	0.69	7.91	.00

consistency of pencil grip) and all four of the handwriting product quality measures. No significant correlations were found between pencil grip and any of the handwriting product quality measures.

Spearman correlation analysis also resulted in significant high correlations, ranging from $r = .75$ to $r = .65$ ($p < .01$) between HHE measures of handwriting efficiency and all of the biomechanical ergonomic factors except for pencil grip, for which significant but low correlations were found.

In addition, significant moderate correlations ranging from $r = .55$ to $r = .43$ ($p < .01$) were found among handwriting efficiency measures and handwriting product quality measures. Of these, the highest correlations were found between handwriting fluency and global legibility ($r = .55$) and unrecognizable letters ($r = .53$).

Correlational analyses also result in significant correlations, ranging from $r = .30$ to $r = .61$ ($p < .01$) among three of the biomechanical ergonomic factors (i.e., body positioning, pencil positioning, and consistency of pencil grip) and five of the computerized objective measures (total time, on paper time, in air time, total length, and in air length). No significant correlations were found between pencil grip and any of the computerized objective measures. No significant correlations were found between on paper length and any of the biomechanical ergonomic factors.

Furthermore, statistically significant correlations ranging from $r = .69$ to $r = .46$ ($p < .01$) were found among handwriting efficiency variables and five of the computerized objective measures of the handwriting process (i.e., total time, on paper time, in air time, total length, and in air length). The highest significant correlations were found between in air time and the number of letters or words produced in a writing sequence ($r = .65$) and between in air time and handwriting fluency ($r = .69$).

Discussion

As handwriting is considered to represent a significant component of children's work at school, one objective of this study was to examine whether biomechanical ergonomic factors related to this task can distinguish between proficient and nonproficient handwriters. In addition, since the examination of work performance includes consideration of work efficiency, measures of handwriting efficiency were also compared between the study groups. Finally, this study was also designed to explore the relationships among biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and spatial or temporal handwriting process variables, to gain further insight into how these factors relate with respect to children's handwriting performance.

Table 2. Correlation Matrix Among Hebrew Handwriting Evaluation Handwriting Efficiency Variables and Biomechanical Ergonomic Factors, Handwriting Product/Quality Measures, and Spatial/Temporal Computerized Objective Measures ($N = 100$)

	HHE handwriting efficiency variables	
	Handwriting fluency	Number of letters or words produced per writing sequence
Biomechanical ergonomic factors		
Body positioning	.75**	.67**
Pencil grip	.29**	.32**
Pencil positioning	.69**	.70**
Consistency of pencil grip	.67**	.65**
Handwriting product quality variables		
Global legibility	.55**	.52**
Letters erased or overwritten	.46**	.43**
Unrecognizable letters	.53**	.47**
Spatial arrangement	.49**	.48**
Computerized handwriting process variables		
Total time	.69**	.66**
On paper time	.51**	.50**
In air time	.69**	.65**
Total length	.51**	.46**
On paper length	.28	.01
In air length	.58**	.53**

Note. ** = $p < .01$; HHE = Hebrew Handwriting Evaluation.

An important finding of the current study was that proficient and nonproficient handwriters differed significantly with respect to all the biomechanical ergonomic factors measured (i.e., body positioning, pencil grip, pencil positioning, and consistency of pencil grip). Unfortunately, there is a paucity of literature with which to compare these results. In one related study, Parush et al. (1998) found significant differences between proficient and nonproficient handwriters of similar age and gender distributions as in the current study for all of the ergonomic factors assessed except for pencil grip and consistency in pencil grip. On the other hand, Schneck's study (1991) indicated that children with handwriting difficulties had less mature grips than those of their peers.

In light of the inconsistent results revealed by the current and previous studies performed, it is apparent that the question with respect to the effects of pencil grip on writing performance is still unresolved. It is possible that the tools and methods used are not yet sensitive enough to provide definitive results, especially given the variation in grips that characterize even children without handwriting difficulties (Dennis & Swinth, 2001; Greer & Lockman, 1998). Therefore, it is recommended that future research be performed to attempt to resolve this question using methods that can overcome the subtle complexities of this issue.

Nevertheless, the overall finding of this study that nonproficient handwriters displayed inferior biomechanics to

those of proficient handwriters is significant when considering how important handwriting is for children to successfully perform their work at school. It is possible that the reduced biomechanical ergonomics that nonproficient writers demonstrate may reflect in part deficiencies in various motor components essential to good handwriting performance (Graham & Weintraub, 1996; Parush et al., 1998; Tseng & Cermak, 1993). For example, poor body positioning may be a manifestation of atypical muscle tone that impacts on the child's ability to stabilize aspects of the upper trunk and arm while simultaneously moving other body parts (Tseng & Cermak). In fact, the results of a recent study by Smith-Zuzovsky and Exner (2004) indicated that optimal body positioning is a significant factor in determining performance in in-hand manipulation skills, something which would seem to be highly relevant in the performance of handwriting tasks. In addition, the researchers observed that children with poor positioning moved frequently in their seats in an attempt to find a more stable and/or comfortable seating position. They suggested that poor body positioning of schoolchildren not only affects the quality of their performance as a result of the biomechanical constraints, but that their attention to the tasks may have been negatively affected. Obviously attention to task is a critical factor in performance of complex activities such as handwriting.

Another example of a potential relationship among deficiencies in body function and poor biomechanical ergonomics during handwriting performance is that the tendency of a child to make multiple changes in pencil positioning may be related to deficiencies in fine motor coordination and in-hand manipulation (Cunningham Amundson, 1992; Exner, 1989).

Proficient and nonproficient handwriters were also compared with respect to handwriting efficiency measures of the HHE. As noted previously, proficient work performance, or in the context of this study handwriting performance, should be performed efficiently. In the current study the measure of handwriting efficiency was operationalized through the observation and documentation of the numbers of letters or words produced in one writing sequence, and by the quantity of written text produced during writing sequences. Obviously, a child who takes frequent breaks when performing a functional writing task and/or does not produce adequate text in between successive writing breaks, is not an efficient handwriter. Unfortunately, previous studies have relied solely on overall handwriting speed to examine the efficiency of handwriting performance.

Results of Mann-Whitney analysis in the current study, which indicate that significant differences exist between

proficient and nonproficient handwriters in the amount of pauses they make and the number of letters or words they produce during each writing sequence, suggest that this information should be considered when performing a comprehensive assessment of handwriting. Further research is needed to establish the clinical utility of this approach.

The second study question related to the relationships among biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and spatial/temporal handwriting process variables, in performance of handwriting. Results of the current study indicated that a number of significant relationships exist among these variables. For example, statistical analysis revealed that use of poor biomechanical ergonomics with respect to the factors assessed, except for pencil grip (i.e., body positioning, pencil positioning, and consistency of pencil grip), was found to have significant moderate to low correlations with components of handwriting quality, such as legibility, letter appearance, and spatial arrangement. The fact that the correlations found among biomechanical ergonomic variables and the handwriting product quality were not higher seems to indicate that other client body functions, such as perceptual-motor skills, behavioral, and/or intelligence capabilities may also impact on the child's handwriting ability (Cornhill & Case-Smith, 1996; Tseng & Cermak, 1993; Tseng & Murray, 1994).

As previously noted however, no significant relationship was found between pencil grip and any of the handwriting product quality variables. These results are in line with the findings of Parush et al. (1998), in which no significant correlations were found among these variables between proficient and poor handwriters in second and third grades. Similar findings were revealed in other studies as well (Burton & Dancisak, 2000; Dennis & Swinth, 2001). In fact, Ziviani and Elkins (1986) found that handwriting legibility did not seem to be adversely affected by even the most atypical grip patterns. Nevertheless, these findings differ from those of Schneck (1991) who found that poor writers had lower grip scores than their classmates with good handwriting. It is important to point out however, that whereas Schneck recruited first-grade students for her study, the other studies relied on older participants who were primarily in second or third grade and above. Thus it is possible that greater variability of mature and immature grip patterns, to be expected among the younger first graders, could partially account for the differences among these study results.

Hence, observation of these biomechanical ergonomic factors as part of a comprehensive handwriting evaluation may supply the therapist with clues about possible underlying mechanisms of poor handwriting performance. More

research is suggested to establish whether this relationship is a valid one.

Results of correlational analyses in the current study also indicated that significant high correlations exist among measures of handwriting efficiency and the observed biomechanical ergonomic factors of body positioning, pencil positioning, and consistency of pencil grip. In contrast, the correlations between pencil grip type and handwriting efficiency measures, although significant, were lower. These results suggest that a child's ability to perform handwriting tasks efficiently is, at least in part, related to the biomechanical ergonomics they use during handwriting performance. Unfortunately, the lack of research on these issues limits comparison of these results to those of other researchers. More research is recommended to explore these issues further.

Another interesting research finding from this study was that significant moderate correlations were found among handwriting efficiency measures and measures of handwriting product quality. Once again, research on this issue with which to compare these findings is lacking. It could be suggested that, at least in part, the efficiency and fluency with which nonproficient writers perform handwriting tasks could be related to the degree of effort they use in producing letters accurately and in the spatial organization of their writing (Berninger et al., 1997). Future research could be performed to explore this possibility.

This study was also designed to examine the relationships among biomechanical ergonomic measures and objective computerized measures of the handwriting process. Results indicated that all the biomechanical ergonomic criteria measured, with the exception of pencil grip, significantly correlated to handwriting process variables, with exception to on-paper length (i.e., total/in air time, total/in air length). Specifically, the highest correlation ($r = .60, p < .01$) found was between body position and in air time.

The relationships among ergonomic factors and the handwriting process have received little attention in the literature, despite the fact that previous handwriting experts have called for this issue to be studied (Bonney, 1992). Thus, the current study, in which objective spatial and temporal data collected online during the actual handwriting process were related to findings of structured observations of biomechanical ergonomic factors throughout the performance of the handwriting task, provides new information that suggests that interplay of these variables be considered in planning treatment for nonproficient handwriters.

This study's finding that pencil grip and temporal measures of the handwriting process (i.e., total time, on paper time, and in air time) are not significantly correlated strengthens those of other studies in which no differences

were found between global measures of writing speed and types of pencil grips (Koziatek & Powell, 2003; Sassoon et al., 1986; Ziviani, Hayes, & Chant, 1990). The combined results of these studies seem to highlight Bonney's (1992) statement questioning the impact of pencil grip on handwriting.

Overall, the results of studies such as this one provide an important contribution by highlighting the significance of the assessment of biomechanical ergonomic factors in order to better understand why certain children have difficulty in handwriting function and proficiency.

Recent literature has provided objective evidence to support the observations of clinicians that the performance of nonproficient writers is often characterized by the tendency to pause as they are writing (Benbow, 1995; Kaminsky & Powers, 1981). This evidence was revealed through the use of computerized data collection systems, which identified specific spatial and temporal measures of the handwriting process that were significantly different in children with handwriting difficulties as compared to children without such difficulties (Rosenblum et al., 2003b). Results of the correlational analyses in the current study indicated that observed measures of handwriting efficiency in the HHE significantly correlated with all but one of the computerized handwriting process variables (i.e., on paper length). These results suggest that these structured criteria of handwriting efficiency provided through the HHE can be used to further reveal the difficulties nonproficient writers experience in the handwriting process itself.

Recent literature has provided some clues into possible underlying mechanisms that may be associated with discontinuities that often characterize inefficient writing performance. For example, some researchers have suggested that deficits in perceptual-motor skills, including handwriting, are associated with deficiencies in children's ability to perform a motor program with little conscious effort, referred to as the automatization stage of learning a motor skill (Bonney, 1992; Rasmussen & Gillberg, 1999).

In addition, Meulenbroek and Van Galen (1984) suggested that pausing during handwriting performance may serve to give the child opportunity to plan the execution of the next segment, selecting optimal size, speed, and angle, as well as making adjustments in wrist and finger position. Further, it has been suggested that children with discontinuous writing patterns may need to prepare and execute movements sequentially, whereas children who write in a continuous pattern are able to write while simultaneously planning and preparing for upcoming movement execution (Schoemaker et al., 1994).

Another possible mechanism underlying writing dysfluency relates to the suggestion that children with writing

problems are aware that their performance is inaccurate and attempt to compensate through increased use of visual feedback (Hulstijn & Mulder, 1986; Schoemaker et al., 1994; Wann, 1987).

Finally, Schoemaker et al. (1994) considered that handwriting dysfluency may stem from biomechanical factors. For instance, a biomechanically unstable or “noisy” system will produce more natural oscillations that show up as dysfluencies in the velocity signal.

In summary, our results suggest that nonproficient handwriters perform significantly differently than proficient handwriters on biomechanical ergonomic factors tested as well as to their efficiency in handwriting performance. Furthermore, significant relationships were found among certain biomechanical ergonomic factors and measures of handwriting product quality, as well as to measures of handwriting efficiency and objective computerized measures of the handwriting process. Because our study design cannot allow for a direct causal relationship to be inferred, further research is necessary to confirm and determine the extent of these relationships.

Implications for Practice and Future Research

Handwriting deficiencies are one of the primary causes for referral to occupational therapy treatment among school-age children (Barnes, Beck, Vogal, Grice, & Murphy, 2003). Effective management of handwriting problems involves identification and remediation of specific areas of difficulty (Bonney, 1992). The results of the current study support inclusion of measures of biomechanical ergonomic factors and of handwriting efficiency within a comprehensive handwriting evaluation protocol. In so doing, clinicians may better refine their treatment planning and the outcome measures that they can use to monitor treatment effectiveness.

Moreover, information provided by the current research adds to the growing compilation of data regarding various phenomena that may characterize nonproficient handwriting. Previous research has revealed the significance of including measures of the handwriting process to better understand performance of nonproficient handwriters (Rosenblum et al., 2003a, 2003b, 2004). The current research suggests that clinical observations regarding biomechanical ergonomic factors and handwriting efficiency that seemed to characterize children with handwriting difficulties can be substantiated by use of standardized measures. Furthermore, the fact that these factors are associated with one another as well as with handwriting product quality and measures of the handwriting process may help in furthering current conceptualizations regarding handwriting

difficulties. However, it is recognized that more research is necessary to confirm and expand on these findings.

Limitations

It is important to qualify the results of the current study by stating that the study design employed a limited sample size of third-grade Israeli schoolchildren whose primary means of verbal and written communication is through the Hebrew language. In addition, all participants used their right hand while writing. Further research on a wider sample of children from different age groups, diagnostic categories, cultures, and including left-handed handwriters, will help to determine the generalizability and clinical implications of our findings. Furthermore, although this study found associations among certain biomechanical ergonomic factors, handwriting product quality, handwriting efficiency, and objective computerized temporal and spatial data related to the handwriting process, direct causal relationships cannot be inferred. Although our research provides a promising first step in this direction, future research could include a systematic examination of the interactive roles of the cognitive, perceptual-motor, behavior, and ergonomic factors that result in nonproficient handwriting. It is hoped that such information can then guide clinicians in developing optimal assessment and treatment for children with poor handwriting. ▲

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