

Effect of Robotic-Assisted Three-Dimensional Repetitive Motion to Improve Hand Motor Function and Control in Children With Handwriting Deficits: A Nonrandomized Phase 2 Device Trial

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KEY WORDS

- handwriting
- motor skills
- motor skills disorders
- robotics
- therapy, computer-assisted

OBJECTIVE. We explored the efficacy of robotic technology in improving handwriting in children with impaired motor skills.

METHOD. Eighteen participants had impairments arising from cerebral palsy (CP), autism spectrum disorder (ASD), attention deficit disorder (ADD), attention deficit hyperactivity disorder (ADHD), or other disorders. The intervention was robotic-guided three-dimensional repetitive motion in 15–20 daily sessions of 25–30 min each over 4–8 wk.

RESULTS. Fine motor control improved for the children with learning disabilities and those ages 9 or older but not for those with CP or under age 9. All children with ASD or ADHD referred for slow writing speed were able to increase speed while maintaining legibility.

CONCLUSION. Three-dimensional, robot-assisted, repetitive motion training improved handwriting fluidity in children with mild to moderate fine motor deficits associated with ASD or ADHD within 10 hr of training. This dosage may not be sufficient for children with CP.

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We conducted a Phase 2 exploratory therapeutic trial to see if task-oriented robotic-assisted three-dimensional repetitive motion training of the hand would help children experiencing difficulty in handwriting attain the functional goals of improved legibility and speed. Fluid and legible handwriting is an important daily task for people of all ages, and dysgraphia is an important reason for referral to occupational therapy (Hammerschmidt & Sudsawad, 2004; Reisman, 1991). Estimates of dysgraphia in children range from 5% to 20%, and it is a common coimpairment with other learning disabilities. For example, Asperger noted “atrocious” handwriting in his description of several children with the syndrome that today bears his name (Henderson & Green, n.d.), and the prevalence of motor deficits in children with autism spectrum disorder (ASD) approaches 10% (Fuentes, Mostofsky, & Bastian, 2009; Ming, Brimacombe, & Wagner, 2007). In addition, handwriting is often impaired in children with attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD).

Pediatric dysgraphia is associated with problems in visual perception, visual-motor integration, cognitive planning, and fine motor coordination (Rosenblum & Livneh-Zirinski, 2008; Volman, van Schendel, & Jongmans, 2006), but the relative strength and contributions of these variables to dysgraphia are not well understood. Nonproficient handwriters have been found to show far less consistency than proficient handwriters in letter width, letter height, and

elevation of the pen or pencil above the paper ($p < .03$; Rosenblum, Chevion, & Weiss, 2006). Some researchers have found that slow handwriters seem to rely more on visual feedback than normal-speed writers, who rely more on proprioception (Tseng & Chow, 2000). Nonproficient handwriters are also very slow and often have difficulty copying class work.

Previous studies have demonstrated the feasibility of using haptic technology to teach glyph formation (Lally, 1982; Macloud & Proctor, 1979; Popescu, Burdea, Bouzit, & Hentz, 2000; Solis, Avizzano, & Bergamasco, 2002). Haptic technology uses the sense of touch as the human-computer interface. In this study, the interveners (i.e., the authors) programmed the computer to adjust the amount of mechanical assistance it provided, thereby encouraging users to learn active control of movement. More advanced technology uses sensors attached to the patient to adjust the robotic assistance automatically (Krebs, Volpe, & Hogan, 2009; Ma, Trombly, & Robinson-Podolski, 1999; Munih & Bajd, 2010; Van Peppen et al., 2004). Robotic-assisted repetitive motion training is an emerging therapy for gross upper-limb rehabilitation after stroke (Staubli, Nef, Klamroth-Marganska, & Riener, 2009) or traumatic brain injury, as well as for hand rehabilitation (Brewer, Klatzky, & Matsuoka, 2008; Bütefisch, Hummelsheim, Denzler, & Mauritz, 1995; O'Malley, Ro, & Levin, 2006). Bluteau, Coquillart, Payan, and Gentaz (2008) demonstrated that haptic guidance also improves visual-motor tracking, one of the key components of the handwriting process (Berninger, 2009; Graham & Harris, 2009).

The purpose of this study was to evaluate the safety and efficacy of a small gaming console, the Falcon (Novint Technologies, Albuquerque, NM), in delivering three-dimensional repetitive fine motor training to children with poor functional handwriting. The specific clinical and functional research questions were as follows:

1. Would the robotic-assisted repetitive motion training improve fine motor control?
2. Would the robotic-assisted repetitive motion training help children scribe glyphs more consistently?
3. Would robotic-assisted training increase functional efficacy as measured by handwriting speed and glyph reversals?

Method

Research Design

The study used an uncontrolled pretest-posttest design in two cohorts. We obtained parental consent and participant

assent at the intake session. The Western Institutional Review Board approved the study protocol and also determined that the Falcon met the U.S. Food and Drug Administration's criteria for a Class 1 investigational device.

Instruments

We measured fine motor control using the Motor Coordination subtest of the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI; Beery, Buktenica, & Beery, 1989). The Motor Coordination subtest was normed by 3-mo age groups and has an interrater reliability of .93. We collected data on glyph size consistency, letter reversals, and letter memory using the random number and uppercase letter order subtests of the Test of Handwriting Skills-Revised (THS-R; Milone, 2007) and the random lowercase letter order subtest of the Print Tool (Olsen & Knapton, 2006). We measured speed by counting the number of letters copied from the copy subtest of the Evaluation Tool of Children's Handwriting (ETCH; Amundson, 1995) with an indication of 20 s and compared the quantity with the age-adjusted norms established in the THS-R (test-retest reliability = .83). We administered the VMI as a potential confounding factor. The VMI has been shown to be related to handwriting legibility in kindergarteners (Daly, Kelley, & Krauss, 2003), although its ability to predict handwriting performance in first grade has been questioned (Marr & Cermak, 2002).

Participant Selection

We recruited a purposive convenience sample of children in Grades K-5 in 2009 and 2010. For the 2009 cohort, the school's itinerant occupational therapist nominated children at a rural public school near Eugene, Oregon. For the 2010 cohort, families near Corvallis, Oregon, were informed of the study opportunity by teachers and pediatric occupational therapists and through newspaper advertisements.

To be eligible, children had to meet the base prerequisites for writing: orientation to written language, single-handed utensil or tool manipulation (Brief Assessment of Motor Function [BAMF] score ≥ 6 ; Parks, Cintas, Chaffin, & Gerber, 2007), and ability to recognize all letters of the alphabet. The children had to have illegible writing or legible writing but at a speed of less than the 16th percentile for their age and gender and had to be able to grasp a pen, speak and understand English, follow instructions, and devote at least 20 min to the assigned tasks. Exclusion criteria were as follows: inability to pass the informed assent screener, unwillingness to sign or mark the informed assent documents, uncontrolled spasticity, cerebral palsy (CP) other than the hemiplegia type, or severe autism or

intellectual disabilities that prevented productive interactions with adults.

Intervention

We developed a bundle of custom haptic software and hardware, My Scrivener™, to interface with the Falcon, modifying it from a gaming console to a socially assistive robot (Matarić, Tapus, Winstein, & Eriksson, 2009; Palsbo, Marr, Streng, Bay, & Norblad, 2011; Figure 1).

The software generates a three-dimensional haptic pathway when the user types in one or more letters, numbers, or punctuation glyphs. We coded the stroke sequence of each glyph following the conventions in Handwriting Without Tears (HWT), a handwriting instructional curriculum widely used in the United States (Olsen, 1999). Children were matched to the HWT curriculum appropriate for their ability on the basis of their pretest scores. The interveners (Palsbo and Hood-Szivek) customized the haptic pathway according to the goals of the training session, including speed, glyph size, height of pen lift off the paper, number of repetitions, amount of haptic force, and left- or right-handed stroke patterns. Children who reversed letters and numbers in the pretest spent more of their robot time with a proprioception exercise that consisted of closing their eyes and guessing which glyph

or letter sequence the robot was scribing. Children who wrote slowly spent more of their robot time racing the robot. A typical session included a 10-min review of the letters and numbers covered in the previous sessions, 10 min with robot-assisted glyph formation under the supervision of the interveners (who would adjust speed or letter size during the session and provide verbal feedback), and 10 min on the workbook lesson. Sessions were conducted 3–5 times per wk for 4–6 wk, for a total of 15–20 sessions per child.

Intervention Administration and Fidelity

The intervener for the first cohort (Palsbo) was trained and certified in the HWT curriculum but was not a clinician. The intervener for the second cohort (Hood-Szivek) was a registered and licensed pediatric occupational therapist who had several years of experience in school-based therapy and had been trained in the HWT curriculum. The first intervener demonstrated how she provided the intervention for the first cohort to the second intervener. Both interveners kept a daily log for each child, recording the HWT lesson pages used, notes of glyphs that needed additional work, progress on speed and letter size, and number of minutes using robotic assistance.

Data Collection

Both authors collected data at the intake and exit sessions, but not all participants were administered all tests because some became highly agitated during administration or were unable to recall glyphs. The children wrote on the single-lined paper used in the Print Tool. We added administration of the VMI Motor Coordination subtest to the second cohort. The modified data collection protocol led to different sample sizes for various analyses. Author Susan Palsbo, who had completed the self-training scoring courses for the ETCH, THS–R, VMI, and VMI Motor Coordination subtest and was also certified to score the Print Tool, conducted all scoring. Scoring was unblinded, but we selected the specific outcome measures used in analysis because they were objective.

Data Analysis

Rosenblum and colleagues found that nonproficient writers have more variability between glyphs than proficient writers (Rosenblum, Chevion, & Weiss, 2006; Rosenblum, Dvorkin, & Weiss, 2006), so we computed the ratio of the height to the width of each letter and number glyph. The desired outcome was to reduce the standard deviation of the height:width ratio. Several children changed from print to cursive writing, and because the height:width ratio for the same letter may be different

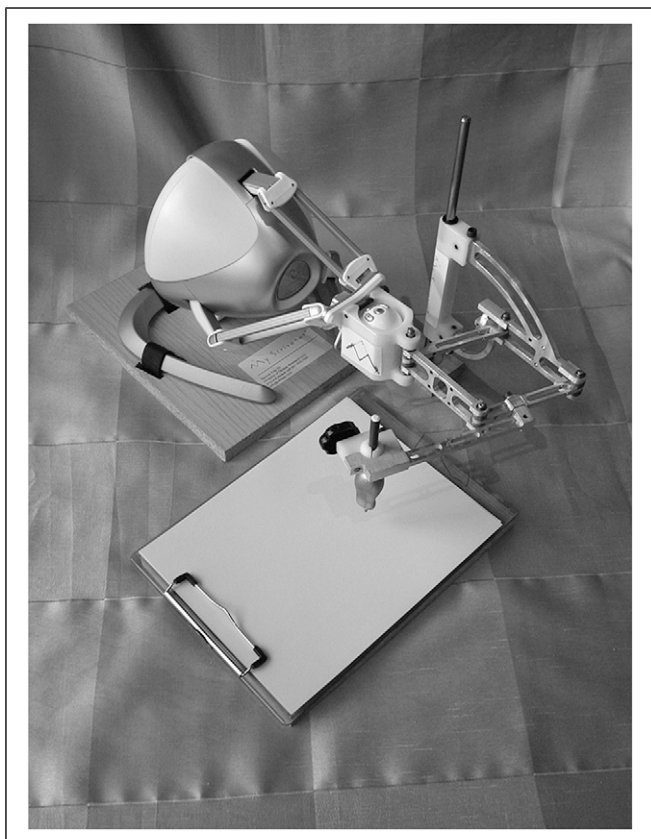


Figure 1. Haptic device used in the trial.

Image courtesy of Susan E. Palsbo.

between printing and cursive (e.g., lowercase *f*), we needed to control for this change. We subtracted the target ratios for the HWT model print and cursive alphabets (mean and standard deviation of 2.0 and 2.5 for print and 1.5 and 0.8 for cursive) from each child's print or cursive assessment. We calculated the difference between the desired and actual ratios before and after the intervention. Because of the small number of study participants, we compared the pretest–posttest percentiles using the Wilcoxon signed-rank test using SPSS Version 13 (SPSS, Inc., Chicago). Children were grouped as follows: origin of dysgraphia (neuromuscular, learning, no known origin), discrepancy between actual age and VMI result, print or cursive writers, age ≥ 9 yr or < 9 yr, and lowest 30th percentile of the Motor Coordination subtest. Only near-significant comparisons are reported in the following sections.

Results

Participant Demographics

Twenty-two children were recruited to the study. Of those, 2 children were excused after the initial screening because their legibility and handwriting scores were higher than the 25th percentile of national age-adjusted norms. One child withdrew for logistical reasons, and 1 withdrew because of behavioral issues. The final study population consisted of 18 children (6 in the 2009 cohort and 12 in the 2010 cohort) ages 5–11 yr who were enrolled or about to enroll in kindergarten through 4th grade. The participants were predominantly male (78%, $n = 14$) and White (78%, $n = 14$); 1 was Pacific Islander and 3 were of mixed race. No children were Hispanic or Latino. Thirteen (72%) were right handed, 2 (11%) were left handed, and 3 (17%) were indeterminate.

Table 1 shows the number of participants with parent-reported learning and neuromotor impairments. Six children with no specifically diagnosed learning or neuromuscular impairment were referred to the study because of very slow handwriting speed (below the 25th percentile). At least half of the children were currently

receiving or had previously received school-based occupational or speech therapy under an individualized education program, including 5 who had had previous exposure to HWT. Parents reported 7 children with current speech limitations. All children had fair finger motor function; 3 scored 8 and 15 scored 9 on the BAMF.

Clinical Efficacy: Motor Control (Second Cohort Only)

We administered the VMI Motor Control subtest to the 12 children in the second cohort and computed their age-adjusted percentile performance. The posttest motor control percentiles improved from a pretest mean of 29 (range = 0–88) to 42 (range = 0–99.8). A series of two-tailed Wilcoxon signed-rank tests were used to compare the change in percentiles (Table 2). The test approached significance at the $p < .10$ level for children age 9 and older, children with learning disabilities (i.e., ASD, ADD, ADHD), and children in the lowest 33rd percentile of motor control for their age.

Two children with ASD showed substantial improvement in motor control; 1 child moved from the 27th to the 68th percentile and the other from the 7th to the 23rd percentile. Of the 5 children with no identified diagnoses or learning disabilities, Motor Control subtest percentiles improved for 3, including 1 who improved from the 18th to the 45th percentile, and declined (by 2 percentile points) for 2. Two of the 3 children with CP had co-occurring intellectual or pervasive developmental disorders, and their percentiles were unchanged; the youngest of these children dropped from the 12th percentile to the 1st percentile.

Functional Efficacy: Consistent Glyph Formation

Figure 2 shows the pretest and posttest standard deviations of the differences between the actual glyph height:width ratio for 14 children and the normed glyph height:width ratio. Ten of the 14 children had more consistent glyph formation. The Wilcoxon signed-rank test for the paired differences in the standard deviations showed near significance, with $p = .09$ and Cohen's $d = 0.49$, a medium effect size.

Table 1. Number of Participants With Neuromotor and Learning Impairments

Neuromotor Impairment	Learning Impairment						Total
	No Reported Disability	ADD or ADHD	Autism Spectrum Disorder	Pervasive Developmental Delay	Intellectual Disability	Auditory Processing Disorder or Deafness	
No reported neuromotor disorder	4	1	4	0	1	2	12
Cerebral palsy	1	0	0	1	1	0	3
Other neuromotor disorder	1	1	1	0	0	0	3
Total	6	2	5	1	2	2	18

Note. ADD = attention deficit disorder; ADHD = attention deficit hyperactivity disorder.

Table 2. Pretest–Posttest Change in Age-Adjusted Percentile for VMI Motor Control Subtest Scores

Group	Wilcoxon Signed-Rank Test
All ($n = 12$)	.09*
Children <35th percentile ($n = 8$)	.11
Children with cerebral palsy ($n = 3$)	.29
Children with learning disabilities ($n = 6$)	.08*
Children age 9 or older ($n = 4$)	.07*
Children age 8 or younger ($n = 8$)	.89

Note. VMI = Beery–Buktenica Developmental Test of Visual–Motor Integration.

* $p < .10$.

Functional Efficacy: Handwriting

The therapy goals for all 5 children with ASD included improving speed and writing at a grade-appropriate size. All children with ASD met their cursive and speed goals. Two children who moved to cursive doubled or tripled their speed (from 4 to 9 letters and from 5 to 15 letters in 20 s).

Three of the 18 children reversed 8 letters or numbers at pretest. Their reversals in the posttest evaluation were 0, 2, and 3.

Adverse Events

There were no injuries during this pilot study.

Discussion

The purpose of this study was to conduct a preliminary evaluation of the safety and efficacy of robotic-assisted, three-dimensional repetitive motion fine motor training in two environments. We used a haptic computer–user interface to improve handwriting in children with fine motor impairments arising from various disorders. The robot delivered a precise program of active therapy with multi-sensory (visual, tactile, and optional auditory) feedback.

We believe that the repetitive three-dimensional pathways the robot provided encoded the motor patterns in the children (Kami et al., 1995). Children with large numbers of letter reversals before the intervention had none or fewer than three after the intervention. Several weeks after the intervention concluded, one child said, “It still feels like the robot is moving my hand” when writing his family’s grocery list. It is possible that the neural pathways encoded through the robotically guided repetitive motions alleviated the cognitive demands of the three-dimensional planning for glyph formation, particularly the starting point of each letter, thereby allowing the child to concentrate on shape and size (elements of legibility). Visual–spatial processing may also have improved, but we did not directly measure this.

The younger children who improved their speed appeared to do so because they improved their ability to recall the letters, whereas several of the older children improved their speed partly because they transitioned to cursive. In addition, speed may have improved because the children relied less on visually directed processes and more on proprioceptive processes.

It is not clear why the robot was more effective for the older children (Grades 3–5) than for the younger children. We observed that the older children seemed to interface better with the computer and were more willing to allow the device to guide their hand, whereas some of the younger children were more interested in guiding the robot. Younger children (K–2) in the 2009 cohort were learning the D’Nealian font in the classroom, so these children received conflicting guidance on the exemplar glyphs, which they found confusing.

Smits-Engelsman and Van Galen (1997) concluded that inconsistent letter size, form, and orientation arise from neuromuscular “noise.” It is possible that the older

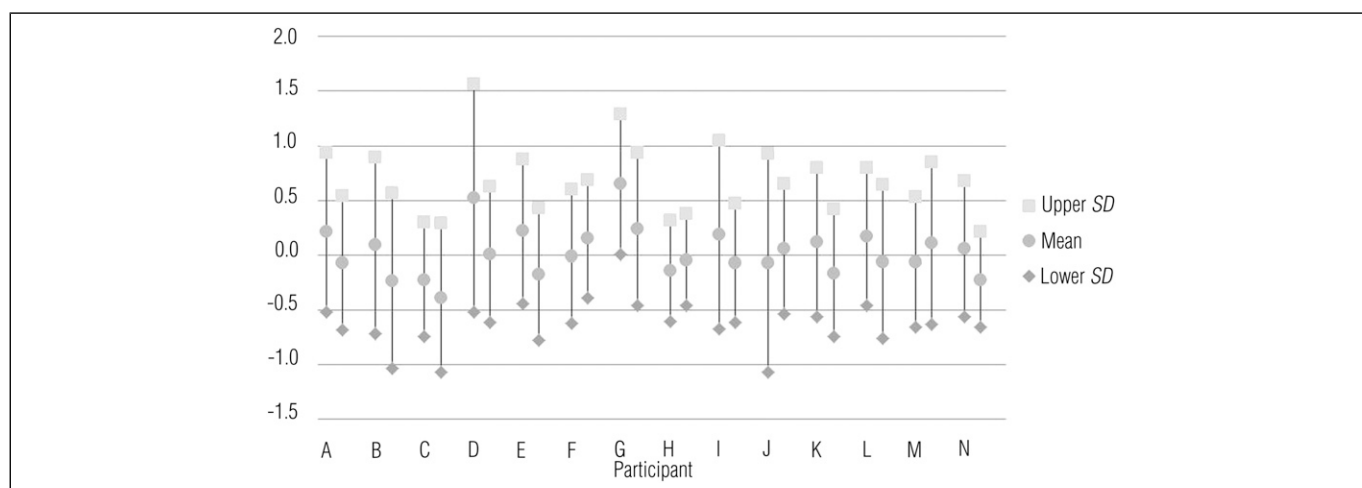


Figure 2. Participants’ pretest–posttest means and standard deviations (SDs) from target glyph height:width ratio.

children's more mature neuromuscular system enabled the robot to be more effective with them and that practicing with the very consistent robot helped them learn how to dampen the neuromuscular noise. We also prompted the children to constantly self-evaluate letter size and form and to make consistent glyph size a priority.

Two children with tactile hypersensitivity did not like to be required to hold onto the pen so the robot could guide their hand. We suggest that tactile hypersensitivity be included in screening and possibly exclusion criteria in further studies using robots. Despite their dislike, both children substantially improved in glyph consistency. The remaining 16 children found the robot very engaging, and most of them, even those with attention deficits, stayed on task for the full 25–30 min, day after day.

Findings for motor control in children with CP were less impressive than we had anticipated on the basis of prior research. Forced-use therapy has been found to be effective in hemiplegic CP (Sung et al., 2005), and unforced repetitive motion games using the Wii (Nintendo Games, Redmond, WA; Deutsch, Borbely, Filler, Huhn, & Guarrera-Bowlby, 2008) improved gross motor upper-limb movement for three adolescents with CP (Cook, Meng, Gu, & Howery, 2002; Fasoli et al., 2008).

Our results may have been contaminated because 2 of the 3 children had coimpairments and were receiving concurrent non-study-related interventions, such as *botulinum* toxin injections. We did not have sufficient power for our heterogeneous convenience sample of young children with CP to perform advanced statistical analysis. Further research is needed to ascertain whether more sessions of robotic training would be effective for these children. Reprogramming the software to include a combination of active exercise and active resistance may also be helpful.

A 7-yr-old boy with CP and intellectual disability made noteworthy gains during the study. Before the intervention, he could write 11 upper- and lowercase alphabet glyphs from memory. After the intervention, he had learned nearly the entire upper- and lowercase alphabets. Although his fine motor skills as measured by the VMI Motor Coordination subtest did not improve significantly, many glyphs were closer to being scored as correct after the intervention.

Implications for Occupational Therapy Practice

The intervention was intensive but not particularly time consuming (8–10 hr), yet most children improved their functional writing. Other researchers have also found significant improvements in handwriting with an 8–10-hr

curriculum focusing on the mechanics of letter formation (Case-Smith, 2002; Denton, Cope, & Moser, 2006; Mackay, McCluskey, & Mayes, 2010; Marr & Dimeo, 2006). Ten hours of focused handwriting instruction could be completed within a single quarterly reporting period required by the Individuals With Disabilities Education Act Amendments of 1997, with benefits lasting the rest of the academic year.

Because many children with ADD, ADHD, ASD, and CP receive motor therapy in schools, an affordable and portable robot can complement school-based therapist-directed interventions to improve functional handwriting outcomes. A robot can deliver the HWT curriculum with a parent volunteer under the occasional supervision of a school-based occupational therapist. At a cost of less than \$1,000 per workstation, it could make economic sense for many school districts to meet their federally required therapy hours using this type of robot and software. It would also be easy for children to continue to work with the training program when school is out of session.

In summary, the results of this study have the following implications for occupational therapy practice:

- Functional improvements in handwriting (increased speed and consistent letter shapes) may be achieved for children with deficits arising from ADD, ADHD, or ASD, through 8–10 hours of repetition motion training.
- Fine motor repetitive motion training in three dimensions can be provided by a desktop robot console for sale to the general public.
- A practical and objective measure of change in functional handwriting is to measure the standard deviation of difference between actual glyph height:width ratio and normed glyph height:width ratio, over time. This procedure allows comparisons when children have mixed manuscript and cursive lettering.

Limitations

This pilot study had several limitations, many relating to clinical outcomes measurement. For example, the VMI Motor Coordination subtest directs test takers to connect dots and to stay within boundaries rather than to perform the more challenging task of tracing a line. Consequently, the scoring rubric did not capture all improvements in motor control that were obvious to the researchers and to the children. The scoring rubric also failed to identify 1 child who did not correctly complete the over and under drawings before the intervention but completed them correctly after the intervention.

We also struggled with the absence of a valid instrument for functional measurement of fine motor control.

Previous reviews were not able to identify any single writing assessment tool that is normed and culturally robust and has high interrater reliability (Marr & Palsbo, 2010), although the Handwriting Proficiency Screening Questionnaire, developed for Hebrew glyph writers, shows promise (Rosenblum, 2008). Because slow writing was a frequent reason for referral to the study, we focused on improving writing speed. However, it appeared that most children slowed down their speed during the timed evaluation test, giving us invalid measures of actual writing fluidity. The study testing protocol included counting the number of letters written while copying a standard sentence from the ETCH and comparing this number to age-adjusted norms for the THS–R. Because 7 of the 8 children age 9 or older switched from print to cursive during the intervention, we could not distinguish how much of the increase in speed resulted from better motor engagement versus writing in cursive. From a functional perspective, however, we believe why there was improvement does not matter as much as that there was improvement.

A threat to generalizability is the small number of children in this study and our inability to assess how representative they were of all children with dysgraphia. In addition, we did not measure improvements in self-esteem or social and family inclusion. Another threat to causal validity is that the small number of participants did not allow us to distinguish among effects arising from use of the robot, personalized instruction, and the HWT curriculum. The procedures used by the device itself were standardized because they were programmed into the software; the verbal prompts and lesson plans, however, were customized, creating the potential for a therapist effect that can be tested in a larger study design. It is possible that the children would have shown the same improvement from personalized instruction in the HWT curriculum without using robotic assistance. The next research step is to control for various treatments and to increase the power for computations of effect size for various impairment origins and age groups.

Conclusion

Task-oriented robotic-assisted three-dimensional repetitive motion training of the hand may be helpful for children with dysgraphia. An inexpensive and portable gaming console can provide customizable repetitive motion training in school and outpatient clinical settings. Functional improvements in glyph formation and speed can be obtained in 10 hr of individualized instruction and robot-assisted guidance for many children with ADD,

ADHD, ASD, or intellectual disabilities in the lowest 25th percentile of handwriting proficiency. Children with CP may need more than 10 hr to show an effect. In conjunction with the HWT curriculum, the device can be used to deliver and reinforce evidence-based handwriting instruction between sessions by school-based therapists. The results are promising and warrant a larger trial with a control group to determine how much improvement results from robotic-guided repetitive motion compared with instructor-directed repetitive motion. ▲

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