

# A Novel Instrument for Quantifying Grip Activity During Handwriting

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**ABSTRACT.** Chau T, Ji J, Tam C, Schwellnus H. A novel instrument for quantifying grip activity during handwriting. *Arch Phys Med Rehabil* 2006;87:1542-7.

**Objective:** To describe and exemplify a noninvasive instrumentation system that uniquely records grip forces exerted on the barrel of the writing utensil along with typical temporal and kinematic parameters.

**Design:** Exploratory case series.

**Setting:** A tertiary care, pediatric rehabilitation hospital.

**Participants:** Convenience sample of 6 primary school children with spastic hemiplegic cerebral palsy (CP) with documented fine motor difficulties and 6 children with no known handwriting difficulties.

**Interventions:** Not applicable.

**Main Outcome Measures:** Grip and normal forces during handwriting.

**Results:** The instrumentation revealed nontrivial correlations between normal and grip forces ( $0.55 \pm 0.16$ ), a temporal delay between normal and grip forces ( $97.7 \pm 16$ ms), and a consistent grip-to-normal force ratio ( $4.3 \pm 1.5$ ), across all participants. Grip force distributions agreed intuitively with qualitative observations of individual grasps of the writing utensil. Further, 5 new parameters derived from grip force measures statistically differentiated between able-bodied children and those with hemiplegic CP.

**Conclusions:** The proposed instrumentation provides new insight into grip and normal force coordination and has the potential to uncover discriminatory grip force characteristics between writers with and without handwriting difficulties. Further study with larger populations is required to define functional ranges for the new grip measures.

**Key Words:** Biomechanics; Dysgraphia; Grip; Handwriting; Rehabilitation.

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**H**ANDWRITING IS A CRITICAL skill for school-aged children.<sup>1,2</sup> The ability to produce fluent and legible work is important for expressing, communicating and recording ideas, for high achievement in school, and for the cultivation of self-esteem.<sup>3,4</sup> Children in school use fine motor skills to

complete 31% to 60% of their daily tasks, with 85% of those tasks involving pencil and paper.<sup>5,6</sup> Example activities include composing a story, doing math questions, writing phone messages,<sup>7</sup> completing writing assignments, and composing long answers to test questions.<sup>1</sup> The reported prevalence of handwriting difficulties among school-aged children is nontrivial, varying between 10% and 34%,<sup>8,9</sup> with the severity of the problem typically warranting referral to occupational therapy. Typical assessments of handwriting difficulties<sup>10</sup> have been based on measures of speed<sup>11</sup> and judgment of the written product.<sup>12</sup> Handwriting, however, is a complex and dynamic process,<sup>13,14</sup> which is not adequately characterized by the written product alone. As a result, increasing emphasis has been placed on the quantitative study of the handwriting process through computerized instrumentation.<sup>1</sup> The overwhelming majority of these computerized instruments have consisted of digitizing tablets,<sup>13,15-18</sup> connected to a laptop or desktop computer. Other reported instrumentation includes a small number of custom developed writing utensils or surfaces<sup>19-21</sup> and most recently, tablet personal computers.<sup>22</sup> Studies deploying digitizing tablets have largely focused on the measurement of kinematics, temporal parameters, and normal or axial pen forces.<sup>23-25</sup> Aside from the pioneering work of Herrick and Otto,<sup>19</sup> none of the previously reported instruments measures grip forces during handwriting. Herrick and Otto<sup>19</sup> suggested that a strong correlation exists between barrel and pen point pressure and that barrel pressure variability is an important distinguishing characteristic of individual handwriting. Knowledge of dynamic barrel pressures or forces may shed light on the relationship between grip force and handwriting function, the nature of which is contested by studies<sup>26,27</sup> that did not have instrumentation to directly measure grip strength during handwriting. Clinical acumen also suggests that grip force may be an important determinant of functional writing. For example, occupational therapists routinely observe "knuckles turning white," signs of premature fatigue, slipping of the writing utensil, or a stiff nonfluid grasp, all suggestive of inappropriate force distribution along the barrel. In brief, although grip forces appear to be potentially important measurements for the assessment of handwriting function, there is, at present, no readily available instrumentation for their quantification.

Here we describe an instrumentation system, constructed largely from off-the-shelf hardware and capable of simultaneously measuring grip and normal pen forces along with position and timing. Grip forces are those exerted radially on the barrel of the writing utensil, while the normal force is the downward force applied perpendicularly to the writing surface at the tip of the writing utensil. It is anticipated that such an instrumentation system may provide valuable process-related information for routine evidence-based assessment and habilitation of graphomotor skills such as drawing and handwriting.

## Instrumentation System

As shown in *figure 1*, the instrumentation system is composed of 3 main components, a pressure-sensitive liquid crystal display (LCD) writing surface, a desktop computer, and an instrumented writing utensil. An optional fourth component is

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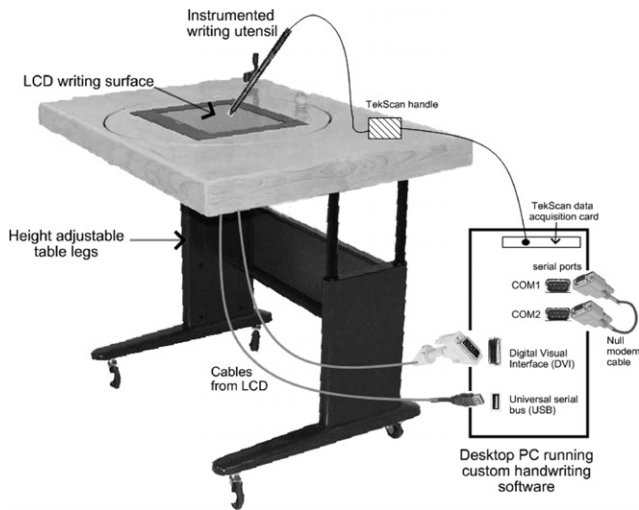
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**Fig 1.** The custom handwriting instrumentation consisting of instrumented writing utensil, a desktop computer with the custom writing software, LCD writing surface, and optional height-adjustable table. Abbreviation: PC, personal computer.

a height-adjustable table within which the writing surface may be embedded, flush with the table surface. Each main component is described in turn.

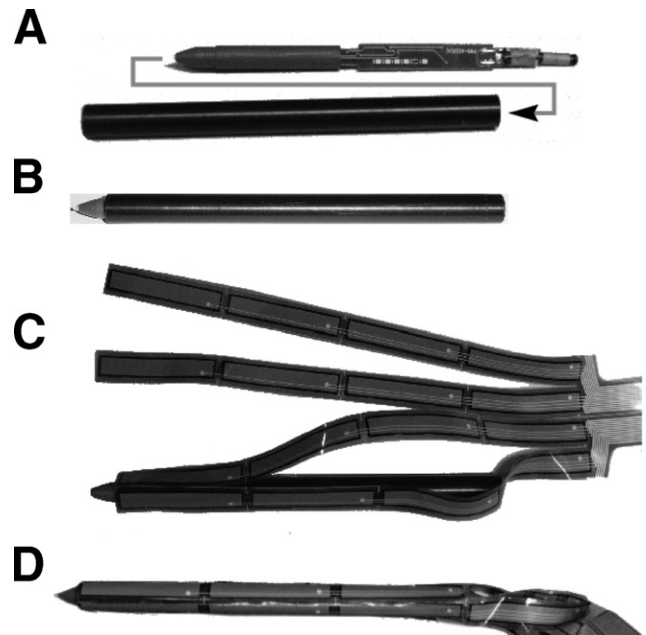
**Writing surface.** The writing surface consists of a CINTIQ 15SX<sup>a</sup> interactive and pressure-sensitive thin film transistor active matrix LCD display. The CINTIQ technology offers a letter-sized writing surface (30.5×23cm) that is electronically inked by a wireless stylus. This specific CINTIQ LCD model provides 512 levels of sensitivity to forces applied normally to the writing surface. Other models (ie, 17SX, 21SX) may also be used, each providing successively larger writing areas, with the latter boasting twice the force sensitivity and introducing pen tilt mensuration as well. The LCD writing surface can be placed on top of a table or wheelchair tray or optionally embedded into a height-adjustable table.

**Writing utensil.** The following materials and tools are required to assemble the instrumented writing utensil: a model UP-813E-01A or UP-911E-01 wireless stylus<sup>a</sup> of nonuniform diameter along its length for inking the writing surface, a block of Delrin plastic,<sup>b</sup> a lathe to machine the pen barrel, model 9811 paper-thin pressure sensors<sup>c</sup> (pressure range, 6.9–172kPa; individual sensor dimensions, 203×76mm; sensor thickness, 0.15mm), spray-on foam adhesive,<sup>d</sup> and regular 1.3cm (0.5-in) wide masking tape. The instrumented writing utensil is constructed by the following procedure.

1. Using a lathe, machine a cylindrical barrel 11mm in diameter and 147mm high out of Delrin acetal polyoxymethylene resin.<sup>b</sup>



**Fig 2.** Trimming the model 9811 force sensors for use as grip sensors.



**Fig 3.** Construction of the writing utensil. (A) Delrin barrel and Tablet pen. (B) Tablet pen inserted into the Delrin barrel. (C) Adhesion of force sensors to barrel. (D) The completed pen with grip sensors attached.

2. Remove the outer shell of the manufacturer's pen and transfer the interior contents to the custom-made cylindrical barrel. The resulting pen should be able to ink the CINTIQ Tablet.<sup>a</sup>
3. Carefully cut the model 9811 sensor array<sup>c</sup> along the dashed lines as indicated in figure 2. Discard the top and bottom row of sensors and retain the 4 inner strips.
4. While holding the tip of the pen, uniformly spray a generous layer of foam adhesive<sup>d</sup> along its barrel. Make sure this step is carried out in a well-ventilated area.
5. As shown in figure 3, adhere the 4 retained strips of the model 9811 pressure sensor,<sup>c</sup> one at a time, along the length of the barrel, starting at the edge proximal to the pen tip. For each strip, ensure that at least 8 sensor pads are securely fastened to the barrel surface to accommodate natural variations in grip height. Wipe away any excess glue with a damp cloth.
6. Tape the sensors with 1 layer of masking tape to ensure adhesion to the curved barrel surface. Let dry for 24 hours.
7. Carefully remove the masking tape. Where necessary, apply small amounts of glue to any areas where the sensor may not have completely adhered to the curved barrel surface.

By this procedure, we obtained the instrumented pen (weight, 15.2g; diameter, 12mm) shown in figure 3, which is comparable to a newly sharpened model D308 primary school pencil<sup>e</sup> (weight, 11.10g; diameter, 10.32mm) in mass and geometry.

**Desktop computer and software.** The desktop computer (Windows XP, Pentium IV, 3GHz, 1GB of random access memory) contains the acquisition hardware and software for the synchronized acquisition of grip forces, normal forces, and spatiotemporal data. For grip force measurements, install a Super Receiver Rev. 4 data acquisition card<sup>c</sup> into an available peripheral component interconnect slot. Install the F-Scan software<sup>c</sup> on the desktop computer. For normal force and spatio-



Fig 4. Plunger and cylinder for calibrating normal force measurements. The writing utensil has been inserted into the hollow cylinder. Small weights can be placed on the flat cap to calibrate normal force readings as described in the text.

temporal measurements, install the custom “writing” software (freely available from the authors), written in C++. The writing software can emulate a blank piece of paper, a lined piece of paper or a paper version of a handwriting test, such as the CHES-M test,<sup>28</sup> displaying 2 lines of text. Once launched the software automatically triggers data recording and page inking when the applied normal force on the writing surface exceeds zero. Recording is stopped manually by right-clicking on the computer mouse.

**Final assembly.** Place the LCD flat on a table or within the cut-out portion of a custom table. Connect the LCD writing surface to the computer via an available universal serial bus port and the digital-video interface port, as indicated in figure 1. Connect the grip sensors to a TekScan FSC-1 handle,<sup>c</sup> which in turn is connected to the data acquisition card through the supplied cable. Connect serial ports 1 and 2 via a null modem cable for synchronizing grip and normal force recordings. All requisite connections for the handwriting instrumentation are shown in figure 1. With the specific hardware and software described previously, the sensor lag times were under 10.6ms and 3.8ms for the normal and grip force readings, respectively.

**Instrument Calibration**

Two sensors, namely, the LCD writing surface and the barrel sensors, should be calibrated to known values of force. For the writing surface calibration, machine a hollow “calibration” cylinder 14cm in height out of Delrin<sup>b</sup> with a 16mm interior diameter to accommodate the custom writing utensil described earlier. Also machine a flat cap, 25mm in diameter, with a plunger 39mm in height and 16mm in height. To calibrate the LCD surface, place the calibration cylinder on the LCD, insert the writing utensil (prior to grip sensor attachment) into the calibration cylinder and cap the top of the cylinder. Sequentially load and unload the cap with small slotted disks<sup>f</sup> ranging in mass from 5 to 250g and record the corresponding readings on the LCD. Weigh the writing utensil and the calibration cylinder cap. Using the following relationship,

$$\text{Normal force} = (\text{mass of pen} + \text{mass of cap} + \text{mass of slotted disks}) \times g$$

where  $g$  is  $9.8\text{m/s}^2$  is the acceleration of gravity, develop a calibration curve to translate all LCD readings into force units

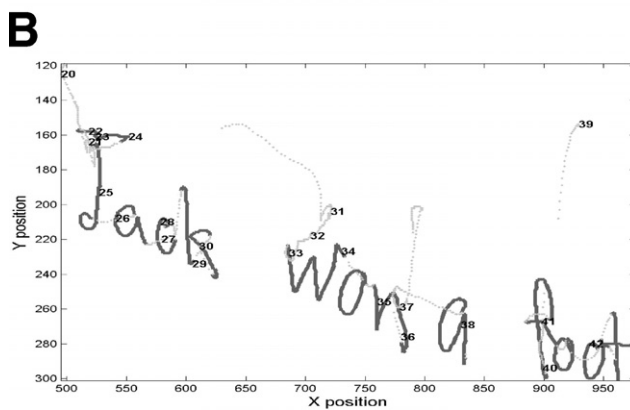
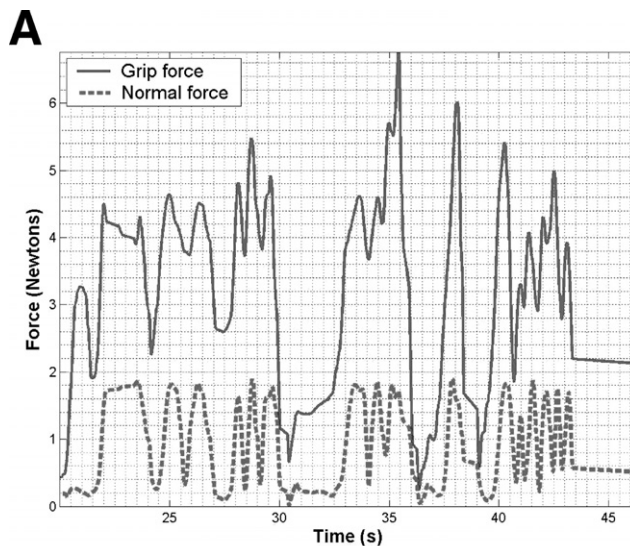


Fig 5. (A) A 25-second sample of grip and normal force profiles from a proficient writer and (B) the corresponding written product. The superimposed numbers represent the time in seconds, indicating the progression of writing. Both the actual writing (dark grey lines) and the in-air movement (light grey dotted lines) are shown.

of newtons. The calibration cylinder and flat cap with plunger are depicted in figure 4.

The barrel sensors are calibrated prior to adhesion to the writing utensil. Lay the sensors on a flat surface and uniformly apply several known loads. Alternatively, use a PB100D calibration device.<sup>c</sup> In both cases, the built-in functions within the F-Scan software (version 5.24) are used for calibration. Prior to each grip sensor recording session, load the calibration data file and apply the tare operation while the pen is laid flat to mitigate inadvertent sensor activation in the unloaded state. Both calibration curves for the normal force and grip sensors are available from the authors and would be valid for similarly assembled instrumentation.

### Data Acquisition

With the instrumented utensil described earlier, the F-Scan software would record 32 pressure values (4 sensor strips  $\times$  8 sensor pads per strip) for each sampling period. Through the F-Scan software, configure recording to start on receipt of an external trigger through the second serial port (COM2). Set the sampling frequency for the barrel sensors to 94Hz. This corresponds to the nominal sampling rate of the LCD display. The custom-developed writing software communicates to the F-Scan software through the COM1-COM2 serial port connection. Logging of normal force and horizontal and vertical pen tip position via the LCD begins automatically on the start of writing. Simultaneously, the recording of grip forces is triggered by the custom software which sends a "data-terminal-ready" signal to the COM1 serial port. This signal is received at the COM2 serial port via the null modem cable. In this way, both barrel pressure and normal force recordings are initiated simultaneously. Because normal and grip force measurements entail separate hardware systems, the data are actually acquired asynchronously. However, both sets of data are time stamped for easy off-line cross-referencing.

### METHODS

We now show the types of measurements that the proposed instrumentation can provide. We collected quantitative data from 6 able-bodied children with no known handwriting diffi-

culties (4 boys, 2 girls; all right-handed; age,  $6.7 \pm 0.6$ y) and 6 children with spastic hemiplegic cerebral palsy (CP) (4 boys, 2 girls; 5 left-handed; age,  $8.3 \pm 1.6$ y) and fine motor difficulties as indicated by their scores on the Beery-Buktenica Developmental Test of Visual-Motor Integration<sup>29</sup> ( $71.2 \pm 4.7$ ), the Quest Dissociated Movement<sup>30</sup> subtest ( $73.2 \pm 19.6$ ), and the Quest Grasp<sup>30</sup> subtest ( $57.4 \pm 21.3$ ). The protocol was approved by the research ethics boards of the affiliated hospital and university. All participants freely consented to the study. Kinematic and kinetic data were logged while the participants copied 2 lines of text on the tablet with the instrumented writing utensil, using their dominant, unaffected hand. To minimize possible interference with natural handwriting, the TekScan handle was placed on the table close to the participant's writing hand, such that there was no undue tension on the cable between the stylus to the TekScan handle.

### RESULTS

The top panel of figure 5 depicts the total grip and normal force profiles for a writer without handwriting difficulties, over a 25-second period of printing, while the bottom panel is the corresponding writing sample annotated with time stamps. Total grip force is the sum of the forces measured by the 32 individual grip sensor pads. Three interesting observations can be immediately made. First, the grip force and normal force appear to be correlated ( $r = .67$  in this example). Herrick and Otto<sup>19</sup> observed this correlation but did not provide any quantification thereof. This correlation is intuitively reassuring, implying that the application of barrel force and the exertion of downward force are highly coordinated activities. Second, the normal force appears to lag the grip force. In this example, the lag is 103ms as determined by cross-correlation maximization of grip and normal force profiles. In agreement with common sense, this temporal lag suggests that one adjusts his/her grip prior to adapting the downward force applied to the page. The third observation to note is that the total barrel force is much larger than the normal force at the corresponding time instant. In this example, the average total barrel force is 4.4 times the average normal force. This suggests that during handwriting, most of the energy expended by the hand is used to maintain a

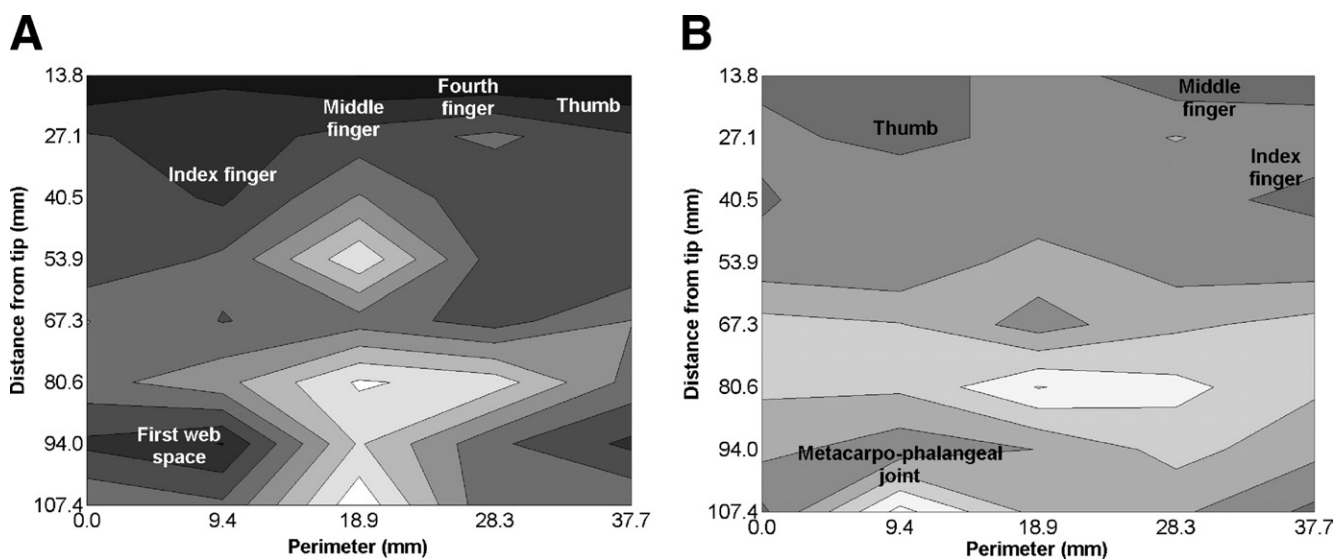


Fig 6. Average grip force distribution over 2 minutes of writing for (A) a proficient and (B) a nonproficient writer. Darker shading indicates higher forces.

stable grip on the writing utensil and a much smaller fraction of effort is required to actually push the pen downward. These 3 trends were common to both groups of participants; that is, there were no between-group statistical differences. The overall values for grip-to-normal force correlation, grip force lag, and average grip-to-normal force ratio were  $0.55 \pm 0.16$ ,  $97.7 \pm 15.9$ ms, and  $4.3 \pm 1.5$ , respectively.

If we imagine the sensors unwrapped from the pen and laid side by side, we obtain a unique visualization of grip force distributions. For example, in the left panel of figure 6, we plot the average force distribution over a 2-minute period for a proficient writer. Darker regions indicate higher forces. From this contour plot, we recognize that the individual had 2 main areas of high force contact with the barrel, namely, within a band 14 to 30mm from the pen tip and in a region centered on 94mm above the tip. By examining the child's pencil grip via video review, we see that this force distribution reflects his quadrupod grasp with open web space, where 3 fingers and thumb contact the barrel near the apex of the pen. The region of high force distal to the pen tip corresponds to the point at which the pen rests within the first web space, seemingly in a supportive role. In contrast, the unfolded force distribution from a child with CP is plotted in the right panel of figure 6. We note that force values are generally reduced, indicating a weaker grasp. Unlike the previous distribution, local force peaks are less prominent. Rather, there is a band of elevated forces from 13.8 to 53.9mm above the pen tip. This distribution arises from the participant's tripod grasp with the thumb slightly rotated toward the pen, closing the web space. In general, careful study of these force distributions can reveal areas of unusually high or inadequately low forces, for particular letter forms, and thereby help to target remedial efforts.

## DISCUSSION

The instrumentation also has potential to elucidate quantitative differences between writers with and without handwriting difficulties, as summarized in table 1. In particular, we point out that certain grip-related quantities, never considered in previous studies that we have examined, but afforded by the present instrumentation, statistically differentiated between writers with and without handwriting difficulties. For example, the proficient writers tended to grip the utensil closer to the pen tip, as estimated by their lower grip height (*t* test,  $P=.045$ ) defined as the force-weighted average position. It also appears that participants with CP had weaker (lower maximum grip force) and less adaptive grasps. The latter can be inferred from the reduced grip force variability relative to normal force variability. Here, variability is estimated by the interquartile range. Further, the diminished ratio of grip-to-normal force optima implies that fewer grip force adjustments are made per change in downward force. Surprisingly, most of the measures commonly reported in handwriting studies deploying digitizing tablets did not provide discriminatory information between the 2 groups of children.

## Study Limitations and Other Applications

The kinetic friction of the writing utensil against the LCD surface appears to be less than that of the pencil on paper interface. The reduced friction may influence writing performance and hence the coefficient of kinetic friction should be quantified in future studies. The normal force appears to saturate at 1.5N. A softer pen tip with a mechanism to transfer tip forces to the barrel would alleviate this problem. The normal forces should be considered cautiously in the absence of pen inclination angles. The comparisons reported here between

**Table 1: Example of Quantitative Measures Afforded by the Proposed Instrumentation**

Measures	Able-Bodied Participants (n=6)	Participants With Hemiplegic CP (n=6)
<b>Grip measures</b>		
Grip height (mm)	35.40 ± 13.68	51.49 ± 10.43*
Maximum grip force (N)	7.28 ± 1.35	5.19 ± 1.36*
Grip force spread <sup>†</sup>		
Normal force spread	2.94 ± 0.67	1.61 ± 0.62*
# Grip force maxima		
# normal force maxima	1.14 ± 0.18	0.94 ± 0.11*
# grip force minima		
# normal force minima	1.14 ± 0.19	0.93 ± 0.11*
<b>Temporal measures</b>		
In air time <sup>15</sup> (s)	69.87 ± 11.30	75.22 ± 9.40
Contact time <sup>15</sup> (s)	50.021 ± 11.39	43.701 ± 9.49
Movement time <sup>15</sup> (s)	34.918 ± 10.82	31.898 ± 8.53
<b>Stroke measures</b>		
Stroke duration (s)	0.55 ± 0.11	0.74 ± 0.33
Stroke length (mm)	6.54 ± 1.88	7.92 ± 2.96
No. of strokes	70.33 ± 12.75	61.50 ± 40.39
<b>Velocity measures<sup>‡</sup></b>		
Dysfluency <sup>18</sup>	196 ± 65	174 ± 98
Average x velocity <sup>17</sup> (mm/s)	37.25 ± 3.54	42.966 ± 11.88
Average y velocity <sup>17</sup> (mm/s)	48.96 ± 11.82	50.10 ± 17.14
Average tangential velocity <sup>17</sup> (mm/s)	36.09 ± 9.22	43.37 ± 21.78*
Average coherence <sup>17</sup>	0.17 ± 0.27	0.17 ± 0.13
<b>Normal force measures</b>		
Median normal force (N)	0.70 ± 0.29	0.91 ± 0.44
Peak normal force (N)	1.50 ± 0.00	1.47 ± 0.07

NOTE. Values are mean ± standard deviation. Horizontal lines in the last 3 grip measures indicate ratios.

\*Significant difference ( $P < .05$ ) between proficient and nonproficient writers.

<sup>†</sup>Spread is measured by interquartile range.

<sup>‡</sup>Velocity measures do not include in-air movements.

writers with and without CP only illustrate that the instrumentation may elucidate some previously unidentified grip activities during the process of handwriting. Clearly, controlled experiments with larger sample sizes are required to make statements about population differences.

Other potential applications of the proposed instrumentation in physical rehabilitation research and practice might include quantifying the impact of commonly prescribed handwriting interventions (eg, grip adaptations) and remedial exercises, investigating the quantitative determinants of functional printing, such as the requisite ranges of grip and normal forces, and pinpointing pathologic grip deviations to better inform clinical decision making in the treatment of graphomotor difficulties.

## CONCLUSIONS

We have described a novel instrumentation for capturing grip biomechanics along with spatiotemporal parameters and normal forces during handwriting activities. Based on the small sample recordings presented herein, this instrumentation may provide additional insight into graphomotor difficulties particularly relating to grip forces and their spatiotemporal distribution.

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### Suppliers

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- c. TekScan Inc, 307 W First St, South Boston, MA 02127-1309.
- d. Zytek Inc, 524 Watson St E, Whitby, ON L1N 1A7, Canada.
- e. Dixon Ticonderoga Co, 195 International Pkwy, Heathrow, FL 32746.
- f. Boreal Laboratories, 399 Vansickle Rd, St. Catharines, ON L2S 3T4, Canada.