Computer-based haptic control assessment of 3-D manipulation and drawing skill with analytical application of machining metrics

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Three-dimensional manipulation tasks, or constructional praxis, are a neuropsychological function that has possessed limited assessment sophistication. We describe a novel computer simulation for stimulus presentation and data capture that uses a peripheral haptic device to provide quantitative assessment of drawing (or graphomotor) skill and to characterize the dynamics of motor execution in 6 degrees-of-freedom. A set of original quantitative analyses are proposed to operationalize motor precision based on evaluation techniques used in industrial machining processes. Factors considered to be influential in the haptic device use were tested, such as pixel width of virtual objects created during computer-based drawing, specifically reproduction of the standard Rey-Osterrieth Complex Figure. A semi-automated skill assessment method was demonstrated to provide greater detail, accuracy and objectivity than a manual-based approach. The simulation and data capture system may be applied to other stimuli (geometric figures) and paradigms used in the quantification of motor abnormalities.

Practitioner Summary: Quantitative analysis methods are needed for detailed and accurate evaluation of human ability in 3D manipulation tasks. A novel method was developed to assess jitter in motor-control in computer-based drawing tasks. The width of drawing implements or rendered strokes on the computer screen appear to influence the degree of jitter. This quantitative analysis method was shown to be more accurate and objective than conventional manual-based scoring of drawing ability.

Keywords: Three-dimensional manipulation, neuropsychological assessment, Rey-Osterrieth Complex Figure, computerized motor tests, haptic simulation

1. Introduction

The capacity to use tools for communication represents one of the highest evolutionary achievements (Makuuchi et al., 2003; Sayim and Cavanagh, 2011). In neuropsychology literature, the skills in which parts are moved in three dimensions to form a single assembly are referred to as constructional praxis skills (Benton, 1979). Optimal constructional praxis performance in standard figure reproduction requires visuoperceptual analysis (Guerin et al., 1999; Laeng, 2006) and use of memory retrieval (Caplan, 2006; Kim et al., 2009). Pre-motor planning and prehensile control of a drawing or writing implement, in concert with sensory guidance, are used in reproduction of linear and angular translations of the standard within a defined space on a drawing surface (Woodworth, 1899; Ogawa et al., 2009). Impairment in any of these visuo-perceptive, graphomotor and output-monitoring processes used in completing the reproduction can result from congenital, degenerative or Traumatic Brain Injuries (TBIs); therefore constructional praxis is a principal target of neuropsychological assessment and rehabilitation (Stiles et al., 1997; Russell et al., 2010).

1.1 The Rey-Osterrieth Complex Figure (ROCF) Standard

The ROCF standard (Figure 1) is commonly used for neuropsychological assessment of constructional praxis and graphomotor control (Tupler et al., 1995; Luzzi et al., 2011). The ROCF is constructed using 39 straight-line segments forming enclosed rectangles or triangles, as well as a circular component with three
solid dots in the interior. For over 70 years, the ROCF has been deployed as a test of visuo-perception, constructional praxis, graphomotor control and figural recall from immediate or delayed memory (Hamby et al., 1993; Bernstein and Waber, 1996). It has been applied in evaluation of a variety of clinical-neuropsychological patients across the age spectrum, from children with TBI (Schwartz et al., 2003) to elderly with Alzheimer’s disease (Bigler et al., 1989). Consequently, use of the ROCF for neurocognitive and/or motor-skill assessment allows comparative reference to a substantial body of previous neuroscience-related literature.

![Figure 1. The Rey-Osterrieth Complex Figure.](image)

Traditional paper-and-pencil neuropsychological tests assessing constructional praxis, including the ROCF, allow for measurement of production time and errors associated with a final, static reproduction; however, they are otherwise limited in capacity to capture more complex motor topography dynamically (e.g., sequential actions in two- or three dimensional (D) space). Although computerized neurocognitive and motor tests have been widely available since the 1990s, they are restricted principally to keyboard (e.g., Reeves et al., 2007), mouse (e.g., Cunningham et al., 2012), joystick (e.g., Kang et al., 2008), digitizing tablet (e.g., Erasmus et al., 2001) or voice-recognition input (e.g., Reeves et al., 2007). In addition to omitting graphic implements, many tests do not provide data with high temporal and spatial resolution. Therefore, there is a need for accurate and replete analysis of constructional praxis using input devices that can record both reproduction results and kinematic motor-output dynamics, for example, a 3-D-capable haptic device. Such analysis can support greater diagnosticity in evaluation of patient motor control.

A computerized version of the ROCF integrating a haptic device was developed previously (Li et al., 2013; Kaber et al., 2014). The simulation records freehand drawings, processes and normalizes drawing strokes, and facilitates interactive scoring modeled after the Rey-Osterrieth 36-point system (Knight and Kaplan, 2003). The system segments the ROCF into 18 units and scores each on accuracy of construction and location relative to other units, based on specific measurements in certain instances and on human judgment determinations in others. The 18 distinct unit scores are then summed to obtain the raw score for the entire figure. The semi-automated scoring system was designed to work as an alternative to traditional labor-intensive diagnosis procedures conducted by clinicians with subjective evaluation criteria. Scoring was based on existing pattern recognition techniques adapted to streamline the process and improve precision. Both the drawing system interface and a separate flexible scoring system interface were tested. Li et al. (2013) made comparison of system output with outcomes of the traditional paper-based ROCF test performed by unimpaired users. They found both the computerized and paper versions to have sensitivity to functional differences between dominant and non-dominant hand use. The computerized scoring software also appeared to be valid for generating ROCF scores, which were consistent with manual scores determined by a trained rater for the same drawing stimuli.

Although results have shown advantages of the computer-based system over the traditional paper-based task, there was some evidence that the scoring algorithms could be modified to improve assessment
accuracy. For example, the original semi-automated system used an ellipse-fitting method that did not support reliable scoring of reproduction of a circular unit in the standard figure. The system also used a “two-end” approach for approximating linear strokes as part of line-segment based units. Consequently, additional information between the two endpoints of a line was overlooked. Reducing each stroke to a “perfectly” straight line eliminated the ability to observe important details, such as tremors occurring during the drawing process. For the present research, a novel approach was identified to improve the fidelity of the scoring algorithms while maintaining the details of the original drawing strokes.

1.2 Jitter Assessment

As described above, ROCF reproduction is performed by combining visuo-perceptive, graphomotor and prehensile control of a stylus. If any of these elements is impaired, the accuracy of the standard will be affected. In manufacturing, machining processes determine the final geometry and dimensions of a part, as well as surface texture or finish (Schrader et al., 2000). Like accuracy in ROCF unit reproduction, the smoothness of machined part surfaces depends on three groups of factors, including: geometric, work material, and vibration or machine tool (Groover, 2004). Among these three groups, the latter is most similar to human errors in graphomotor control or use of a drawing implement. In manufacturing, machine vibration resulting from a lack of dynamic stiffness of one or several elements of a system, comprising the machine tool, tool holder, cutting tool and workpiece material, is called machine jittering (Quintana and Ciurana, 2011).

The concept behind jitter assessment in reproducing or copying a standard figure is analogous to the evaluation of surface roughness in metal-part machining (Shahabi and Ratnam, 2009). Surface roughness of machined parts is caused, in part, by shaking of a tool tip at a workpiece. Tool turbulence may be considered similar to jittering of the human hand during a standard copying process. With this in mind, we formulated a double-roughness analysis approach (i.e., assessment of inaccuracy relative to either side/edge of an element in a drawing unit) to evaluate human jittering in ROCF reproductions. Jitter was assessed in the X-Y drawing plane as well as the Z dimension, perpendicular to the plane.

Considering further machining processes, the diameter of a cutting-tool tip may also substantially influence the surface roughness of a metal part. Similarly, the width of the head of a drawing implement in ROCF reproduction may influence graphomotor precision, particularly with respect to jitter and duplication. In general, it is expected that the human hand is susceptible to greater error with coarser reproductive tools. That is, lower resolution feedback in drawing decreases user sensitivity to jitter and degrades control. Consequently, we also considered the width of drawing strokes in ROCF reproduction to be influential in jitter and that larger strokes widths would cause greater jitter. We therefore tested whether increasing graphical stroke width (i.e., the number of pixels comprising the width of a stroke) in computer-based display of graphomotor output, would lead to greater jittering, reflecting effects of cruder implementation.

2. Methods

2.1 Participants

A total of 8 persons (2 female, 6 male) were recruited from the North Carolina State University campus and participated in the experiment. They were paid for their participation. Participants ranged in age from 18-25 years. All had strong right-handed preferences as defined by scores on the Edinburgh Handedness Inventory (Oldfield, 1971) greater than 90 (on a 100-point scale), and all had normal intelligence as reflected in naïve administration of the Block Design (BD) subtest of the Wechsler Adult Intelligence Scale, Third Edition (WAIS-III; Wechsler, 1997). None had prior experience with the form of motor-control testing employed in the study (i.e., the ROCF reproduction) or the use of a haptic device with a computer system for test delivery.

2.2 Apparatus

The experiment apparatus included a high-performance graphics computer and a SensAble Technologies PHANTOM® Omni® haptic device that allowed for user motor inputs to the test-simulation in 6 degrees-of-freedom (DOF). The Omni also provides a realistic force-modeling capability in 3 DOF. Participants could feel the resistance of a display cursor against a virtual drawing surface through the haptic device. The virtual drawing surface was presented on a 19-inch flat panel display mounted horizontally in a custom wood workstation. The workstation also included a sunken area for the Omni in order to allow the tip of the stylus
control to be positioned within a few millimeters of the display surface (to simulate actual drawing behavior). The resolution of the projected image was set at 1024 X 768 pixels (but can be varied in application). The (X, Y) coordinate pairs of haptic stylus positions on the actual tabletop drawing surface were mapped to pixels on the display of the virtual drawing surface with drawing stroke width (line thickness) manipulated in the experiment.

Figure 2. Experiment apparatus including Phantom Omni Haptic Device, ROCF standard, and computer monitor embedded in worktable.

With respect to motor-control data capture, the Omni device records the position of the tip of the stylus in the X, Y and Z planes at a sampling rate of 50 Hz. Therefore, the device supports both dimensional and temporal analysis of participant performance in the ROCF test. The data can be used to derive complex kinematic measures for describing motor control. By comparison with traditional human-judgment, not only is this setup effective for ROCF performance analysis (which is typically based on the 2D graphomotor/drawing output) but also it provides data on motion in a third spatial dimension (Z). The latter is an important response in terms of determining when drawing of a stroke begins and ends.

2.3 Procedure

Participants were asked to copy (i.e., reproduce, not trace) the ROCF using their non-dominant hand and to draw each element as accurately as possible, including shape, size and proportion (Meyers and Meyers, 1995). The non-dominant hand was used to induce uncoordinated motor performance, such as what might be observed for patients with congenital, degenerative or traumatic brain injuries. Impairment of motor skill, strength and coordination, as well as cognitive planning and memory use, have previously been observed as physical and cognitive characteristics of non-dominant hand performance (Khan et al., 2003). Each participant completed two ROCF reproductions as part of the experiment with different graphical stroke widths.

2.4 Scoring

Bitmap images of participant reproductions of the standard figure were created from the temporal and dimensional data captured by the Omni and stored by the ROCF simulation software for the figure-scoring process. A stroke was defined as transport of the stylus in a downward direction in Z-space, making contact with the virtual drawing plane, accelerating while dragging the stylus across the plane, decelerating and either lifting the stylus in the Z dimension or rotating the trajectory to create a new element on the plane.

The resolution of the participant reproductions in the present study was relatively low due to the small size of the figure and large stroke widths used in the original prototype apparatus (Li et al., 2011). Consequently, the reproduction strokes were subjected to multi-step image processing to improve resolution. A morphological-filtering method was applied to generate a boundary of the image. In specific, a structuring element or outline was passed over a test unit reproduction and fit to the reproduction. The output image for analysis was defined based on the resulting size and shape of the structuring element. Related to this, in order to extract the outer contour of the overall image or drawing units in the image, interior holes were filled,
and a “canny-edge” detection method was used to track the outer boundary, including initially marking the boundary, maintaining its location as close as possible to the raw drawing, and not remarking the boundary during image processing. Thus, we obtained an exact pixel-based outer boundary of the figure and each drawing unit with high resolution. In general, this process results in a higher resolution boundary image than that of the original unit reproduction.

Subsequently, the color images generated by the test simulation were transformed to gray-scale. An erosion-filtering method was applied to the test reproductions to eliminate isolated drawing (black) points, which were regarded as noise. A binary-detection criterion for stroke identification was set based on gray-scale changes in the image. The edges of strokes were redefined based on a percentage or degree of gray from initial detection. The newly generated images were regarded as raw images, including unit boundaries and interior strokes, upon which all analyses were subsequently based.

Finally, the new boundary image for each unit was enlarged in order to reduce the size of the pixels, and specific stroke contours were extracted. In this way, contours were plotted at a resolution $10^6$ times higher than in the original ROCF reproduction. This process was performed to ultimately increase the accuracy of the jitter assessment.

2.5 Analytic Methods

Jitter was assessed using different methods for ROCF line segments and circular units. The two-end approach to analysis of line-segment based units in the original system (Li et al., 2011) was coarse and insensitive to motor effects, such as tremor. In the new system, a linear-regression fit was used to assess the level of jitter in line-segment-based units. The regression was computed for all points comprising a stroke as part of any segment. The standard deviation of these points from the linear-model fit operationalized jitter, where a higher deviation indicated a higher magnitude of jitter.

The present work focused on the assessment of jitter in the ROCF circular unit reproduction (see Figure 1). The limitations of the semi-automatic ellipse-fitting method employed in the original system (Li et al., 2011) for scoring the circular unit of the ROCF were identified above. In order to assess jitter for the circular unit in the figure, a circular regression model (Downs and Mardia, 2002) was fit to the outer boundary image obtained from the image processing of a participant's reproduction. We analyzed the degree of perfect circularity of the reproduced circumference, excluding three solid dots in the interior of the circle. The fittest circle was identified with the minimum sum of squares, which was also considered as the measure of jitter in the unit reproduction. In specific, line segments were drawn from the center of the circle to all points on the outer boundary. The differences between each line segment and the radius of the circle were calculated. The summation of all the differences divided by the number of line segments was established as an “average roughness index”. This index, which is very similar to a measure of surface roughness evaluated in a machining process, can be regarded as a raw assessment of the level of jitter in the circle reproduction. The resulting sum of differences was divided by the radius of the fittest circle to eliminate the influence of scaling of the size of the figure on the index.

Equations for calculation of the level of jitter for the exterior (exterior jitter) and interior (interior jitter) boundaries of unit elements are shown below along with the calculation for double jitter; that is, the combined magnitude of the exterior and interior roughness of the circumference, as well as the difference between the interior and exterior index values (i.e., duplication):

\[
J_e = \frac{\sum_{l=1}^{n_e} \sqrt{(x_l - x_0)^2 + (y_l - y_0)^2}}{R \times n_e} \quad (1.1)
\]

\[
J_i = \frac{\sum_{l=1}^{n_i} \sqrt{(x_l - x_0)^2 + (y_l - y_0)^2}}{R \times n_i} \quad (1.2)
\]

\[
J_d = \frac{\sum_{l=1}^{n_d} \sqrt{(x_l - x_0)^2 + (y_l - y_0)^2}}{R \times n_d} \quad (1.3)
\]

\[
D = J_i - J_e \quad (1.4)
\]

where $J_e$ is the level of jitter for the exterior boundary, $J_i$ is the level of jitter for the interior boundary, $J_d$ is the double jitter level (considering both interior and exterior boundaries) or roughness index, $R$ is the radius of
the circle, \( n \) is the number of line segments used in the regression analysis, and \( D \) is the level of duplication of effort in unit reproduction. All of these values are scale free and represent novel indices for motor control evaluation.

### 2.6 Variables

During test trials as part of the experiment, participant ROCF reproductions were displayed in both 8-pixel and 1-pixel stroke widths. These widths represented two levels of the independent variable. The order of presentation of the different widths included half the participants seeing the 8-pixel width first and the other half seeing the 1-pixel width first.

Wilcoxon pairwise tests (a non-parametric version of the t-test) were conducted to evaluate whether the jitter-assessment method was sensitive to the stroke-size manipulation. We expected that, similar to use of a blunt implement (pencil) in actual drawing, the 8-pixel width rendering would yield higher values of jitter than the 1-pixel width on the four dependent measures, including: (1) level of exterior boundary jitter, (2) level of interior boundary jitter, (3) double jitter, and (4) the degree of unit duplication (repeated effort in unit drawing).

### 3. Results

The levels of jitter and duplication for the 8-pixel and 1-pixel width reproductions of the circle unit are presented in Figure 3. It can be observed that all response measures were, on average, higher for the 8-pixel-width images. The Wilcoxon pairwise tests revealed that pixel width had a statistically significant influence on the double jitter level (\( p < 0.005 \)), interior jitter level (\( p < 0.005 \)) and level of duplication (\( p < 0.005 \)). No significant effect was observed for exterior jitter. These test results were supportive of our hypothesis that the new jitter measures would be sensitive to the graphical stroke width manipulation.

![Figure 3. Results of the jitter assessment at 8- and 1-pixel widths with standard deviations (indicated by error bars).](image)

Figure 3 also reveals that the coarser stroke rendering with an 8-pixel width led to greater levels of jitter, as compared to the 1-pixel width stroke rendering across all response measures. This finding is akin to the use of a larger tool tip in machining, which produces greater forms of vibration. These findings are consistent with the expectation that finer instrumentation leads to superior motor control and higher resolution in figure reproduction. Administration of the current apparatus is thus optimized for assessment or diagnostics on graphomotor performance at the 1-pixel width.

### 4. Discussion

The natural direction of methods for quantifying constructional praxis and other neuropsychological-assessment domains is to implement semi-automated and computerized methodologies that mitigate human
error and the opportunity for subjective interpretation. A further need exists for electronic data capture of motor topography characterizing prehensile control of graphomotor-production tools in order to improve diagnosticity in motor ability assessment. The method introduced in this work involves processing high-resolution spatial and temporal data for determining kinematic parameters of motor movements for subsequent inference and diagnostics on, for example, impairment or rehabilitation progress.

We described a set of novel analyses based on parallels between machining process evaluation in manufacturing operations and motor control in human behavioral research. The experiment demonstrated that assessment, or inspection methods focusing on machining performance, can be extended to human performance evaluation.

Expanding upon the computerized ROCF scoring system introduced by Li et al. (2011), we defined specific methods to improve system efficiency and accuracy for determination of jitter in motor control, based on static figure reproductions. This capability was not part of the previous software system. The enhancements in scoring information and precision over previous efforts included circular regression analysis to evaluate circle reproductions. The experiment as part of the study revealed sensitivity of the novel kinematic measures to manipulations of the resolution of user feedback. Results also trended in the manner expected, including increased jitter in motor control with coarser visual feedback on figure reproduction. From a clinical perspective, the capability to assess jitter in the ROCF task may allow for greater diagnosticity in evaluation of motor impairments ranging from planning to forms of control.

5. Conclusions

The field of neuropsychological-test administration and scoring is shifting in an automated direction. The cross-disciplinary integration developed through this work represents a novel approach that might be advantageously applied to other psychometric tests of visual-motor performance. The results of the study bolster prior studies showing that the collection of temporal and spatial data in reproduction tasks leads to more accurate analysis and assessment of a patient's motor performance over traditional, non-computerized methods (Elble et al., 1990; Stanley et al., 2010). The computerized nature of the proposed method greatly decreases the probability of human error in scoring and also provides quantitative anchors of constructs that are otherwise subjectively interpreted in prior scoring systems. The proposed method illustrates how to move the field of neuropsychology forward by improving the measurement of static reproductions and the quantification of dynamic motor typography and the use of display-screen capabilities.

Limitations of this work include the differences in operation of the haptic device versus the use of a regular pencil, with respect to the drawing implement itself and to the surface on which the figure reproduction is copied. Improvements in haptic-device construction are therefore necessary to better relate the results of these efforts to general graphic-implement use. Additionally, while 6-DOF devices are impressive in capability, they nevertheless are not entirely free of some unnatural constraints on motion and may not be superior in naturalistic feel to use of a graphics tablet. Furthermore, this preliminary study validating the jitter analysis focused largely on one of 18 ROCF units (the circular unit). Follow on work should expand this study to include an analysis of kinematic responses on several other units.

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