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Handwriting: Three-Dimensional Kinetic Synergies in Circle Drawing Movements

Alexander W. Hooke, Sohit Karol, Jaebum Park, Yoon Hyuk Kim, and Jae Kun Shim

The purpose of this study was to investigate central nervous system (CNS) strategies for controlling multifinger forces during a circle-drawing task. Subjects drew 30 concentric, discontinuous clockwise and counter clockwise circles, at self and experimenter-set paces. The three-dimensional trajectory of the pen's center of mass and the three-dimensional forces and moments of force at each contact between the hand and the pen were recorded. Uncontrolled Manifold Analysis was used to quantify the synergies between pen-hand contact forces in radial, tangential and vertical directions. Results showed that synergies in the radial and tangential components were significantly stronger than in the vertical component. Synergies in the clockwise direction were significantly stronger than the counter-clockwise direction in the radial and vertical components. Pace was found to be insignificant under any condition.

Keywords: handwriting, synergy, finger, force, prehension

The seemingly simple act of drawing is one of many marvels of the central nervous system (CNS). Whether writing a word or drawing a basic shape, we are able to generate a sort of code that is both universally recognizable, yet individually unique. The complex joint torques and rotations within the arm, wrist, and digits, working together to create a precise and singular output, make any multidigit coordination task, particularly drawing, an excellent gateway to understand the (CNS) control of human movements (Dounskaia, Van Gemmert, &Stelmach, 2000).

An object in space, such as a pen in one's hand, has six degrees of freedom (DOF). Three of these describe its position and three others describe its orientation. These six DOF can be manipulated by actuators, hand and fingers in the case of drawing with a pen, working along six kinetic DOF, three corresponding to force and three corresponding to torque in three-dimensional space. While pen grips vary between users, instrumenting a device capable of individual digit force measurement limited the study to those using a tripod grip (Koziatek and Powell 2003). In this grip, the pen has contacts with four parts of the hand: the thumb, index, middle and interdigit webbing between the thumb and index. One can consider each of the

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contacts as an actuator with six kinetic DOF and when working simultaneously a total of 24 kinetic DOF must be synergistically controlled to attain the desired movement of the pen although it is uncertain if the webbing can be considered as an actuator with six independent DOF. Under these circumstances, an infinite number of actuator force combinations can create an identical pen trajectory. This is known as kinetic redundancy (Shim, Latash, & Zatsiorsky, 2005a, 2005b). How the CNS handles these extra DOF is a fundamental question in human motor control that has varying proposed solutions. One such solution suggests that the CNS considers the extra DOF as abundant versus redundant (Gelfand& Latash, 1998; Latash, 2000). When confronted with a redundant system, the CNS does not employ a single solution by eliminating redundant DOF, but rather governs families of solutions that are each capable of accomplishing the desired task using all DOF available (Zatsiorsky & Latash, 2004). That is, the CNS uses the excessive DOF as a task-specific tool for control via neural correlations of elemental variables that stabilize particular performance variables, and such a correlation of elements can be functionally defined as a synergy (Latash, Gorniak, & Zatsiorsky, 2008).The framework of the Uncontrolled Manifold (UCM) analysis is a tool used to quantify synergies and will be used to measure the digit synergy strength in this study (Latash, Scholz, Danion, &Schoner, 2001; Schöner, 1995; Shim, Hsu, Karol, & Hurley, 2008).

Recent experiments have found that complimentary multidigit synergies can simultaneously exist in prehension grasping tasks (Shim, Latash, & Zatsiorsky, 2003; Shim, Latash et al., 2005b; Zatsiorsky & Latash, 2004).One synergy relates to grasp stability, i.e., ensuring an object not to be dropped via normal force control in static grasping, and the other relates to object orientation stability, i.e., ensuring an object not to be rotated via both normal and tangential digit force control (Shim, Lay, Zatsiorsky, & Latash, 2004; Shim, Park, Zatsiorsky, & Latash, 2006). These complimentary synergies follow the principle of superposition proposed in robotics which suggests that complex tasks performed by a multiple elements can be broken into independently controlled subtasks without interference between them (Arimoto& Nguyen, 2001; Arimoto, Tahara, Yamaguchi, Nguyen, & Han, 2001). The present study will extend this notion of the multidigit force synergies to the realm of drawing in three-dimensional space.

In the case of drawing circles, the dynamics of the pen motion can be logically broken down into three orthogonal components of control. First, there is a radial component causing the centripetal acceleration of the pen and the force of this component creates the curvature during circle drawing. Second, there is a tangential component causing deviations to a mathematically perfect circle via forces tangential to the circles edge. Third, there is a vertical component constituting the pen motion normal to the writing surface (i.e., often parallel to gravity). Given that drawing is another form of grasping task requiring extremely high precision and accuracy, one can predict that the digit forces, while grasping the pen, will yield strong synergies between hand-pen contact forces across all three of these components. However, it is also likely that the radial and tangential components will have stronger synergies underlying their stability than that of the vertical. Errors in the radial and tangential components will cause misshapen and possibly illegible script while errors in the vertical component can range from lifting the pen from the surface to tearing through the paper without having adverse effects on the image's appearance, suggesting that the CNS would employ a strategy emphasizing radial and tangential components.

The directionality during circle drawing and pacing of manual movements have also been investigated in previous research. Recent studies investigating joint kinematics and control during circle drawing found no identifiable differences in control ability between the clockwise and counter clockwise direction (Bosga, Meulenbroek, & Swinnen, 2003; Tseng & Scholz, 2005). In addition, from a handwriting perspective, writing is comprised of a series of loops in both the clockwise direction—such as 'b', 'm,' and 'p'—and counter-clockwise direction—such as 'd,' 'o,' and 'w'—as well as others that consist of both clockwise and counter-clockwise parts, suggesting that controls in both directions may be well developed through life-long handwriting experience. The current study is designed to investigate this directional dependence of drawing synergies at the kinetic level using synergy strength by comparing between the clockwise and counter clockwise directions.

Previous studies on pacing control, some of which use drawing as the task, indicate that rhythmic movements are generated by internal clocks originating in the cerebellum (Spencer & Zelaznik, 2003; Welsh, Lang, Suglhara, & Llinas, 1995). In addition, it has also been shown that the invariant relative timing of handwriting may be a self-identifiable characteristic of one's handwriting (Knoblich & Flach, 2003). This suggests internal rhythm might be a component of handwriting and susceptible to perturbations to one's natural rhythm. The effect of external pacing on handwriting performance at a kinetic level will also be investigated in this study. A recent study on fractal dimensions of handwriting grip force addressed this issue and found pacing and grip-force to be controlled by independent processes(Fernandes and Chau, 2008). However, the study addressed only the radial forces relative to the pen rather than the components relative to the task. The present study will address the synergistic relationships between the task relevant components of forces among the effectors. It is hypothesized that given the inherently internal nature of handwriting pacing, forcing one to match an external pace will adversely affect the drawing performance indicated by lower synergy strength in the externally-paced condition than the self-paced condition.

While no prior work has been able to directly study kinetic digit synergies during drawing, previous investigations have inspired four hypotheses. 1) Pen-hand contact synergies during circle drawing will exist across the radial, tangential, and vertical components. 2) Hand-pen contact force synergies will be stronger on the radial and tangential components than the vertical component. 3) There will be no significant difference in synergy strength between the clockwise and counter-clockwise directions. 4) Synergy strength will be greater in the self-paced condition than in the externally-paced condition.

Methods

Participants

Twenty-four subjects, 12 male and 12 female, age 22 ± 2.4 years, volunteered as subjects for this study. All subjects were right handed. Subjects' participation was also limited by the pen grip technique used. Due to the design of the testing instrument, only subjects using the common grip of the tripod grasp—the tip of the thumb, the tip of the index finger, the lateral surface of the distal phalanx on the middle finger—and a 4th contact at the metacarpophalangeal (MCP) webbing between the thumb and index finger were tested. Subjects were screened for neurological, psychological, and any other potentially confounding health conditions. The right hand length and width were measured from the middle finger tip to the lunate of the wrist and between the MCP joints of the index and little fingers, respectively. The average hand length of the subjects was 17.9 ± 3.2cm and the width was 8.0 ± 1.2cm. The Institutional Review Board (IRB) at the University of Maryland approved the procedures used in the experiment. All subjects received both written and verbal instructions for the test procedures. Informed written consent was obtained from all participants in the study.

Apparatus

The Kinetic Pen was used as the writing utensil for this study (Hooke, Park, & Shim, 2008). The Kinetic Pen was equipped with 4, six-dimensional sensors (Nano-17, ATI Industrial Automation, Garner, NC, USA) and a plastic, noninking tip (Figure 1A).

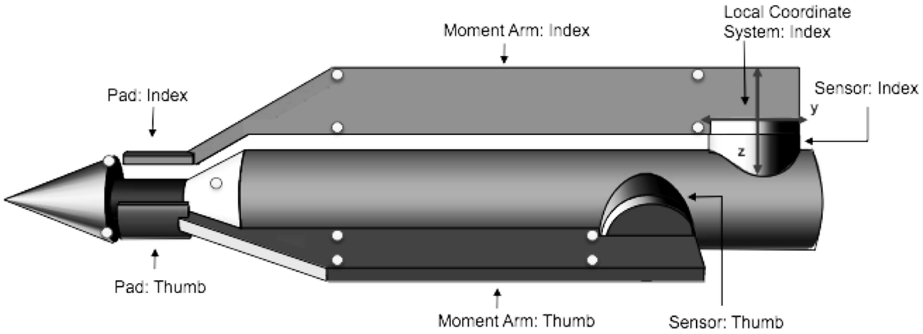
Participants drew on a writing surface created by mounting 14 × 14 × 0.5cm square, transparent Plexiglas plate atop a six-component sensor (Nano-17, ATI Industrial Automation, Garner, NC, USA). The mounting of the plate was secure such that it had no movement during the drawing task. A piece of white construction paper was affixed to the Plexiglas with a circular template printed on it to guide subjects for circle drawing tasks.

A four-camera motion capture system (Vicon Motion Systems Inc., CA, USA) was used to obtain kinematic data from the pen and the drawing surface. Subjects were seated within a calibrated volume of 100 cm × 100 cm × 100 cm. An array of 11 reflective, markers (3 mm in diameter) was placed on the Kinetic Pen. Three markers were on the drawing end, four defining the thumb sensor and extended arm, and four defining the index sensor and moment arm. An array of four reflective markers was mounted to the construction paper on the drawing surface to define the global reference system.

Each of the force sensors, both for the drawing surface and in Kinetic Pen, were calibrated by the vender to be accurate to the following resolutions: 1/640 N in F_x, F_y, and F_z and 1/128 Nmm in M_X, M_Y, M_Z. A total of 30 analog signals from the sensors were sent to two synchronized 12-bitanalogue-digital converters (PCI-6031 and PCI-6033; National Instrument, Austin, TX,USA) to be processed and saved by a customized LabVIEW program (LabVIEW 7.1;National Instruments). The force sensors sampled data at 50Hz. The time-varying three-dimensional coordinates of each reflective marker were sampled at 100Hz and recorded synchronously with the kinetic data from the force sensors.

The drawing surface was orientated with one edge parallel to the table edge with approximately 30cm of table space between the two edges. A 30cm^2 wood block with a height of 4.5cm was placed on the table between the subject and force plate. Subjects were told to hold the pen with their natural handwriting grip and all subjects reported that the pen gripping was comfortable. The wires from four sensors were bundled together and the bundle was taped to the posterior part of the subject's forearm with about 20cm of slack between the taped area and the pen (Figure 1B). This preparation was made to minimize the effect of the wires' weight putting unwanted forces and torques on the pen.

A



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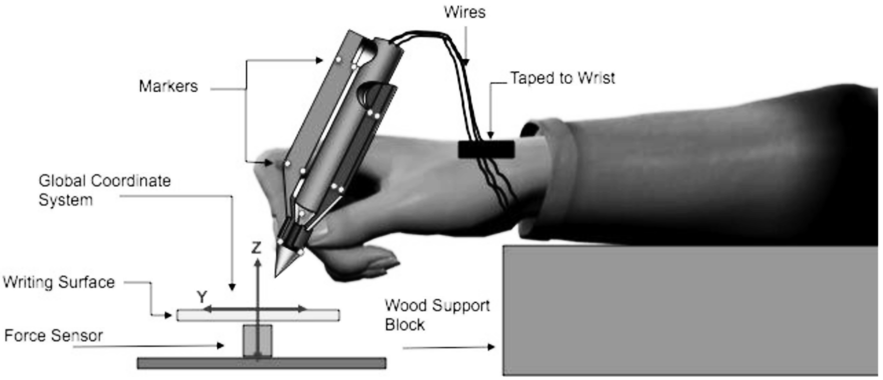

Figure 1 — A) Schematic of Kinetic Pen. Pen contains four, six-component sensors, thumb and index shown above. Each sensor is equipped with a moment arm running along the long axis of the pen. Each moment arm has a rounded grip pad with each pad corresponding to a single, unique contact point with the hand: thumb, index, middle, and webbing at the thumb-index MCP joint. Nine reflective markers were mounted to the pen. Each sensor had a local coordinate system in which the y-axis runs parallel to the long axis of the pen, the z-axis normal to the sensor's surface and the x-axis orthogonal to the y- and z-axes. B) Schematic of experimental setting showing a subject holding the Kinetic Pen with reflective markers attached. The three-dimensional and contact forces and torques between the hand and the pen were recorded from the six DOF sensors implemented in the pen and pen tip force was recorded from the same type of force sensor underneath the writing surface with the surface sensor's coordinate system defining the global coordinate system. The writing surface was made of Plexiglas.

Experimental Procedures

Participants were instructed to draw circles 3cm in diameter at whatever speed they felt most "comfortable" while maintaining as close to a geometrically accurate circle as possible, pausing briefly between concentric circles for approximately 0.5 s while keeping the pen-tip on the surface. These practice trials were quickly analyzed to determine their pacing for the external pacing condition in the following drawing tasks.

For the drawing tasks, subjects were asked to draw circles 3cm in diameter on the drawing surface with a template of the circle. Using this basic task, four conditions were tested. There were two different paces: self-paced and externally-paced. Each pace condition was done in both clockwise and counter-clockwise directions, yielding 4 total variations (2 paces × 2 directions). The order of the conditions was balanced across subjects. One trial was done for each condition and each trial consisted of drawing 30 concentric, but discontinuous circles. A target position 1.5 cm above the circle center was the starting point of the pen tip. Subjects placed pen tip on the target, drew a circle in the assigned direction, returned to the starting position, and began the next concentric circle. In the externally-paced condition, subjects tried to match their circle drawing pace to an audible metronome omitting beeps. The frequency of these beeps was unique to each subject and was determined by the pacing of the self-paced practice trials. Subjects were told to begin a circle on a beep, complete that circle on the next beep, and begin the next circle on the third beep, repeating this pattern for 30 circles for each trial. Both pace conditions were run for the clockwise and counter clockwise conditions. The circles were centered about the center of the drawing surface such that the force sensor beneath the surface was in the center of the circle.

The circle center on the drawing surface was considered as the origin of the global reference system. The global Z-axis was normal to the drawing surface, positive pointing upward. The global Y-axis was parallel to the drawing surface and perpendicular to the Z-axis and table edge, positive pointing away from the subject. The global X-axis was orthogonal to the global Y- and Z-axes, following the right-hand-thumb rule. The local coordinate system was aligned local at each sensor such that the y-axis ran parallel to the pen's long axis, the x-axis ran tangential to the curvature of the pen's body, and the z-axis passed through the pen's body, normal to the surface curvature.

Data Processing

Identification of Pen Tip Kinematics. The three-dimensional coordinates of the pen tip were needed to identify the performance of subjects but could not be directly recorded as the drawing surface was a force plate versus the digitizing tablets commonly used in kinematic handwriting studies. Before each participant's data collection, the experimenter recorded a 15 s, exclusively kinematic trial in which the pen tip remained stationary and the pen body was pivoted around it. This allowed the pen tip to be treated as an instantaneous joint center (Gamage&Lasenby, 2002; Holzreiter, 1991). The three-dimensional position of this joint center was identified as the pen-tip and tracked relative to the other eleven markers on the pen.

Circle Separation. During each pace-direction condition, the kinetic and kinematic data for all 30 circles were saved as individual files. To separate these individual circles, the local minima of the magnitude of the pen-tip velocity were used as a cut points. The first 5 circles and the last 5 circles were disregarded for each condition to eliminate the effects initiating and finishing the trial.

Transformation of Digit Forces Into Global Reference Frame. Data collected in this study were considered in multiple reference frames. The kinematic data recorded by the motion capture system and the pen-tip force data were considered in the global reference frame, denoted [X, Y, Z]. The force data collected from each digit was in a reference frame local to each digit, denoted [$F(t)_{xi}$, $F(t)_{yi}$, $F(t)_{zi}$] where *i* corresponds to the contact points: thumb, index, middle, and webbing. As the goal of this study was to investigate synergistic actions between each of the hand-pen contact forces, a direct, linear relationship between the digit forces, pen-tip force and the acceleration of the pen was necessary. To make this comparison, the digit force local reference frames underwent a rotation such that they were expressed in the global reference frame.

Using the three-dimensional coordinate data from the motion capture system, the orientation of the Kinetic Pen relative to the global reference frame was computed. From this orientation, the rotations that each local reference frame must undergo, such that the digit forces are known in the global reference system were determined. These Euler angle rotations about the X-, Y-, and Z-axes are denoted $\theta(t), \varphi(t)$, and $\Psi(t)$, respectively (Eqs. 1 and 2). Rotation matrix R(t) denotes the necessary rotation about each of the global axes.

$$R(t) = R_X(\theta(t)) \cdot R_Y(\phi(t)) \cdot R_Z(\psi(t)) =$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta(t) & \sin\theta(t) \\ 0 & -\sin\theta(t) & \cos\theta(t) \end{bmatrix} \begin{bmatrix} \cos\phi(t) & 0 & -\sin\phi(t) \\ 0 & 1 & 0 \\ \sin\phi(t) & 0 & \cos\phi(t) \end{bmatrix} \begin{bmatrix} \cos\psi(t) & \sin\psi(t) & 0 \\ -\sin\psi(t) & \cos\psi(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} F(t)_{Xi} & F(t)_{Yi} & F(t)_{Zi} \end{bmatrix} = \begin{bmatrix} F(t)_{xi} & F(t)_{yi} & F(t)_{zi} \end{bmatrix} \cdot R(t) \quad (2)$$

Where i = (thumb, index, middle, and web). XYZ and xyz represent the global and local reference systems, respectively.

Transformation To Radial and Tangential Components. Three different components were considered with regards to the motion of the pen: components along the radius of the circle, tangential to the curvature of the circle, and parallel to gravity (i.e., normal to the drawing surface). To accommodate for this analysis, the X and Y components of the digits and pen-tip were transformed to represent the radial and tangential components of the curvature. The Z components did not change, as they were already vertical and orthogonal to the X-Y plane.

The Z-axis rotation was determined using the kinematics of the pen tip. A vector r was created pointing from the instantaneous location of the pen-tip to the center of the circle template on the drawing surface. The $F(t)_{Xi}$ and $F(t)_{Yi}$ components were rotated about the Z-axis such that one component of the rotated force was parallel to r becoming the radial force $F(t)_{ri}$. The magnitude of this rotation is denoted $\lambda(t)$ (Eq. 3). The other component of the rotated force, by definition of being perpendicular to the radial and vertical forces, was the tangential force F_{ti}. In this case, each set of digit forces and the pen tip force were rotated as the rotation is global.

$$\begin{bmatrix} F(t)_{ri} & F(t)_{ti} & F(t)_{vi} \end{bmatrix} = \begin{bmatrix} F(t)_{Xi} & F(t)_{Yi} & F(t)_{Zi} \end{bmatrix} \begin{bmatrix} \cos\lambda(t) & \sin\lambda(t) & 0 \\ -\sin\lambda(t) & \cos\lambda(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Where i = (thumb, index, middle, web, and pen-tip), global forces = (X, Y, Z), r = radial, t = tangential, v = vertical, λ = magnitude rotation about Z axis

Uncontrolled Manifold (UCM) Analysis. The framework of the Uncontrolled Manifold (UCM) analysis was used to quantify the digit synergies (Latash, Scholz, Danion, &Schoner, 2001; Schöner, 1995; Shim, Hsu, Karol, & Hurley, 2008). UCM analysis allows quantifying synergistic actions of multiple elemental variables (e.g., finger forces) that are acting together in a redundant motor system. The following equations were constructed in such a way that the synergistic actions of hand-pen contact forces could be investigated in three dimensions through UCM analysis (Eqs. 4–8).

$$[U]\begin{bmatrix} F(t)_{r_{thumb}} \\ F(t)_{r_{index}} \\ F(t)_{r_{middle}} \\ F(t)_{r_{web}} \end{bmatrix} = \begin{bmatrix} ma(t)_{r_{COM}} - F(t)_{r_{tip}} \end{bmatrix} \tag{4}$$

$$[U]\begin{bmatrix} F(t)_{t_{thumb}} \\ F(t)_{t_{index}} \\ F(t)_{t_{middle}} \\ F(t)_{t_{web}} \end{bmatrix} = \begin{bmatrix} ma(t)_{t_{COM}} - F(t)_{t_{tip}} \end{bmatrix} \tag{5}$$

$$[U]\begin{bmatrix} F(t)_{v_{thumb}} \\ F(t)_{v_{index}} \\ F(t)_{v_{middle}} \\ F(t)_{v_{web}} \end{bmatrix} = \begin{bmatrix} ma(t)_{v_{COM}} - F(t)_{v_{tip}} - W \end{bmatrix} \tag{6}$$

where F(t) = force over time, [U] = unity matrix (1 × 4), (thumb, index, middle, web) = hand-pen contacts, tip = pen tip on drawing surface, (r, t, v) = radial, tangential, vertical components, m = mass of pen, a = acceleration of pen's COM and W = weight of pen.

For each force component (i.e., radial, tangent, and vertical), there is a four-dimensional (i.e., four pen-hand contact points) vector *F(t)* on the left hand side of each equation. Change in the right-hand side (ΔRHS) of the equations ($\left[ma(t)_{r_{COM}} - F(t)_{r_{tip}}\right]$, $\left[ma(t)_{v_{COM}} - F(t)_{v_{tip}} - W\right]$, and $\left[ma(t)_{t_{COM}} - F(t)_{t_{tip}}\right]$) can be expressed in terms of the changes in the four-dimensional vector *F(t)* and the unity matrix [*U*]. Assuming that the mean time trajectory of the RHS over all twenty circles is the trajectory actually achieved by the CNS, one can construct the following equation with the condition of ΔRHS(t) = 0 for the mean trajectory of RHS(t) over twenty circles.

$$\Delta \text{RHS}(t) = [U] * [\Delta F(t)] \tag{7}$$

Each manifold can be linearly approximated via the null space spanning the basis vector e(t) (Eq. 8).

$$0 = [U] * e(t) \tag{8}$$

The total variance ($V_{TOT}(t)$) of four-dimensional space across the twenty circles was resolved into two components. The vectors *F(t)* were broken into their projection on, and orthogonal to, the null space (UCM). The variance within the UCM per degree of freedom ($V_{UCM}(t)$) was calculated. This component of total variability causes no change to RHS mean value. The variance orthogonal to the UCM ($V_{ORT}(t)$) was also calculated. This component of total variability causes change in RHS mean values (i.e., errors in RHS). An index called ΔV was computed to account for varying magnitudes of variance between subjects and tasks by normalizing the V_{UCM} per UCM dimension by the V_{TOT} per degree of freedom (Eq. 9).

$$\Delta V(t) = \left(\frac{V_{UCM}(t)}{3} - \frac{V_{ORT}(t)}{1}\right) / \left(\frac{V_{UCM}(t) + V_{ORT}(t)}{4}\right) \tag{9}$$

A positive ΔV indicates that V_{UCM} is greater than V_{ORT} and consequently a synergy between the individual forces. Greater ΔV values represent greater kinetic synergy between pen-hand contact forces. That is, the four individual force components compensate for each other's errors to achieve the constant trajectory of circle drawing. The ΔV index was computed for the whole circle over 20 consecutive, time-normalized circles starting with the 6th circle for each condition.

Statistics. A within-subjects ANOVA was run with factors of Pace [2 levels: self and external], Direction [2 levels: clockwise and counter-clockwise], and Component [3 levels: radial, tangential, and vertical]. In addition, analyses were run comparing the significance pen-tip location on digit synergies as a function of time and pen-tip position. Appropriate post hoc comparisons and contrasts were performed for any differences detected as well as to examine significant interactions. Experiment-wise error rate was set at alpha = .05 with appropriate Bonferroni corrections.

Results

Kinematic and Kinetic Signals

All subjects performed the task while following a circular path centered on the origin with a radius of 1.5cm (Figure 2A). Figures 2B-D show the sum of the digit forces acting on the pen recorded by the sensors on the pen and the force of the pen tip on the drawing surface recorded by the drawing surface sensor during a ten second window from a single subject. Forces along the radial direction are illustrated in Figure 2B. When the digit force sum is larger than the pen tip reaction force, the pen is moving across the drawing surface as the forces acting on the pen (i.e., the digit forces) are larger than the forces resisting movement of the pen (i.e., frictional forces on the drawing surface) in the radial direction. Forces along the tangential direction are illustrated in Figure 2C. Here, similar to the radial direction, the sum of digit forces and pen tip reaction force are in phase with one another with the sum of digit forces having larger amplitude. This exemplifies the digit forces overcoming the frictional forces of the drawing surface to create movement of the pen. In the vertical direction (Figure 2D), the sum of digit forces matches those of the pen-tip forces in the opposite direction, indicating that there is a balance of forces in the vertical direction and there is minimum movement of the pen in the vertical direction. These force comparisons show that the force transformations from local to global coordinates and from Cartesian to radial and tangential components are qualitatively accurate. There are small differences between the sum of the digit forces and pen tip forces. These differences are minor and seem to be caused by the uncertainty of sensors and their propagations during digit sum calculations (Figliola& Beasley, 2001; Shim et al., 2003; Taylor, 1997).

Uncontrolled Manifold Analysis

Illustrated in Figure 3, the variance components within (V_{UCM}) and orthogonal (V_{ORT}) to the UCM are compared for each directional synergy over the temporal duration, controlling for direction and pace. It is apparent in Figure 3 A-D that the V_{UCM} tends to peak when the circle is about halfway completed for both the radial and tangential components with the radial component always having the highest peak values. The vertical component of V_{UCM} is more temporally stable than the other two components with a much more subtle peak occurring between the 20% and 40% range of the circle. The V_{ORT} (Figure 3E-H) shows less temporal change than V_{UCM} and the vertical component is always greater than the radial and tangential components. The synergy strength quantified by ΔV remains above 1.0 for the radial and tangential components and above 0.4 for the vertical components. It should be noted that there does not appear to be a significant drop in ΔV during the initiation and termination of the circle duration, nor are there significant changes in the error at these times, suggesting that the synergies are not dependent on the acceleration of the pen.

The average of the ΔV time function was used for statistical comparisons of components, paces, and directions. The average ΔV supported the first and second hypotheses that synergies would exist across all control components and that the radial and tangential components would yield stronger synergies than vertical

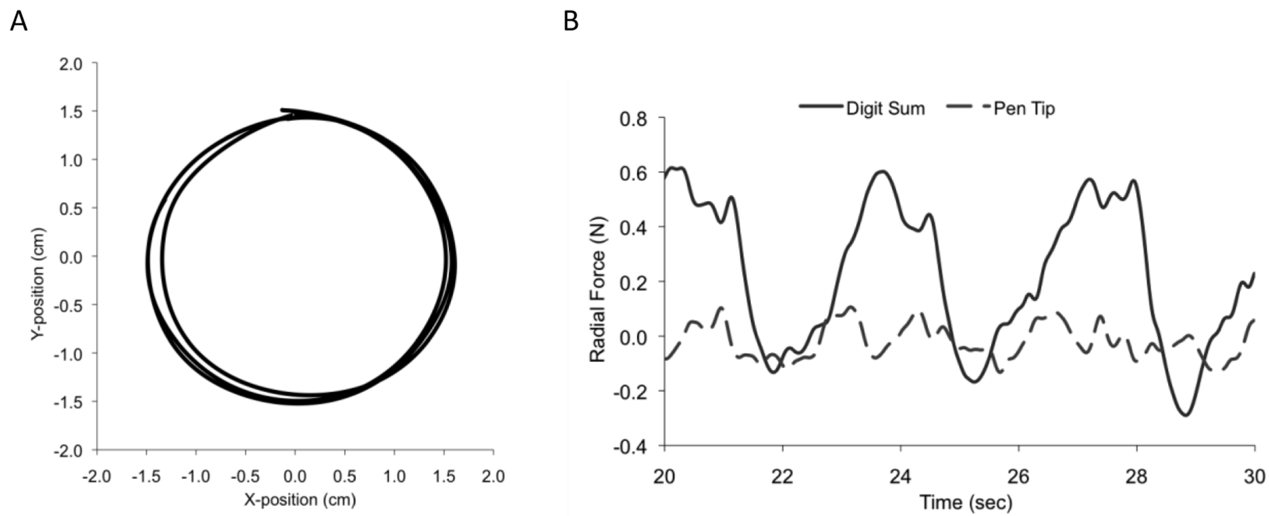

Figure 2 — An example of a single subject's performance for the drawing of three consecutive circles. A) The two-dimensional pen tip trajectory on the writing surface. X- and Y-axes are parallel to the mediolateral and anteroposterior axes, respectively. The remaining plots show the summed digit force components on the pen compared with the pen-tip force along the B) radial C) tangential and D) vertical components.

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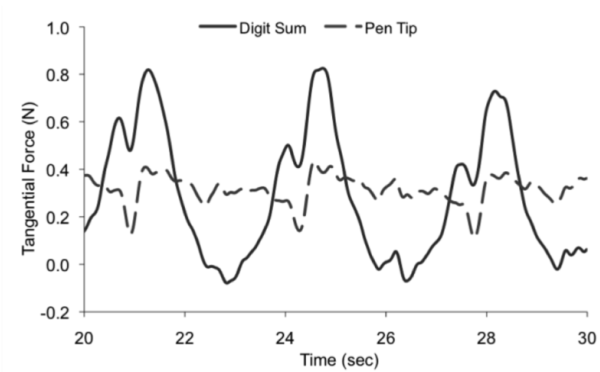
C



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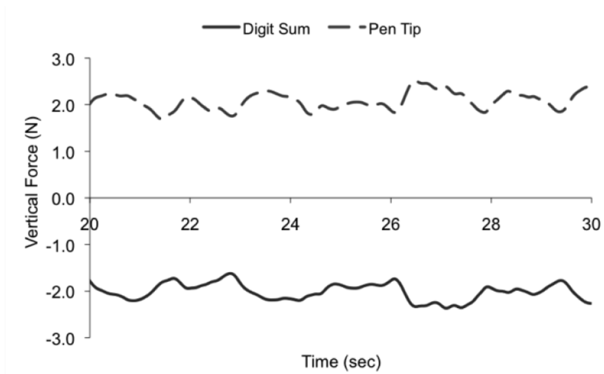

Figure 2 ***(continued)*** — An example of a single subject's performance for the drawing of three consecutive circles. A) The two-dimensional pen tip trajectory on the writing surface. X- and Y-axes are parallel to the mediolateral and anteroposterior axes, respectively. The remaining plots show the summed digit force components on the pen compared with the pen-tip force along the B) radial C) tangential and D) vertical components.

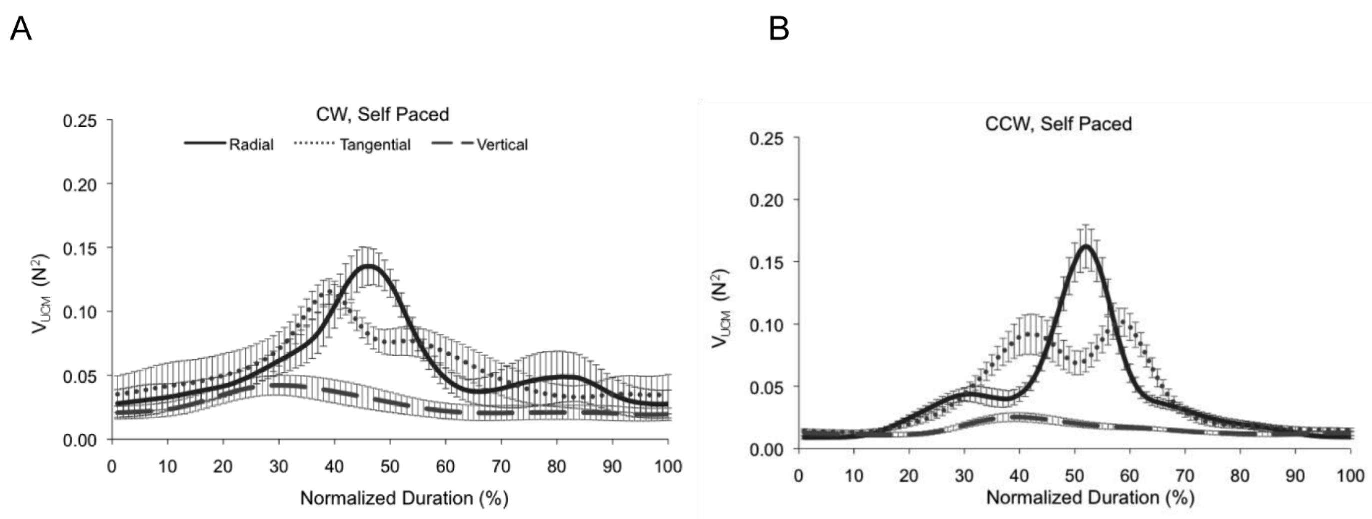

Figure 3 — Plots of variance components over time across radial, tangential, and vertical components for each direction-pace condition using time normalization. A-D) Variance within the UCM, E-H) Variance orthogonal to the UCM, and I-L) Synergy strength measured by ΔV. Sets of four describe: clockwise, self-paced; counter-clockwise, self-paced; clockwise, externally-paced; and counter-clockwise, externally-paced, respectively. Means and standard errors across all subjects are presented.

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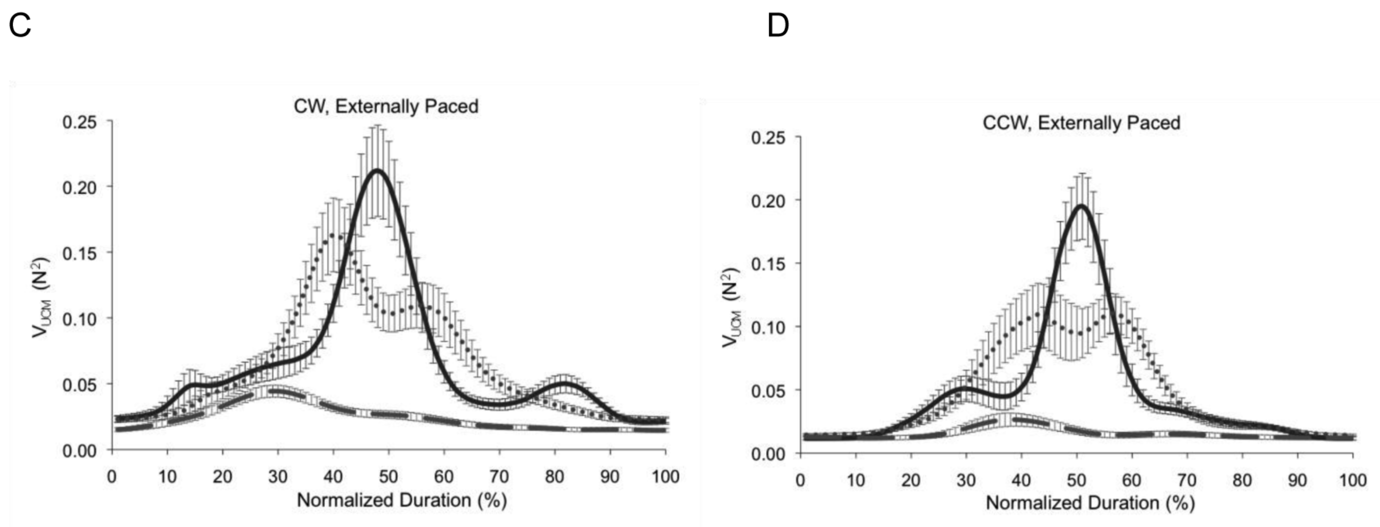

Figure 3 *(continued)* — Plots of variance components over time across radial, tangential, and vertical components for each direction-pace condition using time normalization. A-D) Variance within the UCM, E-H) Variance orthogonal to the UCM, and I-L) Synergy strength measured by ΔV. Sets of four describe: clockwise, self-paced; counter-clockwise, self-paced; clockwise, externally-paced; and counter-clockwise, externally-paced, respectively. Means and standard errors across all subjects are presented.

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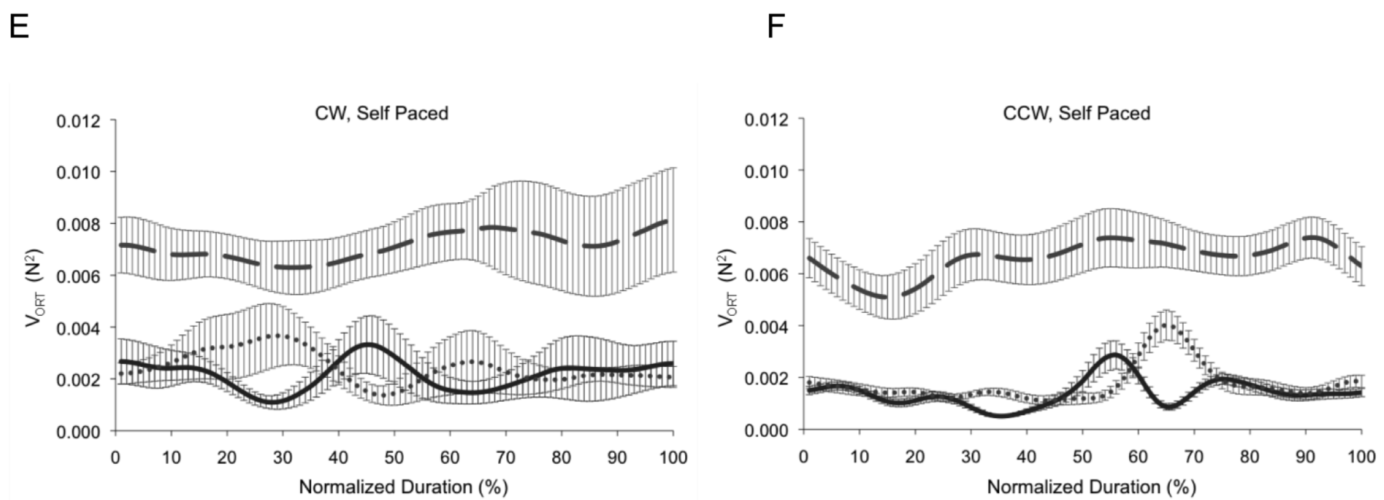

Figure 3 *(continued)* — Plots of variance components over time across radial, tangential, and vertical components for each direction-pace condition using time normalization. A-D) Variance within the UCM, E-H) Variance orthogonal to the UCM, and I-L) Synergy strength measured by ΔV. Sets of four describe: clockwise, self-paced; counter-clockwise, self-paced; clockwise, externally-paced; and counter-clockwise, externally-paced, respectively. Means and standard errors across all subjects are presented.

component, respectively. ΔV for the radial, tangential, and vertical components was significantly greater than zero. ΔV was also significantly greater in the radial and tangential components than in the vertical component under all directional and pace conditions as illustrated in Figure 4. These findings were supported by three-way ANOVA which showed a significant COMPONENT effect [F(2,22) = 99.2, $p < .0001$]. Pairwise comparisons between components showed that the vertical component was significantly smaller than both the radial component [$p < .0001$] and tangential component [$p < .0001$], but the radial and tangential components showed no significant difference between each other [$p = .6093$].

The analysis partially supported the third hypothesis that there would be no significant difference between clockwise and counterclockwise directions. It was identified that there was a significant difference between directions with the clockwise direction having a greater ΔV than the counter-clockwise direction. This was only true for the radial and vertical components. This trend was very evident in the vertical component where the ΔV values had a difference of almost 0.3 and nearly insignificant in the radial component where the ΔV values had a difference of less than 0.03. These findings were supported by a significant DIRECTION effect [F(1,23) = 17.6, $p < .0001$] and significant DIRECTION × COMPONENT interaction [F(2,22) = 18.4, $p < .0001$], but a nonsignificant DIRECTION × PACE × COMPONENT interaction [F(2,22) = 1.6, $p = .219$]. Subsequent pairwise comparisons between component-direction combinations showed that ΔV values in the clockwise direction were significantly larger than the ΔV values in the counter

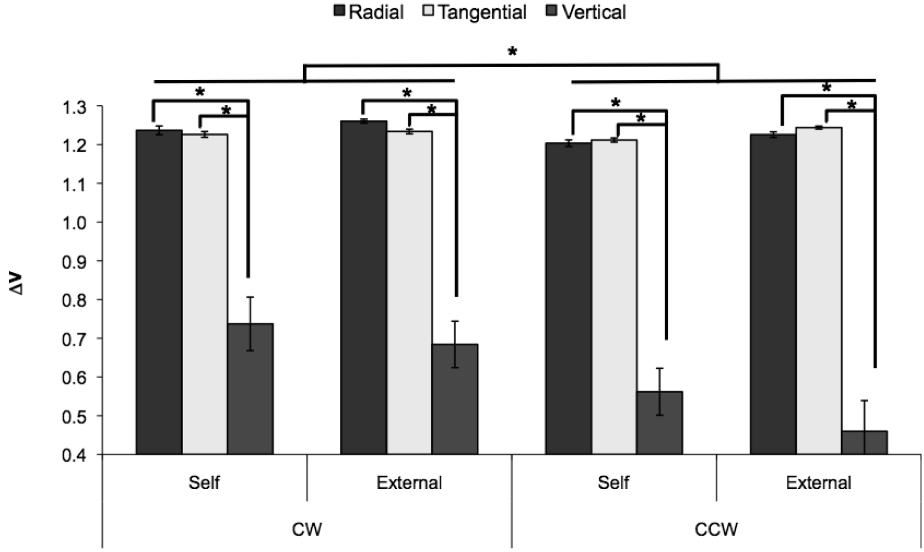

Figure 4 — Synergy strength, measured by ΔV, for radial, tangential, and vertical components, across pace and direction conditions. Means and standard errors across all subjects are presented. * indicates statistical significance at the 0.05 level.

clockwise directions in the radial and vertical components [$p < .001$] and [$p = .05$], respectively.

The fourth hypothesis, that the self-paced condition would yield greater ΔV values than the externally-paced condition, was not supported. No significant differences were identified between the paces. Within each component, ΔV in the self-paced condition was always within 0.1. This was supported by nonsignificant effects of PACE [$F(1,23) = 0.3$, $p = .617$], PACE × COMPONENT interaction [$F(2,22) = 0.9$, $p = .418$], and DIRECTION × PACE interaction [$F(1,23) = 0.06$, $p = .806$].

Clockwise Versus Counter-Clockwise

The ΔV in the clockwise direction was significantly greater than in the counter-clockwise direction in the vertical component. To investigate this further, ΔV was normalized by position and plotted such that one could see how ΔV changes with position of the pen tip on the circle. The vertical component showed a difference between directions on certain parts of the circle (Figure 5).

Discussion

This study investigated the multidigit synergies along three dynamic, orthogonal components of pen kinetics during circle drawing across varying pacing and directional conditions. Given that previous studies have indicated that multidigit synergies in other grasping tasks are broken into task related components (Shim et al., 2004; Shim et al., 2006), and that drawing is a task requiring extensive precision and accuracy, it was hypothesized that multidigit force synergies, as measured by ΔV, would be present across the radial, tangential, and vertical control components. Furthermore, the small range of V_{ORT} along the radial and tangential components compared with the vertical component suggested that stronger synergies exist along the radial and tangential components (Shim et al. 2010). To extend findings of previous kinematic drawing studies to the kinetic domain, the relationships between digit force synergies and direction and pace were investigated. Previous studies showed no significant pen-tip kinematic differences between the clockwise and counter-clockwise directions (Bosga et al., 2003; Tseng &Scholz, 2005). Therefore a difference in synergy strength between these directions was not expected. Lastly, drawing kinetics would confirm the findings of previous pacing studies indicating an inherently strong internal pacing aspect of drawing by showing decreased synergy strength under an externally-paced condition (Knoblich&Flach, 2003).

Radial, Tangential, and Vertical Components

Synergies existed across all control components and were significantly stronger on the radial and tangential than vertical component. Not only were the synergies present in these two directions, but they were overwhelmingly strong. Previous studies using the ΔV index on tasks with extensively proven synergies have yielded ΔV values from as low as 0.2 up to 0.8 (Shim, Latash et al., 2005b; Zatsiorsky, Gao, & Latash, 2006). The ΔV in this study were well above that, exceeding 1.0 in the radial and tangential control components and ranging from 0.4 to 0.8 in the "weaker" vertical component. Given the high precision level of the system involved

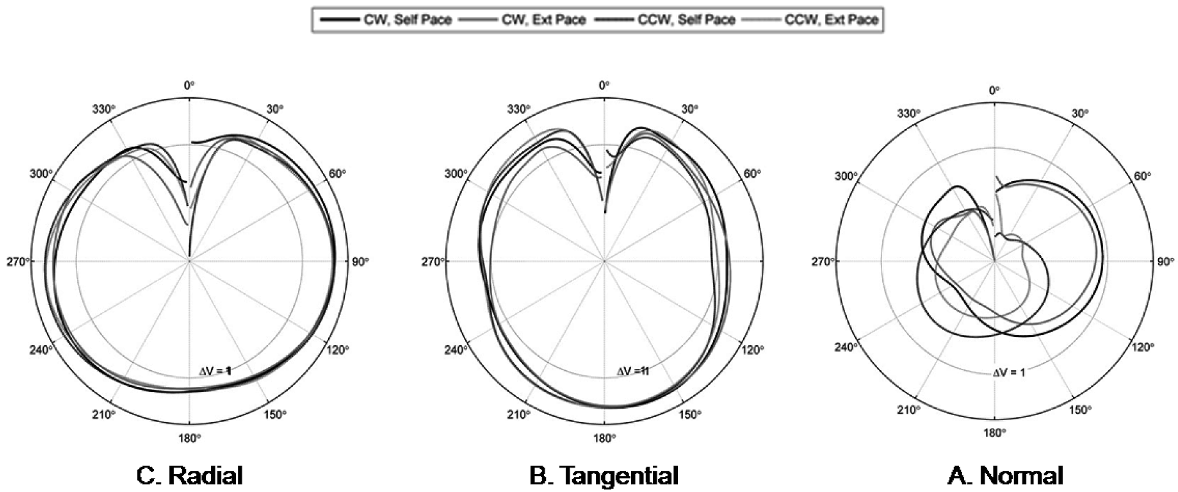

Figure 5 — Illustration of direction and pace conditions on synergy strength over absolute position, measured by ΔV, in the A) radial, B) tangential, and C) vertical component. The dotted circle represents $\Delta V = 1$.

in the task, drawing, these results are not surprising. That is, the manual dexterity necessary to write words, where errors on the scale of millimeters can render script illegible, is very high relative to the dexterity necessary grasp a static object. As the level of complexity of the task increased from grasping to drawing, so should the level of precision with which the task is controlled, indicated here by high ΔV values during drawing. Furthermore, the smaller ΔV values close to the start and finish of each task result from the necessity to change the synergy from "start, to "draw a circle" to "stop". Viewing each of these three elements as individual motor tasks, the synergy, reflected by the ΔV values, decreases as the task changes.

It is noticeable that the V_{UCM} shows a peak in the middle of the trajectory for the radial and the tangential component in all conditions while the V_{ORT} and the ΔV trajectories do not show such a peak. Given the prominence of the peak in the V_{UCM} trajectory, it would be expected that a similar peak would appear in the ΔV trajectory. This is not the case due to the normalization by degrees of freedom of the V_{UCM} and V_{ORT} components in the ΔV computation. The higher degrees of freedom seen in the V_{UCM} component effectively neutralize the significance of this peak in the ΔV.

It is interesting to compare the findings of this study with those of previous studies which showed multiple, complimentary synergies (Shim et al., 2004; Shim et al., 2006; Zatsiorsky & Latash, 2004). In the case of the current study, the UCM can be understood physically as a quantification of the flexibility of the CNS to accomplish the assigned task. In both the current study and the studies mentioned above, the components yielding the strongest synergies were those in which the margin of highly consequential errors was smallest. This can be more clearly understood by comparing this study with previous grasping studies. In the case of object-grasping prehension, such as holding a glass of water, orientation control was found to have the strongest synergies. Orientation is controlled by the resultant torque applied on the object and as such has a very small window of acceptable errors, i.e., preventing a handheld water glass from spilling. Its complimentary component of grasping forces have a larger window of acceptable values, i.e., whether you drop or crush the glass, with synergies weaker than those of orientation control (Zatsiorsky & Latash, 2004). This idea is maintained in the current study. Here, the components with the smallest range of acceptable errors were the radial and tangential components as errors in these components would yield messy and illegible drawing or writing. This limited range was accompanied by stronger synergies in those components, similar to the strong synergies in orientation control in prehension. The range of acceptable errors in the vertical components of drawing are relatively larger than those in the radial and tangential components as vertical errors only cause lighter/darker lines. This suggests that the CNS might be utilizing synergies that are not only task dependent but also able to prioritize components within a task to optimize the drawing performance. This could be further tested in an experiment in which subjects write on a very delicate piece of paper that will tear of any excessive force is applied. In such a situation, the range of acceptable error in the vertical force component would be greatly reduced and the response by the CNS in terms of control of kinetic synergy components could yield more knowledge of this system. More specifically, such an experiment would test the robustness and adaptability of the synergies identified in the current study.

It is to be noted that the synergies computed in this study are in the finger force space. Some previous studies have employed the mode space analysis using the UCM approach to identify synergies at the motor command level, by excluding the biomechanical factors that might alter the force production pattern during grasping and prehension (Danion et al. 2003). Given the complex grasping pattern during the drawing task executed in this study, extracting the effect of biomechanical variables was not a possibility.

Clockwise Versus Counter-Clockwise

It is apparent that the significant directional differences of the vertical component come from the 0° to 180° range, or right half of the circle. While the ΔV value approaches 1 in the clockwise direction, it is less than 0.5 in the counterclockwise direction within that range. One possible explanation can be derived from the results of a study by Dounskaia, in which subjects preformed one circle drawing task and a series of line-drawing tasks in which the coordination of the fingers and wrist were controlled in different ways. She found that this part of the circle requires a more complex joint coordination than other parts due to the fact that the wrist is flexing while the fingers are extending (Dounskaia et al., 2000). However, why this results in a ΔV decrease exclusively along the vertical component is currently unknown. It can be argued that during this range of angles, the position of the hand becomes more squished and fist-like, increasing joint stiffness. Increased joint stiffness has been shown to cause decreased handwriting fluency which may account for the drop in synergy strength (van Den Heuvel, van Galen, Teulings, & van Gemmert, 1998). In addition, van Den Heuvel showed that increased processing demands cause joint stiffness as well increase pen tip vertical forces. While increased pen tip vertical forces do not necessarily decrease pen control in the vertical component, this association between joint stiffness and control in the vertical component may explain why ΔV dropped uniquely in that component. However, fist-like pose seems to occur for the CW direction as well, so it is not clear if this idea can adequately explain the reduced ΔV in the vertical component of force for the right half of the CCW circle. It is to be noted that V_{UCM} reaches its peak in the middle of the trajectory for the radial as well as the tangential direction, thus suggesting greater task synergies. However the values of V_{ORT} do not change during the trajectory. Further investigations into this finding should include the kinematic measurement of the digits and hand. This would allow experimenters to see if the position of the hand differs depending on the direction and pen tip location.

Self-Pace Versus External-Pace

A relationship between component strength and pacing was hypothesized from the idea that drawing is an inherently self-paced task, thus having to follow an outside pace regulator may adversely affect the force synergies being controlled. Previous pacing studies involving drawing tasks support this idea and have indicated that rhythmic movements are generated by internal clocks originating in the cerebellum (Spencer &Zelaznik, 2003; Welsh et al., 1995). This clearly did not prove to be the case as under no circumstances was there a significant difference in synergy strength between paces. A possible explanation is that the controlling synergies are robust and flexible enough that they can easily make temporal adaptations or that the task of having subjects match an external pace based on their individual, "comfortable", pace, determined by their internal clock did not differ enough from their normally paced writing. A future study could test the latter of these possibilities by having subjects draw at a range of non-self-selected paces and comparing the synergy strength to those in which the subjects pace themselves.

Currently the Kinetic Pen is the only writing apparatus reported which provides three-dimensional forces and moments of force at each contact between the pen and hand. Previous research on handwriting kinetics has focused on force relationships between the writing surface and pen-tip (van Den Heuvel et al., 1998; Wann&Nimmo-Smith, 1991), as well as one-dimensional grasping forces on the pen (Herrick & Otto, 1961). A more recent attempt at measuring pen grip forces investigated total grasping force as well as digit-force specificity via contour plots (Chau, Ji, Tam, &Schwellnus, 2006). These techniques are limited in their inability to implement inverse dynamics due to their uni-dimensionality. By using inverse dynamics, one can calculate joint torques and possibly muscle forces during an actual handwriting task using the Kinetic Pen. Such a technique has potential to make great progress in understanding the etiology of writer's cramp and other focal dystonias (Cohen &Hallett, 1988; Sheehy &Marsden, 1982).

Clinical Applications

Techniques used here could be developed for possible clinical use as handwriting is already a common tool used in identifying the presence, severity, and treatment effects of many movement disorders. More specifically, the ability to look at individual digit kinetics and how the digit synergies are functioning could potentially provide great clinical insight. The demand for such an analytical tool has already been called for by some Parkinson's studies who hypothesize that patients' difficulties with writing stems from the inability of patients to release, not generate, digit forces (Van Gemmert, Teulings, &Stelmach, 2001). Similarly, some studies on children with Developmental Coordination Disorder (DCD) have also shown handwriting as a reliable metric to assess the motor performance. Many of these studies deal with kinematic scaling as a key identifier of neurological problems (Contreras-Vidal, Teulings, &Stelmach, 1998; Contreras-Vidal, Teulings, Stelmach, & Adler, 2002; Teulings, Contreras-Vidal, Stelmach, & Adler, 2002; Van Gemmert et al., 2001). Therefore running a similar study with a comparison between writing sizes would provide a baseline of kinetic synergies for the normal population to which patient populations cold be compared.

Conclusion

Previous research suggests that multifinger synergies to stabilize the resultant moment of a prehensile object are more likely to be present during drawing (Latash, Danion, Scholz, Zatsiorsky, &Schoner, 2003; Shim et al., 2004; Shim, Olafsdottir, Latash, & Zatsiorsky, 2005) in addition to the force synergies the current study investigated. However, multisynergies to control the moment of the pen was not investigated in the current study and it opens an avenue for a future study. The techniques developed in the current study can be used to study persons with handwriting abnormalities such as Writer's Cramps (Cohen &Hallett, 1988; Marsden & Sheehy, 1990), Parkinson's disease (Contreras-Vidal, Teulings, &Stelmach, 1995; Jankovic, 2008), and children with developmental dysgraphia (Adi-Japha et al., 2007).

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References

Adi-Japha, E., Landau, Y.E., Frenkel, L., Teicher, M., Gross-Tsur, V., & Shalev, R.S. (2007). ADHD and dysgraphia: underlying mechanisms. *Cortex, 43*(6), 700–709. PubMed doi:10.1016/S0010-9452(08)70499-4

Arimoto, S., & Nguyen, P.T.A. (2001). Principle of Superposition for Realizing Dexterous Pinching Motions of a Pair of Robot Fingers with Soft-Tips.*IEICE TRANSACTIONS on Fundamentals of Electronics*. *Communications and Computer Sciences, 84*(1), 39–47.

Arimoto, S., Tahara, K., Yamaguchi, M., Nguyen, P.T.A., & Han, M.Y. (2001). Principles of superposition for controlling pinch motions by means of robot fingers with soft tips. *Robotica, 19*(01), 21–28. doi:10.1017/S0263574700002939

Bosga, J., Meulenbroek, R.G., & Swinnen, S.P. (2003). Stability of inter-joint coordination during circle drawing: effects of shoulder-joint articular properties. *Human Movement Science, 22*(3), 297–320. PubMed doi:10.1016/S0167-9457(03)00045-9

Chau, T., Ji, J., Tam, C., & Schwellnus, H. (2006). A novel instrument for quantifying grip activity during handwriting. *Archives of Physical Medicine and Rehabilitation, 87*(11), 1542–1547. PubMed doi:10.1016/j.apmr.2006.08.328

Cohen, L.G., & Hallett, M. (1988). Hand cramps: clinical features and electromyographic patterns in a focal dystonia. *Neurology, 38*(7), 1005–1012. PubMed doi:10.1212/WNL.38.7.1005

Contreras-Vidal, J.L., Teulings, H.L., & Stelmach, G.E. (1995). Micrographia in Parkinson's disease. *Neuroreport, 6*(15), 2089–2092. PubMed doi:10.1097/00001756-199510010-00032

Contreras-Vidal, J.L., Teulings, H.L., & Stelmach, G.E. (1998). Elderly subjects are impaired in spatial coordination in fine motor control. *Acta Psychologica, 100*(1-2), 25–35. PubMed doi:10.1016/S0001-6918(98)00023-7

Contreras-Vidal, J.L., Teulings, H.L., Stelmach, G.E., & Adler, C.H. (2002). Adaptation to changes in vertical display gain during handwriting in Parkinson's disease patients, elderly and young controls. *Parkinsonism & Related Disorders, 9*(2), 77–84. PubMed doi:10.1016/S1353-8020(02)00013-5

Danion, F., & Schoner, G., ... (2003). A mode hypothesis for finger interaction during multi-finger force-production tasks. *Biological Cybernetics, 88*(2), 91–98. PubMed doi:10.1007/s00422-002-0336-z

Dounskaia, N., Van Gemmert, A.W., & Stelmach, G.E. (2000). Interjoint coordination during handwriting-like movements. *Experimental Brain Research, 135*(1), 127–140. PubMed doi:10.1007/s002210000495

Fernandes, D.N., & Chau, T. (2008). Fractal dimensions of pacing and grip force in drawing and handwriting production. *Journal of Biomechanics, 41*(1), 40–46. PubMed doi:10.1016/j.jbiomech.2007.07.017

Figliola, R.S., & Beasley, D.E. (2001). Theory and Design for Mechanical Measurements. *Measurement Science & Technology, 12,* 1743.
Gamage, S.S., & Lasenby, J. (2002). New least squares solutions for estimating the average centre of rotation and the axis of rotation. *Journal of Biomechanics, 35*(1), 87–93. PubMed doi:10.1016/S0021-9290(01)00160-9
Gelfand, I.M., & Latash, M.L. (1998). On the problem of adequate language in motor control. *Motor Control, 2*(4), 306–313. PubMed
Herrick, V.E., & Otto, W. (1961). Pressure on point and barrel of a writing instrument. *Journal of Experimental Education, 30,* 215–230.
Holzreiter, S. (1991). Calculation of the instantaneous centre of rotation for a rigid body. *Journal of Biomechanics, 24*(7), 643–647. PubMed doi:10.1016/0021-9290(91)90297-Z
Hooke, A.W., Park, J., & Shim, J.K. (2008). The forces behind the words: development of the kinetic pen. *Journal of Biomechanics, 41*(9), 2060–2064. PubMed doi:10.1016/j.jbiomech.2008.03.036
Jankovic, J. (2008). Parkinson's disease: clinical features and diagnosis. *Journal of Neurology, Neurosurgery, and Psychiatry, 79*(4), 368. PubMed doi:10.1136/jnnp.2007.131045
Koziatek SM, Powell NJ (2003) Pencil grips, legibility, and speed of fourth-graders' writing in cursive. The American journal of occupational therapy.: official publication of the American Occupational Therapy Association 57: 284
Knoblich, G., & Flach, R. (2003). Action identity: evidence from self-recognition, prediction, and coordination. *Consciousness and Cognition, 12*(4), 620–632. PubMed doi:10.1016/S1053-8100(03)00070-9
Latash, M.L. (2000). There is no motor redundancy in human movements. There is motor abundance. *Motor Control, 4*(3), 259–260. PubMed
Latash, M.L., Danion, F., Scholz, J.F., Zatsiorsky, V.M., & Schoner, G. (2003). Approaches to analysis of handwriting as a task of coordinating a redundant motor system. *Human Movement Science, 22*(2), 153–171. PubMed doi:10.1016/S0167-9457(02)00157-4
Latash, M.L., Gorniak, S., & Zatsiorsky, V.M. (2008). Hierarchies of synergies in human movements. *Kinesiology, 40*(1), 29–38. PubMed
Latash, M.L., Scholz, J.F., Danion, F., & Schoner, G. (2001). Structure of motor variability in marginally redundant multifinger force production tasks. *Experimental Brain Research, 141*(2), 153–165. PubMed doi:10.1007/s002210100861
Marsden, C.D., & Sheehy, M.P. (1990). Writer's cramp. *Trends in Neurosciences, 13*(4), 148–153. PubMed doi:10.1016/0166-2236(90)90007-W
Schöner, G. (1995). Recent developments and problems in human movement science and their conceptual implications. *Ecological Psychology, 7*(4), 291–314. doi:10.1207/s15326969eco0704_5
Sheehy, M.P., & Marsden, C.D. (1982). Writers' cramp-a focal dystonia. *Brain, 105*(Pt 3), 461–480. PubMed doi:10.1093/brain/105.3.461
Shim, J.K., Hooke, A.W., Kim, Y.S., Park, J., Karol, S., & Kim, Y.H. (2010). Handwriting: Hand-pen contact force synergies in circle drawing tasks. *Journal of Biomechanics, 43*(12), 2249–2253. PubMed doi:10.1016/j.jbiomech.2010.04.033
Shim, J.K., Hsu, J., Karol, S., & Hurley, B.F. (2008). Strength training increases training-specific multifinger coordination in humans. *Motor Control, 12*(4), 311–329. PubMed
Shim, J.K., Latash, M.L., & Zatsiorsky, V.M. (2003). The human central nervous system needs time to organize task-specific covariation of finger forces. *Neuroscience Letters, 353*(1), 72–74. PubMed doi:10.1016/j.neulet.2003.08.079
Shim, J.K., Latash, M.L., & Zatsiorsky, V.M. (2005a). Prehension synergies in three dimensions. *Journal of Neurophysiology, 93*(2), 766–776. PubMed doi:10.1152/jn.00764.2004
Shim, J.K., Latash, M.L., & Zatsiorsky, V.M. (2005b). Prehension synergies: trial-to-trial variability and principle of superposition during static prehension in three dimensions. *Journal of Neurophysiology, 93*(6), 3649–3658. PubMed doi:10.1152/jn.01262.2004

Shim, J.K., Lay, B.S., Zatsiorsky, V.M., & Latash, M.L. (2004). Age-related changes in finger coordination in static prehension tasks. *Journal of Applied Physiology (Bethesda, Md.), 97*(1), 213–224. PubMed doi:10.1152/japplphysiol.00045.2004

Shim, J.K., Olafsdottir, H., Latash, M.L., & Zatsiorsky, V.M. (2005). The emergence and disappearance of multi-digit synergies during force production tasks. *Experimental Brain Research, 164*(2), 260–270. PubMed doi:10.1007/s00221-005-2248-3

Shim, J.K., Park, J., Zatsiorsky, V.M., & Latash, M.L. (2006). Adjustments of prehension synergies in response to self-triggered and experimenter-triggered load and torque perturbations. *Experimental Brain Research, 175*(4), 641–653. PubMed doi:10.1007/s00221-006-0583-7

Spencer, R.M., & Zelaznik, H.N. (2003). Weber (slope) analyses of timing variability in tapping and drawing tasks. *Journal of Motor Behavior, 35*(4), 371–381. PubMed doi:10.1080/00222890309603157

Taylor, J.R. (1997). *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. University Science Books.

Teulings, H.L., Contreras-Vidal, J.L., Stelmach, G.E., & Adler, C.H. (2002). Adaptation of handwriting size under distorted visual feedback in patients with Parkinson's disease and elderly and young controls. *Journal of Neurology, Neurosurgery, and Psychiatry, 72*(3), 315–324. PubMed doi:10.1136/jnnp.72.3.315

Tseng, Y.W., & Scholz, J.F. (2005). Unilateral vs. bilateral coordination of circle-drawing tasks. *Acta Psychologica, 120*(2), 172–198. PubMed doi:10.1016/j.actpsy.2005.04.001

van Den Heuvel, C.E., van Galen, G.P., Teulings, H.L., & van Gemmert, A.W. (1998). Axial pen force increases with processing demands in handwriting. *Acta Psychologica, 100*(1-2), 145–159. PubMed doi:10.1016/S0001-6918(98)00031-6

Van Gemmert, A.W., Teulings, H.L., & Stelmach, G.E. (2001). Parkinsonian patients reduce their stroke size with increased processing demands. *Brain and Cognition, 47*(3), 504–512. PubMed doi:10.1006/brcg.2001.1328

Wann, J., & Nimmo-Smith, I. (1991). The control of pen pressure in handwriting: a subtle point. *Human Movement Science, 10,* 223–246. doi:10.1016/0167-9457(91)90005-I

Welsh, J.P., Lang, E.J., Suglhara, I., & Llinas, R. (1995). Dynamic organization of motor control within the olivocerebellar system. *Nature, 374*(6521), 453–457. PubMed doi:10.1038/374453a0

Zatsiorsky, V.M., Gao, F., & Latash, M.L. (2006). Prehension stability: experiments with expanding and contracting handle. *Journal of Neurophysiology, 95*(4), 2513–2529. PubMed doi:10.1152/jn.00839.2005

Zatsiorsky, V.M., & Latash, M.L. (2004). Prehension synergies. *Exercise and Sport Sciences Reviews, 32*(2), 75–80. PubMed doi:10.1097/00003677-200404000-00007