

3D Kinetic Synergies in Handwriting

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INTRODUCTION

The seemingly simple act of handwriting is one of many marvels of the central nervous system (CNS). Previous handwriting studies have focused exclusively on handwriting kinematics rather than its kinetics due to the technical difficulties to record pen-hand contact forces in three dimensions (3D). Our group has recently developed Kinetic Pen, which is capable of recording 3D forces/moments at all pen-hand contacts (Hooke et al. 2008). The purpose of this study was to investigate central nervous system strategies for controlling multi-finger forces in 3D space during a writing task. This study specifically investigates the synergistic actions of finger forces in three orthogonal dimensions (i.e., radial, tangential, and vertical) for circle drawing. Four hypotheses were tested: 1) Kinetic synergies between the pen-hand contact forces exist in all three dimensions. 2) The radial and tangential components yield stronger synergies than the vertical component. 3) Synergies exist in both CW and CCW directions and the synergy strengths do not differ between them. 4) The self-pacing yields stronger synergies than the external pacing.

METHODS

Twenty-four subjects drew 30 discrete concentric circles using Kinetic Pen (Fig. 1) for each experimental condition, which included two directions (clockwise, CW vs. counter-clockwise, CCW) and two pacing (self-paced vs. external-paced). For the

external-paced condition, subjects drew circles while following metronome beeps. The 3D contact forces and moments of force between the hand and the pen were calculated from recordings of the miniature 3D force/moment sensors (Nano-17, ATI) embedded in the barrel of the pen (Hooke et al, 2008). The pen-hand contacts included thumb, index finger, middle finger, and webbing between thumb and index finger.

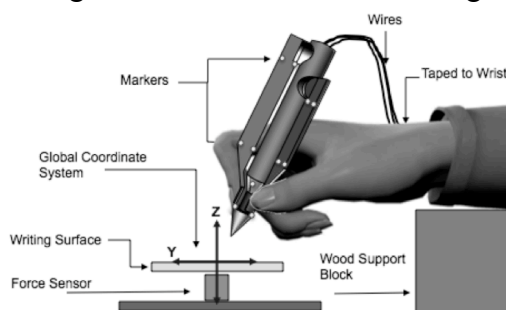


Figure 1: Schematic of experimental setting showing a subject holding the Kinetic Pen with reflective markers attached.

The 3D position of the pen was recorded using a Vicon motion capture system. The 3D position/orientation of the pen was used to transform the local sensor reference frames into the global reference frame. Uncontrolled Manifold Analysis (Scholz & Schöner 1999; Shim et al. 2008) was used to quantify the index of kinetic synergy, $\Delta V(t)$ (Shim et al. 2008) in three orthogonal dimensions: a *radial* component that dictates the pen's motion from the circle edge towards its center, a *tangential* component that dictates the pen's motion tangent to the curvature of the circle, and *vertical* component that dictates the pen's motion perpendicular the writing surface. The total variance [$V_{TOT}(t)$] of four-dimensional (i.e.,

index, middle, ring, and web) space across the circles was resolved into two components. The vectors $F(t)$ were broken into their projection on, and orthogonal to, the null space (UCM) of Eq. 1. The variance within the UCM per degree of freedom [$V_{UCM}(t)$] was calculated. This component of total variance causes no change in the kinematics of the pen. The variance orthogonal to the UCM [$V_{ORTH}(t)$] was also calculated. This component causes change in the kinematics of the pen from the average kinematics (i.e., kinematic errors). Note that $V_{UCM}(t)$ and $V_{ORTH}(t)$ represent CNS abilities to utilize the redundant degrees-of-freedom and to reduce kinematic errors. $\Delta V(t)$, the index of synergistic action between pen-hand contact forces was calculated (Eq. 2).

$$[U] \begin{bmatrix} \bar{F}(t)_{thumb} \\ \bar{F}(t)_{index} \\ \bar{F}(t)_{middle} \\ \bar{F}(t)_{web} \end{bmatrix} = [m\bar{a}(t)_{COM} - \bar{F}(t)_{tip}] \quad \text{Eq. 1}$$

$$\Delta V(t) = \left(\frac{V_{UCM}(t)}{3} - \frac{V_{ORTH}(t)}{1} \right) / \left(\frac{V_{UCM}(t) + V_{ORTH}(t)}{4} \right) \quad \text{Eq. 2}$$

RESULTS AND DISCUSSION

Kinetic synergies existed across all three dimensions and were significantly stronger in the radial and tangential components than vertical component (Fig 2). This suggests that the CNS utilizes kinetic synergies that are not only task dependent but also able to prioritize components within a task to optimize the handwriting performance. The kinetic synergies of radial and tangential forces were much stronger than those found during simple grasping tasks used in previous studies. This may have been caused by the high precision of the manual dexterity necessary to write words, where errors on the scale of millimeters can render script illegible. It is also to be noted that high kinetic synergy existed also in vertical

component ($\Delta V > 0$) although precise control of vertical forces is not required for the optimally drawn shape of circles. The findings were supported by the repeated-measures ANOVA on time-averaged ΔV , which showed significant ($p < .05$) effects of Direction, Component, Direction x Component, Direction x Component x Pace.

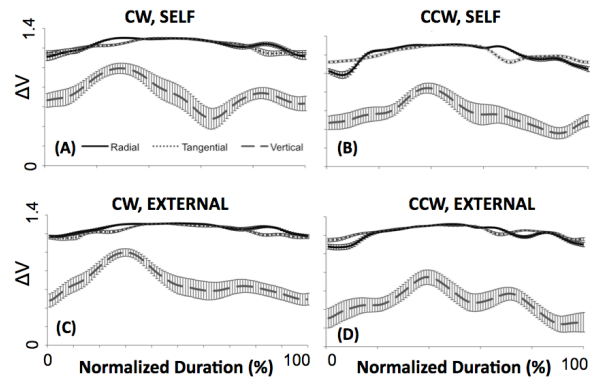


Figure 2: Synergy strength, measured by ΔV , for radial, tangential, and vertical force components.

SUMMARY/CONCLUSIONS

The results of this study suggest that the CNS controls pen-hand contact forces synergistically during handwriting so that the pen's kinematic outputs can be consistent for circle drawing tasks. The kinetic synergy is stronger for the force components, radial and tangential, which are critical for shaping the desired kinematic handwriting outputs, although vertical force component also showed synergistic actions of pen-hand contact forces.

REFERENCES

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