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Handwriting: Hand–pen contact force synergies in circle drawing tasks

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ABSTRACT

This study investigated synergistic actions of hand–pen contact forces during circle drawing tasks in three-dimensional (3D) space. Twenty-four right-handed participants drew thirty concentric circles in the counterclockwise (CCW) and clockwise (CW) directions. Three-dimensional forces acting on an instrumented pen as well as 3D linear and angular positions of the pen were recorded. These contact forces were then transformed into the 3D radial, tangential, and normal force components specific to circle drawing. Uncontrolled manifold (UCM) analysis was employed to calculate the magnitude of the hand–pen contact force synergy. Three hypotheses were tested. First, hand–pen contact force synergies during circle drawing are dependent on the angular position of the pen tip. Second, hand–pen contact force synergies are dependent on force components in circle drawing. Third, hand–pen contact force synergies are greater in CCW direction than CW direction. The results showed that the strength of the hand–pen contact force synergy increased during the initial phase of circle drawing and decreased during the final phase. The synergy strength was greater for the radial and tangential components as compared to the normal component. Also, the circle drawing in CW direction was associated with greater hand–pen contact force synergy than the CCW direction. The results of this study suggest that the central nervous system (CNS) prioritizes hand–pen contact force synergies for the force components (i.e., radial and tangential) that are critical for circle drawing. The CNS modulates hand–pen contact force synergies for preparation and conclusion of circle drawing, respectively.

1. Introduction

The human hand is one of the primary tools used by the central nervous system (CNS) to physically interact with the external world, either while pressing, grasping, or manipulating objects (Valero-Cuevas, 2005). Humans seamlessly produce elegant actions of hand and fingers such as typing on keyboards, playing piano, drinking a glass of wine, and writing words as if these motor tasks are effortless (Shim et al., 2003, 2005a).

The human hand is well structured for a variety of manipulation tasks, exhibiting flexible solutions to the unique control demands presented by these different tasks. However, the same structure may also present control challenges to the CNS because of the extremely high motor redundancy inherent in its system (Chao and An, 1978; Dul et al., 1984; Oliveira et al., 2006). For example, when a hand holds a pen with multiple fingers, the motor task becomes kinetically redundant because there are more contact forces than the forces minimally necessary for the movement outputs of the pen (e.g., pen-tip force) (Shim et al., 2005a; Oliveira et al., 2006; Fernandes and Chau, 2008). Previous studies on multi-finger pressing and grasping have shown that the CNS prioritizes some sub-tasks critical for the achievement of redundant motor tasks to utilize the redundancy (Shim et al., 2003, 2008; Gorniak et al., 2009; Zhang et al., 2009). These studies have defined motor synergies as task-specific interactions of multiple effectors that compensate errors of individual effectors for the successful achievement of motor task. These studies demonstrated that the CNS utilizes the redundant degrees-of-freedom of the system and generates synergistic interactions of multi-finger forces for specific solutions of motor outputs. However, previous studies on multi-finger actions have been limited to relatively simple motor tasks such as multi-digit pressing and grasping. In many of these studies, the motor tasks were also limited to static actions of digits on hand-held objects. The current study employed one of the pinnacles of hand actions, handwriting, as a motor task and investigated dynamic circle-drawing movements in three-dimensional (3D) space using the Kinetic Pen (Bo et al., 2008; Hooke et al., 2008).

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The current study was designed to test the following hypotheses: (1) hand–pen contact force synergies are dependent on the angular position of the pen tip. This hypothesis was based on previous observations of decreases in finger force synergies for current motor tasks in preparation of upcoming motor tasks during pressing and prehension (Kang et al., 2004; Shim et al., 2004, 2005b; Shinohara et al., 2004). (2) Hand–pen contact force synergies are dependent on force components in circle drawing: synergistic actions are greater in the radial and tangential force components of circle drawing compared with the normal force component. This hypothesis was based on the previously reported stabilization of selective variables that are critical during pressing tasks (Shim et al., 2008). (3) Hand–pen contact force synergies are greater in the counterclockwise (CCW) direction than the clockwise (CW) direction in right-handed persons. This hypothesis was based on the previously observed preference of CCW circle drawing in right-handed people (Blau, 1977).

2. Methods

2.1. Subjects

The study included twenty-four volunteer subjects between the ages of 19 and 27, 12 males and 12 females. All subjects were right handed according to Edinburgh handedness test (Oldfield, 1971). Subjects were screened for neurological, psychological, and any other potentially confounding health conditions. Due to the design of the testing instrument, only subjects using the common tripod grasp three-digit contacts—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 webbing between the thumb and index finger were tested. The study protocol was approved by the Institutional Research Board (IRB) at the University of Maryland and informed written consent was obtained from each subject.

2.2. Experimental setup

The Kinetic Pen was used as the writing utensil for this study (Hooke et al., 2008). The Kinetic Pen was equipped with four, six-dimensional force/torque sensors (Nano-17, ATI Industrial Automation, Garner, NC, USA) and a plastic, non-inking tip (Fig. 1A). The hand–pen contact forces were recorded in each local reference system (LRS) of the sensors. Participants drew circles on a writing surface of a 14 cm × 14 cm × 0.5 cm Plexiglas plate mounted 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 writing task (Fig. 1B). 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 3D kinematic data from the pen and the writing surface. Subjects were seated within a calibrated volume of 100 cm × 100 cm × 100 cm. An array of nine reflective, markers (3 mm in diameter) was placed on the Kinetic Pen. Three markers defined the writing tip, three defined the thumb sensor and extended arm, and three defined the index sensor and moment arm. An array of four reflective markers was mounted to the construction paper on the writing surface to define the global reference system (GRS). The force data and kinematic data were synchronously sampled at 100 Hz.

2.3. Experimental procedures

Prior to 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 (Holzreiter, 1991; Gamage and Lasenby, 2002). The three-dimensional coordinates relative to the other nine markers on the pen were determined as the pen tip coordinates. Participants were instructed to draw 30 concentric discontinuous circles 3 cm in diameter at a "comfortable" speed without lifting the pen from the Plexiglas plate while maintaining as close to a geometrically accurate circle as possible, pausing briefly between concentric circles. Participants were instructed to use "comfortable" pause time, and it was approximately 0.5 s on average. No external cue was given to participants to start drawing of each circle. Using this basic task, two conditions were tested: the drawing of circles in CW direction and the drawing of circles in the CCW direction. The order of the conditions was balanced across subjects and each subject drew a total of 60 circles. Subjects used finger and wrist joints more for circle drawing although the experimental settings or instructions did not impose limitations of elbow or shoulder movements.

2.4. Transformation of reference systems

Data, in this study, were collected in multiple reference systems. The kinematic data recorded by the motion capture system and the pen-tip force data [$X(t)$, $Y(t)$, $Z(t)$] recorded by the six-component sensors were considered in the global reference system (GRS). The force data [$x(t)$, $y(t)$, $z(t)$] collected from each digit were in a reference system local to each digit (LRS). Using the known orientation of the Kinetic Pen relative to the writing surface, the amount of rotation about the global X-, Y-, and Z-axes that each LRS had to undergo such that the digit forces were transformed into GRS was found. These Euler angle rotations about the X-, Y-, and Z-axes, denoted $\theta(t)$, $\phi(t)$, and $\psi(t)$, respectively, were determined (Eqs. (1) and (2)). Rotation matrix $R(t)$ denotes the necessary rotation about each of the global axes.

$$R(t) = R_X(\theta(t))R_Y(\phi(t))R_Z(\psi(t)) \tag{1}$$

$$\begin{bmatrix} X(t)_i & Y(t)_i & Z(t)_i \end{bmatrix} = \begin{bmatrix} x(t)_i & y(t)_i & z(t)_i \end{bmatrix} R(t) \tag{2}$$

where i denotes thumb, index, middle, and web, X, Y, and Z represent 3D force components in GRS, and x, y, and z represent 3D force components in LRS.

The GRS was transformed into circle-specific reference system (CRS) in order to calculate the desired three force components (i.e., radial, tangential, and normal) of circle drawing. The $X(t)_i$ and $Y(t)_i$ components were rotated such that one component of the rotated force was parallel to the radial direction becoming the radial force $R(t)_i$. The magnitude of this rotation was denoted $\lambda(t)$ (Eq. (3)). The other component of the rotated force, by definition of being perpendicular to the radial and normal forces, was the tangential force $T(t)_i$. In this case, each set of digit forces and the pen-tip force were rotated since the rotation is global.

$$\begin{bmatrix} R(t)_i & T(t)_i & N(t)_i \end{bmatrix} = \begin{bmatrix} X(t)_i & Y(t)_i & Z(t)_i \end{bmatrix} R_Z(\lambda(t)) \tag{3}$$

where i denotes thumb, index, middle, web, and pen-tip and λ is the rotation angle about the Z-axis. R, T, and N, respectively, represent radial, tangential, and normal force components in CRS and X, Y, and Z represent 3D force components in GRS.

2.5. Uncontrolled manifold analysis

The framework of the uncontrolled manifold (UCM) analysis was used to quantify the hand–pen contact force synergies (Schöner, 1995; Scholz and Schoner, 1999; Latash et al., 2007; Shim et al., 2008). UCM analysis allows the quantification of synergistic actions of multiple elemental variables (e.g., digit forces) acting together in a redundant motor system for the achievement of a specific motor task. The following equations were constructed to investigate the synergistic actions of hand–pen contact forces in 3D through UCM analysis (Eqs. (4)–(6)).

$$[U]\begin{bmatrix} R(\Theta)_{\text{thumb}} & R(\Theta)_{\text{index}} & R(\Theta)_{\text{middle}} & R(\Theta)_{\text{web}} \end{bmatrix}^T = \begin{bmatrix} ma_R(\Theta) - R(\Theta)_{\text{tip}} \end{bmatrix} \tag{4}$$

$$[U]\begin{bmatrix} T(\Theta)_{\text{thumb}} & T(\Theta)_{\text{index}} & T(\Theta)_{\text{middle}} & T(\Theta)_{\text{web}} \end{bmatrix}^T = \begin{bmatrix} ma_T(\Theta) - T(\Theta)_{\text{tip}} \end{bmatrix} \tag{5}$$

$$[U]\begin{bmatrix} N(\Theta)_{\text{thumb}} & N(\Theta)_{\text{index}} & N(\Theta)_{\text{middle}} & N(\Theta)_{\text{web}} \end{bmatrix}^T = \begin{bmatrix} ma_N(\Theta) - N(\Theta)_{\text{tip}} - W \end{bmatrix} \tag{6}$$

where $[U]$ is the unity matrix (1×4), Θ the angular position of the pen tip, thumb, index, middle, web, are the hand–pen contacts, tip denotes pen tip on writing surface, $m\Theta$ is the mass of pen, W the weight of pen, and T the matrix transpose. R, T, and N represent radial, tangential, and normal force components in CRS, respectively. a_R, a_T, and a_N represent acceleration of pen's center of mass in CRS.

For each force component (i.e., radial, tangent, and normal), there is a four-dimensional vector $F(t)$ representing the four hand–pen contact points on the left-hand side of each equation. Change in the right-hand side (ΔRHS) of the equations ($[ma_R(\Theta) - R(\Theta)_{\text{tip}}]$, $[ma_T(\Theta) - T(\Theta)_{\text{tip}}]$, and $[ma_N(\Theta) - N(\Theta)_{\text{tip}} - W]$) can be expressed in terms of the changes in the four-dimensional vector $F(\Theta)$ and the unity matrix $[U]$. The following equation was constructed with the condition of $\Delta\text{RHS}(\Theta) = 0$ for the mean trajectory of RHS(Θ) over thirty circles (Eq. (7)) similarly in previous studies (Kang et al., 2004; Shim et al., 2008).

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

An uncontrolled manifold (UCM) was computed in the space of the four-dimensional mean-free force. It represents combinations of force components that are consistent with a stable value of left-hand side of the equation (i.e., performance variable). The manifold is approximated linearly by the null space spanned by the orthonormal basis vector, $e(\Theta)$, solving the following equation.

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

The total variance ($V_{\text{TOT}}(\Theta)$) of four-dimensional space across the thirty circles was resolved into two components. The vectors $F(\Theta)$ were broken into their

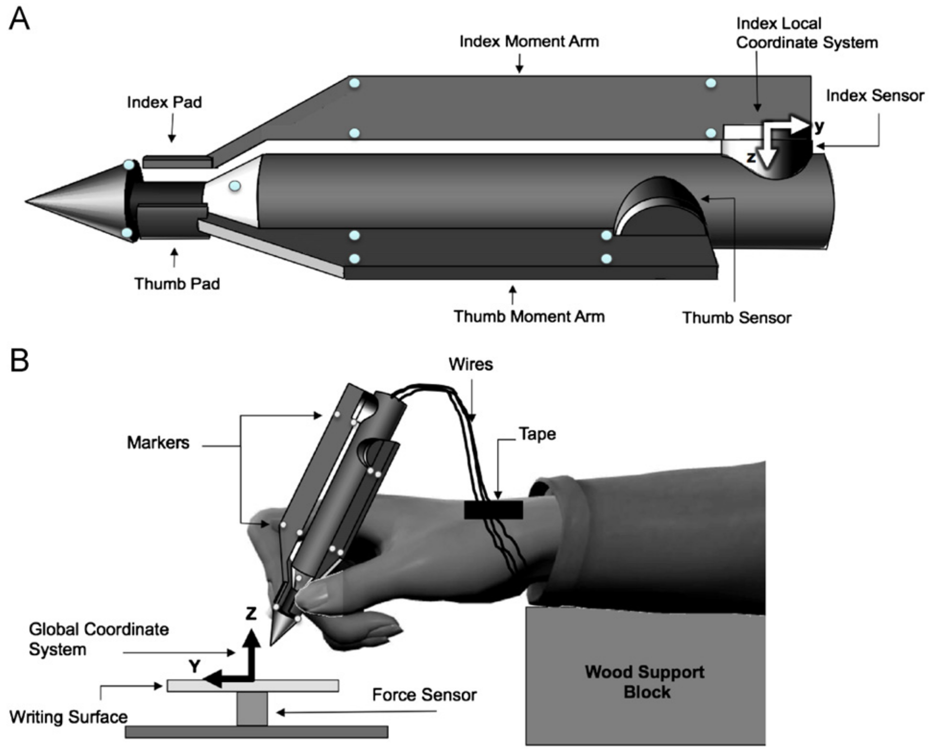

Fig. 1. Schematics of (A) Kinetic Pen and (B) the experimental settings.

projection on, and orthogonal to, the UCM. The variance within the UCM per degree of freedom ($V_{\mathrm{UCM}}(\Theta)$) was calculated. This component of total variability causes no change to the RHS mean value. The variance orthogonal to the UCM ($V_{\mathrm{ORT}}(\Theta)$) was also calculated. $V_{\mathrm{ORT}}(\Theta)$ causes change in the RHS mean values (i.e. errors in RHS). The index of hand–pen contact force synergy, called ΔV, was computed over the 360 evenly spaced angular positions of the pen tip. At each angular position, the difference between V_{UCM} and V_{ORT}, normalizing by the number of dimensions of each component's variance, was computed and defined as ΔV (Eq. (9)). A positive ΔV indicates that V_{UCM} is greater than V_{ORT} and consequently synergistic actions exist between the individual contact forces. Greater ΔV values represent a greater kinetic synergy between hand–pen contact forces (Oliveira et al., 2006; Shim et al., 2008). In other words, ΔV quantifies how well the four individual force components compensate for each other's errors to achieve the constant trajectory of circle drawing.

$$\Delta V(\mathrm{Q}) = [V_{\mathrm{UCM}}(\Theta)/3 - V_{\mathrm{ORT}}(\Theta)/1]/[(V_{\mathrm{UCM}}(\Theta) + V_{\mathrm{ORT}}(\Theta))/4] \tag{9}$$

The integral of ΔV over the entire angular position, ΔV_{area}, was calculated as the overall strength of hand–pen contact force synergy during circle drawing.

$$\Delta V_{\mathrm{area}} = \int_0^{2\pi} \Delta V(\Theta)\, d\Theta \tag{10}$$

2.6. Statistics

In order to test the first hypothesis, circular–linear regression analysis was performed between the angular positions of the pen tip and ΔV at the angular positions for each experimental condition for each subject. In order to test the second and third hypotheses, a within-subject ANOVA was run with two factors: component [3 levels: radial, tangential, and vertical] and direction [2 levels: CW and CCW]. Circular statistics was employed to perform a regression analysis between angular positions (i.e., circular variable) and ΔV (i.e., linear variable) using Oriana software (Kovach Computing Services). The ranges of correlation coefficients across all subjects are reported for each experimental condition for the first hypothesis while the means and standard errors are reported for the second and third hypotheses. The statistical significance was set at $p = 0.05$ for both regression analysis and ANOVA.

3. Results

In general, ΔV values averaged over all subjects for each condition and component showed that the minimum values existed at 0 (i.e., start) or 2π (i.e., end) angle while the maximum values were observed between $\pi/2$ and $3\pi/2$ (Fig. 2). ΔV values were visibly greater for radial and tangential components than for the normal component.

ΔV values noticeably increased during the initial circle drawing phase and decreased during the final drawing phase. The circular–linear regression analysis performed between angular position of the pen tip and ΔV for each direction and each force component showed that correlation coefficients (r) ranged from $r = 0.12$ ($p = 0.006$) to $r = 0.94$ ($p = 6.9\mathrm{e}{-10}$). The correlation coefficients were significant for each circle drawing direction and each force component for each subject (Table 1).

Two-way repeated-measures ANOVA showed that there were statistically significant effects of direction [$F_{[1,23]} = 4.94$, $p < 0.05$] and component [$F_{[2,46]} = 104.06$, $p < 0.001$] while showing no significant interaction of these factors (Fig. 3). The radial and tangential components showed greater ΔV_{area} as compared with the normal component in both CCW and CW directions. The ΔV_{area} of the radial component was greater than that of the tangential component in CCW direction. The ΔV_{area} for CW direction was greater than the area for CCW direction.

4. Discussion

In summary, the results of this study showed that the strength of hand–pen contact force synergy increased during the initial phase of circle drawing and decreased during the final phase. The synergy strength was greater for the radial and tangential components as compared to the normal component. The circle drawing in CW direction was associated with greater hand–pen contact force synergy as compared to CCW direction.

In general, hand–pen contact force synergy existed for all force components, and the synergy strength of circle drawing quantified by ΔV was much greater than those found in previous multi-finger pressing and grasping studies (Latash et al., 2001; Kang et al., 2004; Zhang et al., 2007; Shim et al., 2008). The maximum

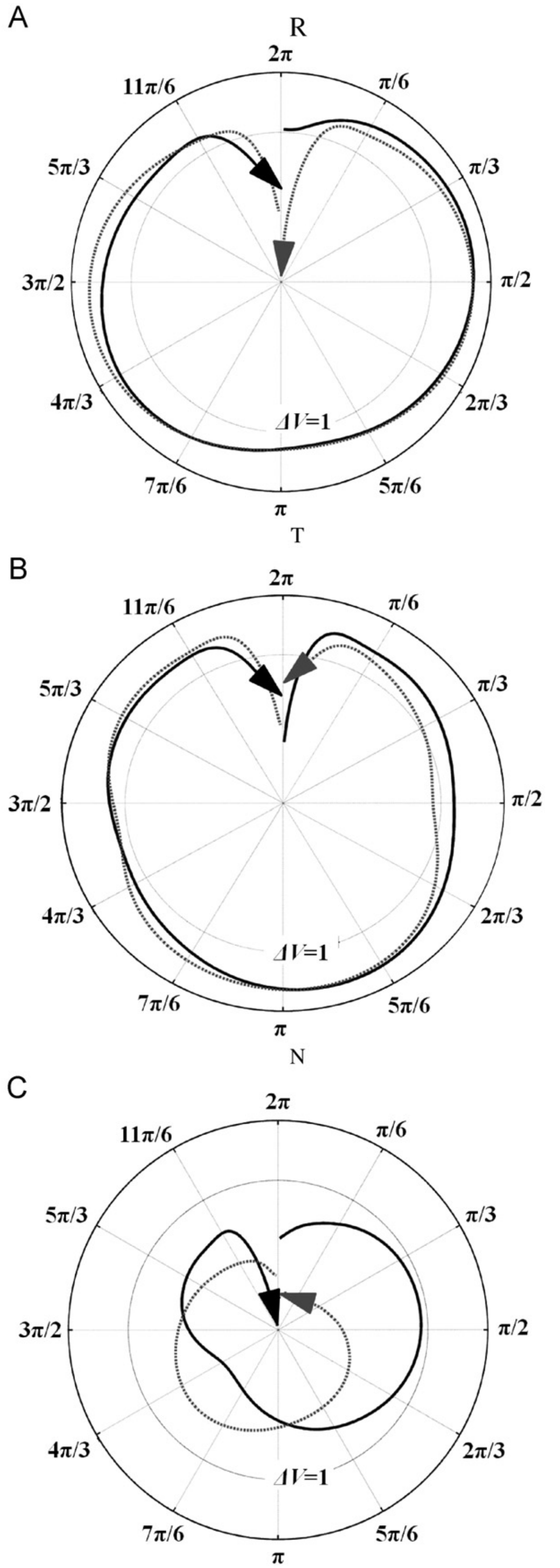

Fig. 2. ΔV for (A) radial, (B) tangential, and (C) normal force components. The dotted/gray and solid/black lines represent counterclockwise (CCW) and clockwise (CW) direction conditions, respectively. *R*, *T*, and *N* represent radial, tangential, and normal components of force, respectively. The arrows indicate the circle drawing directions. The average data across all subjects are shown.

Table 1
Circular–linear correlation coefficients (r) and their statistical significances (p) between pen-tip angular position and ΔV. The r value ranges and their matching p values across all subjects are reported. CCW and CW stand for counterclockwise and clockwise direction conditions, respectively. *R*, *T*, and *N* represent radial, tangential, and normal components of force, respectively. Note that all r values are $p < 0.01$.

Direction	Component	r [min, max]	p [max, min]
CCW	*R*	[0.14, 0.74]	[9.1e-04, 1.7e-12]
	T	[0.15, 0.81]	[3.5e-04, 1.1e-11]
	N	[0.24, 0.94]	[1.8e-09, 6.9e-10]
CW	*R*	[0.12, 0.84]	[6.0e-03, 1.8e-12]
	T	[0.20, 0.65]	[9.7e-07, 1.2e-12]
	N	[0.12, 0.91]	[5.0e-03, 1.8e-08]

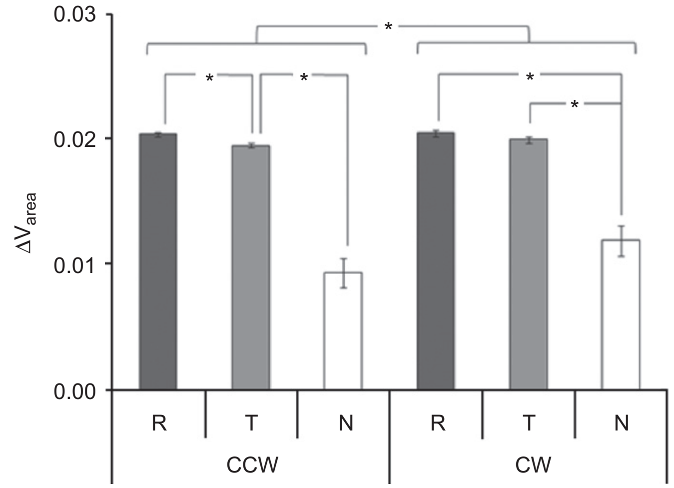

Fig. 3. ΔV_{area} as a measure of overall synergy strength. CCW and CW stand for counterclockwise and clockwise directions, respectively. *R*, *T*, and *N* represent radial, tangential, and normal components of force, respectively. Means and SE's across subjects are shown. $^*p < 0.05$.

values of ΔV reported in the previous studies on pressing and grasping were less than 1 in most of cases while the maximum value of ΔV was greater than 1 for the radial and tangential force components in circle drawing of this study. The maximum ΔV values for the normal force component were, however, smaller than 1. The radial and tangential forces cause the motion of the pen and eventually the pen-tip trajectory on the drawing surface. Thus, the greater synergistic actions of hand–pen contact forces must have been used for consistent circle drawing, as compared with the normal force component, which is not associated with the shape of the circle. Moreover, subjects can modify the normal force at the pen tip, as long as they do not lift the pen or tear the paper, giving them a wide range of normal forces. On the contrary, both radial as well as tangential forces have to be controlled accurately in order to draw a circle, thus requiring greater synergies in these directions.

Previous studies have shown that most right-handed people naturally draw circles in CCW direction and it was explained by the dominance of brain hemisphere (Blau, 1977; Demarest and Demarest, 1980; Woods and Oppenheimer, 1980). Since our assumption was that right-handed people might have developed stronger synergy in circle drawing in CCW direction throughout their learning and experiences of drawings and handwriting of circles in CCW direction, we expected that the hand–pen contact force synergy strength would be greater in CCW direction than inexperienced CW direction. However, we found that the hand–pen contact force synergies were greater in CW direction than

CCW direction. It is currently difficult to speculate as to what contributed to the directional difference in circle drawing synergies and it requires further investigation. However, one can argue from the results found in this study that the brain hemisphere dominance of hand–pen synergy is opposite to that of circle drawing direction and does not follow the claims by earlier studies. Moreover, other previous studies suggested that the preferred CCW direction by right-handed people might not be consistent characteristics (Zendal et al., 2006) and can be easily altered by providing a short practice of circle drawing in different directions (Furlong, 1985). There might have been enough mixture of participants with CW and CCW direction preferences in our study, which we consider as a limitation.

Many previous studies have suggested that the purpose of motor synergy is to be able to perform the motor task with flexibility (i.e., performing a secondary motor task and avoiding external perturbation) and to minimize errors between desired and actual motor outputs (see Latash, in press, for detailed reviews). In handwriting, synergistic actions of hand–pen contact forces may provide flexible solutions (e.g., uneven friction condition of writing paper) and help avoiding illegible characters. Previous studies on multi-digit pressing and multi-digit grasping have shown that the synergistic actions of digit forces for the stabilization of specific motor tasks increase when a motor task is initiated and decrease right before the current motor task changes to another (Kang et al., 2004; Shim et al., 2004, 2005b; Shinohara et al., 2004). Manipulation tasks, in general, are divided into sequence of action phases separated by contact events that define task sub goals (Johansson and Flanagan, 2009). These previous studies have attributed the changes in synergies to the changes in motor task by showing a decrease in synergy strength during the initial motor task and the development of a new synergy for another motor task (Shim et al., 2004, 2005b, 2008). In the current study, when a subject started drawing a circle from just holding the pen still, they were required to “destroy” the existing synergy for holding the pen still and “construct” a new synergy for drawing, resulting in relatively low-synergy strength during the initial phase of circle drawing. When the subject continued circle drawing, the strength of circle drawing synergy increased, as also observed in previous studies on pressing and grasping. However, when the circle was close to being completed, the subject needed to destroy the current synergy for circle drawing and construct a new synergy for “holding”, resulting in reduced synergy at the end.

The current study investigated the synergistic actions of hand–pen contact forces during circle drawing tasks as the first study on handwriting synergy. Investigating other types of handwriting tasks such as line drawing and square drawing would strengthen the claims made in this study.

Conflict of interest

No author has any financial or personal relationship that could inappropriately influence the work submitted for publication.

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