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Motor Variability but Functional Specificity: The Case of a C4 Tetraplegic Mouth Calligrapher

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This study examined the movement coordination in an exceptional tetraplegic individual who has practiced Japanese calligraphy with a mouth-held brush for over 25 years to reach master level. In the experiment, the calligrapher wrote the same Chinese character on a sheet of ink paper multiple times. The uncontrolled manifold analysis revealed the forms of covariation among joint degrees of freedom so as to keep the brush pressure, brush angle, and upright head posture invariant over different realizations of the task while allowing for joint configuration fluctuations that do not affect these task variables. The fact that the 3 task variables were simultaneously controlled further suggested that the acquisition of the skill was not only a matter of learning to control each of the task variables but also a matter of learning to nest different layers of activities that control the multiple functional relationships to the environment in such a way as not to be dysfunctional for one layer to another.

Unlike machines built up out of mechanistic units, organisms are characterized by vicarious function of different units, to borrow Lashley's (1921) term, in which the same goal can be achieved by a large variety of organization patterns (Adolph, Joh, Franchak, Ishak, & Gill, 2008; Bernstein, 1967; E. J. Gibson, 1997; J. J. Gibson, 1966; Kuniyoshi & Sangawa, 2006; Reed, 1996; Sasaki & Nonaka, 2007). Such characteristics can be observed at all levels of the

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organization of living systems, ranging from immune systems (Edelman & Gally, 2001) to action systems (Goldfield, 1995; Reed, 1982). In human behavior, for instance, the situation is not uncommon in clinical settings where a function previously assumed by the movement of one effector system is replaced by that of another effector system. Yet at a lower level, a given effector system is itself often redundant with respect to the function achieved in the world. There are potentially very many ways in which the variability of the components of the redundant effector system is coordinated to meet the requirements of the task at hand, or in Bingham's (1988) terms, to assemble a "task-specific device." Although the issue is quite fundamental to theorizing in psychology, our understanding of how the functional specificity of voluntary action is achieved through a considerable variety of subsidiary processes is at present poor (E. J. Gibson, 1997; Reed, 1989).

Nearly half a century ago, J. J. Gibson (1966) wrote, "Just as perceptions do not depend on specific sensations, so motor actions do not depend on specific muscles" (p. 57), and he went on to classify movement systems based not on anatomical structures but on purposes. Around the same time, asking what determines the structures of motor acts, Russian movement scientist Bernstein (1967) wrote as follows:

> We cannot suppose *effector commands* to be such a standard determinant. These commands are emitted into a system involving at least two types of independent forces (reactive and external forces), they act upon the organ through a non-rigid musculature, and they must also vary between very wide limits in order to accommodate signals coming from the sense organs. These afferent (incoming) signals also cannot act as standard determinants, because signals giving the degree of match or mismatch between movement and effect can only be as variable as the cues which provide them, and, more importantly, the information which they contain is a description of "what is" and not of "what must be done." (p. 147)

The views of these two scientists converged on the point that in the behavior of animals, "what must be done" or "purposes" are primary and the pattern of movements or muscles involved is secondary.

Taking their cue from Bernstein, Latash, Danion, Scholz, Zatsiorsky, and Schöner (2003) contrasted the following two features of movement coordination: First, there are particular attracted relations among outputs of each element. Second, if the output of an element in a particular trial is different from its expected output, the outputs of other elements may change in a compensatory manner such that the overall functional output of the structural unit is left invariant. These two features of movement coordination can be contradictory, if not mutually exclusive, as the former predicts the attraction toward a preferred relationship among the outputs of each element, whereas the latter predicts whatever relationships among outputs of each element as long as the overall functional output remains invariant. It takes some effort to realize that these two features of movement coordination are not identical because the desired patterns of coordination are often specified a priori in experimental studies as the goal of the task (Hong & Newell, 2006). For example, in studies of movement coordination, participants are often instructed to produce a specified relative phase between the limbs as accurately as possible (e.g., Kelso & Zanone, 2002). However, most everyday tasks can be performed successfully with different coordination patterns due to the degeneracy in the tasks and also, except in special cases like dancing, the patterns of movement are usually not directly the performance criterion (Rein, Davids, & Button, 2010).

To explore how the variability of the movement system is structured to meet the demands of a task whose goal is not the production of a specified pattern of coordination, this case study investigated a singular case of a tetraplegic calligrapher. Fumiyuki Makino (hereafter referred to as FM), a member of the Association of Mouth and Foot Painting Artists of the World, is a 45-year-old professional Japanese calligrapher/painter who in a diving accident 29 years ago dislocated vertebrae C4 resulting in tetraplegia. The major sequelae of tetraplegia include loss of all centrally mediated voluntary movement, sensation, and autonomic function below the level of injury (Figoni, 1984). Before the accident FM learned Japanese calligraphy, and after the injury he trained himself to write and paint with a brush gripped between his teeth (Figure 1a). Not only that, FM obtained the official certificate of a professor of Japanese calligraphy in 2004. FM has been painting and writing in this manner regularly for over 25 years. The case of FM presents a unique opportunity to explore different levels of organization of human movement systems. Because skilled action is the outcome of a developmental process (Kelso & Zanone, 2002), by looking at how the variability of the movement system is structured, we may get a glimpse into the issue of what develops when such vicarious action coordination develops. This may potentially further shed light on what underlies the switches in action coordination to achieve the same goal often found in developmental settings (e.g., Slijper, 1942).

The general question proposed in the present study was this: Given the nature of the task of Japanese calligraphy and the nature of the vicarious motor systems, how does the calligrapher flexibly coordinate his movements to meet the demand of the task? The goal of the calligrapher is first and foremost to write characters on a sheet of paper with brush and ink. Chinese and Japanese art of writing using the brush and ink requires a special technique that has to be learned and mastered. The flexible tip of the brush can produce thick and thin strokes when brought into contact with the paper, which depends on the degree of pressure exerted on the tip. When the pressure is increased, the tip spreads and a greater quantity of ink is released; when the pressure lets up, the elasticity of the hairs causes the brush to regain its original shape, and the flow of ink is decreased.

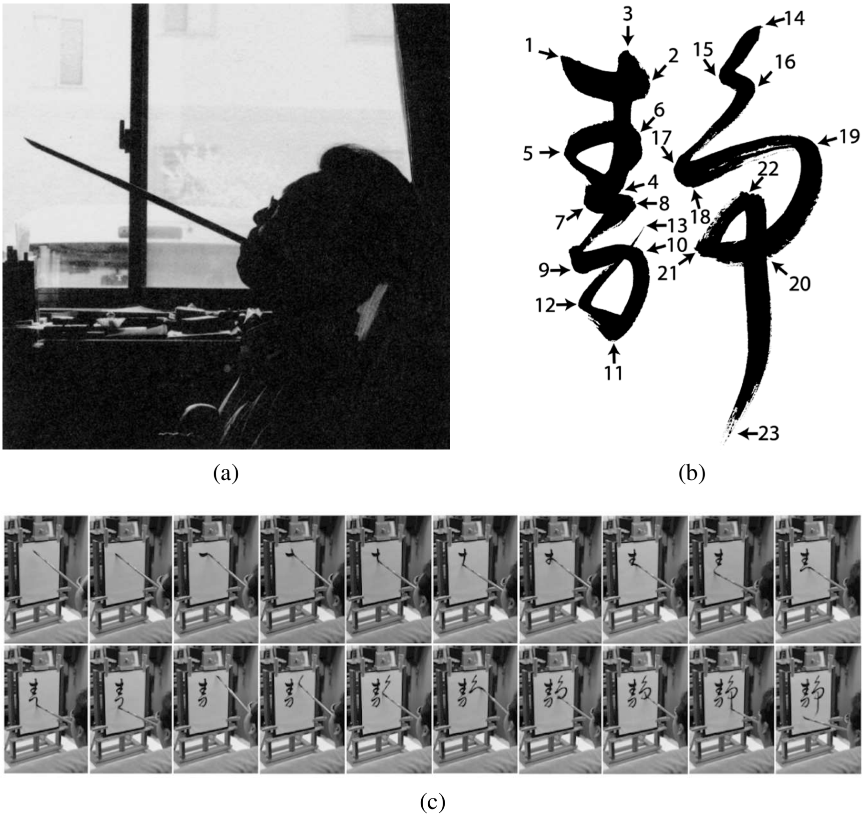

FIGURE 1 (a) FM holding a brush between the teeth. (b) Twenty-three brush events defined for the Chinese character "*shizuka*" (written by FM in one of the trials in this experiment). (c) Progression of writing of the character "*shizuka*" in cursive style by FM.

The amount of ink and the thickness of the brushstroke are determined by how much pressure there is on the brush, and the quantity of ink released at any given moment is proportional to the width of the stroke. To feel the pressure at the brush tip, and to allow for the movement of the brush in different directions, the brush is normally held nearly vertically against the paper plane unlike the way we hold our pen (Billeter, 1990).

A writing brush can bend in any direction, and it is resilient to regain its original shape as soon as pressure is relaxed. A calligrapher needs to feel the brush's contact with the paper in order to control the dynamics of the brush tip interacting with the paper. Thanks to the elasticity of hairs, every variation in pressure is converted into a visible modulation, and at slight easing of pressure the tip straightens again. What the calligrapher does, in effect, is to set up in the brush tip an interplay of antagonistic forces whose outcome he controls (Ishikawa, 2009). In other words, the forms that a calligrapher sets down on paper are not produced by a direct mechanical action but are the indirect results of a complex interaction. Consequently, the relationship between the functional requirements of the task and the patterns of movement is not that of one-to-one mapping, which allows us to describe the range of coordinative solutions as a function of task constraints (cf. Winold, Thelen, & Ulrich, 1994).

The task-specific structure of movement coordination can be quantified using the uncontrolled manifold (UCM) method, which examines whether variability in elemental variables (e.g., joint angles) in a multielement system (e.g., a brush-body system) is exploited to control a task variable (e.g., brush pressure against the paper). The UCM is defined as the set of all elementary variables that leaves a task variable invariant (Scholz & Schöner, 1999; Schöner, 1995). If the task variable is a controlled variable, a higher proportion of the variance in elemental variables in the UCM is expected compared with the uncompensated variance that affects the task variable (Scholz & Schöner, 1999; Schöner, 1995). Several kinematic variables have been shown to be stabilized by covaried changes in joint angles during sit-to-stand action (Scholz, Reisman, & Schöner, 2001), quick-draw pistol shooting (Scholz, Schöner, & Latash, 2000), voluntary body sway (de Freitas, Duarte, & Latash, 2006), spontaneous postural sway (Hsu, Scholz, Schöner, Jeka, & Keimel, 2007), and reaching with a rod task (van der Steen & Bongers, 2011).

Using the UCM method, this study examined the movement coordination involved in an extraordinary yet idiosyncratic calligraphy skill by a remarkable individual. This study was the first to explore movement coordination of a tetraplegic individual using a mouth-held tool, which is a common alternate method for using various tools among tetraplegic individuals (Floris, Dif, & Le Mouel, 2002). In addition, this was the first to explore within the UCM framework the structure of motor variability of a highly trained, complex tool-use skill that has been practiced for many years to reach master level. The main goal of the study was to discover how the variability of the components of the redundant effector system of the calligrapher is structured. If underlying the skill is the functionally specific coordination of movement to solve a motor problem repeatedly rather than to repeat its solution (Bernstein, 1996), a structure of motor variability such that certain task variables remain invariant would be expected, possibly accompanied by forms of covariation among degrees of freedom that compensate for errors so as to keep task-relevant variables stable. Thus, this experiment specifically focused on the following questions: (a) Would the joint configuration variance be structured in such a way as to minimize the variance of the task variables or not? (b) If so, would the compensatory coupling among joint variables contribute to such task-specific structure of variance in the joint space?

The tests were applied separately to hypotheses about invariance of the following task variables: (a) the pressure of the tip of the brush against the surface of the paper, (b) the angle formed between the paper plane and the stalk of the brush, and (c) the head lateral tilt angle on the frontal plane relative to the vertical axis. The first two task variables have been considered important in the skill of brush-and-ink writing. The third task variable, upright posture of the head, is known to be stabilized in various motor skills (Amblard, Assaiante, Fabre, Mouchnino, & Massion, 1997; Pozzo, Levik, & Berthoz, 1995).

METHOD

Equipment and Setup

The brush had the following properties: weight = 40 g, total length = 43 cm, length of the hair = 3.5 cm, diameter at the midpoint = 8 mm. The end of the stalk was wrapped with a silicon tube. FM was seated in a wheelchair with a table attached in front of FM on which an easel was set. A sheet of Chinese ink paper (height: 33.4 cm, width: 24.3 cm) was set on the easel with four pegs. Another small table to place the ink stone was placed on the left side of FM. The position of the paper did not change with respect to the external reference frame during writing.

An eight-camera, 120-Hz Hawk system (Motion Analysis Corp., Santa Rosa, CA) collected the kinematic data. Four spherical retro-reflective markers (0.6 cm in diameter) were attached on the stalk of the brush with double-sided adhesive tape (0.7 cm, 14.5 cm, 22 cm, and 29 cm from the tip of the brush). Four markers (1.9 cm in diameter) were placed on the four corners of the easel to measure the position of the paper. The rest of the markers (1.9 cm in diameter) were applied to the following locations on the body: (a) left and right forehead approximately over the temple, (b) left and right back of the head roughly in a horizontal plane of the front head markers, (c) chin, (d) left and right cheek bones, (e) C1, (f) two markers at C4 level separated roughly by 2 cm, (g) C7, (h) left and right acromioclavicular joints, (i) jugular notch where the clavicles meet the sternum, and (j) xiphoid process of the sternum.

Design and Procedure

Before the data collection a calibration posture was recorded in which FM held the brush forward with the tip of the brush barely in contact with the center of a sheet of paper for 7 s. Then, FM wrote a Chinese character "*shizuka*" (in

Japanese pronunciation) in cursive (*sousho*) style (Figure 1c). The character was chosen by FM himself. To avoid the risk of orthostatic hypotension—decrease in blood pressure upon assuming upright position, which tetraplegic patients often suffer from (Figoni, 1984)—the number of trials was restricted to 10 trials. For all trials, the brush was applied to the ink stone just once before the initial brushstroke. FM's assistant changed and positioned the paper after each trial. Session duration was approximately 40 min including marker placement and removal. FM did not report any discomfort or fatigue during or after the experiment.

Data Analysis

Data reduction. Digitized coordinates of the reflective markers were identified and tracked through each trial using EVaRT software (Motion Analysis Corp., Santa Rosa, CA). After tracking the markers for each trial, the coordinates of each marker were filtered using a bidirectional, fourth-order Butterworth filter with a low-pass cutoff of 20 Hz using MATLAB.

Joint angle calculation. The following three rigid bodies were formed from the recorded data: (a) head-plus-brush, (b) cervical spine (C7-C1 vertebrae), and (c) thorax. The movement of FM was described in terms of three-dimensional orientations represented by Euler angles (cf. Zatsiorsky, 1998) of the head-plus-brush relative to the cervical spine and that of the cervical spine relative to the thorax, which resulted in six joint variables. The angles were calculated relative to the reference position of the calibration posture, where the value zero indicates an alignment of the segmental relations to those of the calibration posture. Local coordinates were defined with *X*-axis fore-aft (lateral bending), *Y*-axis horizontal in the coronal plane (flexion-extension), and *Z*-axis vertical (axial rotation). The rotation sequence chosen was *ZYX* (cf. Hof, Koerhuis, & Winters, 2001).

Due to the paralysis, FM's body below C7 moved little (Figure 2a). Mean standard deviations of Euler angles of the thorax relative to the global frame of reference were 0.49°, 0.31°, and 0.33° about *X*-, *Y*-, and *Z*-axis, respectively. The brush also moved little relative to the head, where mean within-trial standard deviations of Euler angles relative to the head were 0.75°, 0.63°, and 0.68°, respectively. Therefore, the movement of the thorax relative to the global reference frame and that of the brush relative to the head are not reported.

Hypothesized task variables. The hypothesized task variables of the task were (a) the pressure exerted on the tip of the brush, (b) the angle formed between the paper plane and the stalk of the brush, and (c) the head lateral tilt angle on the frontal plane relative to the vertical axis. The brush pressure

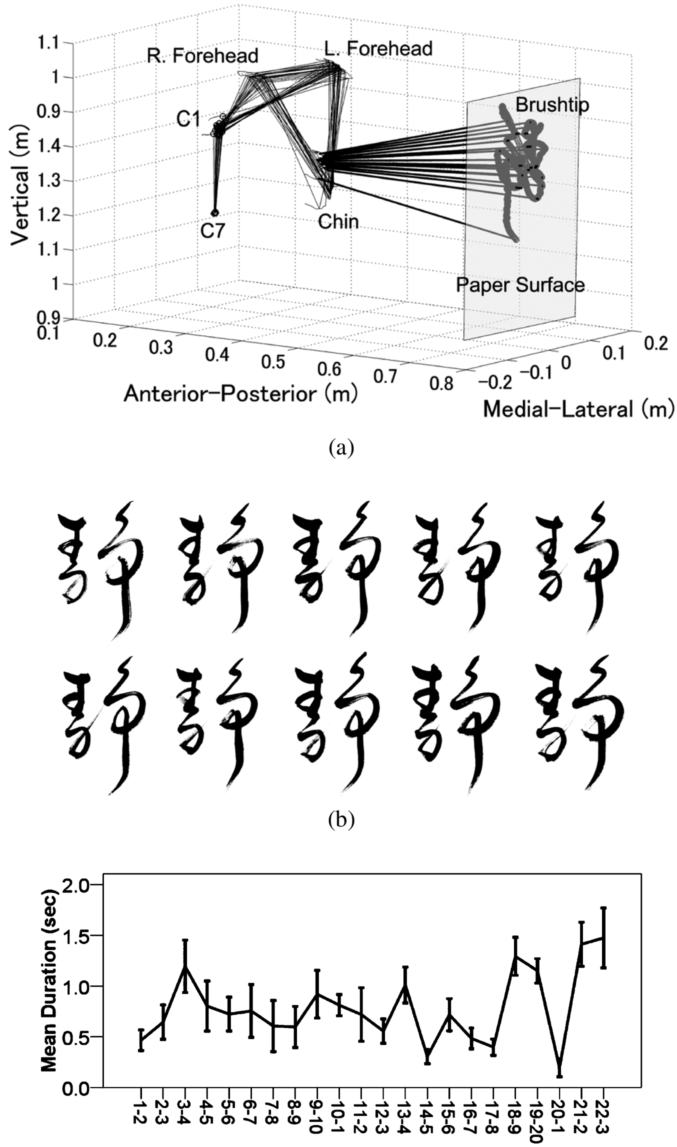

FIGURE 2 (a) Positions of C7, C1, foreheads, chin, and the intersection between the brush and the paper plane for a representative trial. (b) Ten characters written by FM in the experiment. The top row displays the characters written in the first 5 trials, and the bottom row displays the ones written in the latter 5 trials, arrayed from left to right. In the experiment, each character was written on a separate sheet of paper. (c) Mean durations ($\pm$ *SD*) between each event across 10 trials when FM was writing the Chinese character.

was indexed by the measure "how deep the tip of the brush goes under the paper plane if the hair of the brush were rigid," computed from the markers on the stalk. The angle between the paper plane and the stalk of the brush was determined by calculating the angle between the line connecting the two brush markers and its projection on the paper plane. The head lateral tilt angle was determined by calculating the angle between the vertical axis of the head in the calibration posture (the line in the frontal plane orthogonal to the line connecting the two front forehead markers) and that in each trial. The value zero indicates an alignment of the head to the vertical in the calibration posture.

Defining events in brushstrokes. The character written in this experiment consists of the two radicals, left and right. The left radical is written first, followed by the right radical. Each radical is written from top to bottom. Twenty-three brush events were defined in the brush trajectory by picking up the local minima and maxima of the position of the tip of brush on the paper plane (Figure 1b). The beginning of each radical (1 and 14) was defined as the first minimum of the velocity of the brush tip after its contact with the paper surface. For these 23 events, joint variables and task variables were computed.

Defining the Jacobian and UCM analysis. Considering the difficulty in estimating joint centers of the cervical spine, the multiple regression method was adopted to derive the Jacobian that relates the six joint variables to each task variable (de Freitas & Scholz, 2010). The Jacobian that relates the six joint variables to each task variable was derived at each time slice "*i*" of the 23 brush events as the coefficients "*k*" of multiple linear regressions between mean-free joint angles ($\underline{\theta}_i - \underline{\theta}_i^0$, where $\underline{\theta}_i^0$ are the average joint angles across trials) and changes in the mean-free instantaneous value of a task variable ($\underline{r}_i - \underline{r}_i^0$; de Freitas, Scholz, & Latash, 2010), that is,

$$\begin{aligned}\underline{r}_i - \underline{r}_i^0 \approx\ & k_{i,head.flex\text{-}ext}(\underline{\theta}_{i,head.flex\text{-}ext} - \underline{\theta}^0_{i,head.flex\text{-}ext}) \\ & + k_{i,head.rotation}(\underline{\theta}_{i,head.rotation} - \underline{\theta}^0_{i,head.rotation}) \cdots \\ & + k_{i,cervical.lateroflex}(\underline{\theta}_{i,cervical.lateroflex} - \underline{\theta}^0_{i,cervical.lateroflex})\end{aligned} \tag{1}$$

$$\begin{aligned}\underline{\underline{J}}(\underline{\theta}_i^0) \approx\ & [k_{i,head.flex\text{-}ext}, k_{i,head.rotation}, k_{i,head.lateroflex}, k_{i,cervical.flex\text{-}ext}, \\ & k_{i,cervical.rotation}, k_{i,cervical.lateroflex}].\end{aligned} \tag{2}$$

$\underline{\underline{J}}(\theta^0)$ is the $d \times n$ Jacobian matrix obtained for the mean joint configuration across trials, where $d = 1$ and $n = 6$ are the number of dimensions of the task variable and of the joint configuration space, respectively. The null space of the Jacobian matrix represents those combinations of joint angles that leave the task variable unaffected (the UCM; Scholz & Schöner, 1999). The null space is spanned by basis vectors ε_i, solving

$$0 = \underline{\underline{J}}(\underline{\theta}^0) \cdot \varepsilon_i. \tag{3}$$

There are $n - d$ null space basis vectors, so that the null space has $n - d$ dimensions. The basis ε_i of the null space was computed numerically at each time slice of the 23 events using MATLAB. Then, deviations of the vector of joint angles of each trial from the vector of mean joint angles across trials at each time slice, $\underline{\theta} - \underline{\theta}^0$, were resolved into their projection onto the null space,

$$\underline{\theta}_{\parallel} = \sum_{i=1}^{n} \varepsilon_i \cdot (\underline{\theta} - \underline{\theta}^0), \tag{4}$$

and the component perpendicular to the null space,

$$\underline{\theta}_{\perp} = (\underline{\theta} - \underline{\theta}^0) - \underline{\theta}_{\parallel}. \tag{5}$$

The amount of variability per degree of freedom (DOF) within the UCM was estimated as

$$V_{UCM} = (n - d)^{-1} \cdot (N_{trials})^{-1} \cdot \sum \underline{\theta}_{\parallel}^2, \tag{6}$$

where $\underline{\theta}_{\parallel}^2$ is the squared length of the deviation vector $\underline{\theta}_{\parallel}$ lying within the linearized UCM. Analogously, the amount of variability per DOF perpendicular to the UCM was estimated as

$$V_{ORT} = d^{-1} \cdot (N_{trials})^{-1} \cdot \sum \underline{\theta}_{\perp}^2. \tag{7}$$

If invariance in a task variable is brought about by structuring variability in joint space, the overall variability of the configuration perpendicular to the UCM (V_{ORT}) is expected to be smaller than that parallel to the UCM (V_{UCM}). To quantify the relative amount of variance that is compatible with stabilization of the selected task variable, an index of synergy ΔV was calculated. The normalization of the index by the total amount of variance was carried out as described in recent studies (Danna-dos-Santos, Slomka, Zatsiorsky, & Latash, 2007; Klous, Danna-dos-Santos, & Latash, 2010; Reisman & Scholz, 2006; Robert, Zatsiorsky, & Latash, 2008; Tseng & Scholz, 2005; Zhang, Scholz, Zatsiorsky, & Latash, 2008):

$$V_{TOT} = n^{-1} \cdot (N_{trials})^{-1} \cdot \left(\sum \underline{\theta}_{\parallel}^2 + \sum \underline{\theta}_{\perp}^2 \right) \tag{8}$$

$$\Delta V = \frac{V_{UCM} - V_{ORT}}{V_{TOT}}. \tag{9}$$

Separation of stabilization from covariation. Each of the six joint angles from the original 10 trials was combined with every other joint angle in all possible combinations to make a permuted surrogate data set consisting of 10^6 trials. The permuted data set had joint angle pairwise covariation exactly equal to zero, with the same variances of the six joint angles as the original data set. Therefore, V_{UCM} and V_{ORT} of the permuted data set do not depend on the covariation among the joint variables. The ΔV value of the permuted data set (ΔV_{perm}) was calculated to reveal stabilization of task variables that did *not* stem from the covariation among joint variables. To calculate the amount of stabilization of a task variable caused by the covariation among joint variables alone (*CoV*), the difference was taken between the ΔV value of the original data set and the ΔV_{perm} value (i.e., $CoV = \Delta V - \Delta V_{perm}$; for details see Yen & Chang, 2010). A positive *CoV* indicates the contribution of the covariation strategy to stabilize the task variable, and a negative *CoV* indicates the contribution of the covariation strategy to destabilize the task variable. A *CoV* of zero would indicate an absence of contribution of the covariation strategy to the stabilization of the task variable (see Yen & Chang, 2010, for mathematical proofs).

Statistical analyses. ΔV and *CoV* were averaged within each of the following four parts of the character: upper left (event 1–6), lower left (7–13), upper right (14–17), and lower right (18–23) radicals. In addition to descriptive statistics, a Student's two-tailed *t* test was performed to test whether ΔV and *CoV* were significantly different from zero for each of the three task variables in the four character parts. A positive ΔV indicates that joint variance was structured to stabilize the task variables, and a negative ΔV indicates that joint variance was structured to destabilize the task variables. A ΔV of zero would indicate an absence of structure in joint angle variance. The same applies to the *CoV* metric, which considers only the contribution of the covariation among six joint variables. To examine whether there was trade-off between the stabilizations of three task variables, the correlations of ΔV values across each pair among the three task variables were also examined using Pearson's correlation coefficient. The alpha value for a significant effect was set at .05. All statistical analyses were performed in SPSS 16.0.

RESULTS

Sample Movement Trajectory

The three-dimensional movement paths of the foreheads, chin, C1, C7, and the intersection between the brush vector and the paper plane are shown in Figure 2a. The points and lines that connect them represent the locations of segments and their relations at 23 events when FM was writing the character in one trial. Note that the small movement of the neck and the head was amplified at the tip of the brush. C7 moved very little when FM was writing the character.

Dimension of the Character

The characters written by FM were quite consistent across trials (Figure 2b) with dimensions of 108.5 ± 4.8 mm and 100.1 ± 2.3 mm for height and width, respectively.

Movement Time

Average time $\pm$ *SD* it took for FM to write the character (from the first to the last contact to the surface of the paper) was 19.56 ± 2.03 s. The durations between each event across 10 trials ($\pm$ *SD*) when FM was writing the Chinese character are illustrated in Figure 2c.

Task Variables

The mean values $\pm$ *SD* of the three task variables—the brush tip pressure, the brush angle relative to the paper plane, and the head lateral tilt angle—at 23 events during the writing of a Chinese character are presented in Figure 3. The gray line represents the mean values of each task variable, and the black area shows $\pm$ *SD* across trials. The intervals between each event are time normalized to the mean intervals across trials, which are reflected in the scaling of the *X*-axis of the figure.

Inspection of Figure 3a suggests that the brush pressure against the surface of the paper was quite consistent across trials, except when the brush left the paper to move from the left to the right radical (between 13 and 14) where the standard deviation increased. Figure 3b presents the angle formed between the stalk of the brush and the paper. The figure shows this angle remained close to the right angle, about 80 to 85 degrees. Lateral tilt angle of the head relative to the vertical varied little in both across and within trials (Figure 3c). The result suggests that the head was stabilized relative to the vertical, despite the concurrent movement in other directions to maneuver the brush.

Sample Temporal Structure of the Brushstrokes

There was a certain rhythm maintained across trials in the way FM wrote the character. Figure 4 shows a sample progression of resultant velocity of the tip of the brush and that of the pressure of the brush against the paper from one trial, divided into the upper and lower parts of each radical. Following changes

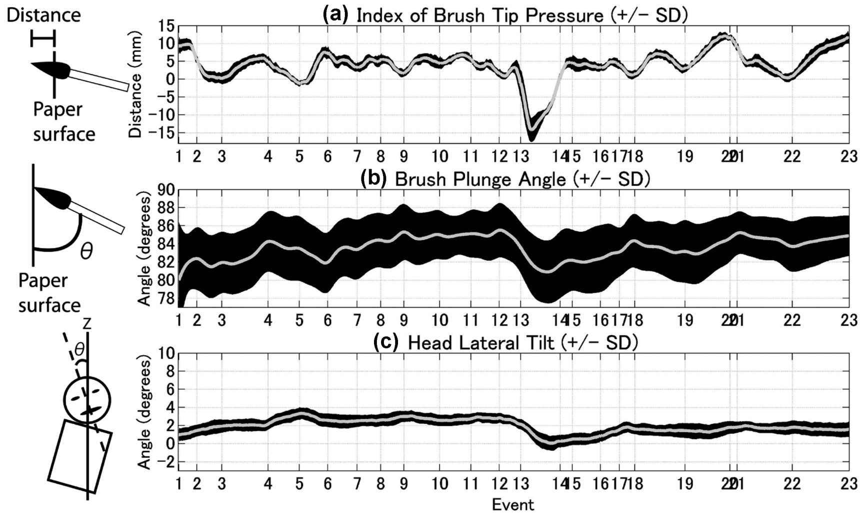

FIGURE 3 Mean values ($\pm$ *SD*) of the three task variables: (a) the pressure on the tip of the brush, (b) the angle between the paper plane and the stalk of the brush, and (c) the head lateral tilt angle relative to the vertical in the reference posture. Intervals between each event are time normalized to the mean intervals across trials, which are reflected in the scaling of the *X*-axis of the figure.

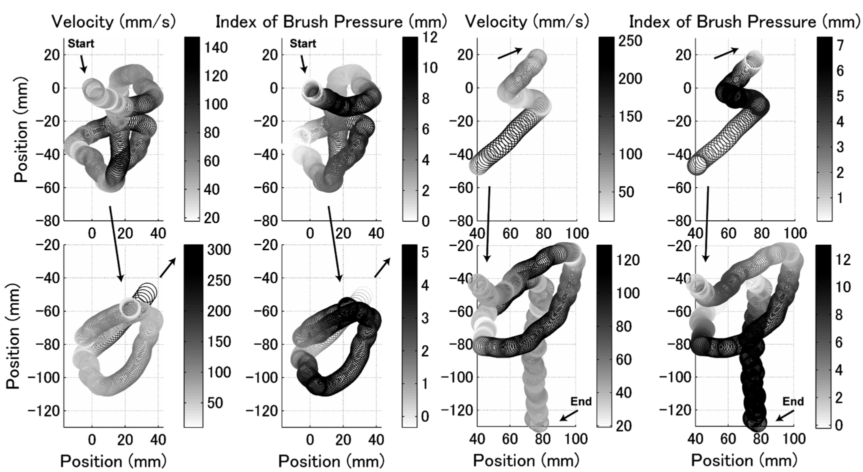

FIGURE 4 Resultant velocity of the tip of the brush (left, mm/s) and the index of the pressure on the tip of the brush (right, mm) divided into the four parts of the character for a representative trial. As the value increases the color gets darker.

in velocity and pressure in the figure helps to reexperience how the writing proceeded. For example, in the first stroke from left to right in the upper part of the left radical, FM began slowly and increased the velocity of the brush toward the end of the stroke before coming to a halt, while in the same stroke the brush was pressed hard against the paper in the middle of the stroke and relaxed toward the end (Figure 4).

Joint Kinematics

The mean movement paths ± *SD* of two body segments that contributed to brush motion at 23 events during the writing of one Chinese character are shown in Figure 5. The black line represents mean Euler angles ± *SD* of head brush relative to the cervical spine, and the gray line represents those of the cervical spine relative to the thorax in three axes at each event.

Writing proceeds from the left radical to the right radical, each of which is written downward starting from the top. Flexion and extension of the head relative to the cervical spine naturally reflected this writing procedure. Figure 5a

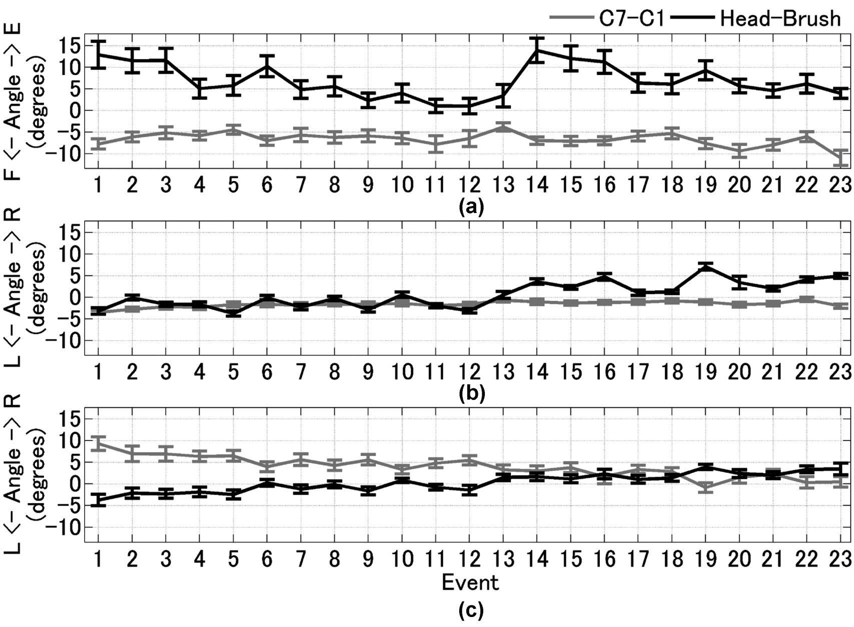

FIGURE 5 Mean joint excursion (± *SD*) of the head brush relative to the cervical spine (black) and the cervical spine relative to the thorax (gray) at 23 events when writing one Chinese character for the axes: (a) flexion-extension, (b) axial rotation, and (c) lateral bending.

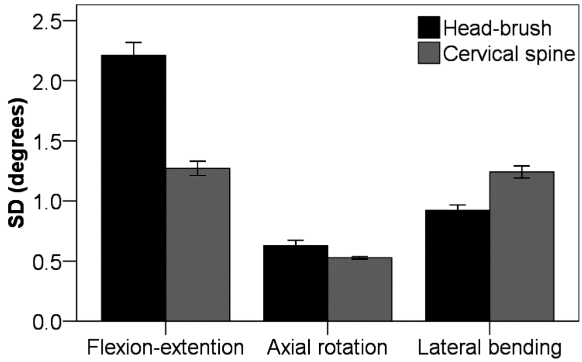

FIGURE 6 Standard deviations of joint angles averaged across 23 events (± *SEM*) as a function of segment and rotation axis.

shows that the head was gradually flexed downward as the writing proceeded, interrupted by the quick extension upward where the brush shifts from the left to the right radicals (between 13 and 14). Similarly, the axial rotation of the head reflected the writing procedure in which gradual rotation toward the right was found (Figure 5b). Inspection of Figure 5a and 5b suggests that in these two axes, the movement of the head was primarily responsible for the control of the brush in these axes. In contrast, Figure 5c shows that the movement of the head and that of the cervical spine exhibited a compensatory, reversal pattern. It is interesting to juxtapose this figure with Figure 3c, which shows little variability of the lateral tilt angle of the head relative to the environment. The movement of the head and that of the cervical spine (Figure 5c) seem to have been coupled in a compensatory manner to stabilize the upright posture of the head relative to the vertical in the stable world (Figure 3c).

Standard deviations of joint angles averaged across 23 events (± *SEM*) as a function of segment and rotation axis are shown in Figure 6. An opening question is whether or not such variability across trials is related to the stabilization of a certain relationship between the tool, body, and environment.

UCM Results Related to Task Variables

The UCM analysis was performed with respect to the three task variables: the brush tip pressure, the brush plunge angle, and the head lateral tilt angle. Results of multiple regression procedure showed that the six joint variables accounted for 70.5% (± 20.2%), 80.1% (± 13.6%), 85.5% (± 10.5%) of the total variance in changes in brush tip pressure, brush plunge angle, and head lateral tilt angle, respectively.

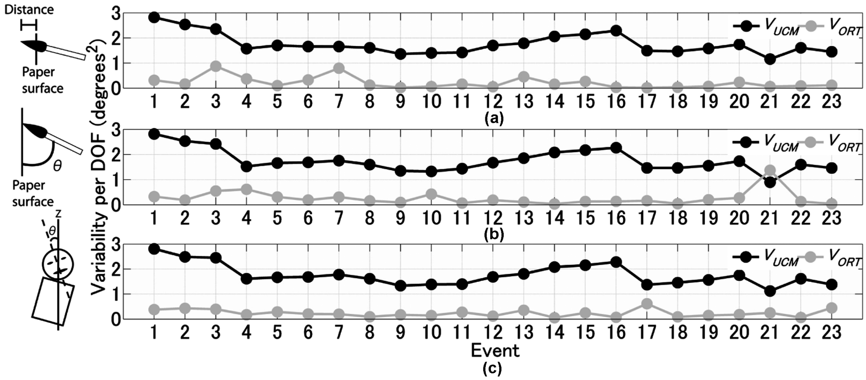

FIGURE 7 Components of joint configuration variability per degree of freedom (degrees^2) lying parallel (V_{UCM}, black) and perpendicular (V_{ORT}, gray) to the uncontrolled manifold for the hypothesis of the following task variables: (a) the pressure on the tip of the brush, (b) the angle between the paper plane and the stalk of the brush, and (c) the head lateral tilt angle relative to the vertical.

The total variance in the joint angle space across repetitions of the writing task was partitioned into V_{UCM} and V_{ORT}, with respect to each of the Jacobians defined for the three hypothesized task variables at each event. To reiterate, V_{UCM} is the component of joint configuration variance that does not affect a task variable, and V_{ORT} is the component of joint configuration variance that affects a task variable. Figure 7 shows the amount of V_{UCM} was generally greater than V_{ORT} for the three task variables at 23 events when FM was writing the character.[1] A Student's two-tailed *t* test confirmed that the normalized difference between the two components (ΔV) was significantly positive for the three hypothesized task variables (brush tip pressure, brush plunge angle, and head lateral tilt angle) at the four parts of the character (upper left [event 1–6], lower left [7–13], upper right [14–17], and lower right [18–23] radicals; $p < .05$). The index of the effects of the compensatory coupling among joint variables on the task-specific structuring of joint variance (*CoV*) averaged within each of the four parts of the character were all significantly greater than zero ($p < .01$), suggesting the presence of contribution from coordination among the joint variables to the task-specific structuring of the joint configuration variance observed earlier (Figure 8). In addition, it turned out that Pearson correlation coefficients between ΔV values of each pair from the three task variables were not significantly correlated in

[1]This result does not mean that the particular values of the task variables were kept constant within one trial but that at each of the 23 events, across-trial variance was structured in such a way as to leave each task variable invariant.

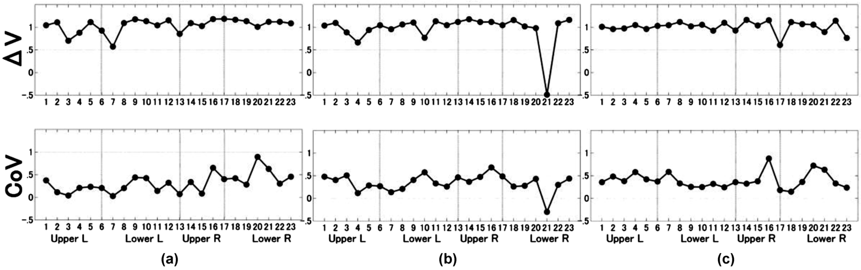

FIGURE 8 Index of task-specific structure of joint configuration variance (ΔV) (top) and index of the contribution from coordinated variation (*CoV*) (bottom) at 23 events (divided into four character parts by vertical dotted lines) for the three task variables: (a) the pressure on the tip of the brush, (b) the angle between the paper plane and the stalk of the brush, and (c) the head lateral tilt angle relative to the vertical.

any of the pairs, revealing that there was no trade-off across the stabilizations of the different task variables. At one point, however, the event 21 for the brush plunge angle, V_{ORT} was greater than V_{UCM} (Figure 7b). There was also a great drop of *CoV* value for the brush angle at the same point, which contradicts the overall tendency of the structuring of joint variance to stabilize the brush angle by means of the covariation among the joint variables, the implications of which are discussed in the following section.

To examine if there was any systematic relationship between V_{UCM}, the R-square values of regression analysis to obtain Jacobian, and V_{ORT}, a multiple regression analysis across the 23 events with V_{ORT} as the dependent variable was performed. It was found that neither V_{UCM} nor R-square values were significant predictors of V_{ORT} in any of the three task variable hypotheses, suggesting that the quality of these fits did not have a significant effect on the analysis of joint variances.

DISCUSSION

This study examined the movement coordination in an exceptional tetraplegic individual who has practiced Japanese calligraphy with a mouth-held brush for many years to reach master level. Specifically, the following two questions were asked: (a) Would the joint configuration variance be structured in such a way as to minimize the variance of the task variables (i.e., $\Delta V > 0$) or not? (b) If so, would the compensatory coupling among joint variables contribute to such task-specific structure of variance in the joint space (i.e., $CoV > 0$)? The answers to both of these questions proved to be yes. On the one hand, evidence was found that joint configuration variances at different phases of writing were structured in such a way as to leave the pressure and angle of the brush and the upright posture of the head invariant across the different realizations of the writing task ($\Delta V > 0$). On the other hand, compensatory coupling among joint variables indeed contributed to the observed structure of joint configuration variance ($CoV > 0$). In addition, no negative interference was found across the three task variables in the task-specific structure of joint configuration variance.

Motor Variability but Functional Specificity

There is evidence that when the Chinese character was being written, joint variability was structured in such a way as to keep the brush pressure, the brush angle, and the upright posture of the head invariant across trials while allowing for joint configuration fluctuations that do not affect these task variables. The three task variables might not be totally independent but are likely to be interrelated. It is probable that the certain "posture" of the brush (i.e., the brush held vertically against the paper) facilitated the feeling and controlling of the pressure at the brush tip as was suggested in the literature (e.g., Billeter, 1990), and the stabilization of the head posture contributed to the visual control of such tool-paper relationships (see Nonaka, Nishizaki, & Sasaki, 2010, for the role of head stabilization in drawing). The constancy of the quality of writing by FM across the trials seems to imply that the control of the brushstroke is secured against possible perturbations (Figure 2b) in which a set of interrelated problems need to be solved according to the Chinese character written. Although no claims are made to having exhausted all possible task variables, the fact that the three task variables in question were stabilized seem to imply that they all participated somehow in the higher order structure of the task of writing the character.

When FM was writing the character, the joint configuration variability was structured in such a way as to leave the three task variables invariant over different realizations of the task ($\Delta V > 0$). Geometrically, there is no obvious way individual degrees of freedom could produce the observed effects with respect to multiple task variables. To further look into how this was achieved, the degrees of freedom at a given time during the movement were scrambled so as to destroy any correlations in the data, and the contribution of covariation among joint variables to the task-specific structuring of the joint variables was separated (Yen & Chang, 2010). The analysis found that the interrelations in the joints arose in the process of compensation of systematic disturbances of the same type ($CoV > 0$; cf. Gurfinkel, Kots, Palstev, & Feldman, 1971). The observed reciprocity in the structure of joint configuration variability cannot be accounted for solely by a set of particular attracted relations among joint variables independent of the functional relations to the *environment* to which these movements contribute. In other words, when FM wrote the same character multiple times, what remained invariant was not the overall pattern of bodily displacements but the functional specificity accompanied by motor variability.

The result of this study seems to provide support for the idea that what underlies the vicarious writing skill of FM is the coalition among elements to stabilize the functional relationships to the environment and to solve a motor problem through a variety of coordination patterns according to the demand of the situation (see Biryukova & Bril, 2008; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Nonaka & Bril, 2012, for similar results).

It would be worthwhile to draw attention to the fact that there was a point where one variable was not stabilized in FM's writing movement. At one point, event 21 for the brush plunge angle, V_{ORT} was greater than V_{UCM} (Figure 7b), suggesting that the results do not simply mean that any task variable would be selectively stabilized. There was also a sharp drop of *CoV* (Figure 8), suggesting that the covariation among joint variables with respect to the stabilization of the brush angle broke down at the same point. Inspection of Figure 3a suggests that the pressure of the brush was the highest just before this point, presumably because FM needed to draw a thick line with the brush that contained less ink than in the beginning (Figure 1b). At the same time, the direction of the brush needed to be changed suddenly in an acute angle against the direction of gravity (Figure 1b). Facing these constraints, the synergy stabilizing the brush angle seems to have disappeared momentarily, although a different synergy that stabilizes a variable other than those studied here might be suspected (cf. Latash, 2008).

Nesting of Functions Into a Coherent Act

In this experiment, no trade-off across multiple task variables was observed in the degree of stabilization of the task variables. The result that multiple functional relationships among body, tool, and environment were simultaneously controlled suggests that the motor problem posed to FM was not simply a problem of producing the desired trajectory of the tip of a tool or that of stabilizing the upright posture of the head alone. For, even if we knew all the rules for forming the trajectory of the tip of a tool or those for stabilizing the upright head posture by coordinating movements, we would still not know how these activities that control multiple environmental relationships were nested into a unified act (Reed, 1988).

Gelfand and Latash (1998) suggested the two possible organizations of a structural unit that has redundant degrees of freedom to achieve a goal. One possibility is that movements are organized in such a way as to reduce the redundant degrees of freedom that do not work with respect to the task. However, if this were the case, although FM might be able to produce a desired relation between the paper and the tool, it would be difficult to meet any other requirement, for example, the stabilization of the upright head posture. In addition, if one of the elements erred or slipped, FM would be unable to produce concurrently other functional relationships required to achieve the goal. The second possibility is that many more elements than necessary participate in the activity of a structural unit with respect to each task such that redundant degrees of freedom are not eliminated but used to stabilize important task variables. If redundant movements are assembled in such a way as to find their own places within the task, such a unit will be able to solve the original task but can also be expected to reorganize successfully if another task is overlapped in such a way for a redundant element to find a job in the concurrent task (Gelfand, 1989). In line with this latter view, Zhang et al. (2008) recently reported that when a secondary task was introduced in a multifinger force production task, indices of task-specific structure of variance stabilizing the primary task variable (i.e., ΔV) stayed nearly unchanged, while the variability in the relation among elemental variables got more tightly constrained. The simultaneous control of multiple task variables observed in the present study, as well as the results of the experiments by Zhang et al. and others (Klous et al., 2010; van der Steen & Bongers, 2011), confirm the organization principle in which motor redundancy is used not only to reduce the effect of perturbation on variability of important task variables but also to provide room for flexible solutions that can be used to perform overlapping tasks.

The presence of contribution of covariation to the task-relevant relationships among the body, the tool, and the environment further implies the use of functional information to specify such task-relevant relationships. Reed (1988) argued that the ability to nest subsidiary activities into a coherent act necessitates the "information about" in J. J. Gibson's (1979/1986) sense. Lateral bending of the head relative to the cervical spine and that of the cervical spine relative to the thorax, for instance, could not be in compensatory counterphase without the use of information about the relative orientation of the head to the stable environment. Likewise, it is unlikely for joint movements to be compensatory coupled to stabilize each of the task variables without the use of information about these task variables. A large body of research has shown that a perceiver can obtain functionally specific information of the task by means of active exploration of patterned energy arrays (Nonaka, Bril, & Rein, 2010; Turvey, Shockley, & Carello, 1999; Wagman & Taylor, 2004). If separate sources of perceptual information that specifies the current states of the task variables at different levels are concurrently picked up, each functional unit may well remain its own master while simultaneously achieving the overall goal of the system, just as was observed in FM's behavior. To substantiate these speculations one needs to analyze what and how information is obtained to allow for such functionally specific nesting of action, which may be a potential topic for future research.

Limitations of the Current Experiment

The current experiment was constrained in a way that most psychological experiments are not, that is, the data analyzed were limited to 10 trials made by a single participant. The single-subject design limits the generality of the results; it cannot allow for claims about general principles when we could be discovering an extraordinary yet idiosyncratic solution discovered by a remarkable individual. Also, the task of brush and ink writing, which requires an actor to control the dynamics of the supple tip of brush rubbed against the paper, is far from simple (Ishikawa, 2009), and it is important to concede that the three task variables considered are by no means the only variables controlled by the calligrapher. The crucial aspect to note is that, however preliminary they are, the present data demonstrate that what underlies the vicarious skill of FM that is learned through intensive practice over many years to reach master level is the principle of task-relevant structuring of redundant motor units, tying together degrees of freedom in a unique context. Further investigation of hand calligraphy is an interesting topic for future research because the data about the skill of brush-and-ink writing, gradually being lost to the increasing use of personal computers in producing written texts (Sulzenbrück, Hegele, Rinkenauer, & Heuer, 2011), is so sparse at present.

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REFERENCES

Adolph, K. E., Joh, A. S., Franchak, J. M., Ishak, S., & Gill, S. V. (2008). Flexibility in the development of action. In J. Bargh, P. Gollwitzer, & E. Morsella (Eds.), *The psychology of action* (Vol. 2, pp. 399–426). Oxford, UK: Oxford University Press.

Amblard, B., Assaiante, C., Fabre, J.-C., Mouchnino, L., & Massion, J. (1997). Voluntary head stabilization in space during oscillatory trunk movements in the frontal plane performed in weightlessness. *Experimental Brain Research, 114,* 214–225.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. London, UK: Pergamon.

Bernstein, N. A. (1996). *Dexterity and its development*. Mahwah, NJ: Erlbaum.

Billeter, J. F. (1990). *The Chinese art of writing*. New York, NY: Rizzoli International.

Bingham, G. P. (1988). Task specific devices and the perceptual bottleneck. *Human Movement Science, 7,* 225–264.

Biryukova, E. V., & Bril, B. (2008). Organization of goal-directed action at a high level of motor skill: The case of stone knapping in India. *Motor Control, 12*(3), 181–209.

Danna-dos-Santos, A., Slomka, K., Zatsiorsky, V. M., & Latash, M. L. (2007). Muscle modes and synergies during voluntary body sway. *Experimental Brain Research, 179,* 533–550.

de Freitas, S. M. S. F., Duarte, M., & Latash, M. L. (2006). Two kinematic synergies in voluntary whole-body movements during standing. *Journal of Neurophysiology, 95,* 636–645.

de Freitas, S. M. S. F., & Scholz, J. P. (2010). A comparison of methods for identifying the Jacobian for uncontrolled manifold variance analysis. *Journal of Biomechanics, 43,* 775–777.

de Freitas, S. M. S. F., Scholz, J. P., & Latash, M. L. (2010). Analyses of joint variance related to voluntary whole-body movements performed in standing. *Journal of Neuroscience Methods, 188,* 89–96.

Edelman, G. M., & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences, 98*(24), 13763–13768.

Figoni, S. F. (1984). Cardiovascular and haemodynamic responses to tilting and to standing in tetraplegic patients: A review. *Paraplegia, 22,* 99–109.

Floris, L., Dif, C., & Le Mouel, M. A. (2002). The tetraplegic patient and the environment. In V. Hentz & C. Le Clercq (Eds.), *Surgical rehabilitation of the upper limb in tetraplegia* (pp. 45–55). Philadelphia, PA: Saunders.

Gelfand, I. M. (1989). *Two archetypes in the psychology of man: The lecture notes for Kyoto Prize*. Retrieved from http://www.israelmgelfand.com/talks/two_archetypes.pdf

Gelfand, I. M., & Latash, M. L. (1998). On the problems of adequate language in motor control. *Motor Control, 2,* 306–313.

Gibson, E. J. (1997). An ecological psychologist's prolegomena for perceptual development: A functional approach. In C. Dent-Read & P. Zukow-Goldring (Eds.), *Evolving explanations of development* (pp. 23–45). Washington, DC: American Psychological Association.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.

Gibson, J. J. (1986). *The ecological approach to visual perception*. Hillsdale, NJ: Erlbaum. (Original work published 1979)

Goldfield, E. C. (1995). *Emergent forms*. Oxford, UK: Oxford University Press.

Gurfinkel, V. S., Kots, Y. M., Palstev, E. I., & Feldman, A. G. (1971). The compensation of respiratory disturbances of the erect posture of man as an example of the organization of interarticular interaction. In I. M. Gelfand, V. S. Gurfinkel, S. V. Fomin, & M. L. Tsetlin (Eds.), *Models of the structural-functional organization of certain biological systems* (pp. 382–395). Cambridge, MA: MIT Press.

Hof, A. L., Koerhuis, C. L., & Winters, J. C. (2001). 'Coupled motions' in cervical spine rotation can be misleading: Comment on V. Feipel, B. Rondelet, J.-P. Le Pallec and M. Rooze. Normal global motion of the cervical spine: An electrogoniometric study. *Clinical Biomechanics, 16,* 455–458.

Hong, S. L., & Newell, K. M. (2006). Practice effects on local and global dynamics of the ski-simulator task. *Experimental Brain Research, 169,* 350–360.

Hsu, W. L., Scholz, J. P., Schöner, G, Jeka, J. J., & Keimel, T. (2007). Control and estimation of posture during quiet stand depends on multijoint coordination. *Journal of Neurophysiology, 97,* 3024–3035.

Ishikawa, K. (2009). *Kaku—Kotoba, Moji, Sho* [Inscription—Language, letters, and calligraphy]. Tokyo, Japan: Chuokoron-Shinsha.

Kelso, J. A. S., Tuller, B., Vatikiotis-Bateson, E., & Fowler, C. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 812–832.

Kelso, J. A. S., & Zanone, P.-G. (2002). Coordination dynamics of learning and transfer across different effector systems. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 776–797.

Klous, M., Danna-dos-Santos, A., & Latash, M. L. (2010). Multi-muscle synergies in a dual postural task: Evidence for the principle of superposition. *Experimental Brain Research, 202,* 457–471.

Kuniyoshi, Y., & Sangawa, S. (2006). Early motor development from partially ordered neural-body dynamics: Experiments with a cortico-spinal-musculo-skeletal model. *Biological Cybernetics*, *95*(6), 589–605.

Lashley, K. S. (1921). Studies of cerebral function in learning: No. III. The motor areas. *Brain, 44*(3), 255–285.

Latash, M. L. (2008). *Synergy*. New York, NY: Oxford University Press.

Latash, M. L., Danion, F., Scholz, J. F., Zatsiorsky, V. M., & Schöner, G. (2003). Approaches to analysis of handwriting as a task of coordinating a redundant motor system. *Human Movement Science, 22*(2), 153–171.

Nonaka, T., & Bril, B. (2012). Nesting of asymmetric functions in skilled bimanual action: Dynamics of hammering behavior of bead craftsmen. *Human Movement Science, 31,* 55–77.

Nonaka, T., Bril, B., & Rein, R. (2010). How do stone knappers predict and control the outcome of flaking? Implications for understanding early stone tool technology. *Journal of Human Evolution, 59,* 155–167.

Nonaka, T., Nishizaki, M., & Sasaki, M. (2010). Dynamics of the act of drawing from life. *Cognitive Studies, 17*(4), 691–712. (In Japanese)

Pozzo, T., Levik, Y., & Berthoz, A. (1995). Head and trunk movements in the frontal plane during complex dynamic equilibrium tasks in humans. *Experimental Brain Research, 106,* 327–338.

Reed, E. S. (1982). An outline of a theory of action systems. *Journal of Motor Behavior, 14*(2), 98–134.

Reed, E. S. (1988). Applying the theory of action systems to the study of motor skills. In O. G. Meijer & K. Roth (Eds.), *Complex movement behavior: The motor-action controversy* (pp. 45–86). Amsterdam, The Netherlands: Elsevier Science B.V.

Reed, E. S. (1989). Changing theories of postural development. In M. Woollacott & H. A. Shumway-Cook (Eds.), *Development of posture and gait across the life span* (pp. 3–24). Columbia: University of South Carolina Press.

Reed, E. S. (1996). *Encountering the world: Toward an ecological psychology*. Oxford, UK: Oxford University Press.

Rein, R., Davids, K., & Button, C. (2010). Adaptive and phase transition behavior in performance of discrete multi-articular actions by degenerate neurobiological systems. *Experimental Brain Research, 201*(2), 307–322.

Reisman, D. S., & Scholz, J. P. (2006). Workspace location influences joint coordination during reaching in post-stroke hemiparesis. *Experimental Brain Research, 170,* 265–276.

Robert, T., Zatsiorsky, V. M., & Latash, M. L. (2008). Multi-muscle synergies in an unusual postural task: Quick shear force production. *Experimental Brain Research, 187*(2), 237–253.

Sasaki, M., & Nonaka, T. (2007). *Akachan* movie database and its ramifications. *14th International Conference on Perception and Action Proceedings* (pp. 77–78).

Scholz, J. P., Reisman, D., & Schöner, G. (2001). Effects of varying task constraints on solutions to joint coordination in a sit-to-stand task. *Experimental Brain Research, 141,* 485–500.

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research, 126,* 289–306.

Scholz, J. P., Schöner, G., & Latash, M. L. (2000). Identifying the control structure of multijoint coordination during pistol shooting. *Experimental Brain Research, 135,* 382–404.

Schöner, G. (1995). Recent developments and problems in human movement science and their conceptual implications. *Ecological Psychology, 8,* 291–314.

Slijper, E. J. (1942). Biologic-anatomical investigations on the bipedal gait and upright posture in mammals, with special reference to a little goat, born without forelegs: II. *Proceedings Series C Biological and Medical Sciences: Koninklijke Nederlandse Akademie van Wetenschappen Amsterdam, 45,* 407–415.

Sulzenbrück, S., Hegele, M., Rinkenauer, G., & Heuer, H. (2011). The death of handwriting: Secondary effects of frequent computer use on basic motor skills. *Journal of Motor Behavior, 43,* 247–251.

Tseng, Y. W., & Scholz, J. P. (2005). The effect of workspace on the use of motor abundance. *Motor Control, 9,* 75–100.

Turvey, M. T., Shockley, K., & Carello, C. (1999). Affordance, proper function, and the physical basis of perceived heaviness. *Cognition, 73,* B17–B26.

van der Steen, M. C., & Bongers, R. M. (2011). Joint angle variability and co-variation in a reaching with a rod task. *Experimental Brain Research, 208,* 411–422.

Wagman, J. B., & Taylor, K. R. (2004). Chosen striking location and the user-tool-environment system. *Journal of Experimental Psychology: Applied, 10*(4), 267–280.

Winold, H., Thelen, E., & Ulrich, B. D. (1994). Coordination and control in the bow arm movements of highly skilled cellists. *Ecological Psychology, 6*(1), 1–31.

Yen, J. T., & Chang, Y.-H. (2010). Rate-dependent control strategies stabilize limb forces during human locomotion. *Journal of the Royal Society Interface, 7,* 801–810.

Zatsiorsky, V. M. (1998). *Kinematics of human motion*. Champaign, IL: Human Kinetics.

Zhang, W., Scholz, J. P., Zatsiorsky, V. M., & Latash, M. L. (2008). What do synergies do? Effects of secondary constraints on multidigit synergies in accurate force production tasks. *Journal of Neurophysiology, 99,* 500–513.