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What is the behavior of a C4 quadriplegic mouth calligrapher constant function of?

Tetsushi Nonaka[*†]
(*)*Research Institute of Health and Welfare, Kibi International University, Japan*
(†)*Advanced Institute of Human Sciences, Waseda University, Japan*
E-mail: tetsushi.nonaka@gmail.com

Abstract

Motor coordination of a professional C4 quadriplegic calligrapher who trained himself to use his mouth to write with brush and ink by gripping a brush between his teeth was reported. Through the analysis of movement during calligraphy, it was found that the movement variability of the head-neck system was exploited to stabilize certain relations between the brush and the paper surface (e.g., brush pressure).

1. Introduction

Unlike machines governed by mechanistic principles, human action system is characterized by its flexibility. The situation is not uncommon in clinical, developmental, or evolutionary settings where a role previously assumed by the movement of one group of body members (e.g., the dominant hand-arm system) needs to be replaced by that of another group of body members (e.g., the mouth-head system) which at first sight might not seem particularly suited for that role. FM, a member of *the Association of Mouth and Foot Painting Artists of the World*, is a 44-year-old professional Japanese calligrapher/painter who in a diving accident 28 years ago dislocated vertebrae C4 resulting in quadriplegia. Before the accident FM learned Japanese calligraphy, and after the injury he trained himself to use his mouth to write and paint by gripping a brush between his teeth, and later obtained the official license of a professor of calligraphy.

Writing with a brush and ink on a sheet of paper requires a fine control of non-rigid brush tip. To ascertain the functional parameters of calligraphy in terms of the dynamic relation between the brush with ink and a sheet of paper, and to further explore how the movement of body members were organized in such a way to meet the functional parameters, the movements of head and neck, and that of the brush relative to the surface of the paper when FM was writing a Chinese character were analyzed using an optical motion capture system. It was hypothesized that the limited movement variability of the head-neck system of FM was maximally exploited to produce a goal-equivalent relation between the brush tip and the paper surface. To test the hypothesis, the amounts of across-trial variability that do and do not affect the functional parameters were compared at different phases of the writing of the same Chinese character.

2. Method

2.1 Participant

FM, a male 44-year-old calligrapher/painter, who, when he was 16 years old, dislocated vertebrae C4 resulting in quadriplegia participated in the experiment. He writes and paints by gripping writing implements between his teeth, and has been painting and writing in this manner for 28 years.

2.2 Equipment and setup

The brush used had the following properties: total weight=40g, total length=430mm, the head of the brush=35mm, diameter at the midpoint of the stalk=8mm. The end of the stalk was wrapped with silicon tube so as to make it easy to hold it with teeth. FM was seated in a wheelchair with a backrest during the experiment. A small table was attached to the wheelchair on which a wooden board to place a sheet of Chinese ink paper (height: 334mm, width: 243mm) was set. Another table was placed on the right side of FM on which ink the stone filled with ink was placed. An eight-camera, 120-Hz Hawk system (Motion Analysis) was used to collect the kinematic data.

Four spherical retro-reflective markers (6.4mm in diameter) were attached on the stalk of the brush with double-sided adhesive tape (70mm, 145mm, 220mm, and 290mm from the tip of the brush). Rest of the markers (19 mm in diameter) were applied to the following locations on the body: (1) left and right forehead approximately over the temple, (2) left and right back of the head roughly in a horizontal plane of

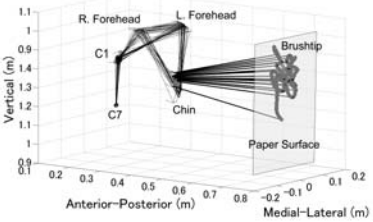

Fig.1. Positions of C7, C1, foreheads, chin, and the intersection between the brush and the paper plane for a representative trial

the front head markers, (3) chin, (4) left and right cheek bones, (5) C1, (6) two markers at C4 level separated roughly by 20mm, (7) C7, (8) left and right acromioclavicular joints (9) jugular notch where the clavicles meet the sternum, and (10) xiphoid process of the sternum.

2.3 Experimental procedure

One Chinese character "shizuka (in Japanese pronunciation)" was written ten times in cǎoshū style (Fig 2). FM's assistant adjusted the position of the paper and changed the paper after each trial.

2.4 Data processing

Digitized coordinates of the reflective markers were identified and tracked through each trial using EvaRT software. After tracking the markers for each trial, the coordinates of each marker were filtered using a bidirectional, 4th-order Butterworth filter with a low-lass cutoff of 20Hz using MATLAB.

By combining the data from the markers, the following three rigid bodies were formed: (a) head-brush, (b) cervical spine (C7 to C1), and (c) thorax. Three-dimensional orientations of the cervical spine relative to the thorax, and the head-brush relative to the cervical spine were represented by three Euler angles [2]. Local coordinates was defined with *X*-axis fore-aft (lateral bending), *Y*-axis horizontal in the sagittal plane (flexion-extension), and *Z*-axis vertical (axial rotation). The rotation sequence chosen was *ZYX*.

As the thorax was nearly still during the entire experiment due to quadriplegia (mean within-trial standard deviations across trials were 0.49°, 0.31°, and 0.33° for *X*-, *Y*-, and *Z*-axis, respectively), thorax movement relative to the global frame of reference is not reported. Similarly, the brush moved little relative to the head (mean within-trial standard deviations across trials were 0.75°, 0.63°, and 0.68° for *X*-, *Y*- and *Z*-axis, respectively), and instead of the brush movement relative to the head, the movement of the whole brush-head system is reported.

Fig.2. Twenty three brush events defined for the Chinese character "shizuka" (written by FM)

The virtual position of the soft tip of the brush if it were rigid was calculated from the markers on the stalk of the brush using virtual marker function implemented in EvaRT software. The distance between the virtual tip of the brush and the paper plane, that is, how far the theoretical 'rigid' brush tip goes under the paper plane, was considered as an index of brush pressure on the paper surface. Also three Euler angles of the stalk of the brush relative to the paper plane (lateral, vertical, and twist) were evaluated. These angles are also equivalent to the head angle relative to the global frame of reference (yaw, pitch, and roll).

2.5 Data analysis

Twenty three brush events were defined in the writing of one Chinese character (Fig 2). The Chinese character consists of two radicals on the left and right side. Writing goes from the left radical (#1 to #13) to the right radical (#14 to #23), and each side proceeds from top to bottom. Event points were defined by the local minima and maxima of the position of the tip of brush in the lateral and vertical axis on the paper plane. When there were multiple candidates for one event, the local minima of the velocity of the tip of brush was also taken into account to select the point.

The uncontrolled manifold (UCM) computational method was used to analyze the structures of joint configuration variance [2]. The Jacobian $\underline{J}$ that relates the six joint variables to each brush kinematics variable was estimated as coefficients of multiple linear regression between across-trial joint configurations and each brush kinematics variable [2]. The UCM was estimated as the null space (ε_j) of each $\underline{J}$:

$$0 = J(\theta_0) * \varepsilon_j \tag{1}$$

At each of the 23 events of the writing of the Chinese character, deviations of each trial's 6-dimensional joint configuration vector from the mean joint configuration (θ_0), $\Delta\theta = \theta - \theta_0$, were projected parallel ($\theta_{para} = \underline{\varepsilon_j} * \Delta\theta$) and perpendicular ($\theta_{para} - \underline{\varepsilon_j} * \Delta\theta$) to the null space. The variance of the length of these projections was computed across the *N*-trials as

$$V_{comp} = (n-d)^{-1} \sum \left(\sum_{i=1}^{n} \varepsilon_j * \Delta\theta \right)^2 / N \qquad (2)$$

$$V_{un} = d^{-1} \sum \left(\Delta\theta - \sum_{i=1}^{n} \varepsilon_j * \Delta\theta \right)^2 / N \qquad (3)$$

where d= 1 and n=6 are the number of dimensions of task space and of the UCM, respectively. Joint configuration variance that leaves the task variable invariant (V_{comp}) and that affects the task variable (V_{un}) were computed for each of the four brush task variables at each of the 23 events using MATLAB.

For the analyses reported in this article, we used the normalized difference between V_{comp} and V_{un} This difference was calculated as $VD = (V_{comp} - V_{un}) / V_{tot}$, where V_{tot} is the total joint configuration variance per DOF. Values of VD between 0 and 1 indicate that relatively more of the variance of individual joint angles is consistent with a stable value of the selected brush kinematics variable than the variance which changes that variable. The closer the value of VD is to 1, the greater is this effect. Differences in this measure across two factors, brush variable (pressure and lateral, vertical, and twist angles) and the position of the brush (upper-left (events 1-6), lower-left (events 7-13), upper-right (events 7-13), lower-right (events 17-23) were tested using ANOVAs using SPSS 16.0.

3. Results and Discussion

3.1 Task performance

The characters written by FM were quite consistent in dimension across trials: 108.5±4.8mm and 100.1±2.3mm for height and width, respectively. Mean time ± 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 seconds.

3.2 Joint kinematics

The mean movement paths ±SD of two body segments that contributed to brush motion at the 23 events during the writing of one Chinese character are shown in Fig 3. The gray line represents the Euler angles of the cervical spine (C7-C1) relative to the thorax. The black line represents the Euler angles of a head-brush system relative to the cervical spine. Almost exact reversals of motion between the two segments were found in lateral bending (Fig 3C).

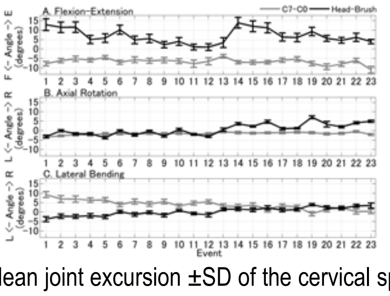

Fig.3. Mean joint excursion ±SD of the cervical spine relative to the thorax (gray) and the head-brush relative to the cervical spine (black) for A. flexion-extension, B. axial rotation, and C. lateral bending

There was little motion of cervical spine in both flexion-extension and axial rotation compared to the motion of a head-brush system, suggesting that the movement of the head was primarily responsible for the movement of the brush in these axes. Fig 3 shows the head rotates to the right and extends upward at the beginning of the right radical (event 14), followed by the gradual flexion of the head downward.

Mean within-trial head angular dispersions relative to the global coordinate frame across trials were 3.71, 3.33, and 0.84 for pitch, yaw, and roll, respectively. The considerably low variability of the angle in the roll axis seems to suggest that the motions of the two segments were coordinated in such a way for the head orientation with respect to the vertical in the environment to be stabilized about the roll axis.

3.3 Brush kinematics

The mean and SD of velocities of the tip of the brush in the vertical and lateral axes on the paper plane are presented in Fig 4A and B. The mean and SD of the values of the index of pressure of the tip of the brush on the paper surface is presented in Fig 4C. The figure suggests that the variability of the brush pressure is very low except at the portion between left and right radicals where the brush briefly takes off the surface of the paper (event 13-14). Fig 5A-C present the mean and SD of angles formed between the brush and the paper plane. Standard deviation is very low for the twist and lateral angle, while that of vertical angle is consistently greater than the other two angles.

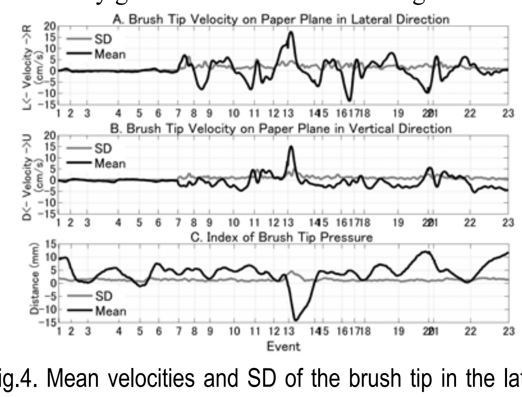

Fig.4. Mean velocities and SD of the brush tip in the lateral (A) and vertical (B) axes on the paper plane, and mean and SD of the value of the index of brush pressure (C). Horizontal axis is scaled in such a way to reflect the mean duration between events according to which time is normalized

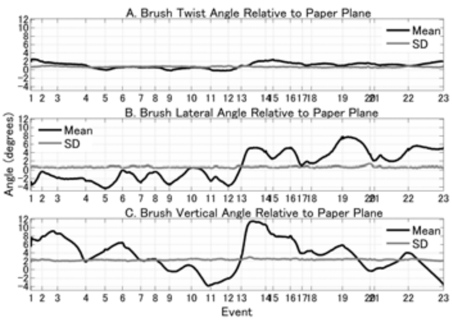

Fig.5. Mean and SD of the (A) twist, (B) lateral, and(C) vertical angles of the brush relative to the paper plane. Horizontal axis is scaled by the mean duration between events according to which time is normalized

3.4 UCM results related to task variables

UCM analysis was performed with respect to the four task variables: brush pressure and the three brush angles relative to the paper plane. As mentioned above, the results of three brush angles relative to the stationary paper plane can also be interpreted as the head angles relative to the global frame of reference.

To compare the four task variable hypotheses, index of the structure of joint configuration variance (*VD*) was examined (Fig 6). For the first and second task variables, brush pressure and the twist angle of the brush, the value of $VD > 0$ at all the events, suggesting that the pressure of the brush tip and the twist angle of the brush (which is equivalent to the roll angle of the head) were stabilized throughout. For the third task variable, brush lateral angle relative to the stationary paper plane (or, head yaw angle relative to the global frame of reference), $V_{comp} > V_{un}$ at all the event points except the event #20 where the brush pressure reaches up almost to the maximum (Fig 4C). In contrast, the forth task variable, the angle of the brush and the paper plane in the vertical axis (or, head pitch angle relative to the global frame of reference), $V_{un} > V_{comp}$ at all the events except the very first brush touch on the paper (Fig 6).

An ANOVA on the mean values of *VD* found the main effect of task variable, $F_{(3,76)}=330.71$, $p<.001$, and an interaction between task variable and part of the character, $F_{(9,76)}=2.25$, $p<.05$. Pairwise, post hoc Bonferroni comparisons revealed that *VD* was always greater for brush pressure, the twist and lateral angles of the brush (roll and yaw angles of the head) than for the vertical angle of the brush (pitch angle of the head), $p<.001$. It was also found that when writing the right radical, values of *VD* for the lateral and vertical angles of the brush were lower than for the twist angle of the brush, $p<.05$, and when writing the lower-right radical, they were lower than both the brush pressure and the twist angle of the brush, $p<.001$.

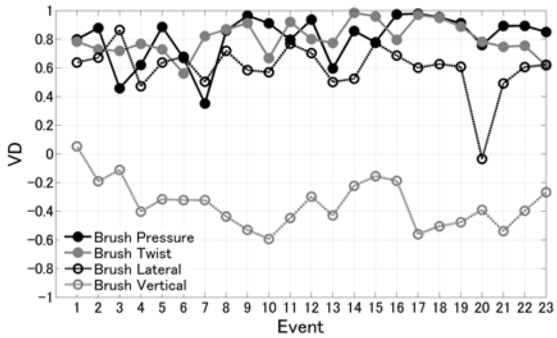

Fig.6. Index of structure of joint configuration variance (*VD*) computed for the four task variables: brush pressure, twist, lateral, and vertical angle of the brush at 23 events

To examine if there was any systematic relationship between V_{comp}, the R-square values of regression analysis to obtain Jacobian, and V_{un}, we performed multiple regression analysis across 23 events with V_{un} as the dependent variable. We found that neither task hypotheses variances nor R-square values were significant predictors of V_{un} 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 synergies in this study.

Taken together, there is evidence that joint variability was structured in such a way to keep the brush pressure and the twist and lateral angle of the brush (the roll and yaw angle of the head) invariant while allowing for joint configuration fluctuations that do not affect these variables when FM writes the Chinese character. In contrast, the joint variability was found to affect the vertical angle of the brush relative to the paper plane (pitch angle of the head).

As the two segments cannot be coordinated without the information to specify the relation between the brush and the surface of the paper, the results suggest the control of movement by dynamic touch, visual or other information detected by FM. Also, it is likely that the stabilization of the angle variables reflect the constraints arising from the stabilization of visual field during the writing of the character. To identify what and how information is obtained to allow for such functional specificity underlying motor variability is a potential topic for future research.

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