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MODELING AND ANALYSIS OF HAND MOVEMENT FOR IMPROVING MOTOR FUNCTION

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Abstract: Skillful motor control of human is achieved by the appropriate motor commands generating from the central nerve system. Internal model in the cerebellum may have great contribution for realizing accurate motor control. In this paper, the model for human motor control on manual tracking to moving visual target was constructed based on the experimental data of the visual tracking test for three groups ; normal healthy adults, patients with cerebellar ataxia and patients with Parkinson disease. Relationship between the model parameters and movement disorders were investigated. Furthermore, the compensation method for improving the motor function of patients were also considered.

Keywords: Motor Control, Visual Tracking Test, Motor Function, Modeling, Predictive Control, Movement Disorders

1. INTRODUCTION

Generation of appropriate motor commands by central nerve system practices the realization of dynamic and skillful motion of human (Rothwell, 1994). Several regions in human brain are concerned with the achievement of motor control. In particular, the cerebellum and the basal ganglia have an important role in motor control (Rothwell, 1994; Ito, 2000). Serious defects in motor control occur when the cerebellum or the basal ganglia has injured. Movement disorder originating from the cerebellum such as cerebellar ataxia develops a lack of accurate movement and troubles in motor learning. Symptom of movement disorder in the basal ganglia such as Parkinson disease is the delay of reaction and non-smooth change of the motion.

Internal predictive model may exist in the cerebellum and contributes the accurate motor control (Ito, 2000). The model of motor control apparatus has been proposed by many reseachers (Sanner and Kosha, 1999; Kawato *et al.*, 1987; Miall *et al.*, 1993). Kawato *et al.* proposed a combinational model of inverse dynamic representation and negative feedback loop (Kawato *et al.*, 1987). Miall *et al.* proposed a representation of the internal model in the cerebellum as the Smith predictor (Miall *et al.*, 1993).

In the past, we have studied the motor functions of the human hand movement through the visual tracking test (Nakamura *et al.*, 1993; Ide *et al.*, 2000). Visual tracking test is one of the effective method for analyzing the human motor functions (Nakamura *et al.*, 1993; Vercher and Zgauthier, 1992). We have previously reported the quantitative evaluation on the relationship between movement disorders and the characteristics of motor functions (Nakamura *et al.*, 1993), the effect of motor learning (Ide *et al.*, 2000), and so on.

In this paper, the model for human motor control on manual tracking to moving visual target was constructed in accordance with the actual data of visual tracking test for patients. First, the characteristics of the motor functions on visual tracking test were analyzed through the data recorded from three groups ; normal healthy adults, patients with cerebellar ataxia and patients with Parkinson disease. Then, the model of motor control apparatus was constructed. The central nerve system for generating the motor commands to a hand was represented by the Smith predictor, and the parameters in the model were determined by reflecting the characteristics of motor functions on visual tracking test. Finally, the characteristics of movement disorders were analyzed through the model which was obtained from the subjects of respective three groups. In particular, the relationship between the parameters in the internal model and the characteristics of the patients with cerebellar ataxia was investigated in detail. Through the above analysis by the models for patients and normal person, the method for improving hand movement of patients with some movement disorders were considered.

2. ANALYSIS OF HUMAN HAND MOVEMENT BY VISUAL TRACKING TEST

2.1 Subjects and data acquisition

The measurement equipment for visual tracking test used in this study is shown in Figure 1. The system consisted of personal computer (NEC PC-9801BX), CRT monitor, digitizer (ADAPTEC KD4030) and magnetic pen (Nakamura *et al.*, 1993). Computer and digitizer was connected by RS-232C cable. Subject holds on a pen by his/her hand and moves it on dizitizer, just then the corresponding green rectangular point (pursuit point) is moved on CRT monitor. Visual target with red circle is also displayed on same monitor. Subject carries out the task to pursue the visual target as correctly and speedily as possible by moving one's hand. Visual target used in the test moves 3 sec long from the upper part to the lower part of the monitor straightforwardly with a constant speed of 3 cm/s. Number of trials of visual tracking test was 20 times for each subject. Number of subjects were 3 healthy normal adults, 11 patients with cerebellar ataxia and 4 patients with Parkinson disease.

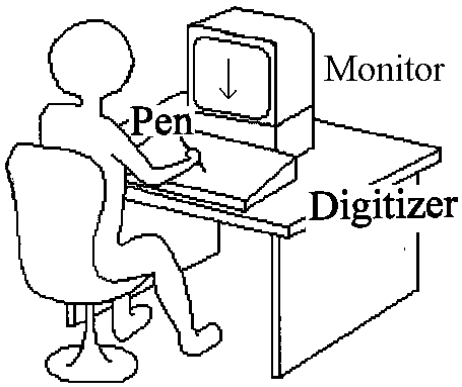

Fig. 1. Measurement equipment for manual tracking to visual target.

2.2 Data analysis

Parameters for extracting the characteristics of the motor functions on visual tracking test were calculated from the recorded data (experimental results were seen in Figure 4). Three parameters were adopted in this study (Ide *et al.*, 2000). First, the position error E_p was defined as

$$E_p = \frac{1}{T}\int_0^T (p_{yd}(t) - p_y(t))^2 dt \qquad (1)$$

where $p_y(t)$ and $p_{yd}(t)$ were the vertical movement of hand tip position (pursuit point) and visual target, respectively. T was the calculation interval. Secondly, standard deviation of velocity for vertical direction V_{SD} was calculated by

$$V_{SD} = \frac{1}{T}\int_0^T (v_y(t) - \bar{v_y})^2 dt \qquad (2)$$

$\bar{v_y}$ was an average of hand tip velocity $v_y(t)$ in calculation interval T. Thirdly, the reaction delay L_E was defined by the time difference of the begining of movement between visual target and pursuit point. The above three characteristic parameters were adopted in this study.

2.3 Characteristics of experimental results

Figure 2 shows the result of parameters transition for each group. Averages of three parameters E_p, V_{SD} and L_E calculated from the respective groups were displayed from the top of the figure. In the position error E_p, the value of both normal subjects and patients with cerebellar ataxia were kept almost constant through 20 trials. The value of E_p for patients with Parkinson disease gradually decreased according to the trials, and finally became almost same value as that of cerebellar ataxia. Normal subjects was the smallest value as compared with those for both patient groups. In the case of standard deviation of velocity

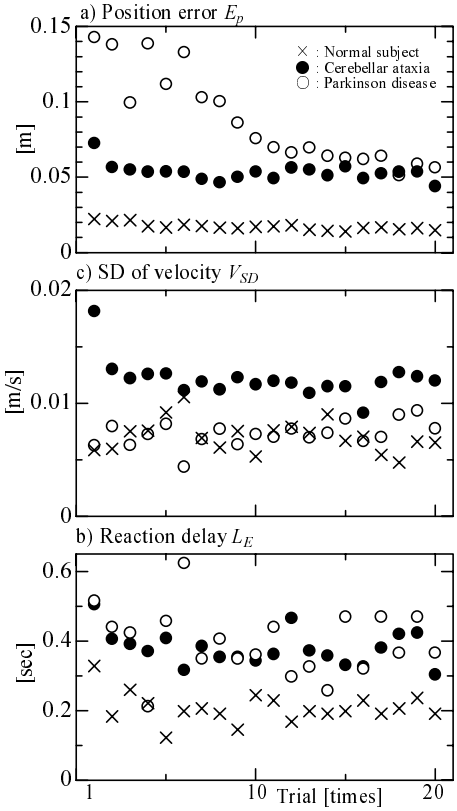

Fig. 2. Quantitative evaluation of hand movement on visual tracking test. Comparison among three groups.

V_{SD}, patients with cerebellar ataxia took the most highest value in three groups. This fact suggests that the patients with cerebellar ataxia could not achieve a smooth pursuit for the visual target. In case of reaction delay L_E, result of normal subjects was the most smallest in three groups. Difference between patient groups could not be seen in L_E.

3. MODELING OF VISUAL TRACKING TEST BY SMITH PREDICTOR

3.1 Signal flow of motor control

Human can achieve a skillful motion in spite of the central nerve system has a time delay. This fact may be regarded as that the control paradigm in human brain has a kind of predictive control strategy. Then the motor control model was constructed as shown in Figure 3(a). In this study, the central nerve system for generating the motor commands was represented by the Smith predictor as one of model predictive control techniques. Signal flow in motor control on visual tracking test was considered as the closed-loop system. Detail explanation for respective parts was described in the following sections.

3.2 Control objective

Accurate representation of dynamics on human hand as controlled objective is complex so that the detail human hand model can not be obtained easily. However, the principal properties of human hand dynamic is able to express the simple mathematical equations. Some researchers have adopted the dynamic model of 2-link robot manipulator as human hand model (Lan, 1997; Kashima and Isurugi 1998). In this study, dynamics of human hand ($f(x(t),u(t-L))$ in Figure 3(a)) was also represented as 2-link robot manipulator. Equation for 2-link arm can be written as

$$M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})+D\dot{\theta}=\tau \tag{3}$$

where M the inertial matrix, and C the coriolis and centrifugal force vector, given by

$$M(\theta)= \begin{bmatrix} I_1+I_2+2m_2l_1l_{g2}\cos\theta_2 & I_2+m_2l_1l_{g2}\cos\theta_2 \\ I_2+m_2l_1l_{g2}\cos\theta_2 & I_2 \end{bmatrix} \tag{4}$$

$$C(\theta,\dot{\theta})= \begin{bmatrix} -m_2l_1l_{g2}(2\dot{\theta}_1\dot{\theta}_2+{\dot{\theta}_2}^2)\sin\theta_2 \\ m_2l_1l_{g2}{\dot{\theta}_1}^2\sin\theta_2 \end{bmatrix} \tag{5}$$

θ_1 and θ_2 were the angles of shoulder and elbow joint. I_1 ($=m_1l_1^2/3$) and I_2 ($=m_2l_2^2/3$) were the inertia, l_{g1} ($=l_1/2$) and l_{g2} ($=l_2/2$) the distance between joint and center of gravity of each link. The values of mass and length of links m_1, m_2, l_1 and l_2 were determined as 1.5 [kg], 1.0 [kg], 0.25 [m] and 0.3 [m], respectively. Matrix D corresponds to viscous friction or stiffness in human arm. Accurate representation of viscousity or stiffness should be considered (Gomi and Kawato, 1997; Stroeve, 1999), but in this study, matrix D was simply established as

$$D=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{6}$$

Actual motor control loop in human includes the reaction delay caused by recepter, axonal conductance, cognitive processing and so on, and the reaction delay is not negligible short. Thus the reaction delay was also considered in the motor control model. Reaction delay L was included in eq.(3) of musculoskeletal model as delay of detection. Therefore, the actual hand motion $\theta(t)$ was observed after L sec.

3.3 Generation of motor commands

Several models for representing motor control, especially for the cerebellum, were proposed in the past (Kawato *et al.*, 1987; Miall *et al.*, 1993). In this study, we adopted the Smith predictor as representing the central nerve system for generating the motor commands. Smith predictor has a internal model and its

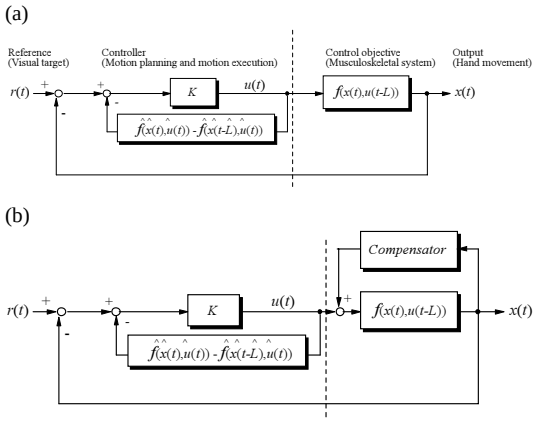

Fig. 3. (a) Model representation of motor control on manual tracking to moving visual target. Central nurve system for generating motor commands was expressed by using Smith predictor. (b) Concept of Hand movement compensation.

feedback loop with the time delay. Internal model in the Smith predictor ($\hat{f}(\hat{x}(t),\hat{u}(t))$ in Figure 3(a)) was assumed to be the same as eq.(3) as

$$M_p(\hat{\theta})\ddot{\hat{\theta}} + C_p(\hat{\theta},\dot{\hat{\theta}}) + D_p\dot{\hat{\theta}} = \tau \tag{7}$$

where $\hat{\theta}$ means the predictive output of the internal model. For generating motor commands τ, error information e was calculated from the sensory feedback information (hand motion $\theta(t-L)$ and target motion $r(t)$) in the body coodinate (joint coodinate) and internal model feedback ($\hat{\theta}(t)$ and $\hat{\theta}(t-\hat{L})$) as

$$e(t) = r(t) - \theta(t-L) + \hat{\theta}(t-\hat{L}) - \hat{\theta}(t) \tag{8}$$

Controller (K in Figure 3(a)) for generating motor commands τ was simply designed as

$$\tau = K_p e + K_v \dot{e} \tag{9}$$

$$K_p = \begin{bmatrix} k_{p11} & k_{p12} \\ k_{p21} & k_{p22} \end{bmatrix} \tag{10}$$

$$K_v = \begin{bmatrix} k_{v11} & k_{v12} \\ k_{v21} & k_{v22} \end{bmatrix} \tag{11}$$

K_p and K_v express the gain matrices for position and velocity, respectively. Adopted controller design formed PD controller.

3.4 Determination of structural parameters

Parameters in the constructed motor control model were determined according to the actual measurement data of visual tracking test for each subject. Prameters to be determined were the reaction delay L in the musculoskeletal model, gain K_p and K_v in the controller, the parameters in the internal model, and predictive reaction delay L_p. The value of L was estabilised as same as actual reaction delay L_E. There are lots of parameters in the internal model. Therefore, the mass of links m_{1p} and m_{2p} were only determined, and other parameters l_{1p}, l_{2p} and D were assumed to be same as true values in the musculoskeletal model given by eq.(3).

In order to determine all the parameters in the model, characteristic parameters E_p and V_{SD} described in 2.2 were used for optimization. Characteristic parameters were calculated from the output of the constructed model, and were symbolized as $\hat{E}_p$ and $\hat{V}_{SD}$. Then, cost function J for optimizing the parameters was created as

$$J = \int \{w_1(E_p - \hat{E}_p)^2 + w_2(V_{SD} - \hat{V}_{SD})^2\}dt \tag{12}$$

where w_1 and w_2 were coefficients and were determined as $w_1 = 1.0$ and $w_2 = 5.0$, respectively. Cost function J was minimized by using least squares method.

4. ANALYSIS OF MOTOR FUNCTION BY SIMULATION

4.1 Experimental data and model output

Figure 4 shows the verification of the constructed motor control model. Model output was indicated by broken line. Left side of the figure shows the result for normal subject, middle one displays that for patient with cerebellar ataxia and right one means that for patient with Parkinson disease. The upper row shows the locus of hand tip position. The middle and the lower row display the variation of hand tip position and velocity, respectively. Obtained model outputs of all subjects were in a good agreement with the measurement data of actual hand momement.

4.2 Comparison of parameters

Parameters concerned with control performance were calculated from the obtained motor control model for each subject, and relationship between those parameters and the characteristics of movement disorders were discussed. In order to investigate the obtained motor control model, following parameters were calculated.

$$J_m = \int \{(\theta_1(t) - \hat{\theta}_1(t))^2 + (\theta_2(t) - \hat{\theta}_2(t))^2\}dt \tag{13}$$

$$R_p = \sum_i \sum_j |k_{pij}| \tag{14}$$

$$R_v = \sum_i \sum_j |k_{vij}| \tag{15}$$

Eq.(13) means the coincidence between the internal model in the Smith predictor and musculoskeletal model. Eqs.(14) and (15) show the magnitudes for position gain and velocity gain, and are corresponded

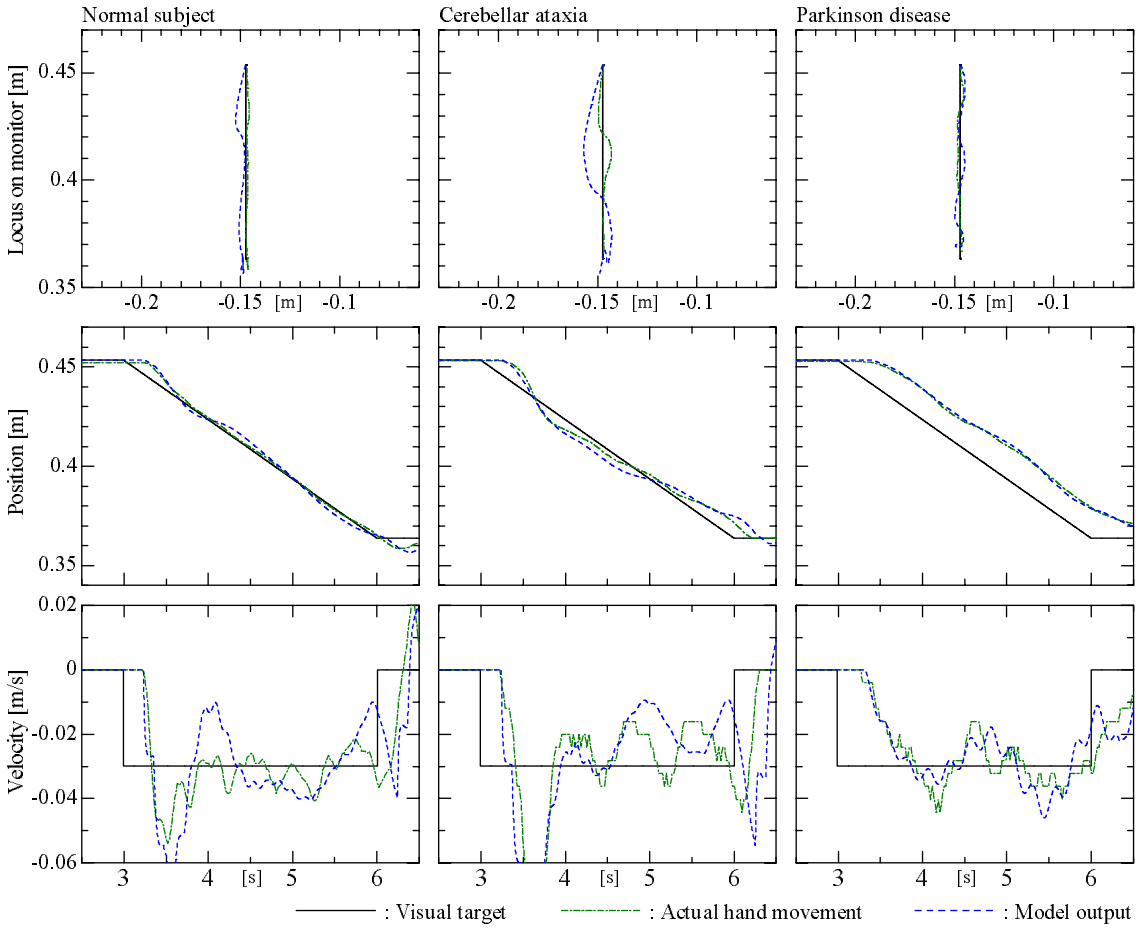

Fig. 4. Comparison of experimental data and model output

to the reactivity. In addition to the above parameters, m_p $(= (m_{1p} + m_{2p})/2)$ and L_p were also examined.

Average of parameters obtained from the motor control model for each group was shown in Table 1. In the coincidence of the internal model J_m, the smallest value for normal subjects (N.S.) and largest one for patients with cerebellar ataxia (C.A.) was obtained. This result suggested that the internal model of the cerebellar ataxia did not grasp the properties of actual musculoskeletal model well. Parameters R_p and R_v were also largest in the normal subjects and were the smallest in the patients with cerebellar ataxia. In the normal subjects, parameter m_p in the internal model was close to the true value m in the musculoskeleteal model expressed by eq.(3).

Table 1. Mean value of parameters concerned with control performance for each group. Numerals in the parentheses show the number of subjects.

Group	J_m[-]	R_p[-]	R_v[-]	L_p[s]	m_p[kg]
N. S. (3)	0.0070	2.93	1.85	0.02	2.99
C. A. (11)	0.0111	2.20	1.19	0.11	3.01
P. D. (4)	0.0108	2.21	1.36	0.17	3.48

4.3 Role of internal model

Coincidence of internal model (J_m) for patients with cerebellar ataxia was the worst in three groups. This will be considered that the internal model in the cerebellum sustains serious defect by a disorder. From the comparison between normal subjects and patients with cerebellar ataxia, magnitude of the gain (R_p and R_v) in the controller and the coincidence of internal model were different. Therefore, the most different point between two groups in the motor control was the role of internal model and reactivity. Reactivity of patients with cerebellar ataxia was slightly slow as compared with normal subjects. The skillful motion could not be achieved due to less activity of inernal model in the cerebellum. Skillful motion in normal subjects will be greatly indepted to that the accurate internal model was constructed in the cerebellum and appropriate values of feedback gain was obtained.

5. DEVELOPMENT OF HAND MOVEMENT COMPENSATION TECHNIQUE BY USING MODEL INFORMATION

5.1 Concept for improving motor function

To Improve the human hand movement is the final goal of this study. The characteristics of hand move-

ment for different patients such as cerebellar ataxia and Parkinson disease were reflected to the model structure which was obtained from the actual experimental data. Therefore, the compensation technique for improving the hand movement of patients can be developed by using the model information. Figure 3(b) shows the concept of hand movement compensation. Compensator in this figure is possible to construct by the information of both the model for the patient and the model for healthy adult. Compensation signal can be generated by the difference between two models.

5.2 Structure of motor control model

In this paper, the Smith predictor was adopted in order to represent the central nerve system for genarating the motor commands. From the controller design point of view, motor control model was constructed in accordance with the idea of model predictive control. Therefore, the structure and its parameters in the model were not directly corresponded to the anatomical structure or physiological findings of human brain.

Adopted Smith predictor is a linear control theory, so there will be some problems for applying it to nonlinear dynamical system. This problem should also be considered in carefull.

6. CONCLUSION

Based on the actual data of visual tracking test for three groups, the motor control model was constructed by using the Smith predictor. Relationship between movement disorder and parameters in the motor control model was investigated, and some findings concerning the role of internal model was obtained. Improvement of this study expects the recovery of hand movement of patients with various movement disorders.

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