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Integration Function and Modeling of the Central Nervous System in Forearm Movement Control

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SUMMARY

In a description of the function of the central nervous system in forearm movement control, the structure of the central nervous system must be considered, together with the control function produced by that structure. In this paper, the motor signal is assumed to originate from the brain, and the forearm movement is defined as the combined cooperative processes (integration) of the reflexes in various portions of the central nervous system, including the brain reflex. Based on this concept, the macroscopic mechanism of the central nervous system is described insofar as this is possible. The forearm movement induced by visual stimulation is then considered, and the response is measured in the frequency domain. A model is constructed for the central functions that describes the frequency response over a relatively wide range and agrees well with the macroscopic mechanism of the central nervous system. This model can be regarded as representing the control-information processing mechanism and function of the biological system in response to the external environment, reflecting the functions of the higher-level portion of the central nervous system, i.e., the brain. With the proposed model the behavior can also correspond to the functions and mechanism of the lower levels, i.e., the brainstem-spinal system, which seems to imply that the brain and brainstem-spinal systems are similar in functional structure but process different information.

1. Introduction

Reasonable movement is produced by the central nervous system in humans in response to the external and internal environments. The generating mechanism of the movement has been approached from various viewpoints in diverse fields such as neurophysiology, neuroanatomy, biological engineering and psychology. However, since the central nervous system is composed of complex neural networks consisting of a large number of neurons and their interconnections, its description is difficult and an integrated description of the system uniting the various disciplines is desired. Recently, in physiology, micromorphological as well as neurophysical approaches such as those using microelectrodes have been utilized, yielding a partial analysis of the neural networks and their axonal connections in the various areas of the central nervous system. The framework and functions of the central nervous system are discussed in comparison with automatic control mechanisms in engineering, and a pathology in a neural system can be interpreted as a fault in an automatic control system.

With this situation as background, this paper discusses, with a model, the control function of the central nervous system in forearm movement. In other words, when the input to the sensory system is visual information, a series of processes in the central nervous system is transferred to the motor system to determine the position of the

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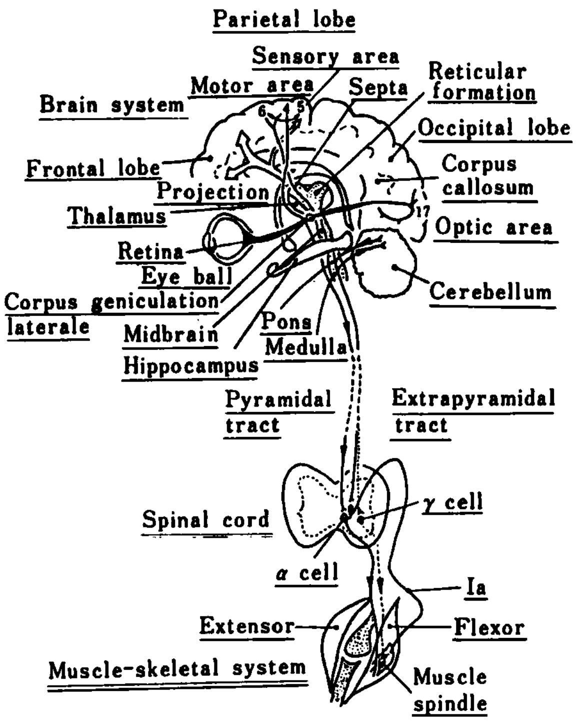


Fig. 1. Replica of motor nervous system.

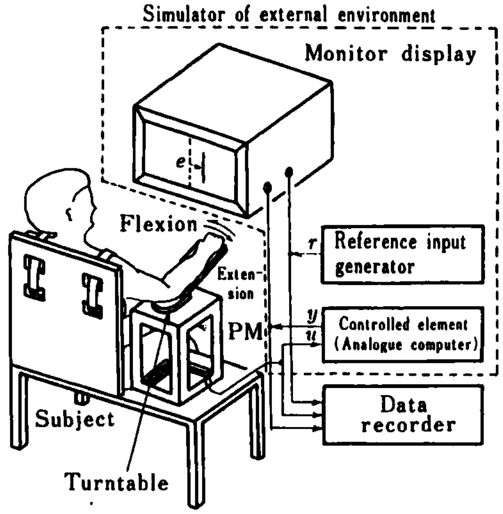


Fig. 2. Experimental system configuration.

fingers. As the first step, the forearm movement is defined as a movement dictated by a cooperative combination of reflexes in various areas of the central nervous system. Based on the reflex concept, the macroscopic mechanism of the central nervous system is described as completely as possible. Then, the object of control is defined as an external environment. The control error between the reference signal and the object output is determined by visual sensation, which is compensated by the control through flexor-extensor movement of the forearm. The visual-forearm control experiment yields the frequency response of the loop transfer system consisting of human subject and external controlled object.

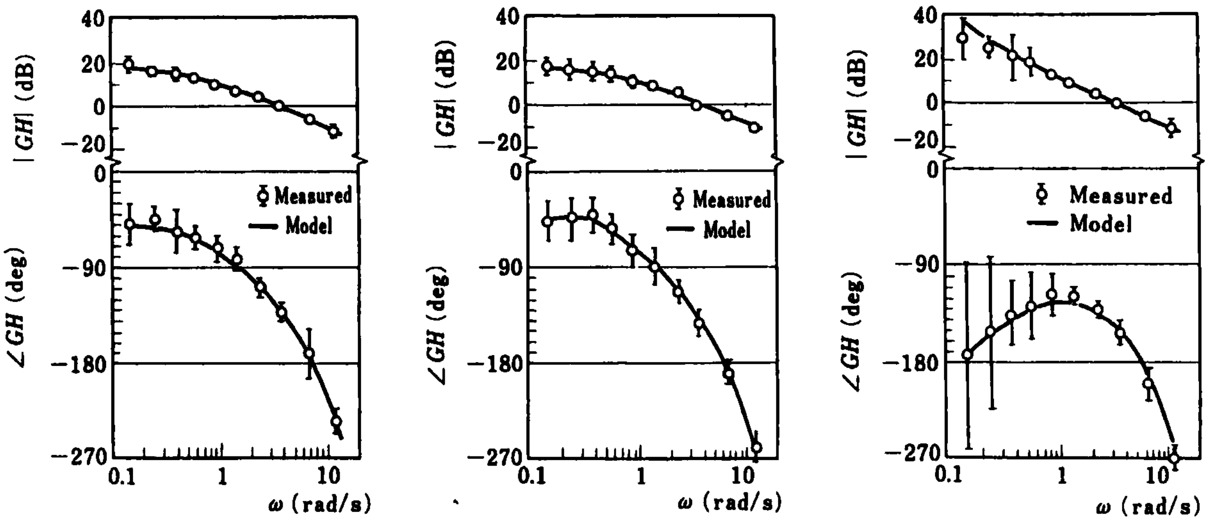
Based on the measured frequency response, the characteristic properties of the loop transfer system are deduced in the range of measured frequency. A model is then derived that is consistent with these properties and describes the macroscopic mechanism of the central nervous system. The model thus constructed is called the functional model of the central nervous system. The components of the model are represented by appropriate transfer functions relating to the functions of the components and to the macroscopic functions of the components of the central nervous system.

2. Macroscopic Mechanism and Function of the Central Nervous System

In the discussion of movement generation, the basic concept is the reflex, and a cooperative combination of reflexes represents the integrated function of the central nervous system [1, 2]. The reflex considers the input-output relationship of the neural network composed of several areas, in accordance with the aim of this paper to apply control theory and to represent neural network function by a transfer function. Consequently, in this section it is assumed that reflex concept can be extended not only to the peripheral nervous system but also to the brain functions, including higher-level thought processes, and the macroscopic mechanism and functions of the central nervous system are discussed.

The reflex concept stems primarily from the morphology of the central nervous system. Figure 1 shows the schematic replica of the areas related to the motor center and major nerve connections. Most of the central nervous system is confined to the brain and spinal cord, and the function of the central nervous system can be regarded fundamentally as an integration of the following two reflexes of the nervous systems.

(1) Brain system. Presently, microscopic physiological examination has reached to the area known as the limbic system, consisting of the cerebral cortex, rhinencephalone, hippocampus and septa. The limbic system is an extremely complex system



(a) $G(S)=1$ (b) $G(S)=\frac{2}{1+S}$ (c) $G(S)=\frac{2}{S}$

Fig. 3. Measured open-loop frequency characteristics and comparisons with central integration function models for $G(s)=1$, $2/(1+s)$ and $2/s$.

connected to the hypothalamus and reticular formations, and is at the same time, a highly integrated system in itself. In other words, the limbic system works as a unit, and functions, together with the cerebellum, to adjust at higher-level the movement by the extrapyramidal tract to the external environment. In this paper, these systems are called the brain system.

As shown in Fig. 1, multi-synaptic connections exist in the brain system to the frontal- and temporal-lobes through the septa and hippocampus. Information on the external environment stored in the cortex is processed by the neural network composed of the limbic system, hypothalamus and reticular formation. This neural network is in a favorable position to adjust at higher-level the motor signal output from the motor area. The motor signal is transmitted to the brainstem-spinal system, and at the same time its duplicate is transmitted to pons and cerebellum through the pyramidal tract. The signal is then returned from cerebellum to motor area through the thalamus. This cerebellum-cerebral system readjusts the output from the motor area and produces a final motor signal well matched to the characteristics of the external environment.

(2) Brainstem-spinal system. The major neural pathways in the brainstem-system consists of the efferent pathways which originate from the pyramidal cells in the cerebral motor area and go to the cerebral cortex through the midbrain, pons and medulla, and the efferent pathways which, conversely, proceed through spinal cord, medulla, pons, midbrain and thalamus to the cortex. The pyramidal tract is primarily the efferent neural pathway from the fourth motor area and reaches the spinal cord frontal cell to control the movement of the main muscle. Other neural pathways pass through the reticular formation and are called the extrapyramidal tract, which functions to influence directly the main muscle and the muscle spindle of the main muscle.

The cerebellum is closely connected to the pyramidal tract through medulla and pons and has the function of adjusting the signals in the efferent pathways. Each of the efferent pathways has its own synaptic effects on the spinal neurons to control the spinal reflexes. A counteracting neural response exists in the spinal reflexes to depress the extensor when the flexor contracts and vice versa. Movement by this connection, however, is not related to the external environment and lacks adaptability to the external situation. Consequently, the role of the brainstem-spinal system is to influence the spinal cord and to modify the fundamental spinal reflex to realize smooth and elaborate movements reflecting the movement signal generated in the brain system, with the external factors taken into consideration.

Integrating these reflexes, the control information processing in forearm movement control, based on visual information, can be formulated as follows.

The visual signal is first projected onto the retina and then transmitted through the corpus geniculation laterale to the cortex visual receptor area (17th area). This visual information is further transmitted to the cortex and is stored as external environment factors. In the brain system, the external information is extracted from the cortex, and an appropriate motor signal is formed as if in the form of a brain reflex, and, finally, the command signal is transmitted to the limbic system from the motor area (4th area) and the pre-motor area (6th area) in the frontal lobe. This motor signal passes down the pyramidal and extrapyramidal tracts to control the spinal reflexes. The result of this control passes up the extrapyramidal tract, referred to by the cerebellum with the efferent signals, to readjust the efferent signals. Finally, joint movements in accordance with the aim of the control is produced by the efferent signal to realize position control of the finger.

3. Visual Forearm Movement Control Experiment

An effective means of examining the control function of the central nervous system is to investigate how the dynamical characteristics of the external environment affects the motional characteristics of the muscle-skeletal system. So as to simplify the subsequent analysis and model construction, an experiment was performed on the flexor-extensor movement of the forearm produced by the counteracting muscles around the elbow joint.

Figure 2 shows the experimental setup, which consists of a chair, turntable and an external environment simulator. On the turntable are attached two steel rods in parallel, spaced by 95 mm, to fix the forearm in position. A potentiometer is also attached to the turntable (PM) to measure the rotational angle (sensitivity 0.1V/deg). The external environment simulator consists of an 11 inch monitorscope, controlled object and a reference input generator. The monitorscope with a display sensitivity of 1.5 cm/V, is placed 50 cm in front of the examinee. When the transfer function $G(j\omega)$ of the controlled object is 1, the circuit gain of the overall experiment system is 1.5 cm (deviation on the CRT screen)/10 deg (angle of rotation of the turntable). A data-recorder is used as the reference input generator and to record data.

The experiment and analysis were carried out as follows.

(1) Five adult males are used as subjects.

(2) The subject sits on the chair, leans back and his upper body and both sides are fixed by bands. An elbow is placed on the turntable.

(3) The maximum range of movement of the elbow joint is determined by its mechanism, while maximum flexor-extensor movement of forearm depends on frequency. As the first step, two traces on the CRT screen are shown to the examinee, one a sinusoidal signal and the other the elbow joint angle. The subject is told to move the forearm as far as he can so that the motions of the two traces are in synchronization. The session is repeated by changing the frequency of the sinusoid. After sufficient training, the subject is told to close his eyes and continue the movement. It is seen from the result with closed eyes that the maximum amplitude of the forearm movement can be retained without visual input for frequencies less than 20 rad/s.

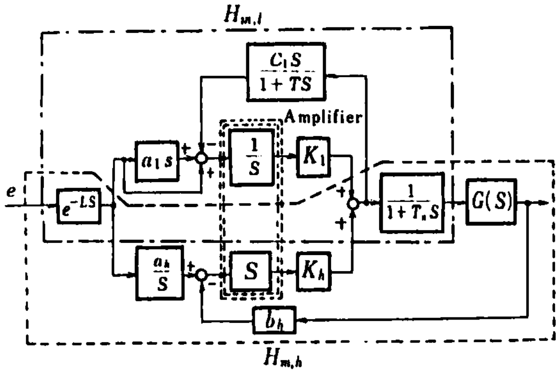
(4) Based on the result of (3), 10 frequencies are chosen in the range of 0.15 to 13 rad/s, and the object signal $r(t)$ is constructed as a composite of these sinusoids. This $r(t)$ and the control error $e(t)$, the difference between $r(t)$ and the output of the controlled object $y(t)$ is shown on the CRT screen by the horizontal position of the vertical line, and the subject is told to retain its reference position by changing his elbow joint angle.

(5) In the experiment, the reference signal $r(t)$, controlled output $y(t)$, control error $e(t)$ and control output $u(t)$ are recorded on a pen recorder and a data recorder. To determine the frequency characteristics $\phi_y(j\omega)/\phi_e(j\omega)$ of the loop transfer system from the stored data, a short-term spectrum analysis is made by a mini-computer [5]. For the waveforms of r and y terminated by $[0, T]$,

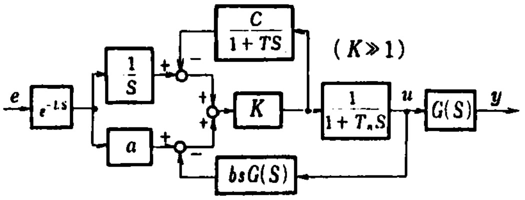
$$\phi_r(j\omega) = \int_0^T r(t)\cdot W(T-t)e^{-j\omega t}\,dt \qquad (1)$$

$$\phi_y(j\omega) = \int_0^T y(t)\cdot W(T-t)e^{-j\omega t}\,dt \qquad (2)$$

$$\Phi_{rr}(\omega) = |\phi_r(j\omega)|^2/T \qquad (3)$$

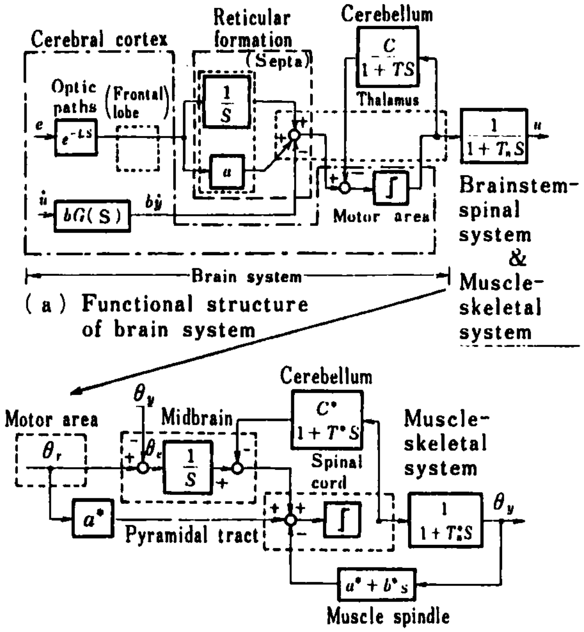


(a) Combination of low-frequency submodel $H_{m,l}$ and high-frequency submodel $H_{m,h}$



(b) Simplified form of H_m

Fig. 4. Block diagram of central integration model H_m.



(b) Functional structure of brainstem-spinal system

Fig. 5. Speculation of functional structure of CNS based upon model structure.

$$\Phi_{ry}(j\omega) = \phi_r(-j\omega)\phi_y(j\omega)/T \tag{4}$$

$$\frac{\phi_y(j\omega)}{\phi_e(j\omega)} = \frac{\Phi_{ry}(j\omega)/\Phi_{rr}(\omega)}{1-\Phi_{ry}(j\omega)/\Phi_{rr}(\omega)} \tag{5}$$

where $\phi_r(j\omega)$ and $\phi_y(j\omega)$ represent, respectively, Fourier transforms of the terminated waveforms of $r(t)$ and $y(t)$. $W(t)$ is the window function, which is assigned in this paper as

$$W(t) = (t/T_1^2)\,e^{-t/T_1} \tag{6}$$

(where T_1 is 40 s)

The data are processed with eq. (5) with a sampling interval of 40 ms and 2 250 sample points. Figure 3 is the result of the calculation on $\phi_y(j\omega)/\phi_e(j\omega)$, which is $GH(j\omega)$, where $(G(j\omega)$, $H(j\omega)$ are the frequency responses of the controlled object and human subject. Figure 3 (a), (b) and (c) correspond, respectively, to $G(j\omega) = 1, 2/(1+j\omega)$, and $2/j\omega$.

These data are the averages of 2 trials of 5 subjects, i.e., a total of 10 trials. The average and the standard deviation are shown by $\overline{\underline{\Phi}}$ in the figure.

4. Construction of the Functional Model for the Central Nervous System

Based on the frequency response $GH(j\omega)$ of the loop transfer system shown in Fig. 3, the functional model for the human central nervous system is constructed. The measured frequency range is divided into a low frequency range (0.1 - 1 rad/s) and a high frequency range (1 - 10 rad/s), and the characteristics and the model for each range are discussed. Then, combining the two characteristics, a model is proposed to describe the human transfer function for the entire range of measured frequencies.

[Low frequency characteristics and model].

According to the measurements, the loop transfer function has a tendency (independently of the characteristics of the controlled object) to exhibit high gain and phase-delay near 0.1 rad/s. For the range 0.2 to 0.3 rad/s, the gain and the phase-delay decrease with an increase in frequency. Near 1 rad/s, there is a tendency for the characteristics of the controlled object to appear directly in the measured response.

Based on these observations, the human transfer characteristic in the low frequency region is regarded in this paper as PI control [7]. The loop transfer model based on PI control can be represented by the block H_{ml} in Fig. 4 (a). The reason for this is as follows.

Letting $K_l \gg 1$, $K_h \ll 1$ and $T \simeq T_N$ in Fig. 4 (a), it follows approximately that

$$H_{m,l}(j\omega) \simeq \frac{a_l}{c_l}\left(1+\frac{1}{j\omega a_l}\right)e^{-j\omega L} \qquad (7)$$

realizing the PI control. $e^{-j\omega L}$ in the above expression is the time-delay element representing the response time, and $1/(1+j\omega T_n)$ represents the macroscopic property of the motor-neuron and muscle-skeletal system, excluding the brain system. Judging from the results of the preliminary procedural experiment described in (3), the characteristics of the forearm movement control system, excluding the brain system, which originates the command signal, is assumed not to affect the characteristics in the frequency domain range below 20 rad/s, and $H_{m,l}$ is constructed so that its characteristic is compensated by $1/(1+j\omega T)$.

[High frequency characteristics and its model].

The loop transfer characteristic in the higher frequency range turns out to be

$$GH(j\omega) \simeq \omega_c e^{-j\omega L}/j\omega \qquad (8)$$

independently of the characteristics of the controlled object. This property was found by D. T. McRuer, et al. [8]. It is understood that eq. (8) is valid near the cross-over frequency ω_c, whereby cross-over frequency is meant that frequency at which the gain of the loop transfer system becomes 0 dB.

One can assume from (8) that the human performs a compensating control for the object by constructing a transfer function inverse to that of the object. From this observation, a model for the human characteristics at high frequencies can be represented by the block $H_{m,h}$ in Fig. 4 (a). In other words, letting $K_l \ll 1$ and $K_h \gg 1$, and contrary to the model for lower frequencies, in the higher frequency model it follows that

$$H_{m,h}(j\omega) \simeq \frac{a_h e^{-j\omega L}}{j\omega b_h G(j\omega)} \qquad (9)$$

Eq. (9) is equivalent to eq. (8).

[Over-all characteristics and its model].

To describe the human transfer characteristics over the measured frequency range (0.1 to 10 rad/s), a combined model (Fig. 4 (a)) is constructed, where the low frequency model of (7) is combined with the high frequency model of (9), with the integrating element in the former and the differentiating element in the latter. We set $a = a_l + a_h$, $b = b_h$ and $c = c_l$. The transfer function of the combined model of Fig. 4 (b) can be described by setting $K \gg 1$ in the frequency range 0.1 to 10 rad/s as

$$H_m(j\omega) = U(j\omega)/E(j\omega)$$
$$= \frac{(1+j\omega a)(1+j\omega T)e^{-j\omega L}}{j\omega[c(1+j\omega T_n)+j\omega bG(j\omega)(1+j\omega T)]} \qquad (10)$$

5. Estimation of the Model Parameters.

The least-mean-square estimation is used to investigate to what extent the model of eq. (1) can simulate the human frequency response and to verify the validity of the model. The similarity between human and model in the time domain can be converted into the frequency domain using Parseval's theorem. In other words,

$$\int_{-\infty}^{\infty}\{h_d(t)-h_m(t)\}^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty}|H_d(j\omega)-H_m(j\omega)|^2 d\omega \qquad (11)$$

where $H_d(j\omega)$ is the human frequency response, $H_m(j\omega)$ is the frequency response of the model and h_d and h_m are the impulse responses, of H_d and H_m respectively.

From the right-hand side of eq. (11), the similarity of the frequency responses of human and model can be represented by the evaluation function

$$Q \triangleq \sum_{i=0}^{p-1}|H_d(j\omega_{i+1})-H_m(j\omega_{i+1})|^2 \Delta\omega_i \qquad (12)$$

where p is the number of measured points in the frequency response and $\Delta\omega_i = \omega_{i+1}-\omega_i$ ($\omega_i < \omega_{i+1}$).

It is experimentally verified that adding a weight $1/\omega_i^3$ to eq. (12) can further improve the agreement between human and model responses in the measured frequency range. Based on this observation, the evaluation function is reassigned as

$$\hat{Q} \triangleq \sum_{i=0}^{p-1}|H_d(j\omega_{i+1})-H_m(j\omega_{i+1})|^2 \Delta\omega_i/\omega_i^3 \qquad (13)$$

Table 1. Estimation of parameters of the model

$G(S)$	a	b	c	L(s)	$\hat{Q}(\times 10^{-2})$
1	10.2	2.97	1.58	0.20	0.55
3	6.80	1.46	3.23	0.14	0.91
-1	11.7	3.47	-1.26	0.16	0.45
$\frac{2}{1+S}$	11.5	0.86	3.57	0.24	0.20
$\frac{2}{c}$	2.58	0.64	0.08	0.24	1.85
$\frac{-2}{1-0.5S}$	13.7	0.48	8.64	0.19	21.9
$\frac{8}{S(1+S)}$	3.06	0.95	-0.18	0.33	3.37
$\frac{8}{(1+S)^2}$	-1.75	-0.58	0.34	0.42	3.54

The parameters can be estimated by substituting the measured data into $H_d(j\omega_i)$ of eq. (13) and minimizing $\hat{Q}$ for each parameter. Table shows the model parameters thus determined, where T and T_n were present at 0.05 sec based on the result of the preliminary procedural experiment (3). A portion of the frequency response corresponding to the values of Table 1 is shown by the solid line in Fig. 3.

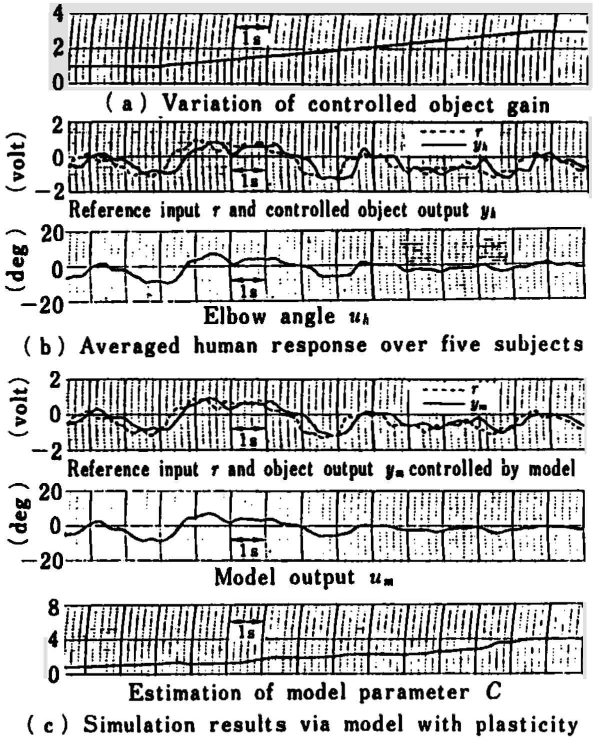


Fig. 6. Comparison between human and model responses to variation of controlled object gain.

6. Identification of the Functional Structure of the Central Nervous System from the Model

This section relates the blocks of the proposed model to the functions of areas of the central nervous system. It is first assumed that:

(1) The central nervous system function is divided into functions of the brain system and functions of the brainstem-spinal system.

(2) The interconnection between cerebellum and cerebrum is considered to be the important feedback mechanism in the brain system. The functional significance of the cerebellum-cerebrum interconnection is considered to be as follows:

The cerebellum monitors the movement by the brainstem-spinal system and the muscle-skeletal system using its simulation function and at the same time facilitates generation of a motor signal matched to the external environment.

(3) The brainstem-spinal system receives the motor signal from the brain system, and operates as a servomechanism to realize the command by referring the command to the internal situation, as a movement of muscle-skeletal system.

(4) Although the situation differs somewhat, depending on the kinds of movement, the internal mechanism of a biological system differs for various levels of training. In the initial stage of training, the movement is mainly controlled by the brain system, but the control gradually shifts to lower levels in the brainstem-spinal system in the course of training. This is called sub-routine transformation. To represent the sub-routine transformation, it is assumed that the brain system and the brainstem-spinal system are functionally equivalent.

(5) The high gain element K in the model is replaced by a relay element representing the counteracting mechanism in the biological system. The relay element can be thought of as a high-gain element when the input is low, as is evident from the describing function method [10].

The proposed model design is based on the relation of the human subject to the characteristics of the controlled object, i.e., external environmental factors. Using assumptions (1) and (2), the functional structure of the brain system can be identified from the functional structure of the model. The result is shown in Fig. 5 (a).

The model can also be used in the identification of the functional structure of the brainstem-spinal system. Considering that the brainstem-spinal system operates primarily on internal somatosensory information, the functional structure of the brainstem-spinal system is identified from the functional structure of the model for $G(j\omega) = 1$, which does not require specification of the external characteristics. The result is shown in Fig. 5 (b). The arrow from Fig. 5 (a) to (b) indicates that the macroscopic characteristic in (b) corresponds to $1/(1+j\omega T_n)$ in (a). The reasoning used in the construction of Fig. 5 (a) and (b) is described below.

(A) Functional structure of the brain system (see Fig. 5 (a)).

(a) Considering that no attenuation is observed below, 20 rad/s in finger movement generated independently of the external environment, the macroscopic transfer characteristic of the brainstem-spinal and muscle-skeletal systems is determined in accordance with assumption (3) as $1/(1+j\omega T_n)$ $(T_n=0.05)$.

(b) In the transfer of the external environment information, once stored in the cortex, into the limbic system, it is understood that multi-synaptic pathways exist in the frontal lobe septa and parietal cortex-hippocampus, selection of information is effected in the septa [11]. The plasticity in this portion is represented in the model by parameters a and b.

(c) Based on assumption (2), the cerebellum is assumed to play the role of feedback element in the brain system. It is understood that the cerebellum acts to modify the dynamical characteristics of the reflex system according to the internal and external parameter changes. From this point of view, the cerebellum is considered to be a feedback element $c/(1+j\omega T)$ with adjustable gain.

(d) The septa is a component of the reticular formation. Since the reticular formation has the central function of integration, the function of the septa is assumed to be the proportional and integrating characteristic $a+1/j\omega$.

(e) Counteracting neuron activities, such as are observed in the flexor-extensor joint movement in spinal ganglion, are observed in two adjacent areas in the motor cortex [12]. This situation is represented as a relay element assumption (5).

(B) Functional structure of brainstem-spinal system (see Fig. 5 (b)).

(a) In the representation of a movement independent of the external situation, it suffices to set $G(j\omega)=1$ in Fig. 4 (b). Then the brainstem-spinal system turns out to be a controller with the muscle-skeletal system as the object of control, represented by $1/(1+j\omega T_n^*)$ [13].

(b) The muscle spindle is understood to be an element with the function of feedback to the spine of information on the length of the muscle and its derivative. This is represented as a feedback element $a^*+j\omega b^*$ [14]. a^* and b^* are thus parameters that change by the control of the γ-system.

(c) The counteracting neuron control in the spine is simulated by a relay element.

(d) The cerebellum is understood to receive a copy of the command from the spine to the muscle-skeletal system as input, and to deliver the output to suppress the function of extrapyramidal tract [15]. The cerebellum is thus regarded as having a simulation function for the muscle-skeletal system, and is represented by $c^*/(1+j\omega T^*)$.

(e) The midbrain reticular formation not only compares the sensory information from the periphery with the interpretations sent from the sensory cortex, but receives the signal from the cerebellum nucleus to deliver the output to form the nucleus rubber pathway and to control (together with the cortex-spinal pathway (pyramidal tract)), the spinal reflexes. These neural pathways are simulated by the model.

In summary of the above discussions of the brain and brainstem-spinal systems, the movements of the muscle-skeletal system are controlled by the brainstem-spinal system. The functional system itself is further controlled by the brain system. Through this hierarchial structure the brain system seems to exert direct control over the movements of the muscle-skeletal system.

7. Plasticity of the Central Nervous System and Its Simulation

Recently, with the development of research on the cerebellum, considerable evidence has accrued that the cerebellum contributes to adaptive control or learning to adapt the biological system to changes in the external environment or internal situation and to modifying the dynamical characteristics of the control system [16]. Based on those facts, we shall in this section assume that the cerebellum modifies behavior to adapt it to the external environment by adjusting the gain in the brain system, and we provide the central nervous system model (see Fig. 5 (a)) with a learning function based on gain adjustment. Using this new, adjustable-gain model, the human response time is simulated for the case when the characteristics of the controlled object change with time, verifying the validity of the functional structure of the central nervous system.

[Adjustment of model parameters].

Based on the theory that the cerebellum basically modifies the behavior of the brain system in accordance with the external environment, one can assume that the model parameters a and b do not depend on gain changes in the external environment. The parameter c turns out to be the important adjustable parameter to provide an internal gain adjustment corresponding to the gain variation in the external environment. It is not certain by what criterion c is being modified, but is may be assumed that some ideal characteristic obtained empirically will be adopted, and c is adjusted internally to compensate for the difference from that ideal characteristic.

In this paper, the forearm movement characteristic without restriction imposed by the external environment $(G(j\omega)=1)$ is regarded as the ideal characteristic. Consequently, when characteristics of the external environment must be taken into consideration, $(G(j\omega)\neq 1)$, the parameter c is modified so that the characteristic $H(j\omega)$ of the overall system composed of the external environment and the internal characteristic $GH(j\omega)$ is in accord with the ideal characteristic. This way of modifying the parameter c can be described as follows [17].

As seen from (1), the parameter c in the loop transfer characteristics $GH(j\omega)$ has the function to cancel the gain of the controlled object is produced, the gain characteristic of the loop transfer system can be held constant by changing c in proportion to the gain of the object. It is assumed that the parameter c takes on a value equal to the gain of the controlled object. It is also assumed that the controlled object has a dynamical characteristic consisting only of gain variation. The anticipated output of the controlled object is then set as

$$\hat{y}(t)=cu(t) \tag{14}$$

This anticipated output $\hat{y}$ is compared with the ideal time response $\tilde{u}(t)$. $\tilde{u}(t)$ is obtained as the inverse Laplace transform of the human response $\tilde{u}(j\omega)$ in the frequency domain when the characteristic of the object $G(j\omega)$ is 1. In other words,

$$\begin{aligned} u(t)&=\mathcal{L}^{-1}[U(j\omega)] \\ &=\mathcal{L}^{-1}[V(j\omega)E(j\omega)]_{G(j\omega)=1} \end{aligned} \tag{15}$$

where $V(j\omega)$ is the characteristic of the loop transfer system as obtained from parameter estimation for $G(j\omega)=1$, shown in Table 1 as

$$\begin{aligned} V(j\omega)&\triangleq[GH(j\omega)]_{G(j\omega)=1} \\ &=\frac{(1+10.2j\omega)e^{-0.2j\omega}}{j\omega(1.58+2.97j\omega)} \end{aligned} \tag{16}$$

The evaluation function representing the agreement of the anticipated output $\hat{y}(t)$ with the ideal time response $\tilde{u}$ is assigned as

$$\eta=(\hat{y}-\tilde{u})^2 \tag{17}$$

The desired value of parameter c is obtained by applying the gradient method to the evaluation function of (17). In other words,

$$d\hat{c}/dt=-k\partial\eta/\partial\hat{c} \quad \text{(k: proportional constant)} \tag{18}$$

$$d\hat{c}/dt=k(\tilde{u}-\hat{c}u)u \tag{19}$$

(constant of proportionality) (20)

[Simulation].

Figure 6 shows a comparison of the responses of human and model when the characteristic of the controlled object is changed from 1 to 3 in 10 seconds, as in (a) of the figure. (b) shows the average response of the 5 examinees, and (c) is the result of digital simulation of the model, with a self-adjusting function added to the schematic diagram of Fig. 5 (a). The model parameters other than c, i.e., a , b and are assigned, respectively, as 10, 2.5 and 0.2 s. The change of the parameter c is determined in (c) by (19), which is similar to the change in gain of the controlled object. From these results it is seen that the biological system can adapt itself to gain variations in the external environment if the gain characteristic of the loop transfer consisting of the external environment and the biological system is maintained constant.

8. Conclusion

This paper treats the design of a model of the functions of the central nervous system based on the assumption that the brain system is the origin of the motor signal. The various ideas appearing in the literature are summarized from a macroscopic viewpoint, and the control characteristics obtained from an analysis of the human frequency response are applied to a discussion of the functional structure of the brain. The proposed model is primarily based on a deterministic description and may not be adequate if the flexibility of the functions characteristic of biological system must be represented. This problem must be solved in the course of relating the model parameters to the characteristics of the external environment. It is also necessary to extend the model to describe the cooperative movement of the multi-joint system and the mechanism for controlling the internal cooperation in the multi-joint movement.

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