Function Analysis Method of Human's Motion Control System

Hiroaki KAWAMOTO* Yoshiyuki SANKAI**

*Sankai Lab, Doctoral Program in Engineering, Univ. of Tsukuba
**Institute of Engineering Mechanics and Systems, Univ. of Tsukuba,
Tsukuba, 305-8573, Japan

Abstract

The purpose of this research is to propose a quantitative analysis method to analyze the relationship between the feedforward controller and feedback controller in a motion learning process, and also to assess the effectiveness of this method by experiments. To analyze the mechanism of motion control systems, we propose 1) a Control Gain Identification Method, 2) a Squared-Error Separation Method, 3) a Gradient Separation Method, 4) a Pattern Correlation Method. The inverted pendulum is used to evaluate the effectiveness of these methods. The experiments show that the proposed methods are effective way to separate the motor control system into the feedforward control and the feedback control. They also disclosed the fact that there are two learning processes; which one perform the feedback control mainly and the other the feedforward control mainly.

1 Introduction

After some practices, one learns to make a skillful and agile motion by adaptation. However, this can not be done with only the feedback information from the sensory receptors. This is because the motion control systems of human being have time delay caused by muscle, proprioceptive receptors, nerve conduction, and nerve information processing. The time delay is about 30~50 [*msec*] in the somatic sensation and 100[*msec*] in the vision. It is hard to make a fast response (10~100 [*msec*]) for a human being using only the feedback[1].

It is confirmed by physiological and praxeological experiments that the feedforward control is used in fast motions. When we make a skillful and agile motion, we must do automatically on a moment judgement. This is considered the decided motion is generated by a motion command. Therefore, the feedforward controller is considered to be the pattern generator.

In real motions, the feedforward control and the feedback control would be properly used depending on the state of motion. Those control systems have not been separated and analyzed quantitatively(see Fig.1(a)). This purpose of this research is to propose a method to separate those systems quantitatively(see Fig.1(b)) and to inquire its effectiveness by experiments.

It is consider significant to separate quantitatively the feedforward control and the feedback control in view of motion learning. For example, if the difference in the motions of novices and experts can be quantified in terms of the difference in control methods, the stage of learning that a person has reached can be identified , and a learner could be given a proper guidance. By analyzing the motion control of a person with movement disorder, movement disorder would be understood correctly and a clue to treatment may be established.

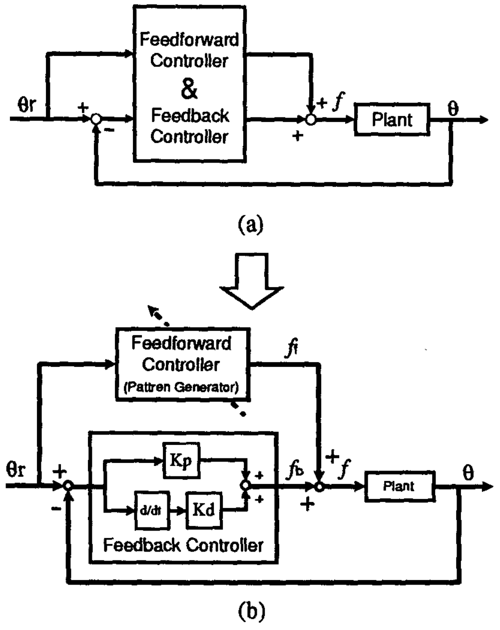


Fig.1 Motion control system

(A) shows that the feedforward and the feedback are mixed, and (B) shows that feedforward controller and feedback controller are separated.

2. Proposal for analysis method

2.1. Control Gain Identification Method

One of the control system while in motions is the feedback control to reduce the difference between the desired value and output which is fed back by using the vision and the somatic sensation. We expect that it is possible to evaluate quantitatively the feedback control property by analyzing the feedback gain in motion learning process.

2.2 Squared-Error Separation Method

We consider to extract the trends of the feedforward force ff shown in Fig.1. The feedforward force ff may be calculated from the measurement f and the calculated the feedback force f_b. However, to find out the trends of the feedforward clearly the difference between the measured force f and the calculated feedback force f_b should be squared.

Therefore,

$$E(t) = e^2(t) = (f(t) - f_b(t))^2 \qquad (1)$$

If the error is large, it would be considered that the feedforward is mainly performed. We could evaluate wether the feedforward control or the feedback control is performed by the squared error $E(t)$ while in motions.

2.3 Gradient Separation Method

To realize the feedback control, the time from the sensory receptor to actuator (e.g. loop time) must be relatively short. But human's loop time for motion control is not so short. the feedforward control is more effective for the motion that the work taken by the feedback control is heavy. We consider that it is necessary to add large force per unit time to perform the quick motion. So we can investigate the separation of those system by evaluating the force per unit time calculated for the motion that need relatively the quick movement

2.4 Pattern Correlation Method

We suggest that the feedforward controller is the pattern generator. It is considered that the patterned motion is acquired as a failure is repeated many times. To evaluate the motion learning process quantitatively, to grasp the similarity between the final trial and each trial would be regarded as essential. Therefore, we adopt the correlation coefficient to analyze similarity.

3. Method and Material

We construct the inverted pendulum as shown in Fig.2 was to analyze properties of human's motion control. If the inverted pendulum is controlled stably in the proximity of 0[*deg*] for the angle of inverted pendulum, the feedback controller would be performed mainly. On the other hand, if the angle of the inverted pendulum is relatively large, it is considered that it could not be controlled with the feedback controller, the feedforward would be performed mainly.

The configuration of experiment system using inverted pendulum is shown in Fig.2. Angular displacements θ_1, θ_2 of each link is measured with the potentiometer, and angular velocity and angular acceleration is calculated. The subject holds the gripper which has the force sensor to detect the subject's input force.

The mechanism of the force sensor is composed of strain gage and phosphor bronze. Link1 is 1.00[*m*] in length and 0.430[*Kg*] in weight, Link2 0.586[*m*], 0.017[*kg*]. At the preparation step, the links of the inverted pendulum are fixed at the initial conditions ($\theta_1(0)=0[deg]$, $\theta_2(0)=-25[deg]$), and then, the subject start to control the inverted pendulum at the moment the start button is pushed to release the lock.

The subject controls the inverted pendulum according to the command ($\theta_2=0$, $\dot{\theta}_2=0$), and repeats until the inverted pendulum can be controlled stably for about 1 minute.

We prepared two subjects (A and B). If the initial angular displacement is too small and the beginning force added late, the inverted pendulum is controlled easily. Initial angular displacement is set larger to analyze the behavior of the feedforward control.

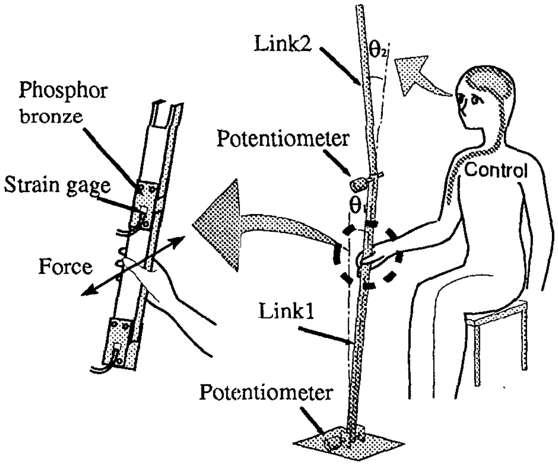


Fig.2 System configuration for experiment

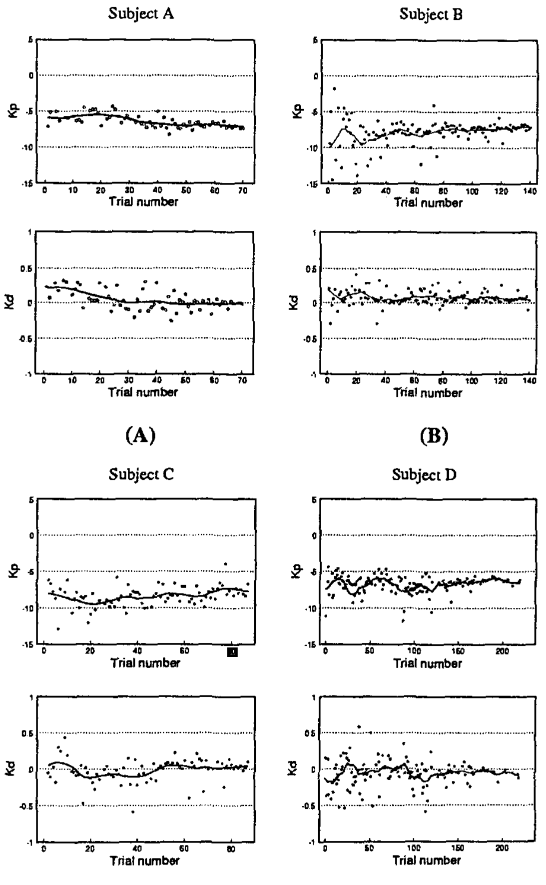
4. Results

4.1. Analysis using the feedback Gain Identification Method

In this experiment, it is considered that the angle and the angular velocity of the inverted pendulum are fed back by using the vision, and the force f_b added to the inverted pendulum is generated with the difference between the desired values and the measured values (θ_2 , $\dot{\theta}_2$) as shown in the feedback block of Fig.1(b). If the feedback control is performed, the force f_b added to the plant is represented as

$$\begin{aligned} f_b(t) &= Kp(\theta_r - \theta_2(t)) + Kd(\dot{\theta}_r - \dot{\theta}_2(t)) + C \\ &= -Kp\theta_2(t) - Kd\dot{\theta}_2(t) + C \qquad (2) \end{aligned}$$

,where θ_2 is the angle of the inverted pendulum, $\dot{\theta}_2$ is angular velocity, *Kp* is the proportional gain, *Kd* is differential gain, and C is offset. The desired angle, θ_r , is 0[*deg*] and the desired angular velocity, $\dot{\theta}_r$, is 0[*deg/sec*]. The feedback gain *Kp* and *Kd* are identified from angle ,angular velocity and measured force with the least squares method.



(A) (B)

(C) (D)

Fig.3 The feedback gain estimated by Control Gain Identification Method

Kp: *proportional gain(top)*, *Kd*: *differential gain(bottom)*. ○: *estimated value*, —: *trends of estimated value*

Figure 3 shows the feedback gains of each Subject estimated by Control Gain Identification Method. The horizontal axis is represented as trial number. The estimated gain is showed versus each trial, and the curve is given by smoothing the gains among 10 trails.

In Subject A, the feedback gains of *Kp* and *Kd* are not varied widely in the early part of the motion learning, and almost constant since approximately 40th trial. The feedback gains of Subject A are almost unchanging compared with Subject B, and he acquired proper feedback gains at approximately 40th trial.

In Subject B, the gain of *Kd* does not vary widely but *Kp* varies widely until approximately 80th trial and since then the behavior of *Kp* is almost constant, i.e. Subject B acquired the proper feedback gains at approximately 80th time.

In Subject C, the gains always have small dispersion for all trials. It means that Subject C controls the inverted pendulum as adjusts the gains.

In Subject D, the gains change variously until approximately 130th trial and since then are almost constant. SubjectD acquired the adequate gains at 130th trial..

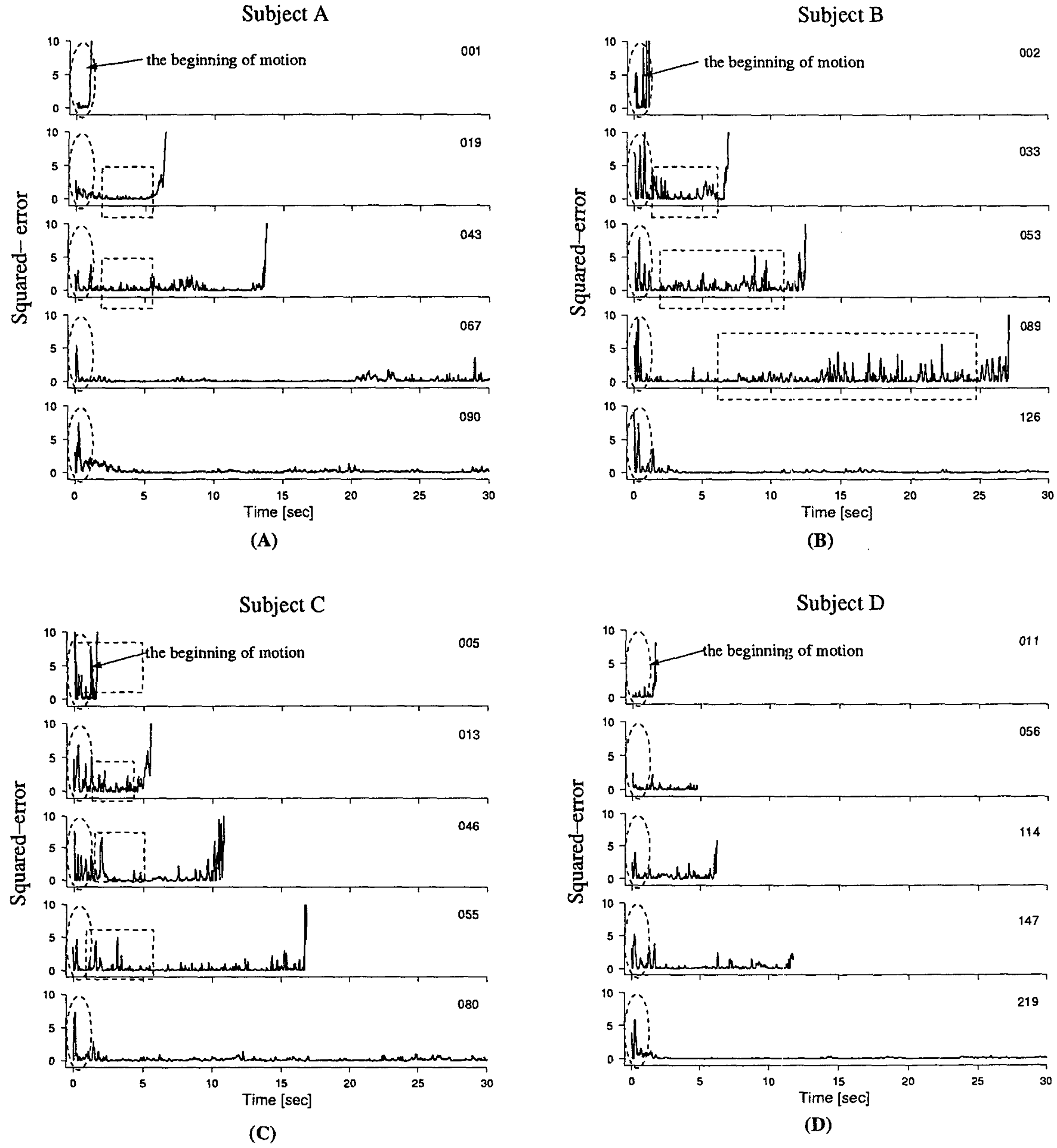
4.2. Analysis using Squared-Error Separation Method

In this experiment, the squared-error *E(t)* of each trail is found from the equation (2) and the feedback gains *Kp* and *Kd* estimated by Control Gain Identification Method for each trail.

Figure.4 shows trends of the feedforward control of each Subject. The number of top right-hand corner of each graph represents trial number. In Subject A, the squared-error is small in the beginning of motion (from 0[*sec*] to 0.4[*sec*]) in the early trials of learning (trail No.1, No.19), and becomes larger in the middle trials of learning (trial No43) in comparison with the early trials.

The squared-error is relatively large in the latter such as trial No67 and No90 (see dashed circle in Fig.4(A)). It means that the feedforward control would be performed instead of the feedback control according to the increase of trials.

The squared-error of Subject B in the beginning of motion is already large at the early trials of learning. It means that the feedforward control would be performed in the beginning of motion for all trials. Subject B would focus on the feedforward control, because the squared-error is large until middle trails (see dashed quadrangle box in Fig.4(B)). Until 69th trail, it is considered that the feedforward control and the feedback control are clearly mixed, because the squared-error repeats an increase and a decrease, and its amplitudes fluctuate large and small during the motion control. But finally, Subject B could obtain the suitable feedback



(A) (B) (C) (D)

The subjects control the inverted pendulum for a long time according to the increase of trials

Fig.4 Trends of the feedforward control indicated by Squared-Error Separation Method

control.

In Subject C, the squared-error in the beginning of motion is large for all trials. Therefor the feedforward control would be performed mainly in the beginning of motion from the early trials likewise Subject B. And the squared-error is also relatively large (see dashed quadrangle box shown in Fig.4(c)) at the middle trials of learning. It means that the feedforward control and feedback control are mixed.

In Subject D, the squared-error is small in the beginning of motion until approximately 114th trial. And then becomes larger (see dashed circle in Fig4(D)). Therefor it considered that the feedback control is mainly performed in the early trials likewise Subject A, and from approximately 114th trial begin to change to the feedforward control gradually.

4.3 Analysis using Gradient Separation

In the case of this experiment, we investigate the gradient of the force in the beginning of motion when the initial degree of the inverted pendulum is large (-25[*deg*]), where the time of the beginning of motion is defined as [ta,tb]=[0.0, 0.4 [*sec*]]. For each trial, the beginning measured force is differentiated and it's maximum value is defined as the force per unit time, expressed by following equation.

$$G.I.(ith) = max\frac{d}{dt}\left\{\sum_{ith}^{ith+N_D}\frac{f_{ith}(t)_{[ta,tb]}}{N_D+1}\right\} \qquad (3)$$

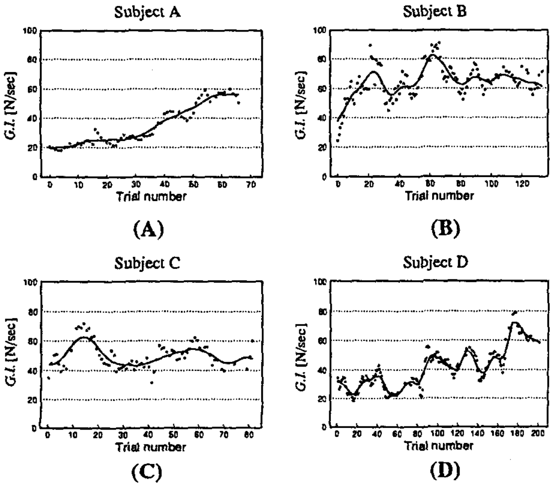
,where G.I.: Gradient Index, *fi*(t):measured force data, [ta,tb]: Interval of the beginning of motion, ND: Number of sampled Data, *ith*: *ith* trial number, max: maximum.

Figure 5 shows the results of each Subject. In Subject A, the force per unit time of the beginning of motion is small in the early trials of learning, and becomes larger gradually according to increasing of trials. In Subject B, the force per unit time of the beginning of motion is large in the early trials compared with Subject A, and becomes larger gradually until 20th trial. The scatter since 80th trial is becoming smaller.

In Subject C, the force per unit time is large likewise Subject C and becomes larger in the early trials. It is almost constant from approximately 30th trial.

In Subject D, the force per unit time is small in the early trials and becomes larger waveringly until approximately 180 trials, and then is almost constant.

Subject A and Subject D would be learning the beginning of motion with the feedback control in the early trial, because the force per unit time is small. On the other hand, Subject B and Subject C would be learning with the feedforward control, because the force per unit time is large. This result of analysis of these learning process using Gradient Separation Method are very much in agreement with the result of the analysis using Squared-Error Method.



(A)

(B)

(C)

(D)

Fig.5 Differentiate value of the beginning force estimated by Gradient Separation Method

4.4. Analysis using Pattern Correlation Method[2]

In the case of this experiment, we assume that the patterned motion is the beginning of motion and find the correlation coefficient for the beginning force (0.0[*sec*]-0.4[*sec*]) of each trial on the basis of the learned beginning force.

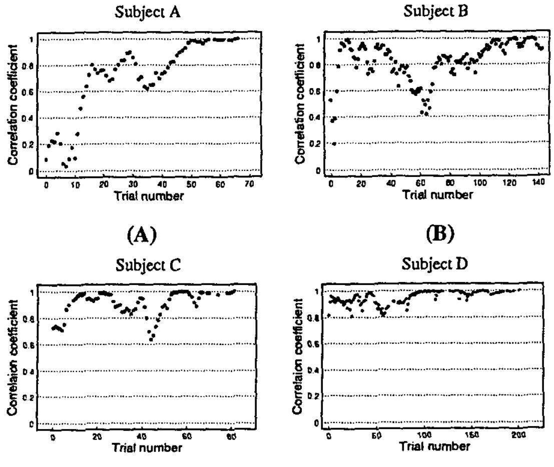
The correlation coefficient, *r*, can be represented as

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\Sigma(x_i - \bar{x})^2)(\Sigma(y_i - \bar{y})^2)}} \qquad (4)$$

,where x_i is the beginning force which has been acquired when the motion learning was finished, $\bar{x}$ is the average of x_i. y_i is the beginning force which is outputted in process of the motion learning, and $\bar{y}$ is the average of y_i.

Figure 6 shows the correlation coefficient for each trial in each Subject. In Subject A, correlation coefficients increase gradually until approximately 30th trial, and then decrease until approximately 40th trial, and begin to increase again. Since approximately 50th trial, the correlation coefficients is almost 1.0. So, the force pattern in the beginning of the motion would become steady.

In Subject B, it is considered that the force pattern in the beginning of motion in the early trials was obtained, because the correlation coefficient is almost 1.0 . The correlation coefficients decrease from 30th trial to 60th trial. But, we find that the correlation coefficient increase gradually at the middle trials. It might be considered that Subject B tried to search another way to control the inverted pendulum in the middle trials.



(A)

(B)

(C)

(D)

Fig.6 Correlation coefficient estimated by Pattern Correlation Method

In the Subject C, the learning process of the force pattern would be much the same as Subject B. The correlation coefficient in the early trials is almost 1.0, but it decrease in the middle trials and since then increase gradually.

Therefor Subject C is already acquired the suitable force pattern in the early trials. But he tried to change to another way in the middle trials, because he could not control to keep the inverted pendulum stably.Finally, he would get back the primary force pattern.

In Subject D, the correlation coefficients are relatively large for all trials. It is considered that the motion of the beginning by the feedforward controller is almost the same as the feedback controller.

5. Discussions

We consider the motion properties of subjects from those method. In Subject A, the beginning force per unit time since approximately 40th trial as shown in Fig.5 (A) increase gradually in spite of the feedback gains are almost constant as shown in Fig.3 (A). Therefore, it means that the feedforward control would be performed instead of the feedback control since approximately 40th trial. The correlation coefficients increase between 40th trial and 50th trial. The feedforward controller would be during the learning in this period. Since then, the correlation coefficients are almost 1.0, so the satisfactory feedforward controller is acquired. The variance of the identified feedback gains is small as shown in Fig.3(A). And considering the squared-error(see dashed quadrangle box shown in Fig.4(A) and section 2.2), the feedback controller of Subject A would be almost established since the early stage of the motion leaning. In Subject B, in the early trials, the correlation coefficients shown in Fig.6(B) are high, and both the squared-error shown in Fig.4(B) and the force per unit time shown in Fig.5(B) are relatively large. It would be considered that the satisfactory feedforward controller is already established. But the satisfactory feedback controller is not established in the early trials, because the feedback gains are varied in this period (see Fig.3(B)). Until middle trials of these experiments, the feedback control is improved, and the feedforward control and the feedback control are clearly mixed. It is considered that Subject B focused on obtaining the feedback controller through whole trials in these experiments.

In Subject C, the learning process is almost the same as Subject C. Because in the early trials, the croreratdion coefficients shown in Fig.6(C) are heigh, the squared-errors shown in Fig.4(C) and the force per unit time shown in Fig.5(C) are large, the feedforward control is already performed. However, Subject D can not keep the inverted pendulum for a long time in the early trials, because he does not acquire the suitable feedback gain. Since approximately 50th trial as shown in Fig.3(C) the feedback gains are not varied wildly, therefor the satisfactory feedback controller would be established. Likewise the case of Subject B, while the feedback controller is improved in the middle trials , the feedback controller and the feedforward controller are mixed considering the squared-error as shown in the dashed quadrangle box of Fig.4(C).

In Subject D, the squared-error shown in Fig.4(D) and the force per unit time shown in Fig5(D) are small in the early trials. It means that the feedback control would be performed in the beginning of motion. The squared-error and the beginning force per unit time increase in spite of the feedback gains are almost constant since approximately 130th trial. Therefor, the feedforward controller would be performed instead of the feedback controller likewise Subject A. The correlation coefficients shown in Fig6(D) are large and are not varied wildly. It is considered that the motion pattern of the beginning by feedforward controller is almost similar to the feedback controller.

6. Conclusion

To analyze the mechanism of motion control system, we could propose the following analysis methods; 1) Control Gain Identification Method, 2) Squared-Error Separation Method, 3) Gradient Separation Method, 4) Pattern Correlation Method.

And we could divide the motion during the motion learning control into the feedback control factor and the feedforward control factor, quantitatively by using theses methods.

These methods would be regarded as essential to analyze the human's control system, especially, the motion of handicapped person or aged person who need rehabilitation.

7. References

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