CHARACTERISTICS OF A COMPENSATORY MANUAL CONTROL SYSTEM WITH ELECTROCUTANEOUS FEEDBACK

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ABSTRACT

Electrocutaneous stimulation using electric pulse trains is one of the most effective cutaneous displays for tactual communication systems. This paper deals with the human operator's characteristics in compensatory manual tracking system including an electrocutaneous display. Firstly, an electrocutaneous manual compensatory tracking system which consists of a random noise generator, a low-pass filter, a multichannel stimulator, a stimulus pulse energy controller, an isolator and a computer was constructed. Secondly, human operator's characteristics under several parameter situations in a compensatory tracking system, i.e., display transformation method, display gain, and pulse frequency, was evaluated from Root Mean Square values (RMS) of control errors and transfer functions of human operators. Thirdly, differences between human operator's control performance in various cutaneous and visual tracking displays were discussed. As a result, the optimal condition for an electrocutaneous display in a tracking control system was presented and human operator's control performance in electrocutaneous manual tracking system was found to be as good as that in vibro-tactile though inferior to that in visual.

INTRODUCTION

Several previous investigations have been concerned with human performance in compensatory manual tracking tasks [1],[2],[3]. Compensatory tracking has been proved a useful tool for research into the characteristics of the human operator in man-machine systems. Most experiments have used a continuous visual display for indicating the magnitude and direction of the tracking

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error[1]. Tactile displays offer the possibility of analogous one dimensional and spatial displays. Several investigators have proved that tactile displays can be used successfully to construct an effective sensory substitution system for prosthetic limbs, sensory prostheses and so on[4],[5],[6],[7].

Stimulation of tactile sense can be accomplished with electrical, mechanical, thermal, and chemical stimuli. It has been established that the most practical method for communication purposes is the mechanical and electrical. Investigators that have experimented with tactile tracking include Durr[8], Geldard[10], Hirsch and Kadushin[11], Howell and Briggs[12], Weissenberger and Sheridan[13], Seely and Bliss[14], Alles[15], and Hill[16]. Most of this research is concerned with tactile tracking with mechanical or vibro-tactile stimuli. Investigations concerning with manual tracking with electrocutaneous feedback has been carried out by Szeto[17], Schmid and Bekey [18], and Anani and Körner[19]. Szeto proposed seven kinds of electrode tactual codes and evaluated the effectiveness of them from RMS value of control error. Schmid et al. used a two dimensional electrocutaneous display to estimate the behavior of the spinal cord injury handicapped from the transfer function of the human operator in tracking tasks. Anani et al. studied human operator performance in tracking system including an afferent electrical nerve stimulation. Though researchers indicated above have actively investigated manual tracking tasks with electrocutaneous feedback, there has been little research on compensatory tracking tasks.

In general, human operator behavior in manual tracking tasks depends on various tracking system parameters - the type of command signal, command signal bandwidth, display gain, closed loop gain, the type of display transformation and controlled element dynamics[20]. Manual tracking experiments in the past involve varying these parameters. The present research emphasized varying the type of display transformation and stimulus pulse parameters as well as other classical parameters, display gain and command signal bandwidth. From this approach, it should be possible to find the optimal stimulus condition in manual tracking tasks with electrocutaneous feedback. The difference between electrocutaneous stimulation and other display modalities will also be investigated.

INSTRUMENTATION

Electrocutaneous communication can be accomplished with several stimulus waves and information transmission codes. However, pulse stimulation is usually chosen with the information codes, magnitude, pitch and location of the perceived pulse stimulus. In this series of experiments, magnitude and pitch of pulse stimulus were chosen as information codes. The use of those codes are important for constructing a simple electrocutaneous communication system since it allows to build the system under the use of less electrodes, though location code can transmit a larger amount of information.

Fig. 1 shows the experimental setup used. The experiment system includes a computer(PDP 11/40), multichannel simultaneous stimulator, stimulus energy controller, isolator, electrodes, low-pass filter with cutoff frequency adjustable, random noise generator and joystick. The output of stimulator was isolated by the photo-coupling type isolator and was presented on to the skin of a subject via two sets of wet electrodes. The two sets of electrodes were placed on the skin above the biceps brachii(Fig. 1). Two electrode sites were located 100 mm apart along the longitudinal axis of the biceps brachii. At each site were three electrodes placed 20 mm apart perpendicularly to the muscle's length. The two outer electrodes at each site were connected and used as a common, and negative pulses were applied to each central electrode.

In previous paper the authers reported that the magnitude sensation of electrocutaneous stimulation was strongly related to the stimulus pulse energy[21]. For this reason, stimulus pulse energy and frequency were used as stimulus parameters relevant to magnitude and pitch codes in electrocutaneous information, respectively.

The task of the subject in this experiment is to eliminate tracking error by manually adjusting a joystick in response to command signals. The command signal to the system is white noise through a low-pass filter. Movement of joystick, which consists of a dial and potentiometer, produced an analog voltage output proportional to the displacement from the center position. Error signals, the voltage difference between command and joystick output, were calculated using operational amplifiers. After the detection of the error signals, they were sampled at the rate equal to pulse rate of stimulation used. These sampled error signals were put into computer via analog-to-digital converter and used to modify pulse parameters. Pulse energy and pulse frequency of stimulus were varied according to the sampled tracking error signals. The electrode site near the shoulder was stimulated when tracking error was possitive, and electrode site near the elbow was stimulated when tracking error was negative. The selection of stimulus sites according to the direction of tracking error was performed using computer controlled relay device. A computer controlled multichannel simultaneous stimulator was used to produce stimulus pulse trains with appropriate parameters corresponding to sampled tracking error signals. The energy of each pulse was regulated by a stimulus energy controller associated with constant current isolator. The details of multichannel stimulator and stimulus energy controller have been described in other papers[22],[23],[24].

Throughout the experiment, the dynamics of the joystick were kept constant. The stroke of joystick movement was about 90 degrees in each of clockwise and counterclockwise directions from the center position. As a controlled element, position vechicle was used.

Subjects were researchers of experience. One of them performed all of experimental tasks. The results for the subject are shown in the following sessions.

EVALUATION OF THE MAGNITUDE CODE

The magnitude code information will be transmitted to a subject intermittently, when pulse stimulation is used. Human operator performance in this manual control system with magnitude code electrocutaneous feedback is considered to depend on the pulse frequency of stimulation used. The use of pulse stimulation with long pulse interval may cause the decrease of human operator controllability because of the decrease of transmitted feedback information per unit time.

The first experiment was conducted to investigate the relation between human operator controllability and pulse frequency. In the second experiment, human operator behavior in a manual tracking task with several system parameters were measured under the use of the optimum stimulus frequency estimated from the first experiment.

EXPERIMENT I ---- VARYING STIMULUS PULSE FREQUENCY

METHOD

Pulse frequency and bandwidth of the command signal were varied. Six or seven kinds of pulse frequencies in the range from 10 pps to 100 pps, and white noise command band-limited at 0.1, 0.2, 0.4, 0.5 and 0.8 Hz, which show cutoff frequencies of low-pass filter(F_C), were used. A subject was required to perform compensatory tracking tasks to each of those command signals, perceiving electrocutaneous feedback with each of those pulse frequency stimulations. Pulse energy of stimulus was varied proportionally according to the increase of tracking errors in the range from minimum threshold to maximum threshold. The display transformation is shown in Fig. 3(a).

Each trial in this tracking experiment was 3.5 minuite long. The trials were performed after the subject had familiarized himself with experimental apparatus and procedures. Tracking errors were recorded into a data recorder (TEAC 260). The data playbacked were transferred into the memory of computer. Tracking errors were squared and integrated in the computer in order to get the RMS values. A RMS value of tracking error was normalized by a RMS Value of command signal. The normalized RMS values of tracking errors were used as a final human operator performance measure in this experiment.

RESULTS AND DISCUSSIONS

Fig. 2 shows the subject's normalized RMS value as a function of stimulus pulse interval. Each curve in the figure corresponds to the experimental results with each bandwidth of command signal used. As shown in Fig. 2, the trial for F_C=0.8 Hz was performed only under the use of stimulations with pulse intervals less than 50 ms, because it was difficult for a subject to track the command signal when stimulations with pulse intervals larger than 50 ms were used. From the inspection of the experimental results, it is found out that (a) the smaller both of pulse interval of stimulation and bandwidth of command signal are, the better the compensatory tracking scores are, and (b) the decreasing rates of RMS scores increase according to the increase of bandwidth of command signal, especially when the stimulations with pulse intervals larger than 50 ms are used.

One possible interpretation of those results may be related to how long the human operator can persist in each of the magnitude sensations evoked intermittently by pulse stimulation. A second possible interpretation may be related to the decrease of directional information of tracking errors under the use of stimulations with long pulse intervals. The subject suggested that the latter interpretation was valid.

To investigate this problem, brief experiments were performed. The experimental procedure was the same as experiment I except that the experimental system contained an additional visual display for exact presentation of directional information of tracking error by means of LED (light emitting diode). The results of the experiment indicated that the tracking scores under the use of stimulation with 100 ms pulse interval in this experiment became approximately equal to those with 10 ms pulse intervals in the previous experiment, while those under the use of stimulation with 10 ms pulse interval were not improved. From the results, it can be concluded that in order to keep good operator performance stimulations with pulse intervals less than 20 ms should be used, and an establishment of exact directional information display is important in a tracking experiment with the use of long pulse interval.

In the following experiments associated with magnitude code stimulation, 10 ms pulse interval was used.

EXPERIMENT II ---- VARYING SYSTEM PARAMETERS

METHOD

Human performance in the tracking system with different transformations and display gains were compared in each experiment. In this experiment display transformation was varied to compare the linear and threshold transformation shown in Fig. 3. In the linear transformation, pulse energy of stimulation varied proportionally according to instantaneous tracking error. In the threshold transformation, pulse energy of stimulation was turned to an appropriate energy level from the minimum sensation threshold, when an instantaneous tracking error became more than a specified value. The linear transformation was tested at several different display gains, and the threshold transformation was done at several dead bands. Each of those experiments was performed at three different bandwidths of command signals. Tracking tasks were same as those in the previous experiments. A normalized RMS value of the tracking error and a human operator transfer function were used as human performance measures. Firstly, the normalized RMS values were computed for each trial, and a gain which indicated the best RMS score was chosen for each bandwidth of command signal in each transformation. After those investigation, another experiment was performed at the best gain in order to estimate the human operator performance from the transfer function. In the experiments associated with RMS score and transfer function, a subject had one and three 3.5 minuite tracking trials for each parameter situation, respectively. Three kinds of variable, tracking errors(e), band-limited command signal(r) and operator output signals(u), were recorded into a data recorder for each trial. It should be noted that the operator output was equal to control value because tracking system used in the experiments had an unity controlled element.

Performance measures were evaluated from the recorded data using a digital computer as mentioned in the above session.

RESULTS AND DISCUSSIONS

Fig. 4(a) shows the relation between the normalized RMS of the tracking error and the display gain for the linear transformation. Fig. 4(b) shows the relation between the normalized RMS of the tracking error and the normalized dead band for the threshold transformation. Each curve in both figures corresponds to the result of each bandwidth of command signal used. The principal features of the results are as follows: (1) For the linear transformation, each set of trials shows the RMS of tracking error decreases when display gain increases. The RMS score has a tendency to keep relatively constant at higher display gain. (2) For the threshold transformation, each set of trials shows the RMS of tracking error has U-shaped characteristics with varying dead band. (3) RMS scores of tracking tasks for the linear transformation are superior to those for the threshold transformation.

The above result(1) suggests that human operator performance in tracking tasks with magnitude code electrocutaneous feedback will not be effected by adaption of the receptor under the skin. This is usually observed in tactual communication systems and causes temporal decrease of display gain during the tracking task. The difference between the results for the linear and threshold transformation indicates that it is important to display the magnitude information of tracking error as well as the directional information in order to keep good operator performance. The decrease of RMS score at lower dead band in the threshold transformation has much to do with instability of the system caused by a large equivalent closed loop gain. The decrease at larger dead band is considered to relate to the decrease of display information accuracy.

Transfer functions are estimated from the following equation,

$$Y_H = F_{RU}(jw)/F_{RE}(jw)$$

where Y_H: human operator transfer function, $F_{RU}(jw)$: cross-power spectral density of closed system input and system output, $F_{RE}(jw)$: cross-power spectral density of closed system input and tracking error.

The two cross-power spectral densities were calculated, utilizing a standard Fast Fourier Transformation program(FFT) in the computer. For FFT analysis, analog data in data recorder were digitized at 10 Hz rate. Proper precautions were taken to reduce aliasing due to sampling by appropriately filtering the data at each step of the operation. FFT were performed for 500 sections of 512 points overlapped by one point with a sampling frequency of 10 Hz. Each cross-power spectral density for each parameter situation was obtained from the average across all of the FFT results. Fig. 5 shows human operator transfer functions. These are results for bandwidths 0.3 Hz, 0.5 Hz and 0.8 Hz at display gain 53 erg/volts and normalized dead band 0.5, which indicated optimum operator performance in previous experiments. Both operator gain and phase shift are plotted. The main difference between the curves is their varying gain. The difference is greater under the use of a command signal which includes higher frequency components. The increase of command signal bandwidth causes the reduction of operator gain. In general, it is well-known that human operator gain decreases in a manual tracking control system with visual feedback when he has command signals which include higher frequency components. This is because he must attend to the whole frequency components which are included in the command signal. Hence, he cannot keep the operator gain constant. The experimental results are interprered in the same way.

The difference between the linear and threshold transformation is not so significant under the use of command signal band-limited at 0.3 Hz. The operator gain characteristics for the linear transformation is evidently superior to that for the threshold transformation under the use of command signals which are band-limited at larger frequency, that is, 0.5 Hz and 0.8 Hz.

EVALUATION OF THE PITCH CODE

METHOD

One type of display transformation was used in this experiment(Fig. 3(c)). The pulse interval of stimulation was proportionally varied according to tracking errors as shown in the figure. The range of pulse interval was from 10 ms to 100 ms, because it is well-known that the operator has excellent frequency discriminability in this range[25]. Minimum level of pulse interval was fixed at 10 ms. The experiments were broken into two parts as well as the previous experiments. In the first experiment, the RMS score of tracking task was determined with varied display gain. In the next experiment, human operator performance was evaluated using human operator transfer functions with the use of the display gain at which an operator showed an optimum RMS score in the tracking task. The experimental procedures and the processing method of experimental results were identical to the previous experiment. Energy of stimulation pulse was set at a comfortable level for a subject.

RESULTS AND DISCUSSIONS

Fig. 6 shows the normalized RMS scores of tracking errors for various display gains. Bandwidth of command signal employed was from DC to 0.3 Hz. Energy of stimulation pulse was 42.4 erg.

The results indicate that (i) the RMS scores vs. display gain shows U-shaped characteristics and (ii) the RMS scores are inferior to those for the magnitude code. The reason for the decrease of RMS score at lower display gains may be explained by the fact that the subjects must recognize the tracking error through stimulation with longer pulse intervals at those gains. In a tracking task with higher display gain, operator will use frequency ranges with a larger just noticeable difference more often to recognize the tracking error. It is considered to be reason why RMS scores at higher display gain decrease.

Fig. 7 shows human operator transfer functions, which includes the results for command signals band-limited at 0.3 Hz, 0.5 Hz and 0.8 Hz. The display gain was 300 ms/volts, which was the optimum gain in above experimental results. From the inspection of the results, it is found that the operator gain with pitch code communication has a tendency to decrease much more than with magnitude code communication, when command signal with higher frequency component is used. The human operator behavior for pitch code communication, however, is apploximately same to that for magnitude code communication. The facts imply that a subject has an inadequate adaptability for the change of command signal bandwidth in a tracking task with pitch code stimulation. The reduction of operator gain under the use of command signal with higher frequency components may be related to information display mechanisms of pitch code communication. When using pitch code communication, information display rate will be varied according to the magnitude of tracking error. With display transformation in Fig. 5, information display rates decrease when tracking error go to zero. Such a decrease of information rate may cause a reduction of operator controllability, because it made it difficult for a subject to track the wide bandwidth command signal with high accuracy.

COMPARISON OF ELECTROCUTANEOUS DISPLAYS

Considering the electrocutaneous displays tested in these experiments, the best is estimated to be the linear transformation using the magnitude code. The next best is the threshold transformation using the magnitude code or the linear transformation using the pitch code. In order to compare these electrocutaneous displays with each other, and with typical visual and vibrotactile displays performance, the equivalent gain and time-delay parameters for the displays were computed, employing the method which was proposed by Hill[16]. The following equation, which is a kind of extended crossover model was used in order to determine the parameters.

$$Y_H = (K/jw)e^{-(jw\tau-(\pi/2))}$$

where K is the equivalent gain, τ is the equivalent time-delay, and $\pi/2$ is phase-lag constant coefficient, which is needed to get the better fit to data at low frequency when a corssover model is applied to a manual tracking system with position vehicle. For vibrotactile displays, the data of Bliss[9], which were obtained from tracking trials using tactile contact and tactile air jet displays, were used. The data of Elkind, McRuer, Bliss and the authors were used for visual displays. All of data were obtained with a position vehicle. The authors' visual and electrocutaneous display data, and Bliss's visual and tactile contact data were the results from one subject. To compare two parameters K, τ, associated with the electrocutaneous display, the results which were best fitted with the crossover model parameters were chosen for each display transformation. Those results associated with $F_c = 0.5$ Hz (linear), $F_c = 0.3$ Hz (threshold) and $F_c = 0.3$ Hz (frequency). Fig. 8 shows the equivalent gain and time delay parameters for position vehicle plotted on the K-τ plane with equal phase margin curves, calculated using the following equation.

$$\pi-[(K\tau+(\pi/2))-(\pi/2)] = a$$

where a is phase margin.

It can be seen in Fig. 8 that performance obtained with each transformation of electrocutaneous displays is consistently ordered from the worst to the best -- threshold, frequency and linear. In the recent practical application of electrocutaneous communication, only the pitch code has been utilized. It should be noticed that the results indicated that the magnitude code was most important in a compensatory manual tracking system. The electrocutaneous displays yield less gain and greater time-delays than the other displays except tactile air jet. Some care, however, must be exercised when the results of Bliss are interpreted, as Hill suggested[16]. The subject is a man of quite excellent tracking ability and his visual gain is much higher than McRuer and Elkind's average data. The gains on both his tactile and visual trials should be scaled down about 30 percent to match that of the average subject. The results in the present research is considered to provide the data of the average subject, because the subject's visual gain and time-delay approximately are equal to McRuer and Elkind's average data, as shown in Fig. 8. If the above mentioned modification for the data of Bliss is done, the electrocutaneous linear transformation with magnitude code offer performance fairly comparable to that obtained with tactile contact display of Bliss, though it is still poorer than visual display.

CONCLUSIONS

The feasibility of electrocutaneous displays in compensatory manual tracking has been demonstrated. Three kinds of electrocutaneous displays, linear transformation, threshold transformation using magnitude codes, and linear transformation using pitch code, have been investigated under the best stimulus conditions.

The results of transfer function analysis indicated that the electrocutaneous display was most effective with linear transformation using magnitude code and least effective with threshold transformation.

When compared with other displays, performance for linear transformation using magnitude code was approximately equivalent to that for tactile contact display. However, equivalent gain was less and equivalent time delay was longer for electrocutaneous display than for visual display.

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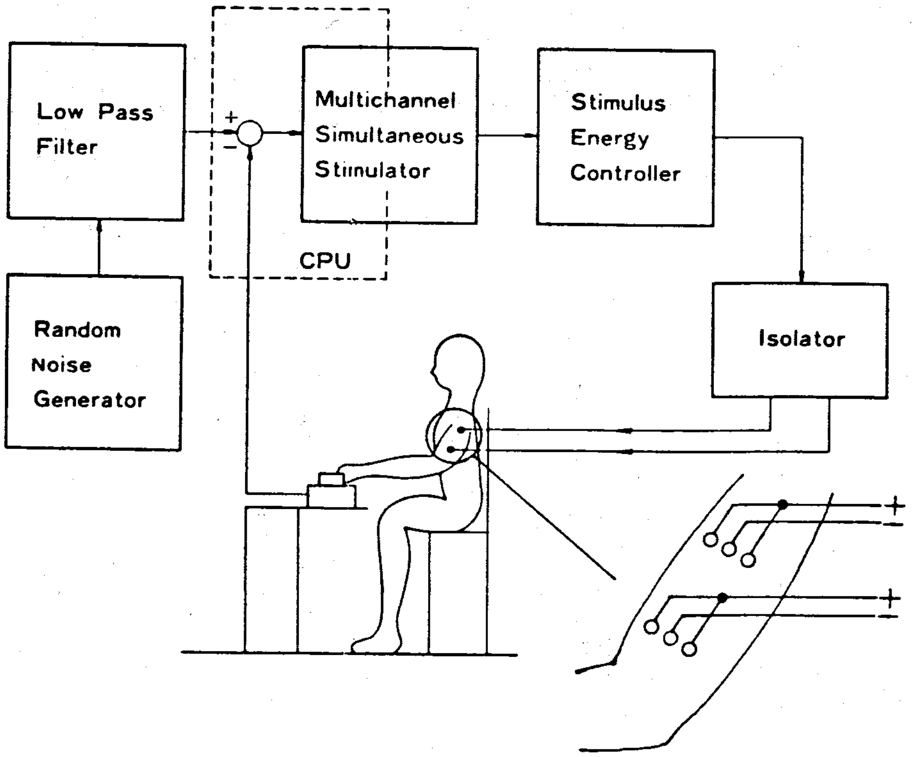


Fig. 1 Experimental Setup.

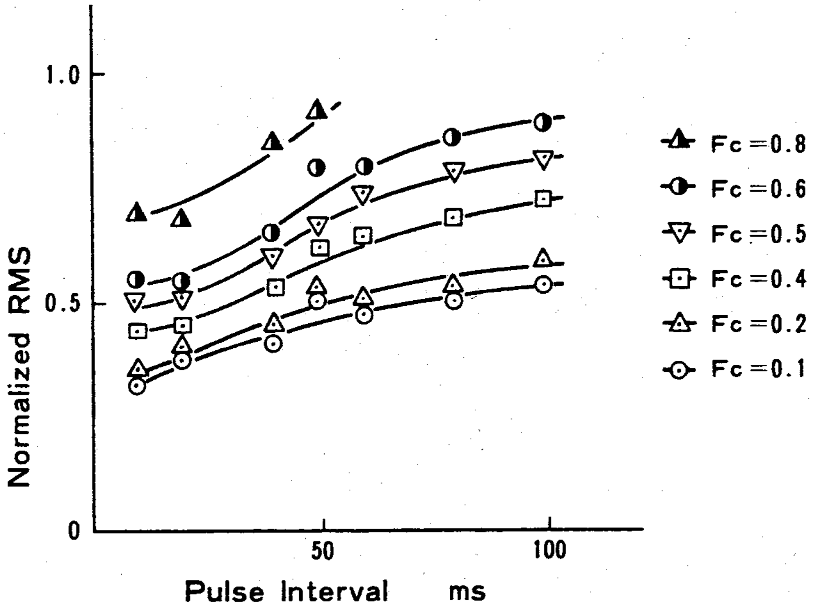
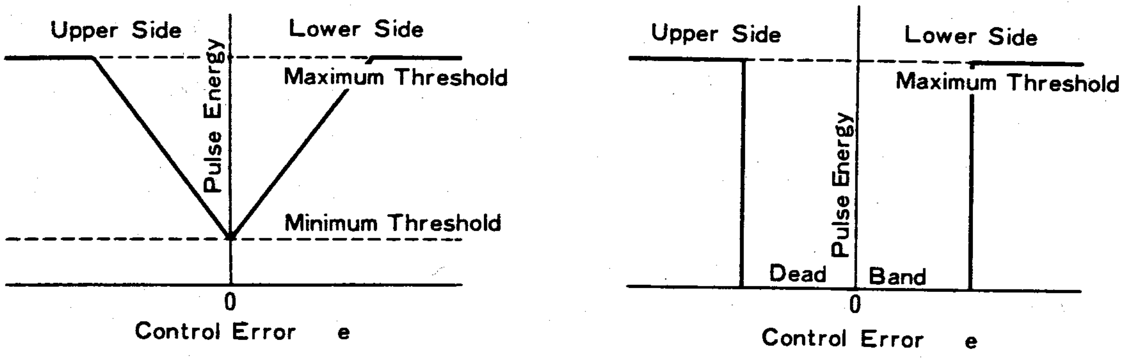
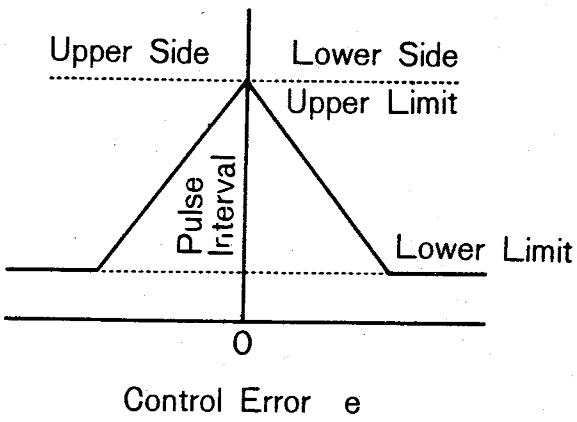


Fig. 2 Relation between Pulse Interval and Normalized RMS Value of Control Error (F_c: Cutoff Frequency of Low-Pass Filter Used to Limit the Bandwidth of Command Signal).



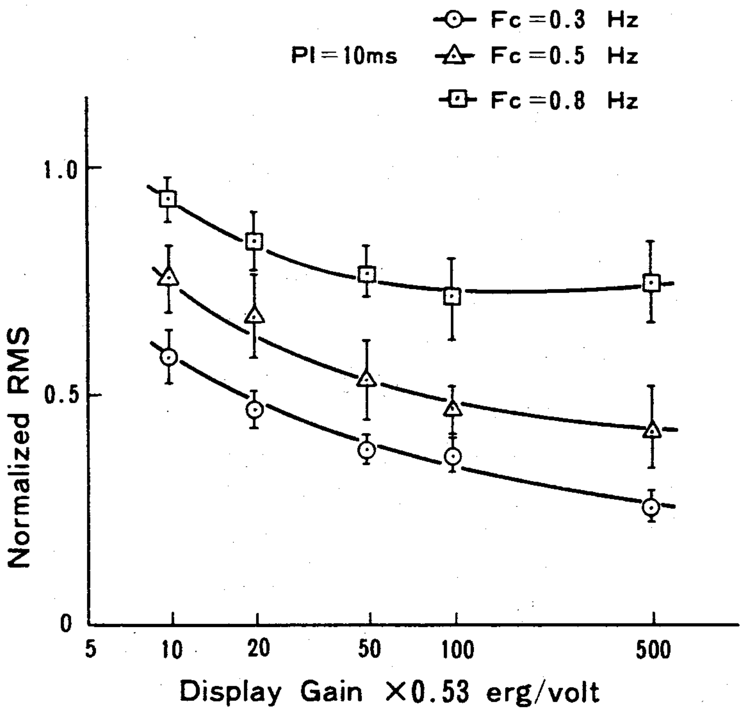
(a) Linear Transformation.

(b) Threshold Transformation.

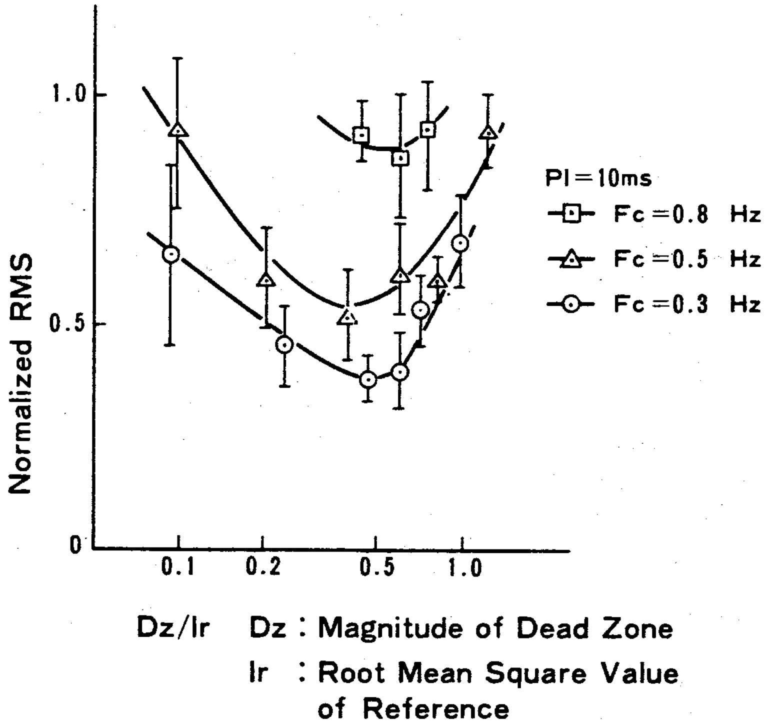


(c) Frequency Transformation.

Fig. 3 Display Transformations



(a) Linear Transformation.



(b) Threshold Transformation.

Fig. 4 Relation between Display Gain or Dead Band and Normalized RMS Value of Control Error (PI: Pulse Interval, Fc: Cutoff Frequency of Low-Pass Filter Used to Limit the Bandwidth of Command Signals).

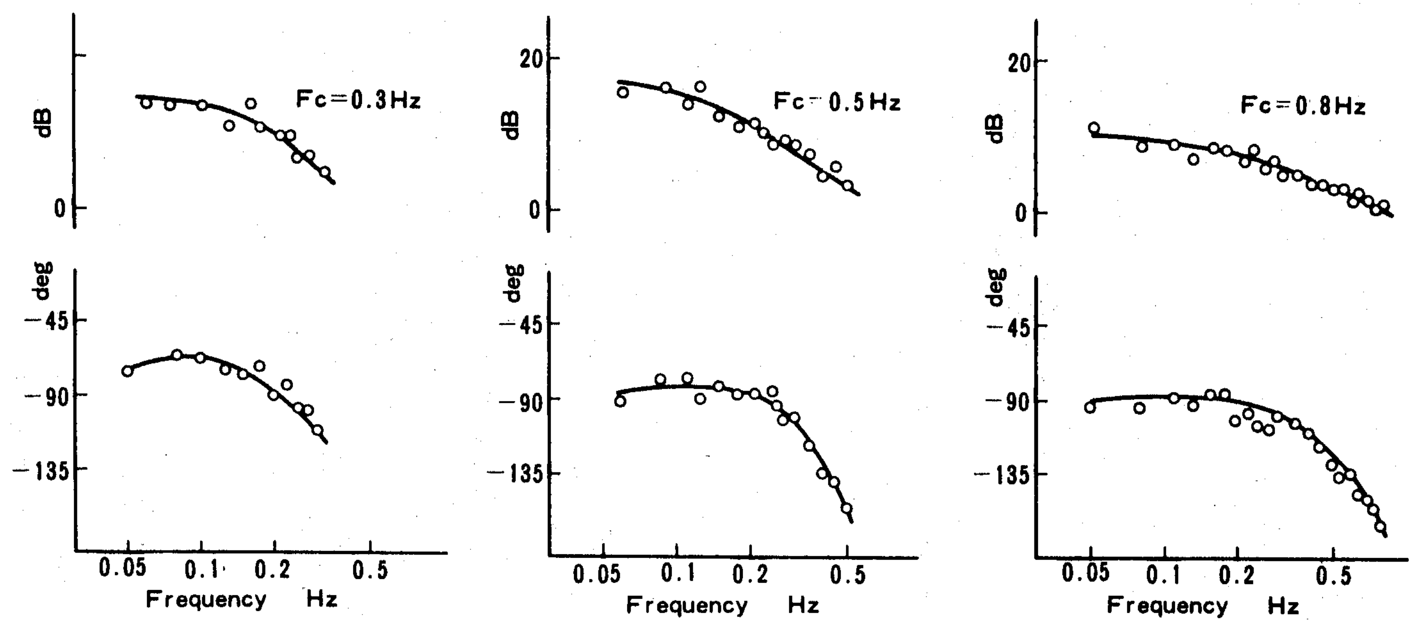


Fig. 5(a) Operator Transfer Functions(Linear Transformation).
(F_c: Cutoff Frequency of Low-Pass Filter Used to Limit the Bandwidth of command signals)

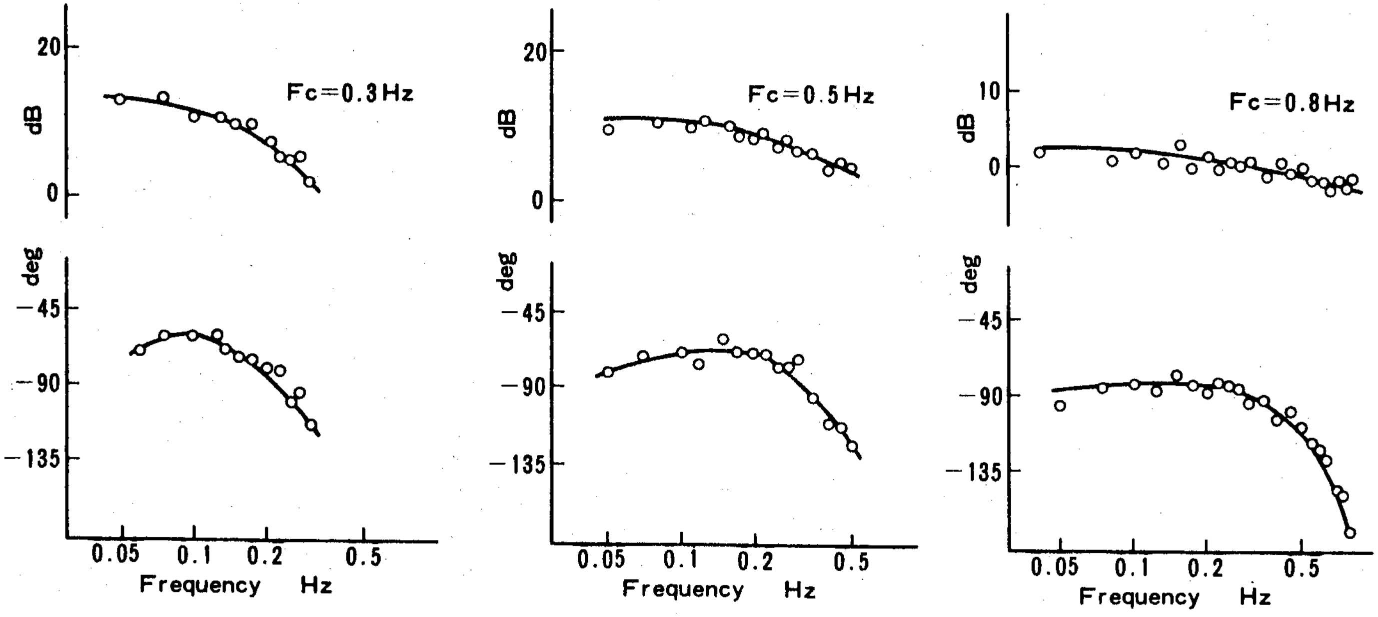


Fig. 5(b) Operator Transfer Functions (Threshold Transformation). (F_c: Cutoff Frequency of Low-Pass Filter Used to Limit the Bandwidth of Command Signals)

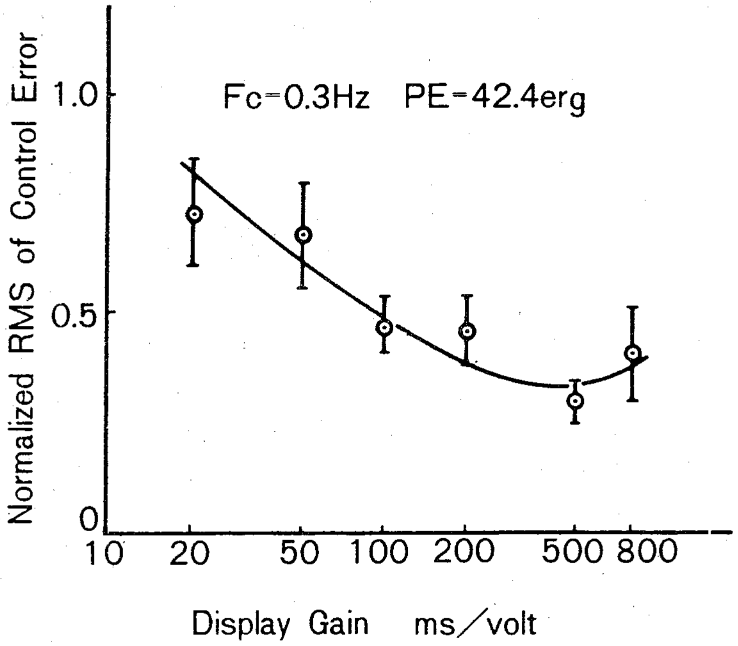
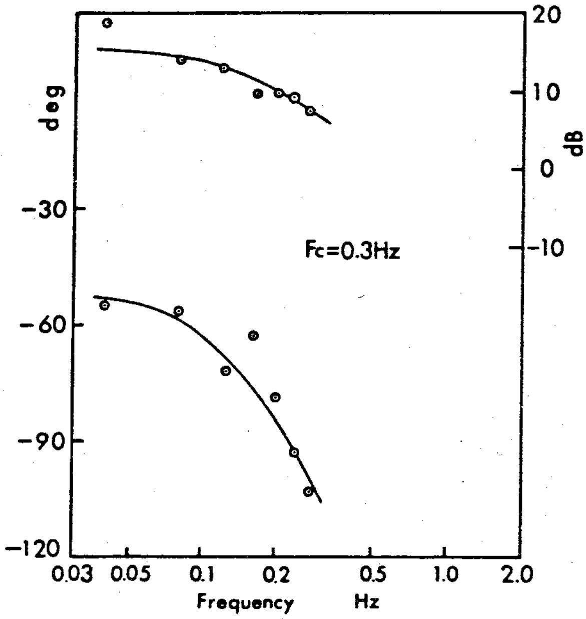
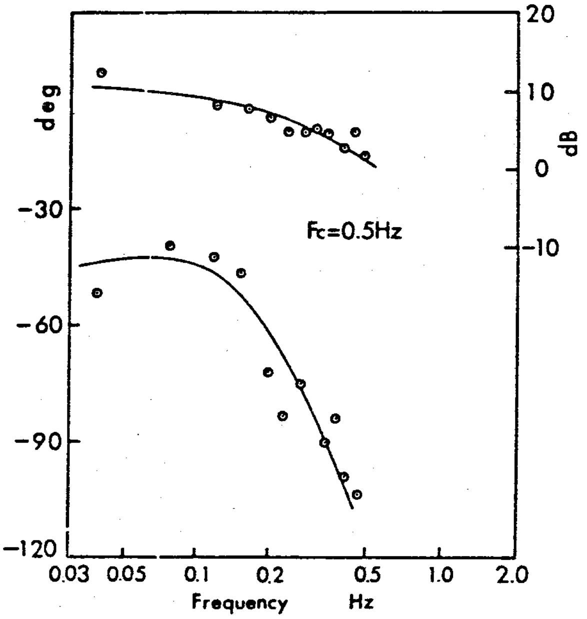


Fig. 6 Relation between Display Gain and Normalized RMS Value of Control Error under the Use of Frequency Transformation(F_c: Cutoff Frequency of Low-Pass Filter Used to Limit the Bandwidth of Command Signals, PE: Stimulus Pulse Energy).





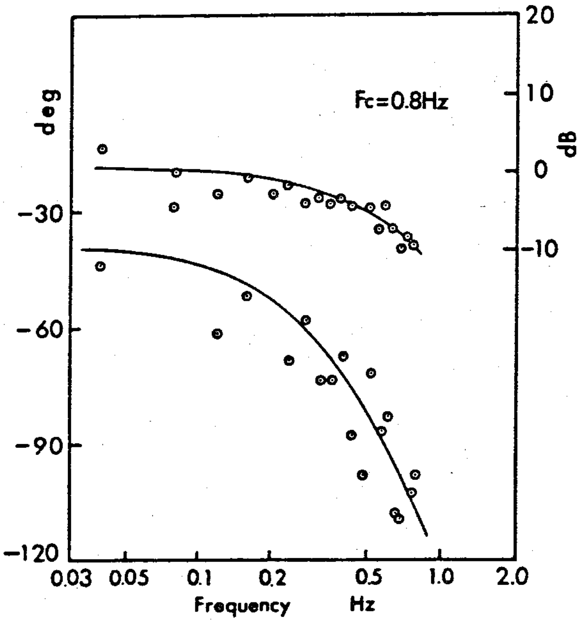


Fig. 7 Operator Transfer Functions (F_C: Cutoff Frequency of Low-Pass Filter Used to Limit the Bandwidth of Command Signals, Stimulus Pulse Energy=42.4 erg).

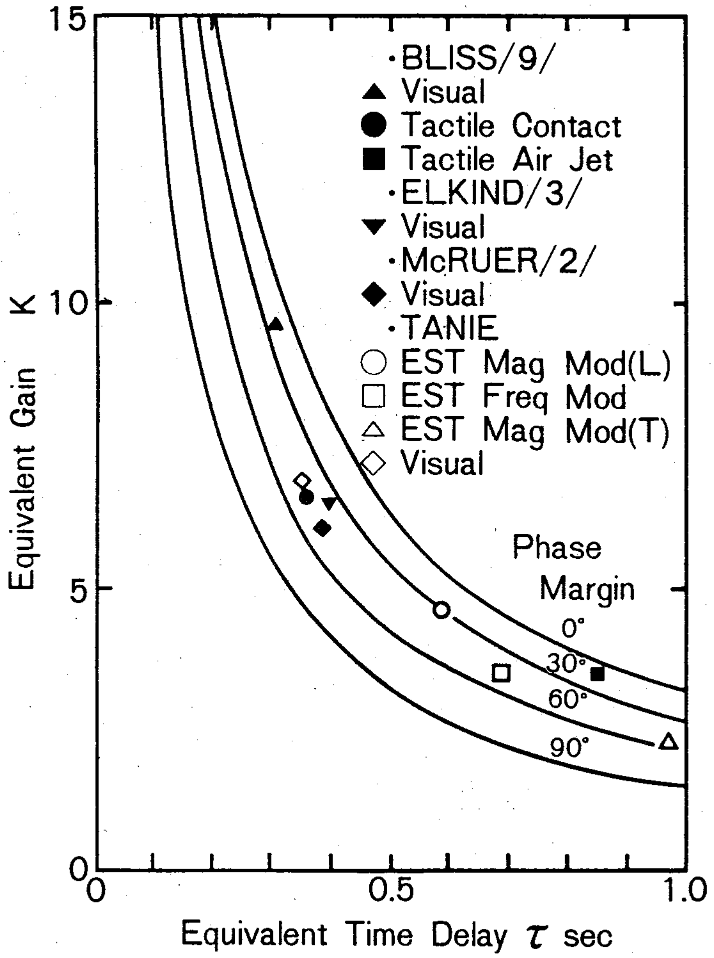


Fig. 8 Comparison of Displays (EST: Electrocutaneous Stimulation, Mag Mod(L): Linear Transformation Using Magnitude Code, Freq Mod: Frequency Transformation, Mag Mod(T): Threshold Transformation Using Magnitude Code, /2/,/3/,/9/: Indicate the Numbers of References).