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AN ANALYSIS OF MYOELECTRIC SIGNALS FOR THE PURPOSE OF APPLICATION TO PROSTHETIC ARMS

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Abstract

This paper is concerned with the basic studies on several methods for processing the myoelectric signals(EMG) to be applied to prosthetic arms. In the case of the static contraction of a muscle the EMG signals were processed by means of rectification and integration, of level-time ratio, of counting the number of peak amplitudes and of frequency spectrum analysis(using FFT). On the other hand, in the case of the dynamic contraction of the muscle the EMG signals were processed by means of frequency spectrum analysis. From these results, several characteristics of the EMG signals were discussed. In the both cases the skin electrodes(wet type) were used and the EMG signals were detected on the biceps of the upper arm.

1. Introduction

EMG signal constitutes one of the essential sources of signals necessary for proper control of prosthetic arms, and especially, EMG controlled prosthetic arms for below-elbow amputees are already being put into practical use. A method of processing of EMG signals widely adopted in these prosthtic arms is relatively simple and consists of rectification and flatening of the EMG signal derived from the same number of control sites on muscles as the degrees of freedom. Though simple as this method may appear, it can achieve its desired purpose since the degrees of freedom required do not exceed two. In the case of a prosthetic arm for a person with seriously damaged arm, however, the degrees of freedom required become much greater, the function of the arm more complicated, and accordingly the amount of control parameter much greater. It is, therefore, an essential prerequisite for proper control of such a prosthetic arm to devise such means of processing EMG signals that can derive as many signals as possible from as small a number of regions of the body as possible.

The present paper tries to analyze from the perspectives of the first approach various characteristics of EMG signals derived from a single muscle. A discussion of EMG from a specific angle such as this calls for clarification of the extent to which a human operator can control the emergence of EMG by his own free will. With this recognition, therefore, the present paper first pays attention to static as well as dynamic contraction motions of a healthy male adult's biceps--the most typical of EMG generating motions that a person can control by his will; and then probes into a method of processing EMG signals that can definitely associate these motions with the corresponding degrees of EMG. To be considered next will be the extent of discernibility of signals emerging from one paticular single muscular region with muscle motions. And the last part of the paper will deal with the speed of muscular contraction, and will also attempt to classify the EMG patterns that emerges as a result of muscular contraction motions into seven categories with the help of discriminant functions of the first and second orders.

2. Measurement of EMG and Data Processing

Among various methods of measuring EMG, we have adopted here the one that makes use of external electrodes because an electrode of this type is easier to handle and much safer in application to human bodies than other varieties such as a burried electrode and an acleate electrode. External electrodes are further subdivided into two different types, a wet type and a dry type. Then in the present experiment, the wet type are employed, since electrodes of wet type have advantage over those of the dry type in that the contact impedance between the electrode and the skin surface is kept stable.

In order to pick up EMG signals, there electrodes were fixed on the skin surface in a line along the direction in which the muscle fibers run and centering around the region where the muscle is most swollen. As a means of amplifying EMG signal output from these electrodes, an differential amplifier(1205C, SAN'EI SOKKI) was employed.

EMG signals obtained from the experiment is first resistered in the data-recorder(R-250, TEAC) along with the timing pulse(period, 200μs.) by way of frequency modulation technique(and at a resistration speed of 15 ips.) All kind of data processing involved in the experiment are read into the computer(NEAC-M4) and carried out by the program written by the NEAC-M4's basic assembler, and the processed data are typed out by the teletype.

3. Proceduree s of Experiment

As explained earlier, the static as well as dynamic contraction motions of a biceps are the subjects of the experiment. The rationable behind the choice of a biceps as the subject of experiment includes, among other things, the fact that the EMG generated by this muscle is of high enough magnitude to be picked up by external electrodes mounted on the skin surface and that various values of the muscle under normal conditions are readily measurable. There are good reasons to expect that this muscle is virtually free from the effects of other synargetic muscles. Thus the elbow's motions can be assumed to stand in a one-to-one correspondence with the muscle's motions. It is therefore possible to assess the contraction force and contraction speed of this muscle respectively by the amount of torque applied on the elbow and by the elbow's speed of rotation. In the remaining part of section 3, we shall deal with the procedures of experiments concerning static and dynamic contraction motions of the biceps.

3.1. An Experiment Concerning the Biceps' Static Contraction Motions

As illustrated in Figure 1(a), the righthand forearm is kept horizontal, with a weight hung down from the wrist and with the upper arm kept straight down. Under this condition, the biceps is considered to be in a state of static contraction, and the force of its contraction can be evaluated in terms of the weight of the load applied to the wrist. The value of EMG generated from the biceps is picked up by the external electrodes in accordance with the procedure explained in above, and is recorded by the data-recorder.

Six weights as a load--i.e.,0.5, 1, 2, 5, 7 and 10 Kg--were employed, starting the experiment with the lightest one and ending up with the heaviest one. The amount of EMG generated under each loading condition was monitored simultaneously through a synchroscope; and the data were recorded for approximately 15 seconds from the moment when the shape of the oscillogram was judged in the subjective opinion of the experimenter to have become sufficiently stabilized. After completion of one round of experiment and before going on to the next round with an increased load, a break of sufficient length was taken so as to enable the subject who was experimented with to recover from exhaustion. The length of such break was not determined beforehand, but was completely left at the discretion of the subject. The experiment was conducted on a total of three male adults of sound physical conditions.

(a) The Experiment of Static Contraction of Muscle.

(b) The Experiment of Dynamic Contraction of Muscle.

Fig. 1 The Method of Experiment

3.2. An Experiment Concerning the Biceps' Dynamic Contraction Motions

In undertaking an experiment concerning the biceps' dynamic contraction, a potentiometer is fixed on the subject's righthand arm as a device to measure the elbow angle. (See Figure 1(b).) This angle detecter is made up of two aluminium bars which are connected with each other at one end and which are fastened with belts at the other ends to the forearm and the upper arm, respectively. With the angle detector fixed on his arm in this manner, the subject is asked to move his forearm 90 degrees from down below to a horizontal direction, keeping time with the rhythm beaten by a metronorm. Upon completion of one round of motions, the subject is asked to repeat the same at a different tempo.

This experiment rests on the assumption that when the subject makes these moves his biceps contracts in direct proportion to the angle of his elbow; with this assumption, the speed at which the biceps contracts is evaluated in terms of the speed at which the elbow is flexed. The potentiometer's output and the output of the biceps' EMG are recorded by the data-recorder as the output data of the experiment. The speed of elbow flection was raised in 6 equal increments starting from the minimum speed estimated beforehand, below which EMG would not be detectable, all the way through the maximum possible speed for the subject. An experiment at each elbow flection speed was carried out only after the subject had made some practice and made himeself sufficiently accustomed to the speed. Before proceeding to a new round of experiment, a break of sufficient length was taken so as to enable the preceding one. This experiment was conducted on one male adult of sound physical conditions.

3.3 Evaluation Methods of EMG

In the present paper, special attention was paid to rectification -integration(RI), analysis of level-time ratio(LT), examination of the number of peaks(PC), and frequency analysis as the EMG processing algorithms which seem to be effective in evaluating the characteristics of the EMG signals. The data obtained from the two sets of experiments; and an attempt was made to evaluate the processed data side by side with the parameters of muscular motions, i.e., force and speed of contraction.

The formula of calculation of RI and LT takes the following form, respectively(T: average time span, Δt: sampling time, N: sampling magnitude per one processed data, α: slice level, 2048: AD c. output corresponding to 0[V]):

$$I=\sum_{i=1}^{N}|X_i-2048|/N \qquad T=\Delta t\cdot N \qquad (3.1)$$

$$LT=\{\sum_{i=1}^{N}\mathrm{sign}(X_i-\alpha)/N\}\times 100\ [\%] \qquad T=\Delta t\cdot N \qquad (3.2)$$

(signX=1, when $X\geq 0$ and signX=0, when $X<0$)

The average number of peaks, PK is calculated in the following way:

$$PK=(M/N)\times 100\ [\%] \qquad T=\Delta t\cdot N \qquad (3.3)$$

The processed data by the frequency analysis is obtained by FFT, and the magnitude of it is evaluated by $\sqrt{(A_n\cos\alpha_n)+(B_n\sin\alpha_n)}$--$A_n\cos\alpha_n$, $B_n\sin\alpha_n$...Fourier coefficient of each frequency component.

4. Results of Experiment

4.1. Characteristics of Rectification and Integration of EMG in case of Static Contraction Motion

Figure 2 summarizes the relationships, observed for one of EMG and the muscular contraction force. The results obtained from the same experiment conducted on the two other subjects are more or less the same. These experiments were carried out in accordance with the procedure specified in section 3.1, and the derived signals were processed with the aid of equation(3.1). Plotted along the horizontal axis of the figure is the muscular contraction force expressed in values of load hung down from the wrist. The vertical axis represents the output value of the AD converter. Each pair of curves in the figure are drawn for each time span of integration and show the upper and lower limits between which data are fluctuated. As can be readily seen from the figure, the muscular contraction force and the rectification-integration value of EMG shows an approximately linear correlation until the former reaches a certain level, and when that level is surpassed, the latter starts increasing at an accelerated rate for each unit increment of the former. The extent of fluctuation of the EMG output values is rather significant, and tends to grow larger as the muscular contraction force increases.

4.2. Characteristics of the Level-Time Ratio of EMG in case of Static Contraction Motion

Figure 3 illustrates the characteristic features of the level -time ratio of EMG in relation to the contraction force. The experiment was carried out in accordance with the procedure specified in section 3.1 and the signals derived were processed with the aid of equation(3.2) In other to illustrate how the level-time ratio varies in relation to the contraction force we are employing in the figure two kinds of the level α: in one case the level-time ratio LT in theabsence of load is set at 0[%], while in the other it is set at 50[%]. For each predetermined time span of observation(T=Δt ·N), one pair of curves are drawn to specify the upper and lower limits of data fluctuation. It is revealed by the figure that in case LT is set at 50[%] in the absence of load by level α, LT remains almost constant for varying values of contraction force. This seems to suggest that the EMG signals are distributed symmetrically with respect to this level of α. It is characteristic of this processing method that it is capable of transforming the relationship between the muscular contraction force and LT rather freely

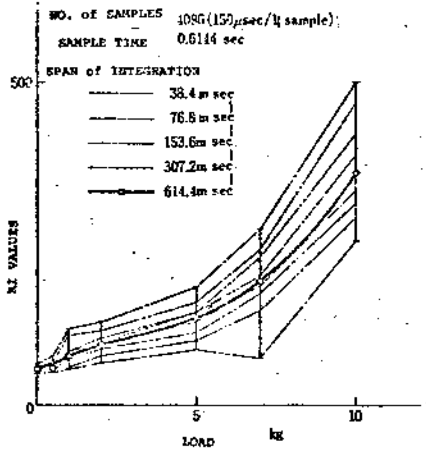

Fig. 2 The Relation between Muscle Contraction Force and Rectification-Integration Values of EMG.

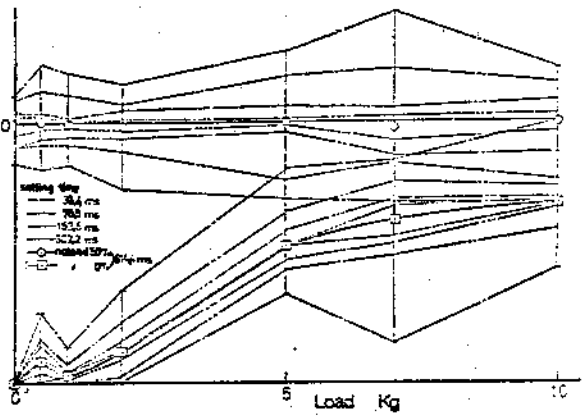

Fig. 3 The Relation between Muscle Contraction Force and Level-Time Ratio of EMG.

by simply changing the level α. Contrary to what was expected before the experiment, however, shifting of the level α was found to be effective only very slightly in removing disturbing factors from the data. If good linearrity is to be required between the contraction force and LT, however, it is best to set the level in such a way that the output in the absence of load becomes zero. And the relationship obtained in this way exhibits almost the same characteristics as those of rectification-integration.

4.3. Characteristics of the Number of Peaks of EMG signals in case of Static Contraction Motion

The relationship between the musclar contraction force and the number of peaks generated by the EMG signal is characteristically shown in Figure 4. In identifying the characteristics of the relationship, the experiment was carried out in accordance with the procedure specified in section 3.1. and the data derived were processed with the aid of equation(3.3). The two curves which summarize the results of experiments conducted on two subjects show a similar trend. Unlike the rectification-integration and the level-time ratio which we described in the preceding sections, the number of peaks decreases as the contraction force increases. This seems to be due to the fact that when the contraction force becomes greater, its effects tend to be superimposed by an accompanying increase in the amount of nerve impulse applied on the muscular fibers, thereby making the effects of the EMG peak pulse less discernible. By the way, the data used in Figure 4 were obtained from a total of 4096 sampling points.

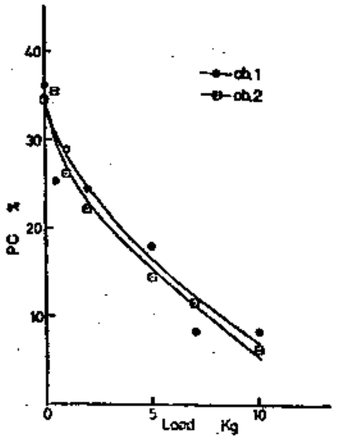

Fig. 4 The Relation between Muscle Contraction Force and the Peaks of EMG Signals.

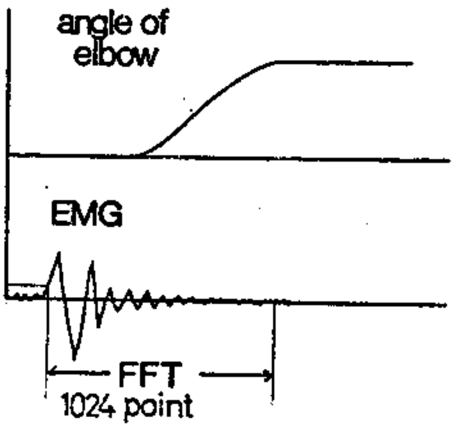

Fig. 5 The EMG Output of Dynamic Contraction of the Muscle and FFT Processing.

4.4. Analysis of Frequency of EMG Signals in case of Static and

Dynamic Contraction Motions of Muscles

Figures 6 and 7 are the results obtained by the frequency analysis, each showing how the frequency component is distributed in the EMG signals derived from static as well as dynamic motions of the biceps. The analysis was carried out on the basis of those data that were obtained in the experiments mentioned in sections 3.1. and 3.2. In analyzing the oscillograph of the EMG recorded during static contraction motions of the muscle, eight different sets of data, each consisting of 1024 point data chosen from the random point on the oscillogrph, were read into the computer; and each of these sets was processed by the fast Fourier transformation technique. Figure 6 is expressed in terms of the average values of the results obtained from the eight rounds of FFT for each frequency level. In the analysis of the EMG recorded during dynamic contraction motions of the muscle, on the order hand, the procedure illustrated in Figure 5 was followed: first the oscillograph of EMG was rectificated and integrated; and the FFT processing was undertaken starting from the point where the integral had exceeded a certain limit value(i.e., 100 when expressed in terms of an AD output) on the assumption that such point would mark a point of emergence of an oscillogram in question. The numbers written in Figure 7 stand for the speeds of elbow flection.

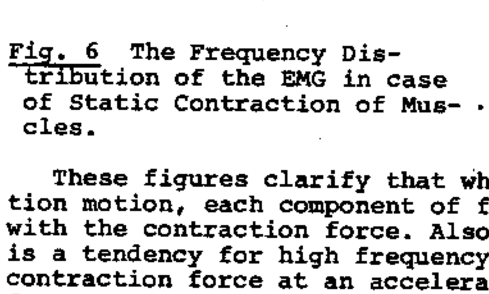

Fig. 6 The Frequency Distribution of the EMG in case of Static Contraction of Muscles.

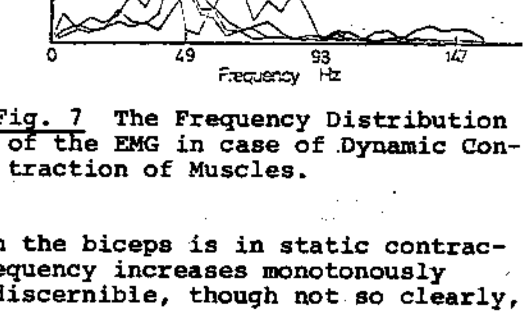

Fig. 7 The Frequency Distribution of the EMG in case of Dynamic Contraction of Muscles.

These figures clarify that when the biceps is in static contraction motion, each component of frequency increases monotonously with the contraction force. Also discernible, though not so clearly, is a tendency for high frequency components to increase with the contraction force at an accelerated rate--i.e., a tendency for the frequency band with high output elements to shift toward the right. When the biceps is in dynamic contraction motion, on the other hand, the pattern of frequency distribution varies depending on the speed of elbow flection, as illustrated in figure 7. More precisely, the frequency components in the neiborhoods of 50, 20 and 70[Hz] tend to increase relatively when the elbow is moved fast.

Though the fluctuation of each frequency component's experimental values was examined, the mode of fluctuation was found to be almost the same in every case, and there was observable no such phenomenon as the one where on the condition of a certain degree of muscular contraction a certain frequency component becomes exceptionally stable. It was found, however, that as a matter of general rule frequency components show a lower degree of fluctuation when the muscular contraction force becomes smaller.

5. Discrimination of the Patterns of EMG's Frequency Distribution in case of Dynamic Contraction Motions of a Muscle

With a view to associating in a definite way a "muscular motion" --a basic body movement which a human being can control by his free will--with the corresponding EMG, we undertook an experiment to compare four different methods of processing data of EMG. As a result of this experiment a monotonous relation was found to exist between the amount of muscular motion and the EMG output after each processing methods, the processed values of EMG behave in a statistical way in relation to the corresponding muscular motions. If these values, therefore, are to be digitalized with sufficient clarity for use as control signals, they must be processed by some proper statistical method of one sort or another before they are put into practical application. The present section, therefore, concerns itself with an attempt we made to classify patterns of EMG's frequency distribution into seven categories with the use of discriminant function --a treatment which we devised in view of the fact that the speed of muscular contraction, as has been clarified in section 4.4., depends on these patterns. More precisely, we examined how well the frequency distribution patterns of EMG picked up from the biceps' single muscle could be discriminated from each other, when doing the elbow-flection of the seven alternative speeds. We chose the speed of muscular contraction motions are more voluntarily controllable than static contraction motions and that some attempts had already been made to discriminate signals obtained from static contraction motions.

5.1. Derivation of Discriminant Function

In preparation for introduction of discriminant functions, a frequency distribution pattern of the EMG concerned is characterized as $X=(X_1, X_2, ... X_d)$ where d stands for the number of elements included in a pattern while t is a symbol indicating that the matrix concerned is a transposed one. We assumed that X is a multi-variable normal pattern(as we can rightly do so on the basis of the relevant data in the past/1/). Under this assumption, the discriminant function which classify optimully this pattern set X to R categories is expressed as:

$$g_i(\vec{X})=b_i-\frac{1}{2}[(\vec{X}-\vec{M}_i)^t\Sigma_i^{-1}(\vec{X}-\vec{M}_i)] \quad (i=1,...R)$$

$$b_i=\mathrm{Log}P(i)-\frac{1}{2}\mathrm{Log}|\Sigma_i| \qquad (5.1)$$

If we denote $\Sigma_1=\ldots.=\Sigma_R=\Sigma$, it is expressed as:

$$g_i(\vec{X})=\vec{X}^t\Sigma\vec{M}_i+\mathrm{Log}P(i)-\frac{1}{2}\vec{M}_i\Sigma_i^{-1}\vec{M}_i \qquad (5.2)$$

where P(i):a priori probability, $M^t=(M_1,M_2,\ldots.,M_8)$:the vector of mean values, M:the mean value of element i, Σ:covariance matrix. Σ_i, Σ and M_i in these discriminant functions can be determined from the so called training set composed of patterns whose categories are already known. For training set χ_i(i=1,...,R), M_i and Σ are expressed in the following way:

$$\vec{M}_i=\frac{1}{N}\sum_{\vec{X}\in\chi_i}\vec{X}\ , \qquad \Sigma_i=\frac{1}{N_i}\sum_{\vec{X}\in\chi_i}(\vec{X}-\vec{M}_i)(\vec{X}-\vec{M}_i)^t \quad (i=1,..,R)$$

Above discriminant functions become the first order in (5.2), and the second order in (5.1).

5.2. Determination of the Training Set and Patternization of EMG

Prior to the derivation of the discriminant functions, the training set must first of all be determined. The data for use in the determination of the training set were collected in accordance with the procedure explained in section 3.2. As mentioned earlier, there are a total of seven categories for discrimination. In deciding the category numbers, the speed of elbow flection was increased in 6 equal increments starting from the lowest level(i.e., 96-position of metronorm indicater), below which EMG could not be detected, all the way through the maximum possible speed for the subject(i.e.,192 -position of metronorm indicater); and the seven different speeds(192, 168, 152, 138, 126, 108 and 96-positions of metronorm indicater) were each attached with one category number, randing from 1 through 7, in the exact order indicated here. A total of 140 rounds of experiment, or 20 rounds each for one category, were conducted. The training set was determined by sampling 15 out of 20 data of each category at random, and on the basis of these data M_i, Σ_i and Σ were determined. Also, P(i) eas assumed to be equal for each category, i. e., P(i)=1/7.

In patternizing the data, the output values of EMG were first processed by the FFT technique in the same manner as illustrated in Figure 5. The processed data were classified into 8 frequency bands --i.e., 0-40, 40-80, 80-120, 120-160, 160-240, 240-320, 320-400 and 400-480[Hz]--and for each band the mean value of amplitudes was caluculated. If the mean value is denoted as X (i=1,..,8), then the oscillograph of EMG is characterized as X=(X ,...,X).

5.3. Results of Discrimination

As shown in Table 1, the percentage of correct discrimination attained by discriminant functions of the first order was approximately 51[%], whereas the one by discriminant functions of the second order was about 72[%]. With smaller numbers of discrimination categories--i.e., 2 to 4 categories in case discriminant functions of the second order were used, and 2 to 3 categories in case discriminant functions of the first order were used--the percentage of correct discrimination was in the order of 90-100[%]. These results seem to suggest that the patterns of EMG are discernible on the basis of the speed of muscular contraction provided that the number of discrimination categories is chosen properly. Therefore, in the future the pattern classification method on the base of the speed of muscular contraction may prove to be a reliable mean for switching control. Unfortunately, however, the percentage of correct discrimination attained by discriminant functions of the first order in case of 7-stage discrimination was far from satisfactory, even though the percentage attained by the discriminant functions of the second order was somewhat better. Perhaps this is partially due to the fact that the subject did not have much excercise in elbow flection movements when the data for determination of the training set were collected, and also to the fact that the choice of elbow flection speed for each category was not sufficiently adequate. It appears that a better percentage of correct discrimination can be achived if these defects are overcome.

Table 1. Percentage of Correct Discrimination [illegible]

Category	[illegible] Second Order	[illegible] Function of First Order
1	90	20
2	83	42
3	60	43
4	56	36
5	[illegible]	20
6	73	53
7	[illegible]	6

Table 2(a) Number of Discrimination Categories and Percentage of Correct Discrimination (Discriminant Functions of Second Order)

No. of Discrimination Categories	% of Correct Discrimination	Combination of Categories
2	100	1-3,?-6,?-5,?-6 1-7,2-3,2-4,2-5 [illegible]
3	100	1-6-7,[illegible] [illegible]
4	[illegible]	[illegible]
5	84.0	[illegible]
6	[illegible]	[illegible]
7	72.5	[illegible]

Table 2(b) Number of Discrimination Categories and Percentage of Correct Discrimination (Discriminant Functions of First Order)

No. of Discrimination Categories	% of Correct Discrimination	Combination of Categories
2	100	[illegible] [illegible] 2-7
3	93.3	[illegible] [illegible]
4	81.0	[illegible]
5	70.0	[illegible]
6	[illegible]	[illegible]
7	51.4	[illegible]

6. Conclusions

From the discussions above, we can draw the following conclusions. (1) Both rectification-integration values of the EMG and the level-time ratio increase monotonously with the muscular contraction force; so do the degrees of fluctuation of their values. This finding of ours is in rather good agreement with those of other reserchers. (2) As the muscular contraction force increases, various frequency components of the EMG increase in almost the same way and so do the degrees of fluctuation of their values. (3) The number of peaks involved in an oscillograph of EMG decreases as the muscular contraction force becomes greater. (4) There exists a mutual correlation between the muscular contraction speed and the patterns of distribution of various frequency components of EMG. And when the patterns of distribution are classified into seven different categories with the aid of discriminant functions of second and first orders, the percentages of correct discrimination attained by the two kinds of functions are respectively 72.5 and 51.4[%]. The percentage is raised to the order of 90-100[%] when the number of categories is reduced to 2-4.

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