Proc. of 5th Int. Symp. on External Control of Human Extremities, ETAN, Yugoslavia, Dubrovnik 1975.

THE MYO-ELECTRIC SIGNAL ANALYSIS FOR ARTIFICIAL UPPER EXTREMITY

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ABSTRACT

The action potential obtained from surface electrodes has been analysed for controlling powered upper prostheses.

Based on the fact that the action potential fundamentally has digital-like characteristics, the new processing method in which myo-electric signal is converted into digital pulses has been developed.

At first, the satisfactory linear relationship was recognized between load and pulse-coded myo-electric signal. And secondly, on the controlability test by using one muscle, the subject could easily differentiate and voluntarily control the myo-electric signal value into 5 grades. Lastly, a set of 8 kinds of control signals corresponding to each of the 8 kinds of the prosthetic movement are isolated by the pattern recognition technique using 6 forearm muscle groups.

INTRODUCTION

It has been an established technique to obtain control signal of powered upper extremities from myo-electric signal with surface electrodes. And myo-electrically controlled hands with one degree of freedom have been used practically and clinically for a long time. Besides, myo-electrically controlled upper extremity prostheses with multi-degrees of freedom have also been investigated and developed[1]. It may be a suitable method that the control signals for powered prostheses are derived from voluntary movements of the phantom limbs. Therefore, if the powered prostheses have multi-degrees of freedom, it should be one of the optimal methods to use pattern recognition technique that discriminates myo-electrical signals of the stump muscles followed by the movements of phantom limbs[2]. It has been reported that the muscles' activities are categorized by using the discriminant functions and the some degrees of freedom of the powered limbs can be controlled by the voluntary movements of the phantom limbs[3]. When we would apply such a pattern recognition technique to myo-electric signals, it may be desirable to get as possible as many categories with less electrodes.

We will describe, here, on the new method to derive as much information as possible concerning to muscle contraction. The myo-electrical signal can be derived from surface electrodes, and are processed in order to obtain digital signals. And then, the experiments to get the control signals for below-elbow prostheses of multi-degrees of freedom will be described. The goal of this research is to construct the control system which makes it possible to control independently and coordinatedly 3 degrees of freedom by means of the stump muscles according to preserved sensation of the phantom movement.

The purposes of experiment are as following.

(a) The number of stump muscles available for the signal source is larger than that of a upper arm or a humeral disarticulation amputee.

(b) The powered artificial limb with multi-degrees of freedom should be controlled coordinatedly and the construction of the control algorithm should become an important problem. However, the below-elbow prostheses with multi-degrees of freedom may require less coordinate movements, since they are restricted into a few movements in usual daily life, and so the signal processing should become easier.

(c) By using this myo-electric processing method described here, the signal to select the category of the movements and to control their forces may be obtained, but not to control the position. Consequently, in order to control position of prosthesis, it should be operated due to another complicated control algorithm (for example, employing the end-point control system or the rate control system) or the difference of the period during the myo-electric signal presented. The positioning of wrist joint of the below-elbow prosthesis is, however, decided by means of residual extremity, so the direction of the terminal device and its movement e.g., hand opening and closing, should be controlled. Therefore, it would become possible to control these functions by means of the time interval when myo-electric signals are presented.

Then we should discuss the voluntary control ability of myo-electric signal both in the below-elbow amputee and the normals.

PROCESSING METHOD FOR THE MYO-ELECTRIC SIGNAL

Generally, the rectified and smoothened myo-electric signal has been used as a control source of powered artificial prostheses. But, it should be desirable to develop a new method of myo-electric signal processing that can offer more accurate and more information in order to control the equipment precisely. D.C. Childress reported about the method in which the myo-electric signals are converted into trains of pulse signals and then, the hand opening-closing is controlled proportionally by them[4]. We have introduced an improved procedure for the pulse-coded myo-electric signals.

The system for pulse-coding

Our interest is the duration when the amplitude of signal is over a certain threshold level. Fig.1 shows the block diagram used in this experiment. The time chart which indicates the principle of our method is also shown in Fig.2.

At first, myo-electric signal derived from surface electrodes is amplified by a differential amplifier (wave form A). Then, the amplified signal is converted into the pulse when the signal potential is higher than a reference voltage by means of an I.C.comparator and a shmitt trigger (wave form B). Lastly, to measure its

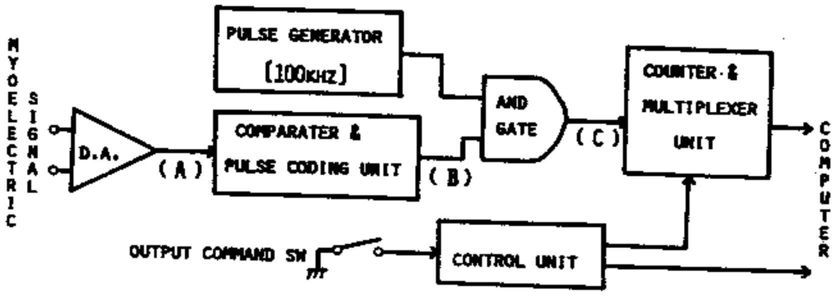


Fig.1 BLOCK DIAGRAM OF PULSE CODING SYSTEM

pulse width an AND gate is used with high frequency clock pulses of 100[kHz] (wave form C). Thereafter, the pulse signals are summed up per unit time (i.e., 100 [ms]) by a control unit. Hence, we call it pulse-coded myo-electric signal.

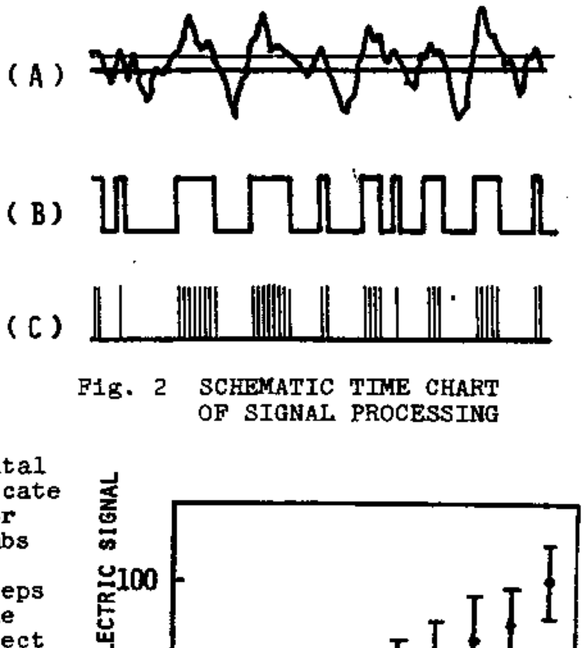


Fig. 2 SCHEMATIC TIME CHART OF SIGNAL PROCESSING

Relation between load and pulse-coded signal

The first study is done for establishing the relation between the pulse-coded myo-electric signal and the load to the muscle as the fundamental experiment, which may indicate whether it is available for controlling artificial limbs or not.

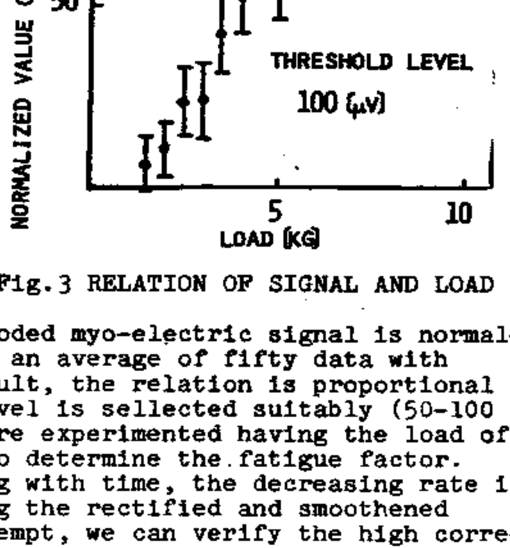


Fig.3 RELATION OF SIGNAL AND LOAD

The activities of Biceps Brachii are recorded in the following manner: the subject is asked to keep his humerus vertically and set his fore-arm horizontally as well as suitably pronated, and the load is on his palm with standing position. In such a position, it is well known that Biceps is mainly supporting the load as a prime muscle 5). So it may be reasonable to measure the relation between the load applied and the myo-electric signal derived from Biceps. One of typical results is shown in Fig. 3. In this diagram, the load is varied from 0 to 10[kg] and the value of pulse-coded myo-electric signal is normalized. And each point indicates an average of fifty data with respect to each load. As a result, the relation is proportional to the load if the threshold level is sellected suitably (50-100 [μv]). Besides, few subjects are experimented having the load of 10[kg] for approximatly 90[s] to determine the fatigue factor. Although the value is decreasing with time, the decreasing rate is not so large compared with using the rectified and smoothened signal method. In such an attempt, we can verify the high correlation between the averaged pulse-coded myo-electric signal and the load. The signal has to be measured quantitatively. In this experiment, the threshold level is varied between 50 and 100[μv] and the refference voltage of the comparator is from 20 to 50[mv].

Accodingly, this result shows that only the high input-impedance amplifier having a gain of about 50[dB] may be necessary in order to control this system. From the practical point of view, this fact would be an advantage for the control system in future.

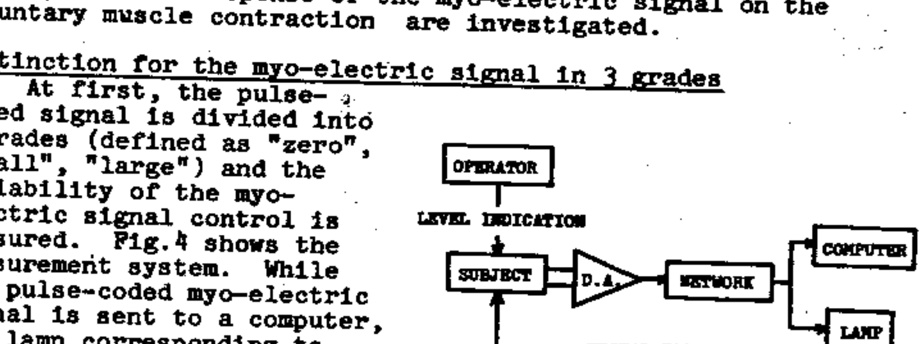
VOLUNTARY CONTROL OF A MYO-ELECTRIC SIGNAL

The relationship between pulse-coded myo-electric signal and the load to the muscle has been already described. It is necessary to investigate the human controlability of the myo-electric signal in order to utilize this method for controlling the powered artificial prostheses. So, the output of one-channel myo-electric signal is divided into several levels, and the human controlability and the response of the myo-electric signal on the voluntary muscle contraction are investigated.

Distinction for the myo-electric signal in 3 grades

At first, the pulse-coded signal is divided into 3 grades (defined as "zero", "small", "large") and the reliability of the myo-electric signal control is measured. Fig.4 shows the measurement system. While the pulse-coded myo-electric signal is sent to a computer, the lamp corresponding to one of the levels among 3 grades turns on so that the subject is able to know the state of the myo-electric signal through a visual feedback. The summing period of the pulse-coded myo-electric signal is 100[ms]. It is easy to hold the levels of myo-electric signal "zero" and "large", but to hold the level of "small" is rather difficult. Therefore, we measure the reliability of the myo-electric signal control in varying the range of "small" level. Here, the myo-electric signal in the "small" level is defined as correct response and the myo-electric signal in other levels is defined as an error. The subjects are four adults (two males and two females), and one of them is a below-elbow amputee (male).

Fig.4 MEASUREMENT SYSTEM



a) b)

Fig.5 RANGE OF "SMALL" LEVEL — CORRECT RESPONSE RATIO

The results are shown in Fig.5. In this figure, abscissa; a normarized value for the range of "small" level, ordivate; the time ratio of a correct response in a single measurement (called as the "correct response ratio" in the following). The results for the activity of the Palmaris Longus of a normal subject are obtained from the experiment with the threshold level of the pulse-coded myo-electric signal as a parameter (see Fig.5a)). From the results, it is obvious that the wider the range of the level and the lower the threshold become, the subject could control myo-electric signal more easily. It seems that the same results are obtained from the experiment with other muscles and subjects. Fig.5b) also shows the results with the stump (right) and the normal side(left) of a below-elbow amputee. In these experiments the threshold level is fixed at 50[μv]. It is noted that there are little differences between subjects or between muscles from the results. Then it may be said that this processing method could be available to the control signal for the powered artificial prostheses.

Learning ability

The myo-electric signal is divided into 5 grades according to the preceding results, and the learning effects of 2 normal subjects due to 5 or 10 days experiments are investigated. The distinction for the levels are arranged by trial and error method, and the reliability of the myo-electric signal control in the three middle levels of myo-electric signal are measured in the same manner as the former experiments. The threshold level is fixed at 50[v], and the muscle used is Extensor Digitorum Communis.

Fig.6 shows the learning curves of the "correct response ratio". Here, each point indicates an arithmetic mean of the "correct response ratio" of three middle levels. Here, it seems that the "correct response ratio" is always limited under 80~90[%] and the subjects are able to achieve theese performances without learning.

In order to utilize this method for the control signal of the powered artificial prostheses, the "error" of the response has to be eliminated. Then, the continuing time intervals of one error are measured in the experiment with a visual feedback (see a histogram in Fig.7). From the figure, the errors are short enough

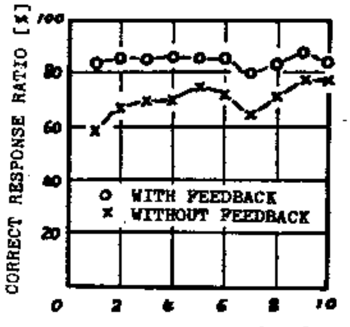


Fig.6 LEARNING CURVE OF "CORRECT RESPONSE RATIO"

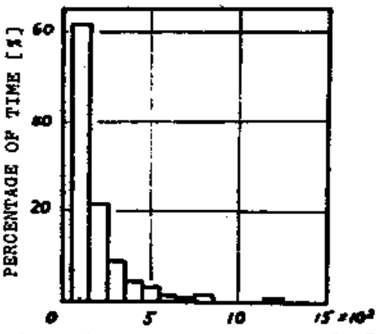


Fig.7 "ERROR CONTINUING TIME INTERVAL

and almost within 500[ms], so it seems to be negligible. Due to the fact that only 4 grades distinction was reported using the rectified and smoothened method of myo-electric signal, and the "correct response ratio" for such method was lower than that of the pulse-coded method, it might be said that the pulse-coded method is superior for control of powered artificial prostheses6).

Response of pulse-coded myo-electrical signal

The response of the myo-electric signal using the same system is investigated (see Fig.4). The myo-electric signal level needed is indicated with a target lamp at mixed up order, while other conditions are same with the learning experiment. Measuring the time delay between the lamp on and the correct response, it is about 450 750[ms]. In the rectified and smoothened method referenciating the myo-electric signal into 4 grades, it was reported that the delay was from 350~700[ms]6). Although, the delay is slightly greater here, because of a fine distinction of myo-electric signal levels, we may decide that this processing method is superior to the rectified and smoothened method judging from the response.

CATEGORIZATION OF MYO-ELECTRIC SIGNALS

The purpose of this experiments is to analyze the control system by myo-electric signals which are obtained from only fore-arm muscles. Suppose that the prostheses have three degrees of freedom i.e., hand opening and closing, pronation and supination and dorsi flexion and volar flexion of wrist joint. Then, we define 8 categories of movement. Those categories are corresponding to each movement of prostheses and 2 coodinated movements i.e., volar flexion + supination and dorsi flexion + pronation, and those movements are supposed to be most frequently used through the activity of daily living. Thus the myo-electric signals for each movement should be discriminated.

Muscles

The muscles for control should be located in the amputation stump and around the surface of the forearm. So the muscles used in this experiments are selected as follows,

(a) Extensor Carpi Radialis,
(b) Extensor Digitorum Communis,
(c) Extensor Carpi Ulnaris,
(d) Palmaris Longus,
(e) Flexor Carpi Ulnaris,
(f) Flexor Digitorum Profundus,
(g) Flexor Carpi Radialis,
(h) Pronator Teres.

In these muscles, the activities of P.L. and F.C.R. have shown almost the same pattern during different movements, so F.C.R. is neglected. If a subject did not have the muscle of P.L., F.C.R. used instead. The muscle of P.T. is neglected, since the activities are relatively small. Therefore, in the following experiments, we use the activities of 6 muscles from (a) to (f).

The patterns of the muscle activities

Myo-electric signals from these muscles are processed through the networks described before, and the data are analyzed by the computer. The movements which generate these signals are grip

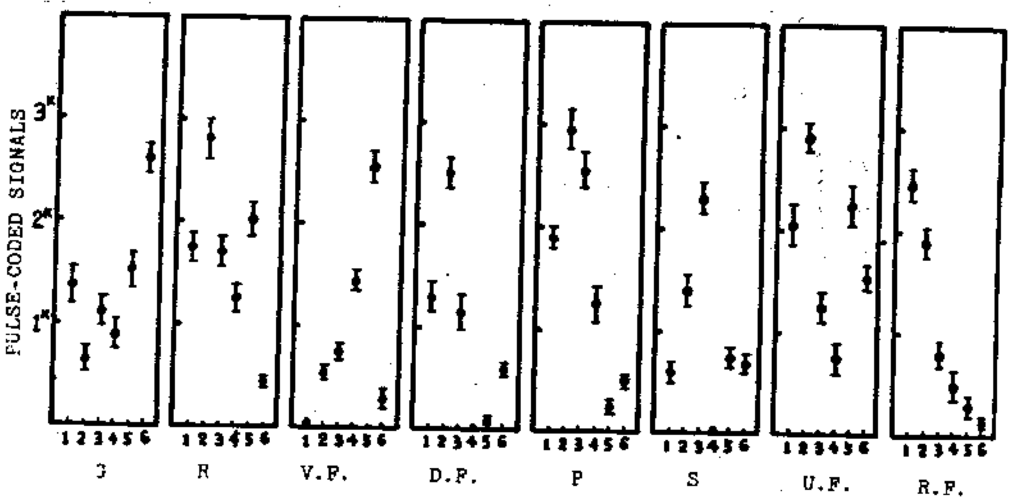


Fig.8 MYO-ELECTRIC PATTERNS OF 8 MOVEMENTS
Muscles; 1=E.C.R.,2=E.D.C.,3=E.C.U.,4=P.L.,5=F.C.U.,6=F.D.P.

and release of a hand(or phantom hand), pronation and supination, volar flexion and dorsi flexion, ulnar flexion and radial flexion of a hand. Ulnar and radial flexions are used to control 2 coodinated movements of the prostheses, since the myo-electric patterns is not constant during these coordinated movements when the subjects control their myo-electric activities.

The examples of myo-electric patterns during 8 kinds of movements are shown in Fig.8. Each pattern of myo-electric activities has own characteristics, and it does not show much variation during the same movement under the same experimental circumstances. The difference between amputee and normals are observed, but between repetitions of the same movements of one subject, either amputee or normal,is not so much difference.

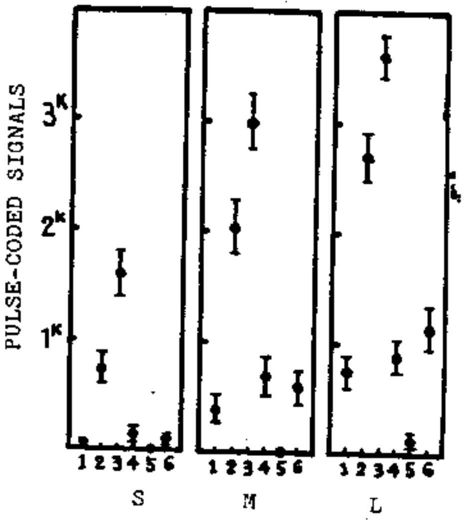


Fig.9 MYO-ELECTRIC PATTERNS OF DIFFERENT MOVEMENTS

When the subject changes the force of muscle contraction of each movement, the characteristics of myo-electric patterns are not much changed, and the output lovels of the pattern moves toward up or down (see Fig.9).

Categorization using the linear discriminant function

In order to construct the control systems of powered prostheses, myo-electric signals in different movements of phantom or real hand are categorized by means of the linear discriminant function. This function is as follows,

$$g_i(X)=X^t\Sigma^{-1}M_i+\log p_i-1/2M_i^t\Sigma^{-1}M_i \qquad (i=1,2,\cdots 8) \qquad (1)$$

where $X=\begin{matrix}x\\x\\\vdots\\x\end{matrix}$, and X is patterns,

M_i is mean vector of X_i,

Σ is covarience matrix and $\Sigma=E[(X-M)(X-M)^t]$

p_i is a priori probability, and it is constant here.

The subjects are one below-elbow amputee and two normals. A set of training data is recorded, and the testing set is also recorded on the same day after the training is done. The testing set is also recorded on the other day to examine the difference between the data. The training set is used to construct the linear discriminant function, and the testing set is used to evaluate the reprodusability of myo-electric patterns. In order to control the contraction force, one muscle concerning mainly to each movement is selected among 6 muscles. Then, as same as the former experiment, the state of the activity of this muscle is indicated with the lamp, and the subject controls the force through a visual feedback.

At first, to investigate how much categories the subject can generate by means of myo-electric patterns, the training set is discriminated by using eq.(1). The results of normal subjects show that 8 kinds of movements can be exactly discriminated. Table 1 shows the result with an amputee, and in this table the discriminant rates of some categories become low. Secondly, the testing set is discriminated with normal subject to evaluate the reprodusability of myo-electric patterns. These results are shown in Table 2. Here, A and B show the results in which the training and testing set are both recorded on the same day, and C shows the result in which the testing set is recorded on the other day. B and C are the results of one subject and A is different one.

From these results, it may be described that normal subjects can generate voluntarily 8 kinds of myo-electric patterns and its reprodusability is fairly high. Concerning to the amputee, however, his ability of generating patterns are less than that of normals, and it is somewhat difficult for him to maintain myo-electric patterns constantly. This system does not have either machine or human learning function, if the machine should have the

Table 1.
Result of categorization with an amputee (training) %

Real Move	Categorizer Decision G.	R.	V.F.	D.F.	P.	S.	U.F.	R.F.
G.	100	0	0	0	0	0	0	0
R.	0	100	0	0	0	0	0	0
V.F.	0	0	100	0	0	0	0	0
D.F.	0	42	0	54	0	4	0	0
P.	0	8	0	20	70	2	0	0
S.	0	2	0	0	0	88	10	0
U.F.	6	12	0	16	4	2	60	0
R.F.	0	0	0	0	0	0	0	100

Table 2.
Result of categorization with normals (testing) %

	A	B	C
G.	100	100	74
R.	60	100	24
V.F.	98	100	100
D.F.	100	92	100
P.	90	84	76
S.	98	100	100
U.F.	76	100	98
R.F.	100	100	100
Average	90	97	84

function, it would be expected that 8 kinds of myo-electric patterns may be generated and reproduced by both amputee and normals.

The categorizer using a linear discriminant function is easily realized by means of weight-coefficients. As the pulse-coded myo-electric signals are thought to be able to offer more information than that of rectified and smoothened signals, it might be possible to discriminated more categories of myo-electric patterns using a linear machine.

Categorization using quadric discriminant function

The quadric discriminant function is introduced to investigate the ability of generating maximum information which are obtained from surface myo-electric signals. This function is as follows,

$$g_i(X)=\log p_i-1/2\log|\Sigma_i|-1/2[(X-M_i)^t\Sigma_i^{-1}(X-M_i)] \quad (i=1----24) \qquad (2)$$

Subjects are one amputee and one normal, and only the training set is recorded. The subjects are asked to change 3 grades of forces corresponding to each of 8 kinds of movements described before. Thus, 24 categories of myo-electric patterns are recorded, and the training set itself is tested using eq.(2). Table 3 shows the results of the normal and Table 4 the amputee. It might be described that both normal and amputee subject can generate 24 categories of myo-electric patterns. The quadric machine, however, is difficult to be realized in the control system of the powered prostheses without assistance of any kind of a computer.

Table 3.
Result of quadric discrimination with a normal (training) %

movement / force	G.	R.	V.F.	D.F.	P.	S.	U.F.	R.F.
L.	100	98	100	90	100	96	98	100
M.	100	98	98	68	98	98	96	100
S.	100	98	96	88	94	96	98	100

Table 4.
Result of quadric discrimination with an amputee (training) %

movement / force	G.	R.	V.F.	D.F.	P.	S.	U.F.	R.F.
L.	26	100	100	100	98	100	100	84
M.	64	78	78	88	58	98	76	72
S.	76	72	98	96	74	82	76	90

CONCLUSION

The first step of investigation with purpose of constructing the control system of multi-degrees of freedom has been described. It is found that so called pulse-coded myo-electric signals can be utilized to control the powered prostheses, and it can offer more information from one muscle compared with conventional method.

A linear machine may be easily implemented from the results of the experiment, and it will bring a very convenient control system for a below-elbow amputee. Thus, the amputee may control his prosthesis with phantom movement of his hand, which was used to move his real hand before his amputation.

24 categories of myo-electric patterns can be easily discriminated using quadric discriminant functions from activities of 6

forearm muscles. This method would be useful for analysis of muscles activities for the other biomechanical or kinesiological investigations as well.

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