DEVELOPMENT OF A MULTIPLE-AXIS MYOELECTRICALLY CONTROLLED PROSTHETIC ARM

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Summary

A new control concept has been developed for controlling a prosthetic arm. This method utilizes a pattern recognition technique to identify and discriminate synergistic muscle action in the back, chest, and shoulder to provide simultaneous control of humeral, elbow, and forearm movements.

An engineering model of an electric motor-driven prosthetic arm and its control was designed and constructed. This experimental model provides broad latitude in adjustments of myoelectric gains, forward speed control gains, velocity and torque feedbacks and adjustments of time constants.

Preliminary engineering tests, using three above-elbow amputees fitted with a makeshift socket and harnessing, demonstrated excellent control quality. Although minor adjustments in myoelectric gains and threshold settings were required, the control circuit designed on the basis of a normal subject's data was suitable for all three amputees. A high degree of positioning accuracy was attained quickly without training.

Introduction

The development of a multiple-axis myoelectrically controlled prosthesis was undertaken to serve the needs of the severly handicapped patient such as the bilateral, above-elbow amputee. The objective was to develop a method of control of an externally powered prosthesis to position and orient the terminal device in a way requiring the least amount of cognitive effort. The method developed allows the amputee to use the kinetic formulae which once served to mobilize the missing part; that is, although the forearm and elbow are missing, the amputee activates the shoulder girdle muscu-

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lature in the same way he previously did when producing these motions. The use of muscles in the accustomed mode for a given movement is a unique conceptual departure from the requirement to learn a totally new and contrived set of motion sequences for control of a prosthesis.

The basic approach was the utilization of a pattern recognition technique to identify and discriminate synergistic muscle action in the back, chest and shoulder to provide simultaneous control of humeral, elbow and forearm movements. Studies toward this objective began in 1913 [1] and feasibility of the approach was demonstrated with a crude model in 1965 [2]. On the strength of the feasibility demonstration, the work presented in this paper was begun in 1966. While the technical status of this development is still experimental, and the problem of reliable control of prehension has not been addressed, the practicality and utility of the pattern recognition method of control has been clearly demonstrated.

Kinesiological Basis

Muscular activity accompanying deliberate coordinated movement occurs in consistent synergistic patterns [3]. Most movement involves the contraction of many muscles, some remote from the point of observable action. Prime movers have little effectiveness without joint stabilizers. This concept of muscle synergistic patterns has been emphasized in the classic studies of Duchenne [4], Beevor [5], and Wright [6], and more recently demonstrated in the electromyographic studies of Hellebrandt and Waterland [7]. Hellebrandt, in particular, states without equivocation that in bodily movement there is a high degree of patterning consistency [8]. This kinesiological phenomenon was attributed to the basic structural similarity in human beings.

Proceeding from the concept that muscles normally perform in synergy, the rationale in this work was to use synergistic, patterns for the control of an externally powered prosthesis. Because movements are characterized by definitive patterns of muscular activity, it was logical that these patterns would also be reflected in their myoelectric signals.

Design for Synergistic Pattern Recognition

Control design data were acquired from a normal male subject using an ergometer to constrain the position and systematically vary the load and torque. The subject exerted effort in isometric muscle contraction typical for forearm pronation-supination, elbow flexion-extension, and humeral inward-outward rotation. A series was arranged systematically to derive myoelectric samples associated mobilizing a single joint as well as those involved in coordinated, multiple joint movements. Torques in the order of 5 percent of maximal effort were imposed.

Fourteen muscle sites were selected for study. The sites, selected on the basis of their participation in upper arm, elbow and forearm movements, were the anterior, middle and posterior heads of the deltoid, the clavicular, manubrial and sternal aspects of the pectoralis major, the upper, upper-middle, lower-middle and lower aspects of the trapezius, the rhomboideus major, the latissimus dorsi, the infraspinatus, and the teres major.

Using previously described instrumentation [9], the myoelectric data were recorded in analog form on a multichannel magnetic tape recorder. The sampling rate was 10 per second, with each trial sustained for 12 seconds, yielding 120 samples for statistical treatment. The magnetic tape recordings of the myoelectric signals from each of the 14 channels were replayed and automatically rectified and integrated for a period of 75 milliseconds to yield numerical values of microvolt-seconds. Automatic analog to digital conversion and card punching eüuipment [9] produced punched cards containing the microvolt-second values for each channel of the myoelectric data. By this treatment, the data were made tractable for computer processing.

A high speed electronic data processor was used as an engineering tool in the design of the pattern recognition network. A multivariate discriminant analysis statistical program called the Multinorm was used to develop weighting coefficients for each of the muscle sites for each motion.

The results of the data processing were examined and the weighting coefficients of four muscle sites (i. e., the clavicular and sternal aspects of the pectoralis major, the latissimus dorsi and the upper aspect of the trapezius) were found to be relatively small for all motions sampled. Those four sites were eliminated since they were relatively unimportant in the motion discrimination process.

Hardware Design

A block diagram of the total control system is presented in Figure 1. Component parts of the control system include myoelectric electrodes, myoelectric amplifiers, pattern recognition networks, and proportional control circuits. The mechanical assembly includes the elbow section with the flexion and humeral rotation actuators, and the forearm section with the wrist rotation and prehension drives.

a. *Myoelectrodes*

The myoelectric signals were detected by specially designed surface electrode assemblies as shown in Figure 2. The specific features of these electrodes provide independence from skin resistance, 60 cycle interference, cable microphonism, and electrical interference generated by the electric motors used in the prosthesis.

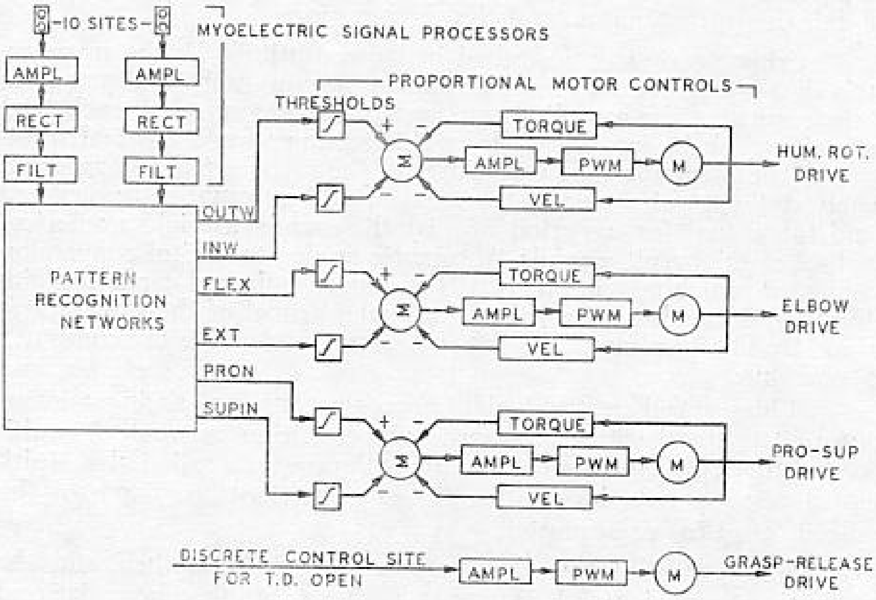

Fig. 1. Block diagram of the multiple axis control system

The sensing units are shielded, active circuit assemblies that detect potentials differentially at the skin surface, provide high input impedance to the skin, and amplify the myoelectric signal 100 times. Four transistors are connected as balanced augmented emitter-followers to give high input impedance. A Fairchild microcircuit provides the amplification. The output is a two-wire balanced signal with a driving impedance of approximately 500 ohms. The units are small in size, easy to apply, and are cast of epoxy resin to provide resistance to common corrosive substances. The electrode coupling surfaces consist of silver-silver chloride pellets spaced two centimeters apart and are an integral part of the assembly. When used with electrode paste the electrodes provide stable half cell potentials with low noise characteristics.

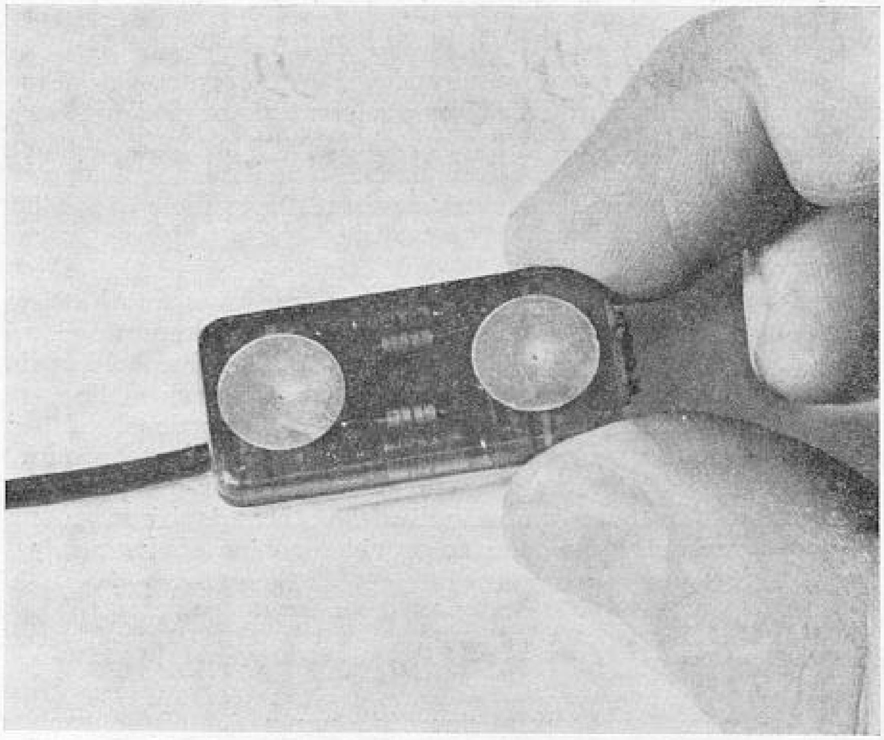

Fig. 2. Surface electrode assembly

b. *Myoelectric Signal Processors*

Ten myoelectric amplifiers, full wave rectifiers and filters were provided to process the signals detected. Thus, the pre-amplified differential signals arriving from the electrode assemblies were further amplified by an additional factor of 1000 to 10,000 with independent gain adjustments for each channel. Bandpass was designed to be approximately 70 to 700 Hertz to enhance the signal with relation to noise, artifact, and cardioelectric signals.

Parallel connected class "B" amplifiers were used to obtain full-wave rectification, and a low pass filter with a time constant of 100 milliseconds was used to smooth the signals.

c. *Pattern Recognition Network*

The results of the data analysis were used to guide the design of a simple resistor network to sort patterns of myoelectric signals.

As shown schematically (Fig. 1) the signals from 10 muscle sites were presented to all of the pattern recognition networks.

The weighting coefficients produced by computer processing were realized in the hardware by means of a resistor network. Each motion recognition channel has associated with a mask containig ten transistors which are driven by the amplified, rectified, and smoothed signals from the ten muscle sites. The currents so produced are summed and a threshold established below which no output is obtained.

The network for each motion, then, produces an electrical output only when the incoming ten signals are so proportioned to cause a weighted, summed result which exceeds the threshold established for that motion. The electrical outputs for each motion are transmitted to the summing points of the proportional control circuits where they are then combined differentially to produce bipolar signals driving the pulse width modulator for three of the four motors. The fourth motor, unlike the others, is driven from a discrete muscle control source to provide opening of the terminal device.

d. *Proportional Control*

The proportional control signal is a summation of the myolectric signals, with velocity and torque feedback signals from the arm assembly. The torque feedback is negative to provide the compliance needed when mechanical constraints to the path of motion are imposed by the object being manipulated as, for instance, when turning a crank.

While there was no reason to effect economy of power drain in the experimental console, since it was operated from power supplies fed by the 60 Hertz power line, the design of a pulse width modulator power output stage was undertaken to provide information for subsequent battery operated designs. Approximately 100 Hertz was used as a sawtooth reference frequency and a subsidiary demodulator feedback loop used to ensure linearity. No motor demagnetization problems were encountered, and the small "buzz" accompanying motor action was not objectionable.

The control console was designed to provide wide adjustment of critical circuit parameters, easy replacement of recognition networks, and display of voltages and currents drawn by the actuators in the arm mechanism to determine optimum circuit design (Fig. 3). This capability for broad latitude in the adjustments permits experimentation to be used in defining requirements for miniaturization.

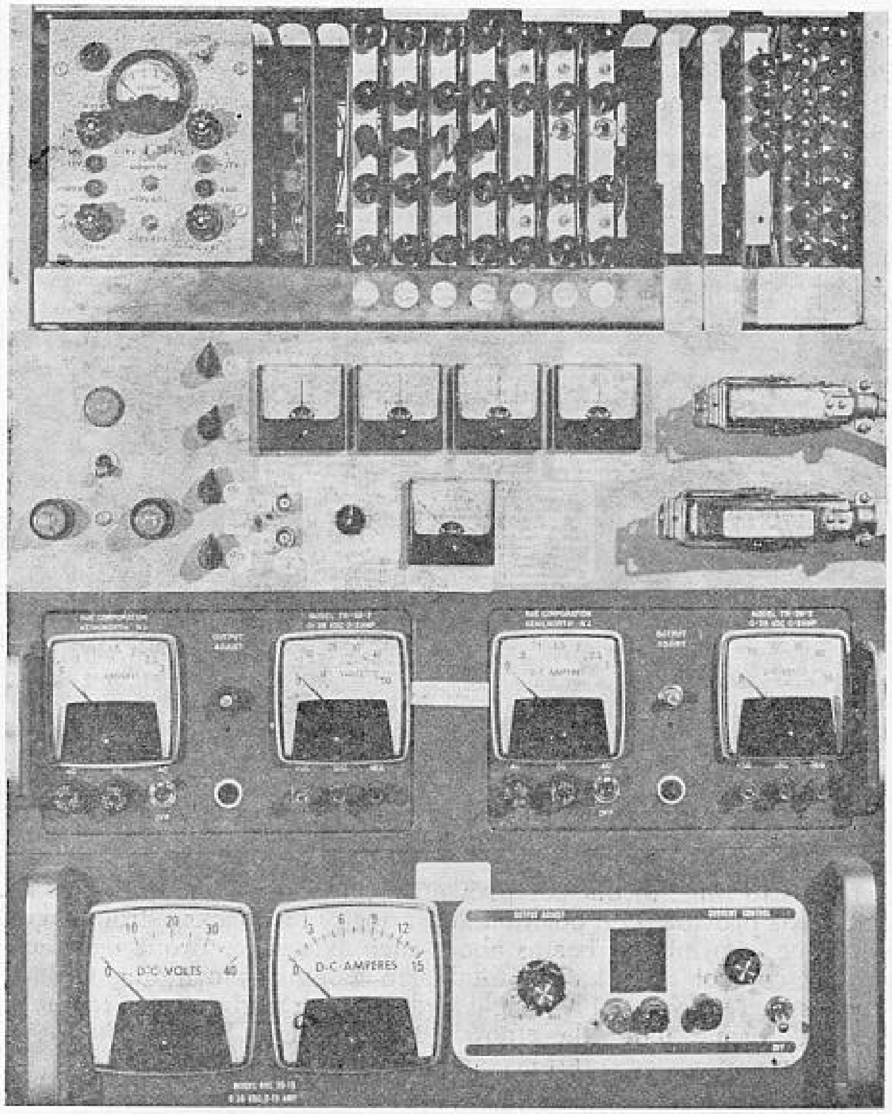

Fig. 3. Console for the multiple axis control

e. Arm Assembly

The electrically powered engineering model prosthetic arm (Fig. 4) provides eight movements about four axes, namely, humeral inward-outward rotation, elbow flexion-extension, terminal device pronation-supination, and terminal device grasp-release. For reasons of efficiency in study pursuits, preference was given to the accessibility of parts and the ease of modifications and replacement rather than to considerations for weight, noise and cosmesis. Inexpensive 12 volt permanent magnet electric motors, driving through worm and spur gears, provide rotational speeds up to about 300 degrees per second. Slip clutches were included in all four motions to limit torque for protective purposes. Potentiometers at each axis provide both position and velocity feedbacks. Strain gages on force transmitting beams about each axis yield torque feedback to the control circuit. The total arm assembly including socket, harness, and power cable weighs eight pounds and delivers 150 inch pounds torque about the elbow, 30 inch pounds each in humeral and terminal device rotations, and 10 pounds pinch force.

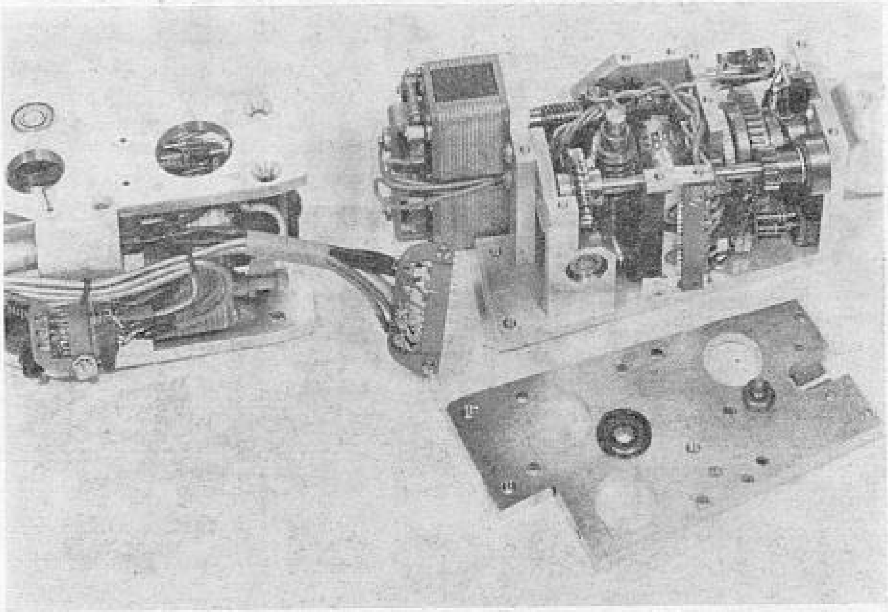

Fig. 4. Engineering model multiple axis prosthetic arm shown partially disassembled

Performance Tests

Preliminary engineering tests, using three amputees fitted with a makeshift socket and harness, demonstrated excellent control quality. Although minor adjustments in myoelectric signal gains and threshold settings were required, the control circuit designed on the basis of the normal subject's data was suitable for all three amputees. A high degree of positioning accuracy was attained quickly without training.

The full dynamic capabilities of the arm could not be explored because of harnessing instabilities. Although the negative torque feedbacks were observed to be useful, as anticipated, the value of velocity feedback could not be evaluated.

With the successful completion of the present phase the problem of terminal device control can now be addressed along with the addition of portable power and refinements necessary for every day wearability. These refinements include fitting and harnessing, practical electrode attachments, miniaturization of the electronics, reduction in weight, and suitable cosmesis.

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