EXTERNAL CONTROL OF EXTREMITIES—GENERAL

ON THE CYBERNETIC RESTORATION OF NUMAN FUNCTION IN PARALYSIS

J. B. RESWICK, W. KO, L. VODOVNIK, W. McLEOD, W. CROCHETIERE

The following paper is a review of different activities of the Cybernetic Systems Group at the Case Institute of Technology, Cleveland, Ohio. The focus is on the problem of paralysis due to high level spinal cord injuries in man and on ways to restore the functional usefulness of paralyzed extremities, applying modern cybernetic concepts.

The work is performed in close contact with Highland View Hospital and Western Reserve University Medical School and thus the necessary cooperation between doctors and engineers is insured.

Let us start with some general (and necessarily simplified) schemes of how the motor function of a human being may be viewed as a cybernetic control system. Figure 1 is a schematic which shows the information paths in a normal person between the brain and two sets of muscles in an arm. It also shows an alternate set of information paths that might be used if the normal paths are broken as would occur in a high level spinal lesion. The motor neuron systems of the muscles have been grossly simplified. Feedforward and feedback paths exist in the efferent and afferent neural paths and through sight, touch, and sound in the normal person. Through adaptation and ontogenetic development, the middle areas of the brain learn how to translate the conscious commands into properly modulated sets of commands to the various agonist and antagonist muscle paths to produce controlled movements. Once started, these processes are reflexive and not under conscious control, except as corrections are needed. Most human motor activity such as walking, chewing, sport activity, and playing musical instruments is of this type of patterned activity.

The crosses at L_1, L_2, L_3 and L_4 indicate a transection of the normal neural control paths. A technique for bypassing such severed

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nerves has been demonstrated at Case. It consists of picking up bioelectric currents from voluntarily controlled muscles such as in the shoulder of a quadriplegic and using this signal to modulate a current which stimulates a paralyzed muscle. By such a system we were able to give prehensile grasp to a patient. The figure shows four such paths.

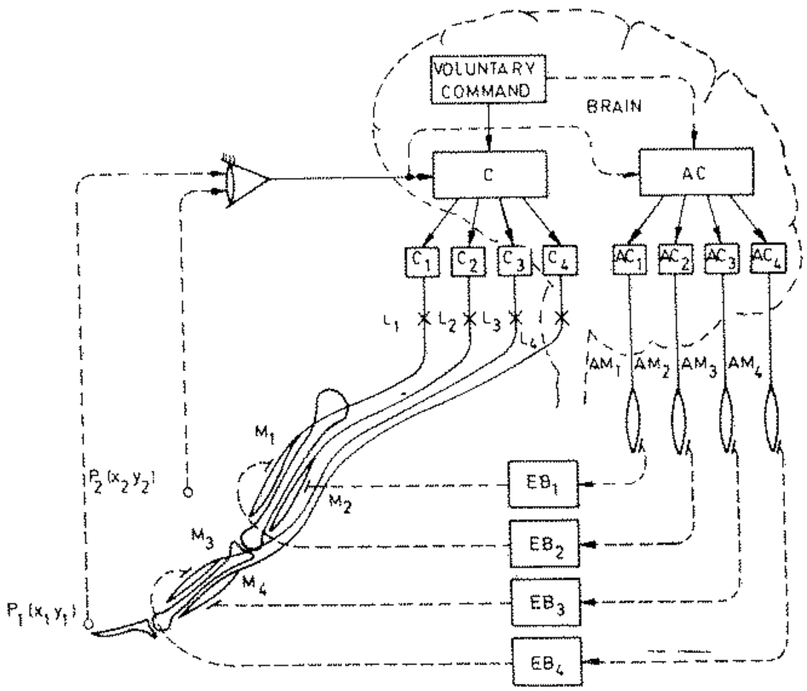

Figure 1. Generalized scheme for neural bypass

Before transection the muscles M_1, M_2, M_3 and M_4 were controlled through »naturally conditioned communication channels«.

The new channels shown in the figure use muscles which must be retrained in new tasks. These new information paths are therefore called »operant conditioned communication channels«.

The problem represented by the need for new learning required by the patient is severe. He must develop new reflexive patterns based on different and often limited sensory feedback. The figure shows a new path for the conscious command and for the usual feedback. Original proprioceptive feedback is missing so an increased burden on visual feedback results. Limited proprioceptive feedback can be acquired in the new muscles and other electromechanical devices may be required to provide a new sense of position and touch (pressure).

It has been hypothesized by our group that a special purpose computer between the brain and the output stimulator system can make it easier for a man to learn to control an extremity. Figure 2 shows a more complicated system where feedback paths and a computer have been added. In this case the man may need only to think of the direction he would have his arm move and send a simple set of signals to the computer which would work out the appropriate sets of signals to the muscles involved. Much of our present research is directed at finding what sort of algorithms are required to implement this concept. We are using a high-speed DDP-116 computer to evaluate proposed algorithms. Also important is the study of operant conditioning to learn to what extent an adult patient can learn to control sets of muscles in totally new tasks.

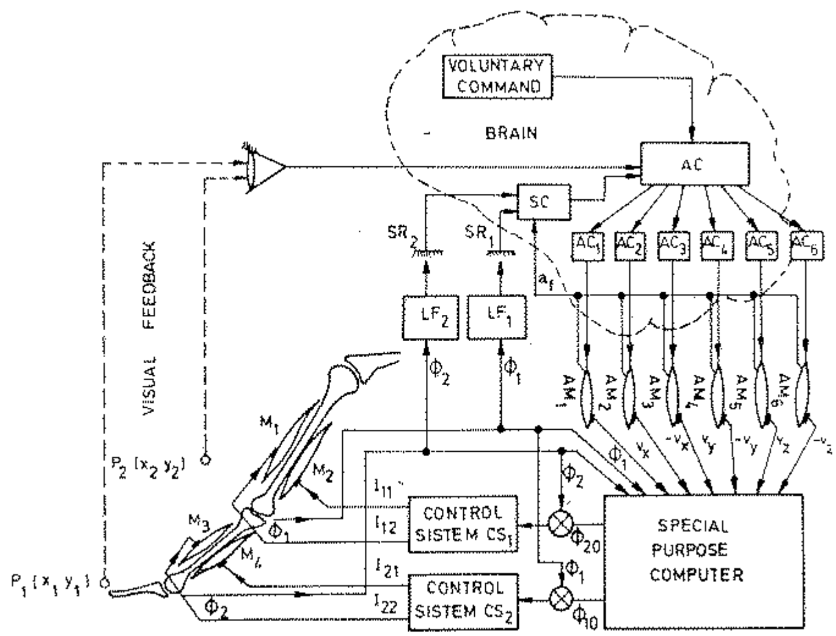

Figure 2. Generalized scheme for neural bypass with computer and auxiliary feedback paths

We see at least three main areas for the development of new engineering systems. They are:

1. Sources of signals
2. Signal transducers
3. Output or activating systems.

Sources of Signals

We have concentrated on signals that may be produced by the quadriplegic with high level lesions. Among the possible signal sources are voluntarily controlled muscles (e. g., eyebrows, neck, shoulder, scalp, etc.); muscles not under voluntary control (e. g., muscles to wiggle the ears); and sound and brain waves. From such muscles one can use movement to activate switches or proportional transducers and one can pick up electromyographic signals from the surface; from just under the skin (subcutaneously) and from deep within the muscle. We have chosen to ignore those signal sources that are part of the daily living of the patient, viz., eating, talking, moving head and eyes, and hearing. We have further decided to concentrate on bioelectric signals obtained from deep within a muscle.

Last year J. Basmajian and his co-workers reported that they were able to train a number of subjects to gain independent control of as many as six isolated motor units in a single muscle, calling them forth at will. A motor unit is a group of muscle fibers that fire under the stimulus of a single neuron. There are a great many isolated motor units in a single muscle.

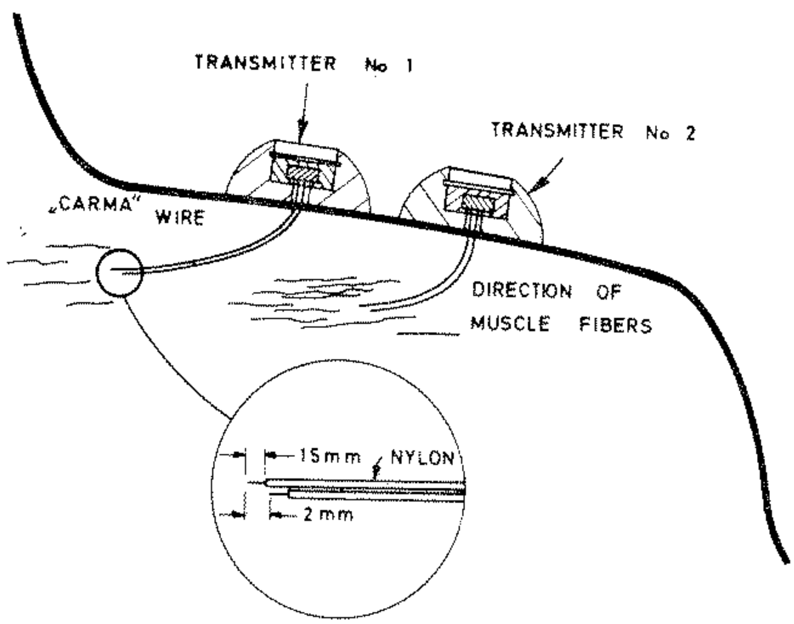

Figure 3. Two pairs of bipolar electrodes inserted in trapezius muscle

This work has suggested to us the possibility of obtaining a high rate of information from one or more electrodes implanted in a single muscle. We have experimented extensively in the trapezius muscle in both normal and paralyzed subjects. Our results show that it is not difficult for a patient to learn to control up to four sets of signals from four sites in the trapezius. We have developed a technique for inserting electrodes in the muscle and providing connectors so that the wire may remain for extended periods. Some of our units have been operating for six weeks with no discomfort, infection or wire migration.

The system is shown in Figure 3*. The wire is called »Carma« wire and is insulated with nylon. The were is .0011 inches in diameter and with insulation is .0015 inches. Its resistance is 700 ohms per foot. We expose 1½ millimeters by carefully dipping the wire in acid. Two electrodes are threaded through the needle and each of them is bent around the tip of the needle such that 1½ millimeters of wire outside the needle is exposed. The method for inserting the wires is shown in Figure 4. The wires are inserted parallel to the muscle fibers. With the needle in place in the muscle it can be checked by measuring EMG output between that signal and a ground electrode placed on the surface of the body. The signal will not be bipolar at this time.

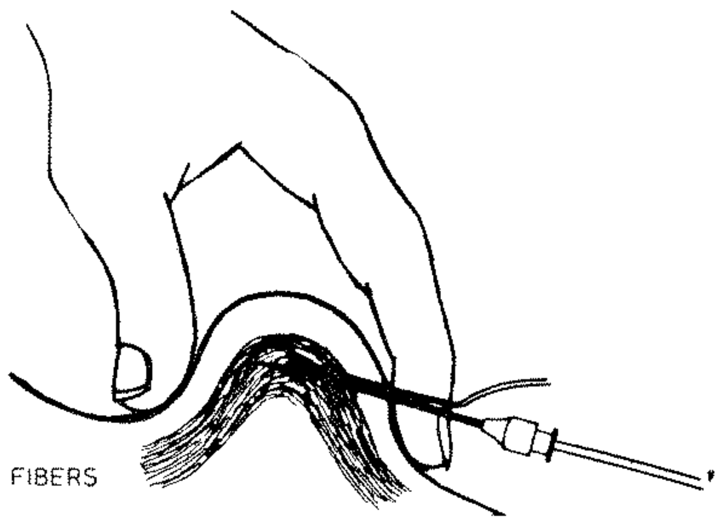

Figure 4. Method of insertig electrodes to lay wires parallel to muscle fibers

With the electrodes in a satisfactory position, the wires coming up through the center of the needle can be pulled out. This causes the

*) This system was demonstrated at the Conference several times, once in connection with the electronic hand developed by Bottomley, et al. The described system was demonstrated on the first day of the Conference. Before leaving the U.S.A., Dr. Reswick had attached 2 FM transmitters with implanted wires on his shoulder as shown in Figure 3. He brought with him two portable FM receivers which he tuned to the frequencies of the transmitters. The participants were able to distinguish audibly the typical sounds of single motor unit electrical discharges. Dr. Reswick showed that he was able to voluntarily control the frequency of discharge.

A second, more informal, experiment was performed in the hotel room of one of the participants. F. N. Möhl, B. Klasson, A. Bottomley and J. Reswick were present. The outputs from the two FM receivers were attenuated and fed into the differential amplifiers controlling the hand position of Dr. Bottomley's arm prosthesis. Dr. Reswick was able, in the period of about ten minutes, to gain voluntary control over the opening and closing functions of the prosthetic hand. It was possible for him to control the direction of movement and its speed on request of those observing the demonstration. He stated that he felt no movement of his muscle and that, as far as he was concerned, he had only to think of the desired response and it occurred.

electrode to be cut by the tip of the needle at the point where they are bent around it. The needle may now be removed and one wire pulled slightly relative to the other until a satisfactory bipolar signal is obtained.

Signal Transducers

Whenever a wire or any other foreign body pierces the skin, the way to infection is present. With this in mind, we have been working for the past five years to develop tiny radio transmitters small enough to be permanently implanted in a muscle. Some of these radios are powered by batteries while others receive radio power through the skin. An experimental unit in a rat has been powered by electrochemical potentials in the body of the rat. These radio transmitters rely on solid state elements (tunnel diodes, varicaps and backward diodes) with special characteristics that are made in our laboratories. The special characteristics we can obtain make it possible to build a transmitter which occupies only one-tenth cubic centimeters, weighs only one-half gram, and draws only two hundred microwatts of power.

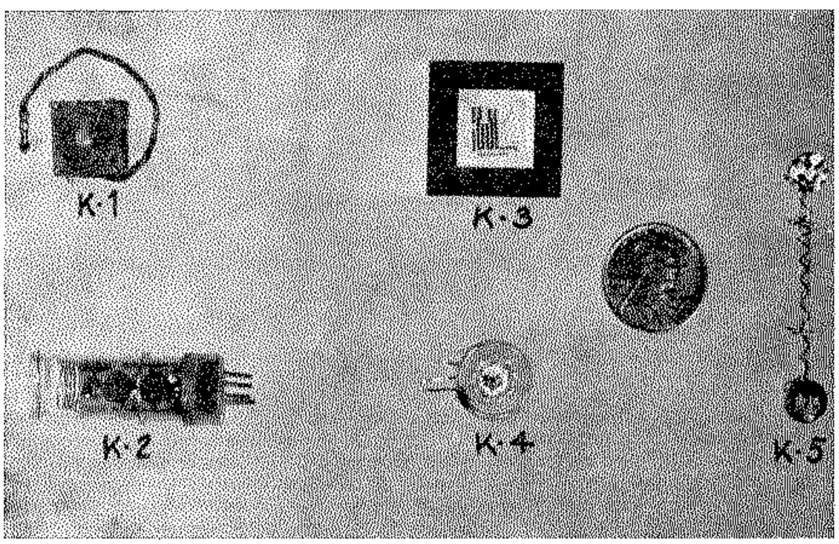

Figure 5. Developmental series of bio-transmitters

Figure 5 shows transmitters that were built during the last five years in the laboratory of Dr. Wen Ko. The K-5 is the latest development. It can be powered by a small battery as shown in the figure or by radio induction as shown in Figure 6. Typical EKG and respiration records obtained from a rat are shown in Figure 7. One record was obtained with a battery-powered radio and another with a radio-powered radio.

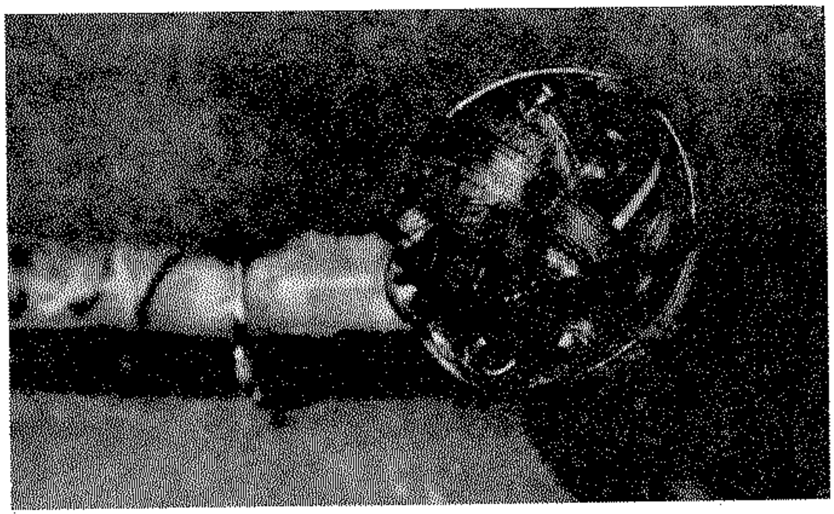

Figure 6. Induction coils and rectifier system for powering K-5 implanted transmitter

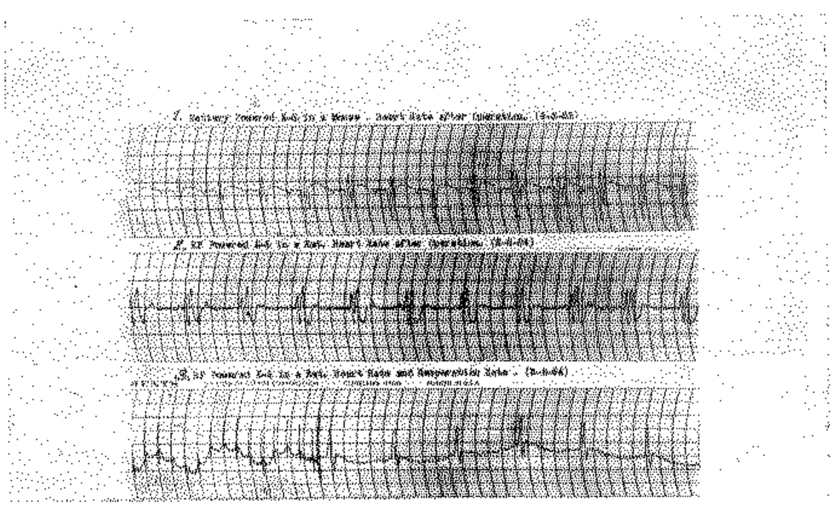

Figure 7. Typical EKG from mouse

We are now using such transmitters to broadcast the »prolonged small fiber after discharge« signals from the medial reticular formation of the tegmentum of the midbrain of a cat in work we are doing on pain suppression by means of electrical stimulation.

Output Systems

We have concentrated on two forms of output systems. The first is an externally powered ortheses which is controlled by both the patient and a computer. The second uses the patient's own paralyzed muscles for movement. While obviously more desirable the second system is much more difficult to achieve at this time much basic research on muscle stimulation must be done. For this reason we are developing both methods of approach.

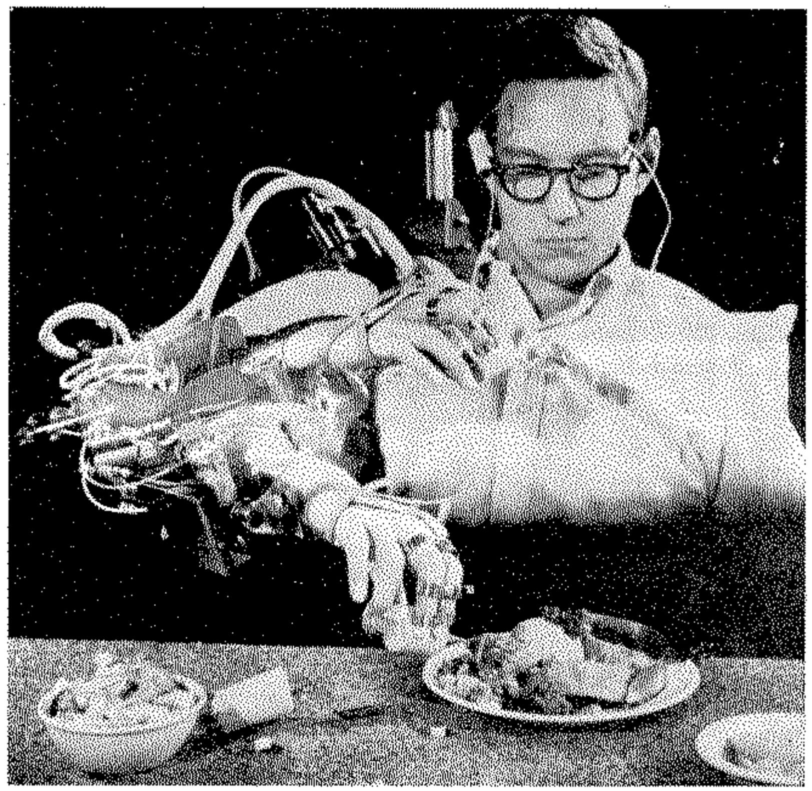

Figure 8. The Case Institute research arm-aid

Figure 8 shows the externally powered system. We program the patterned activity of eating and other movements of daily living on a multichannel tape machine. The patient communicates with this machine by pointing a beam of infrared light at a receptor near the object he wishes to use. Then he moves his eyebrows in logical combinations to start and stop the computer. His arm is brought automatically (as a reflex) to the object he wishes to use (like a spoon). He then consciously guides his fingers around the object using electrical stimulation of his extensor muscles to open his hand The computer guides his spoon to his food; the full spoon to his mouth; and returns the spoon to its place on the table. The object of this system is to study both conscious and reflexive control of a paralyzed limb and to gain experience with controlled electrical stimulation of paralyzed muscles.

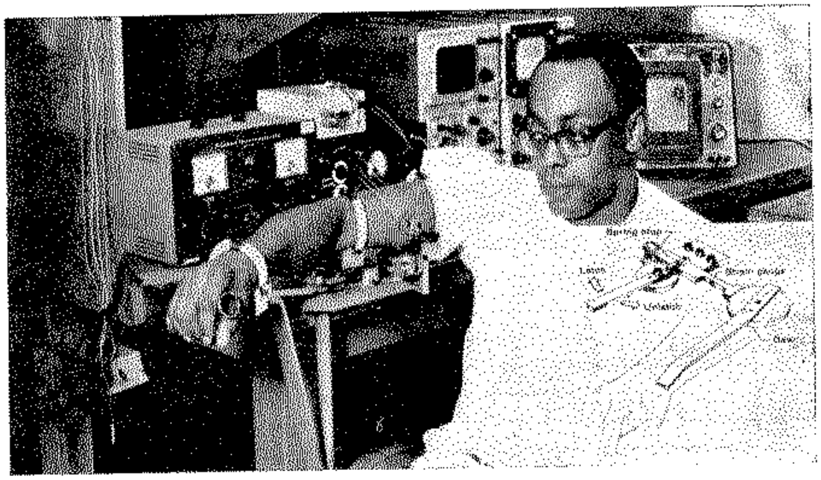

Figure 9. Experimental apparatus for isometric muscle stimulation studies

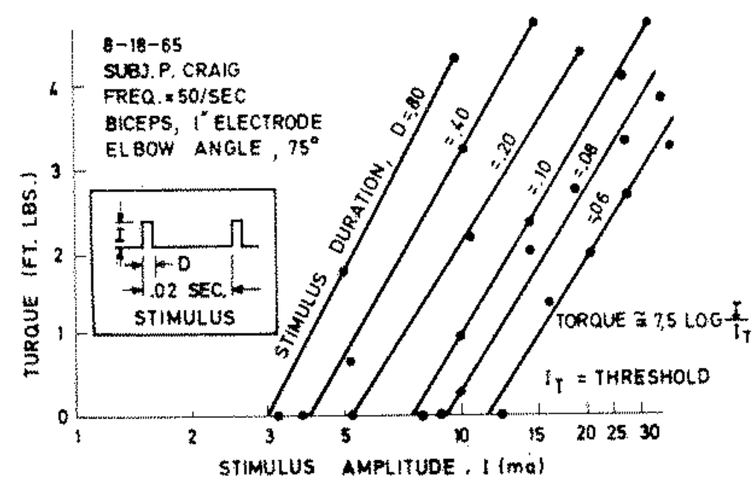

Figure 10. Torque about elbow joint as a function of stimulus amplitude at various stimulus pulse widths

Much of our recent research is concerned with controlled stimulation of muscles. It is important first to learn how the paralyzed muscles can be reliably stimulated and controlled. The following figures represent some of our early results, most of which have been obtained from normal subjects. The test equipment is shown in Figure 9. Our first studies have been confined to isometric muscle contractions. The device measures torque produced about the elbow joint when the biceps and/or triceps are stimulated. We have found that a particular form of stimulating wave does not produce a minimum of pain. This waveform is shown in Figure 10. It is a train of pulses with a period of .02 seconds or a frequency of fifty cycles per second. The pulse width and height can vary. We have been careful to design electronic equipment which provides controlled *current* of the waveform shown independent of the impedance of the surface of the skin. Figure 10 shows the relationship between torque produced, pulse height in milliamperes, and pulse width in milliseconds. As can be seen, either amplitude or pulse width or both may be used as an input or control signal.

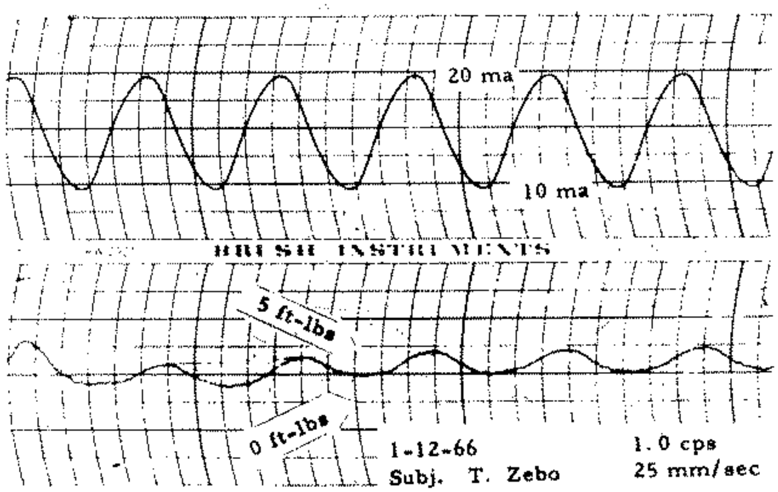

Figure 11. Stimulus modulation and isometric torque as a function of time

This kind of data is useful to engineers to design control systems for direct muscle stimulation. Another kind of data is also useful for design purposes. These are the changes of output torque when a sinusoidally modulated train of pulses is applied to the muscle. Figure 11 shows how the output torque varies when the input signal is sinusoidal at one cycle per second. Such results can be summarized on amplitude and phase versus frequency curves as shown in Figure 12. Also shown in Figure 12 is a mathematical model which fits the curves reasonably well. Our next phase of research will be study the response of the arm in isotonic contraction. We will see how it moves at constant torque. The goal of these studies is to be able to characterize the paralyzed muscle as an engineering output device so that it may be brought under control by the patient.

In conclusion, we have attempted to show through some specific examples of our research work the nature of the cybernetic man-machine system. This system comprises a disabled person and his assistive device. Tremendous progresss has been made in the develop-

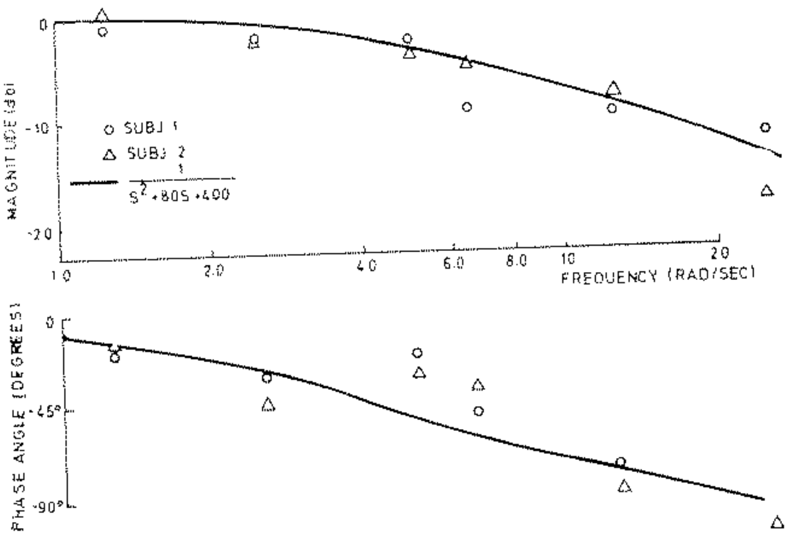

Figure 12. Amplitude and phase angle for sinusoidal response of biceps muscle

ment of complex cybernetic systems for the control of space vehicles. Now is the time for man to turn this technology to the aid of his less fortunate fellow man. But the problems are even more complex than those of space. For now we are trying to duplicate the most sophisticated functions of the human being—both his thinking function and his motor function. Our present technology is able to reproduce only the simplest of these capabilities of man. The progress to date is, however, great and promises much for the future.