AN EXPERIMENT WITH THE CONTROL OF A HYBRID PROSTHETIC SYSTEM: ELECTRIC ELBOW, BODY-POWERED HOOK[a]

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INTRODUCTION

The use of energy sources outside the body for the operation of upper-extremity prostheses has been tantalizing to prosthetic researchers for many years. Nevertheless, such usage has been minimal and without notable success. In fact, to date, very little is known about how to make the optimal use of externally powered prosthetic components.

The results reported here are part of a larger effort by the Design and Development Subcommittee of the Committee on Prosthetics Research and Development (National Research Council) to obtain some answers concerning the relative merits of different control methods of externally powered components in above-elbow prostheses. Also of interest was the applicability of different power configurations (e.g., conventional elbow with externally powered terminal device, externally powered elbow with externally powered terminal device, etc.). This study is concerned with the configuration consisting of an electric-powered elbow and a conventional body-powered hook.

The study was designed to examine, on a controlled basis, the performance of three above-elbow amputees as they used the experimental prostheses to carry out specific tasks. In the first part the electric elbow was controlled by myoelectric signals from muscles of the stump. The

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second part consisted of controlling the elbow by a pull-switch mounted in the harness of the prosthesis. In each case the hook was controlled through a body harness. Training was carefully monitored in both parts of the study.

METHODS AND SUBJECT SUMMARY

After the initial fittings, which are discussed later, the three amputees were seen three times a week (Monday, Wednesday, and Friday) over a 10-week period. During the first 5 weeks, myoelectric control of the elbow was used. The following 5 weeks were devoted to switch control. One subject (D.H.) missed the final three sessions.

The subjects did not use the experimental prostheses except during the laboratory sessions and then only under supervised conditions. During the first 15 minutes of the session, the subject was allowed to practice using his experimental arm under the supervision of an occupational therapist. This was followed by a 15-minute rest period and then another 15-minute practice period. Another 15-minute rest period completed the first hour. The subject then performed the test. After a 10-minute rest the test was repeated. Therefore, the laboratory session lasted approximately 1½ hours for each subject, provided no technical difficulties developed.

The test consisted of moving 12 cylindrical objects from a source tray to three other trays through use of the prosthetic appliance. The three trays were arranged so that approximately 45 deg. of elbow flexion was required from the source tray to the first tray, 90 deg. to the second tray, and 120 deg. to the third tray. The test arrangement is shown in Figure 1. The tester positioned the cylinders on the source tray one at a time and placed each in an optimal orientation for handling with the prosthetic hook. Four cylinders were white in color, four red, and four blue. They were to be placed in the tray which matched their color. In each color set of four cylinders two cylinders were 2½ in. in diameter and 4 in. long with one of them soft and one solid. There were also two smaller cylinders, one soft and one hard, which were ½ in. in diameter and 4 in. long.

The test was scored by measuring the time required to complete the task of moving the 12 cylinders, one at a time, from the source tray to their respective trays and by measuring the number of errors made during this transfer. Dropping a cylinder, even a drop into the appropriate colored tray, was an error if the drop was greater than 1 in. The subject was not graded according to his ability to control prehension forces of the voluntary opening hook.

The subjects were instructed to work as rapidly as possible while trying to hold errors to a minimum. They were also instructed to actively use the prosthetic elbow for all transfers of objects from the source tray to the other trays. This instruction was necessary since it was relatively easy

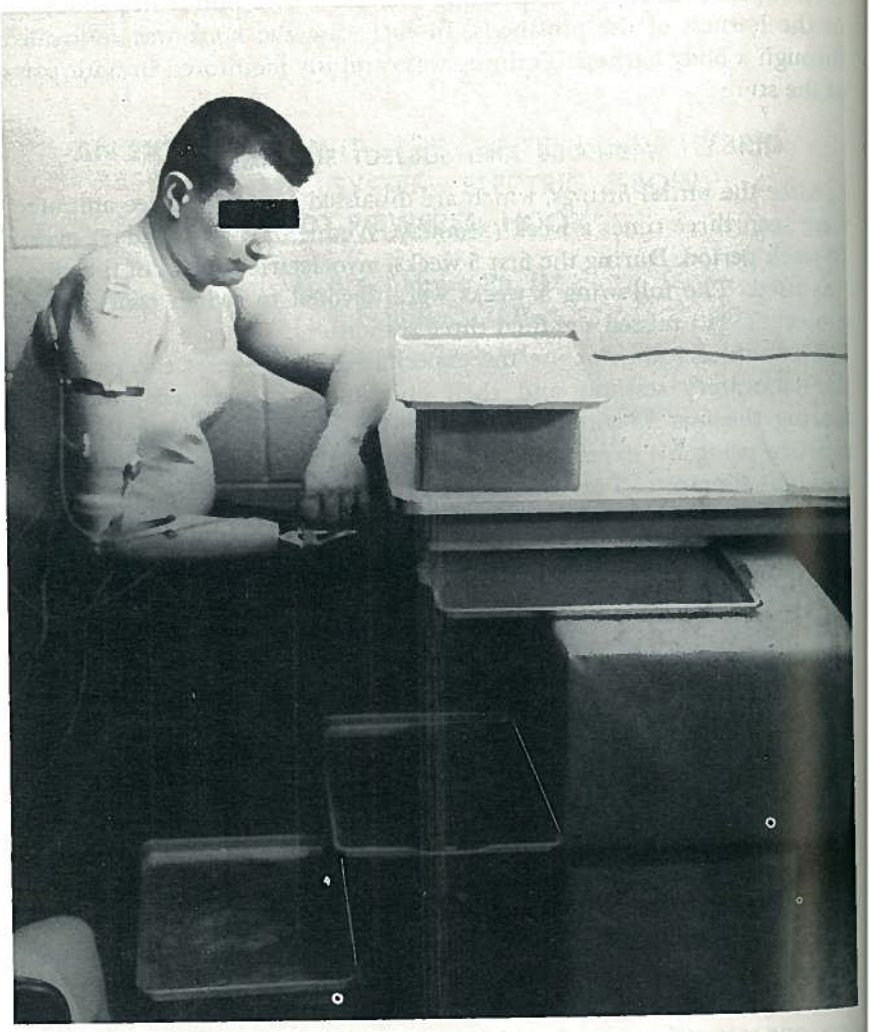

FIGURE 1.—Test arrangement.

for them to make many of the transfers without flexing the elbow. Therefore, each transfer involved flexion of the elbow, although this motion may not have been necessary in all cases.

To establish a baseline for comparison the subjects were first given the test using their conventional body-powered prostheses with which they were reasonably adept. Also, the test was given to a normal subject (male, 35 years old) so that a comparison could be made with a normal physiological arm. Identical restrictions on the use of the elbow for transfering the test objects were imposed on the normal subject as were imposed with the amputees. These special tests were performed only during the first

day of the study. The tests were carried out twice and the scores were averaged to give the baseline values.

Test Subject Information: All subjects were male and were experienced users of conventional prosthetic limbs. Each had used a conventional above-elbow prosthesis for not less than 5 years. Following is a brief informational sketch concerning each subject:

D.H., age: 37, right above-elbow amputation: 1964, traumatic, stump length: 10 in., moderate prosethetic user.
J.H., age: 44, left above-elbow amputation: 1964, traumatic, stump length: 8¾ in., active prosthetic user.
R.W., age: 34, right above-elbow amputation, congenital, stump length: 11¼ in., active prosthetic user.

THE EXPERIMENTAL FITTINGS

The fabrication phase of the study was particularly encouraging because it illustrated that experimental above-elbow prostheses may be fabricated very quickly using a synthetic rubber material (Polysar[c] X414). It was possible to fabricate each experimental prosthesis in about 3 hours. Thus, this thermoplastic material appears ideal for use in the experimental evaluation of new prosthetic concepts for the above-elbow amputee.

Figure 2 shows how the synthetic rubber socket was formed directly on the amputee's stump. This technique, which will not be discussed here, was developed principally by a staff member[d] of the Northwestern University Prosthetic-Orthotic Center.

Each subject was fitted with his own socket and harness but all three used the same electric elbow and the same forearm. The forearm was modified for use on the left or right side. The hook was changed when transferring the prosthesis between the right and left sides.

The electric elbow used in the experiment was one developed at the Veterans Administration Prosthetics Center (VAPC). It would move from the fully-extended position to the fully-flexed position in a little over 1½ seconds with no load in the terminal device. The unit operated at 24 volts and was controlled in a purely "on-off" fashion.

Dorrance[e] 5XA hooks were used for the terminal devices.

The prostheses and subjects are shown in Figures 3, 4, and 5. It is noteworthy that the patient shown in Figure 5 did not use suspension harness other than the control cable. Such harness proved to be unneces-

[c] Registered trademark of the Polymer Corporation, Limited, Sarnia, Ontario, Canada.

[d] Mr. Frederick L. Hampton, C.P.

[e] D. W. Dorrance Co., Inc., Campbell, California.

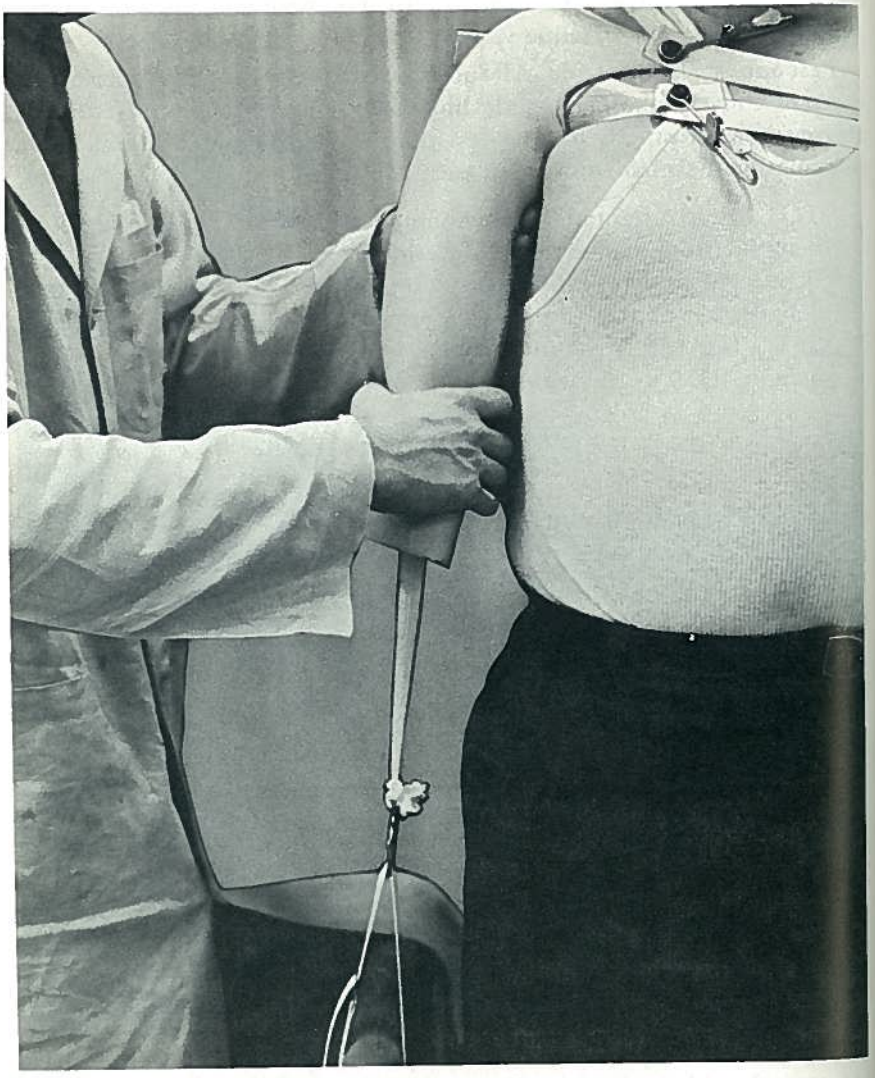

FIGURE 2.—Formation of an above-elbow socket of synthetic rubber.

sary throughout the experimental sessions and this has evoked renewed interest in self-suspension methods for the above-elbow prosthesis.

Originally it was intended that all three subjects would be fitted with a Viennatone[f] myoelectric system in which the output was modified to drive an electric elbow instead of an electric hand. However, subject R.W. was the only one fitted in this manner. The Viennatone electronic package and electrodes are easily visible in Figure 5.

[f] Viennatone of America, Inc., Chicago, Illinois.

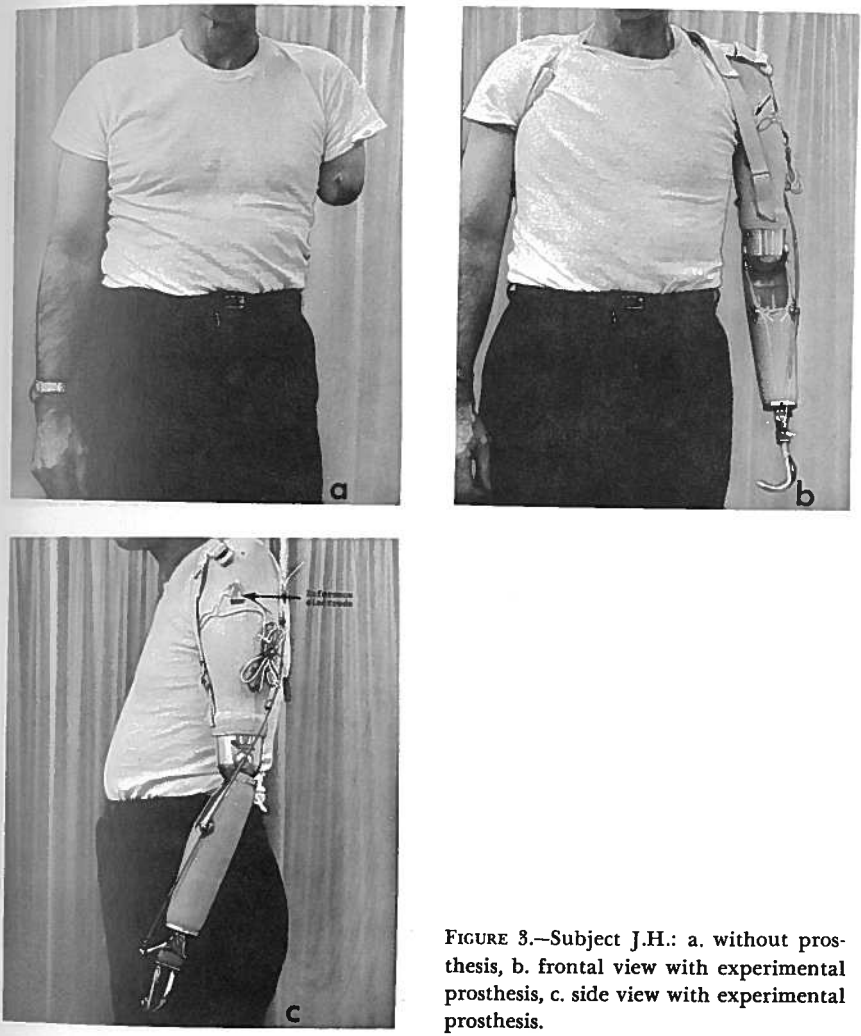

FIGURE 3.—Subject J.H.: a. without prosthesis, b. frontal view with experimental prosthesis, c. side view with experimental prosthesis.

Subject R.W. used this two-state, two-site system by contracting muscles located anteriorly and medially on the stump to initiate elbow flexion. Muscles located posteriorly and laterally were used to initiate elbow extension. Since R.W. was a congenital amputee no attempt was made to identify these muscles.

The circuit for interfacing the Viennatone electronic system with the VAPC elbow is shown in Figure 6. This was necessitated since the Viennatone system had a 12-volt output while the elbow functioned at 24 volts. No attempt was made to miniaturize the interfacing equipment. Therefore, it was physically located on a shelf near the subject and connected to the prosthesis with flexible wire. The interfacing relays

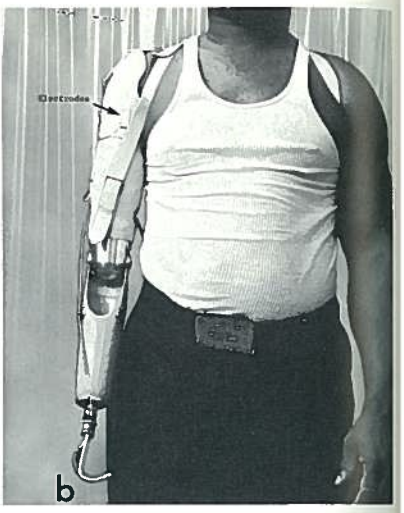

FIGURE 4.—Subject D.H.: a. without prosthesis, b. frontal view with experimental prosthesis, c. side view.

did give an audible output when activated and this no doubt contributed positively to total system performance since they provided additional auditory feedback.

The electronics systems used by subjects J.H. and D.H. for myoelectric signal detection and processing were also interfaced with the electric elbow through relays.

Subjects D.H. and J.H. had strong myoelectric potentials from the biceps but weak potentials from the triceps. In fact, these potentials were so weak that they could not use the Viennatone myoelectric system. Therefore, they were fitted with a three-state myoelectric system developed at Northwestern University. The three-state system required elec-

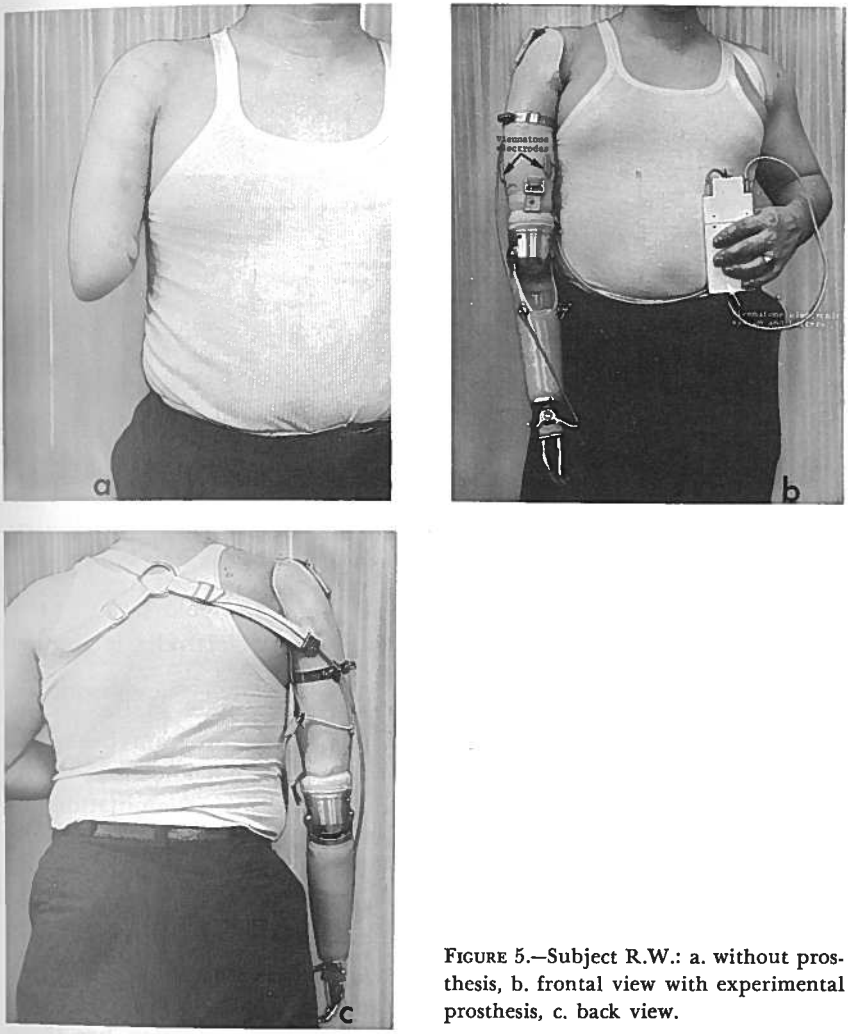

FIGURE 5.—Subject R.W.: a. without prosthesis, b. frontal view with experimental prosthesis, c. back view.

trodes only over the biceps. This three-state system is not necessarily recommended for this application but it was used for lack of a better system at the time the experiments were conducted. In this system a quick contraction of the biceps caused the elbow to extend while a slower contraction produced elbow flexion. In other words, the motions were differentiated by different contraction rates.

Stainless steel shim stock was looped through slits in the synthetic rubber sockets to create electrodes for the three-state systems. This proved to be a very fast method of making temporary electrodes. These are easily visible in Figures 3 and 4. The electrode located on the lateral side is

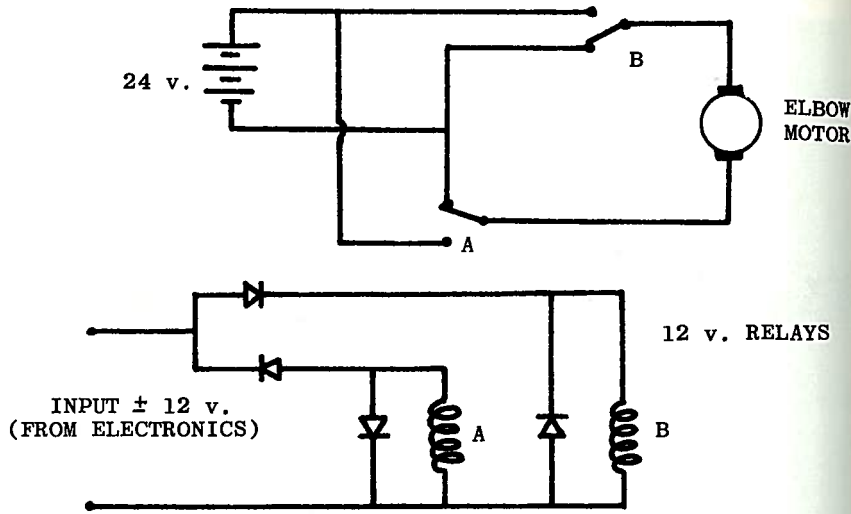

FIGURE 6.—Circuit diagram of interface equipment between 12 v. electronic system and 24 v. elbow. Relay contacts are shown in the deenergized position.

the reference electrode. Rapid positioning of test electrodes is another advantage of the synthetic rubber socket.

There was a definite tendency among the amputees in the testing program, and among others examined before the program began, to have weak myoelectric activity of the triceps. It is not known if this is a general characteristic. The observation is based on examinations of 10 above-elbow amputees. Biceps activity is generally good for the above-elbow amputee having a mid-length or longer stump. It should also be noted that these observations are based on examinations of subjects who had been amputated for several years.

The VAPC pull-switch was used for switch control of the elbow. This switch is shown in Figure 7. A guide of polyethylene was formed around the switch so that it could not pinch the flesh. The switch has three output states which shall be called quiescent, positive, and negative. Although there are three states there are four levels of control. When relaxed or closed the switch is quiescent (off). As it is pulled open the first active state (positive or negative as prearranged) is activated. Greater opening activates the second active state. In the fully open condition the switch is again inactive. These characteristics allow it to be used in series with the control cable for the hook since the switch may be operated when the cable forces are not adequate to open the hook. For forces large enough to open the hook the switch may be adjusted to be in the quiescent state.

Subjects R.W. and D.H. used the pull-switch in series with the control

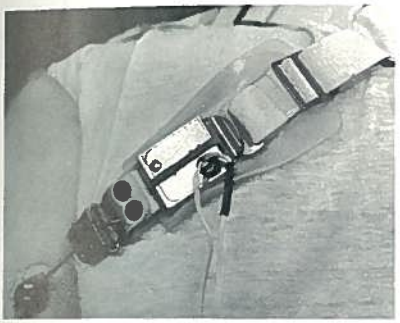

FIGURE 7.—VAPC pull-switch in series with control cable of the hook.

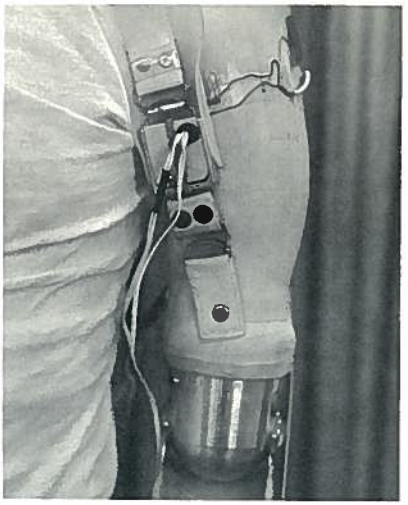

FIGURE 8.—VAPC pull-switch mounted on the anterior aspect of an above-elbow socket.

cable during the switch-control portion of the study. The switch location is illustrated in Figure 7.

Subject J.H. had the pull-switch located on the anterior portion of his upper arm, and it was activated with a motion similar to that used in locking a conventional elbow. This form of control is illustrated in Figure 8. Subject J.H. attempted to use the pull-switch in series with the control cable but did not have good control with it there. The anterior location was considered easier to use since there was not the confusion of having control of the elbow and hook from the same motion although at different force levels.

RESULTS

The time required to perform the tests provided the most information about the value of each form of control. The times for the two tests per session were averaged to give a daily score. These results are shown in Figures 9, 10, and 11. Also shown are the results using the conventional prosthesis and the score of a normal subject.

The large variability of the data, particularly during the first 6 or 7 days, makes it somewhat difficult to analyze. It was decided that the rather simplistic approach of fitting the data with two straight lines might be as meaningful as more sophisticated methods. The slopes were arbitrarily drawn but could be refined by a least squares fit if desired.

The conclusions drawn from the graphical data are highly influenced

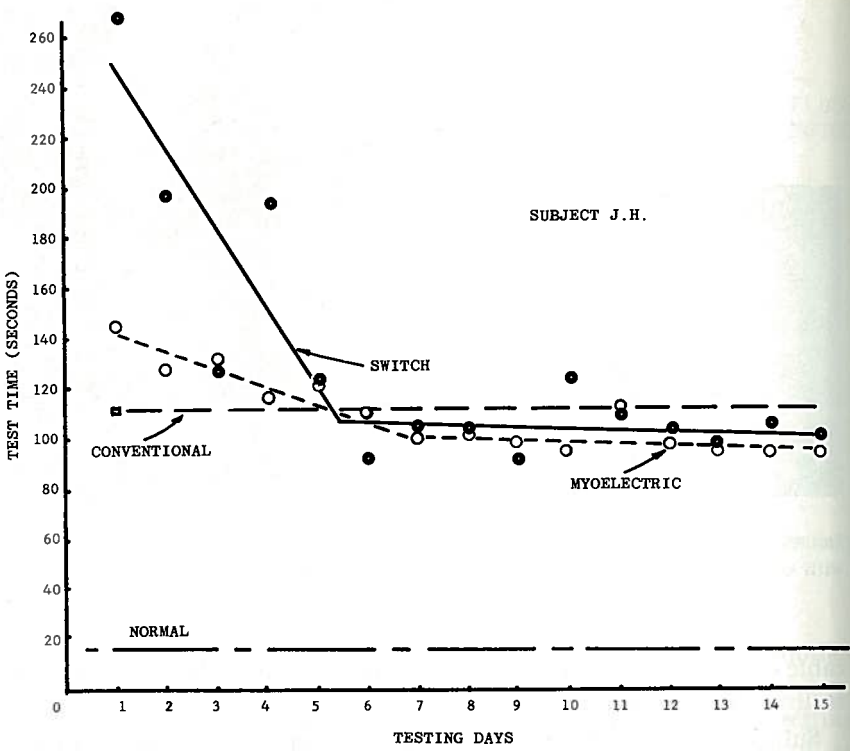

FIGURE 9.—Results for subject J.H. showing the average time required to complete two tests each day versus the testing days. Both myoelectric and pull-switch performance times are shown along with the subject's time using his conventional prosthesis and the time required by a normal subject.

by the way in which the data are viewed. A simple viewpoint, such as the one taken here, may miss the more subtle aspects of the data but should well display its more obvious aspects.

Some observations are rather easily drawn from this data:

1. The variability of the test scores diminished during the first five or six test periods. This most likely was the result of the subject becoming familiar with the test and the operation of the prosthesis.

2. The rate of improvement in test scores decreased sharply after about seven sessions. Test scores were still improving after 15 sessions but at a slow rate.

3. Myoelectric control tended to yield the better test scores.

4. All subjects did as well or better with the externally powered elbow as compared with the conventional prosthesis.

5. The minimum time required by the fastest subject was nearly three times slower than the time required by the normal subject.

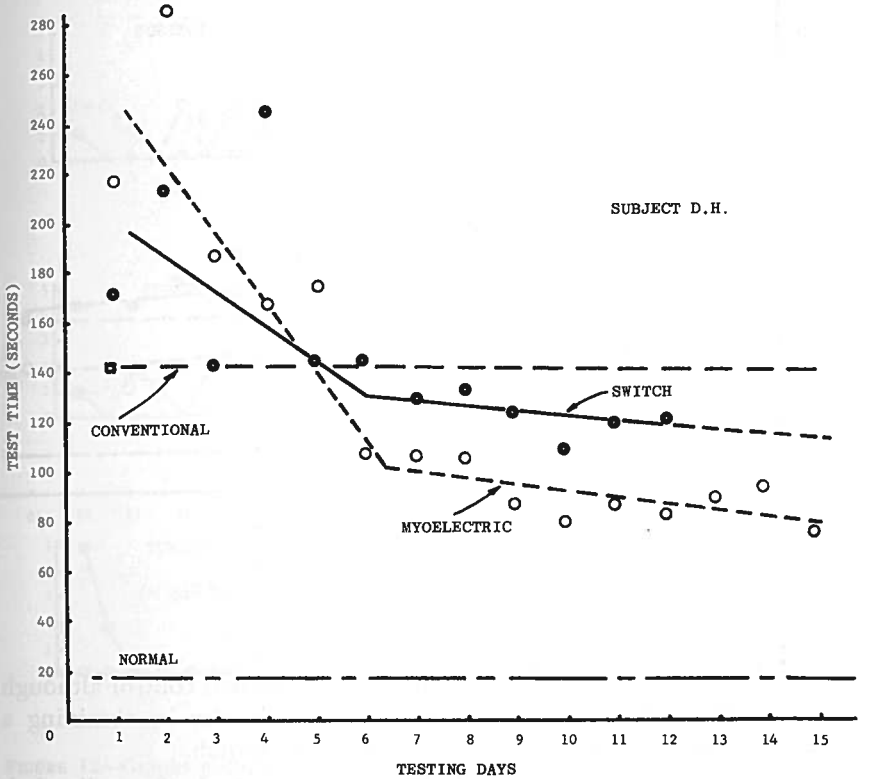

FIGURE 10.—Results for subject D.H. (See caption of Fig. 9.)

The grasp errors are shown in Figure 12. These were not a major problem and most of those recorded were minor drops into the receiving trays. These errors are not averaged on a daily basis and are plotted for each test. The grasp errors did not seem to diminish with time and appear rather random in nature. The average number of grasp errors for all subjects with myoelectric control was 0.38 per test. With switch control the average was 0.62 per test. The larger number of grasp errors with pull-switch control can most likely be attributed to the interaction of the switch with the hook control cable as used by subjects R.W. and D.H.

SUBJECTIVE OPINIONS OF SUBJECTS AND OBSERVERS

Subject J.H. favored the pull-switch control over the myoelectric control even though he scored slightly better with the myoelectric system. He preferred his conventional prosthesis to the externally powered systems.

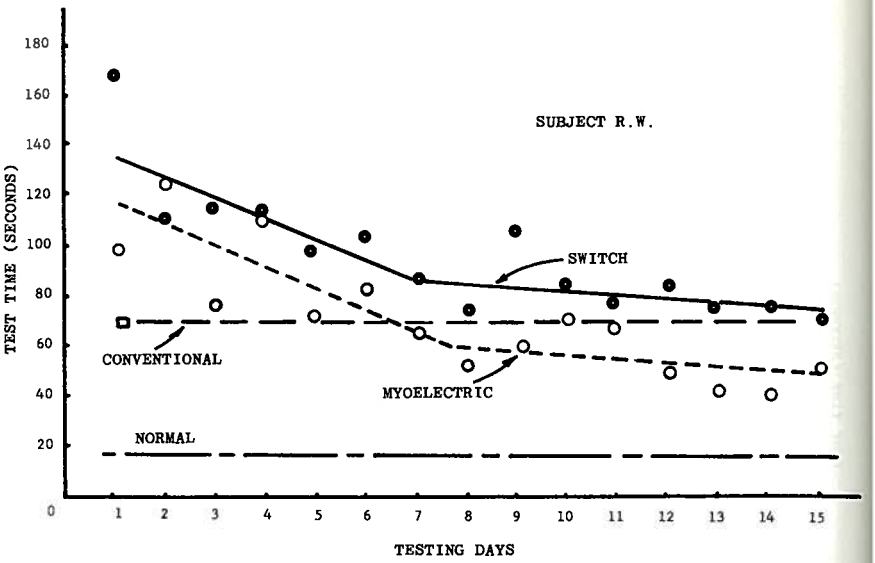

FIGURE 11.—Results for subject R.W. (See caption of Fig. 9.)

Subject D.H. preferred myoelectric control to switch control although the preference was not strong. He indicated difficulty in obtaining a "feel" for the location of the active modes of the switch.

Subject R.W. preferred myoelectric control to both the pull-switch control and the conventional elbow. This opinion, of course, might change if the electric elbow proved not to be reliable in daily use. Nonetheless, he felt the powered elbow gave him definite advantages in terms of speed (no waiting to lock or unlock the elbow) and ease of operation. As opposed to switch control subject R.W. felt the myoelectric system give him more positive control and control which was not dependent upon body location. He indicated that he could not sense the switch position and felt that more practice would not improve his control of the switch.

The authors preferred the two-site, two-state myoelectric control system. Of course, the one subject using this system was a very highly skilled prosthetic user and this contributed to the overall appearance and performance. The three-state myoelectric control system used in the study was not considered optimal for elbow control. Nevertheless, it was felt that this control was preferable to the pull-switch in operation.

It appeared that locating the pull-switch on the anterior part of the upper arm was preferable to its being located in series with the control cable to the hook. When located anteriorly there is more isolation be-

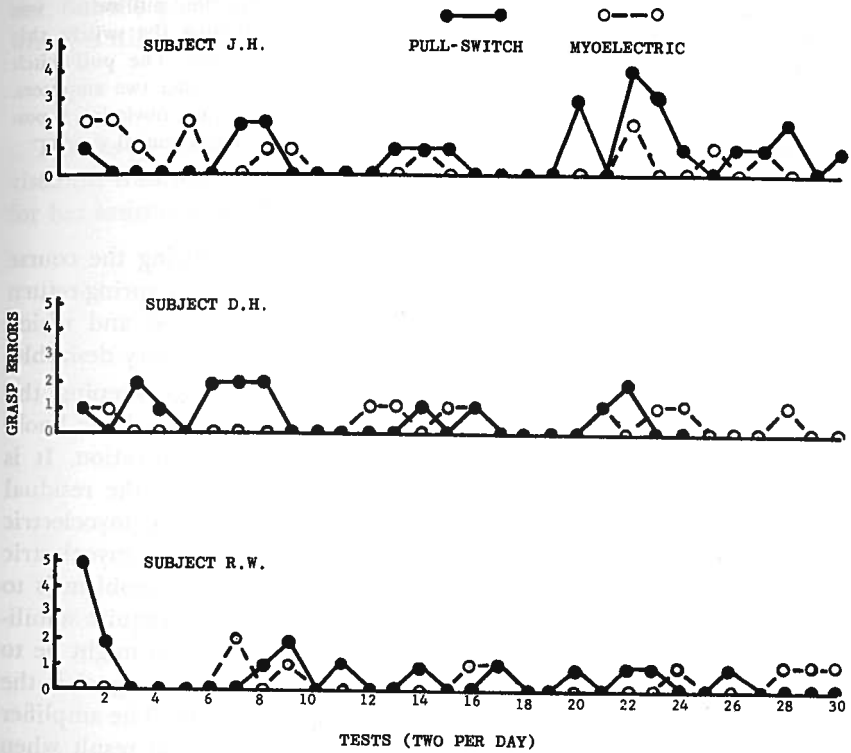

FIGURE 12.—Graphs showing the number of grasp errors made by each subject on each test (myoelectric and switch control).

tween elbow and hook function and the motion used for switch actuation is the already familiar elbow-locking movement.

The occupational therapist involved with the study (Miss Fran Rizzo, O.T.[8]) gave this opinion of the two control schemes:

> The amputees' ability to improve speed of operation of the electric elbow seemed dependent mainly on the quality of sensory cues and feedback offered by the particular control system, judging from the behavior and comments of the subjects. The EMG in most instances provided more accurate anticipation of the forearm position in space. The disadvantages of the pull-switch in this respect apparently stemmed from the fact that the switch control settings were not always distinct; the amputee easily "forgot" the particular setting in which the pull-switch remained (flexion or extension). In other words, errors in maintaining the flexion or extension settings and errors in moving directly from flexion to extension (or vice versa) were still being made up to the final trials. Returning the switch to closed position sometimes necessitated exaggerated body motion

[8] Occupational Therapist, Rehabilitation Institute of Chicago.

(scapular adduction). However, in the one case where the pull-switch was located anteriorly, visual cues were utilized when positioning the switch; this would be an obvious hindrance during functional activities. The pull-switch attached to the terminal device control strap, tested by the other two amputees, does not permit simultaneous hook opening and elbow motion, obviating a possible practical advantage of the powered elbow over the conventional system.

OBSERVATIONS

The pull-switch needed to be adjusted frequently during the course of the study as did its relative position in the harness. A spring-return mechanism on the switch which could be easily adjusted and which would not age or wear as did the rubberbands would be very desirable.

It was observed that all three subjects had difficulty keeping the muscles of the stump relaxed while they operated the prosthetic hook. All were able to accomplish this but it required concentration. It is assumed that the above-elbow amputee tends to contract the residual biceps and triceps as a form of socket stabilization. The myoelectric potentials from this activity may be enough to activate a myoelectric system attached near these muscles. One solution to this problem is to use an externally powered terminal device which does not require stabilization of the stump during its operation. Another solution might be to arrange the electronic system so the processed myoelectric signal is the difference between the signals from the biceps and triceps. The amplifier gains could then be adjusted so that a null signal would result when the two muscles are contracted simultaneously. Some prosthetic systems employing myoelectricity do use this principle. However, the Viennatone system used in this study did not. Of course, the three-state, single-electrode systems cannot operate in this manner.

CONCLUSIONS

It is concluded that an externally powered elbow and body-powered hook are a reasonable configuration for the above-elbow amputee. This hybrid arrangement seems to be of particular value when it allows coordinated movement of the elbow and terminal device. Subject R.W. made particularly good use of this feature when the elbow was controlled myoelectrically.

The results show that the major improvements in prosthetic performance by the subjects occurred during the first five to seven sessions. Therefore, for this type of prosthetic system and perhaps other systems of similar complexity, it would appear that 8 to 10 hours of training spaced over several days would be adequate to bring the amputee to a performance level in the neighborhood of his ultimate performance level. Of course this conclusion is based on a small sample and a very limited

test, but the similarity of the results with all three subjects makes it one which is difficult to avoid.

ACKNOWLEDGMENTS

Thanks go to Miss Fran Rizzo who so patiently and efficiently supervised the training and testing of the subjects and to Miss Carole Herhold for her assistance with the preparation of this report.