BELOW-ELBOW CONTROL OF AN EXTERNALLY POWERED HAND[a]

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I. INTRODUCTION

A. Goals of the Study

The use of myoelectric signals to control an externally powered hand would seem to offer a below-elbow amputee advantages over other means of control, such as electric pull-switches. In previous studies, such as that of the Seventh Workshop Panel on Upper-Extremity Prosthetics, CPRD, various externally powered terminal devices have been compared, but such variables as design and different subjects make a *direct comparison* between EMG and other types of control difficult.

The purpose of this study was to reduce the number of variables so that the speed of learning, final performance speed, and incidence of error in a simple manipulation test would allow quantitative comparisons to be made. Each subject performed the test with both types of control and only wore the device in the laboratory so that practice time could be controlled. Therefore, for each subject, the only variable was the type of control.

B. Systems

The hand used in this study was the Viennatone MYOMOT MM3D, shown in Figure 1 with EMG control. As described in the report of the Seventh Workshop Panel, this system consists of two electrode units with preamplifiers, a control amplifier, rechargeable battery pack, and the hand itself. The EMG system provided on/off control, so that there was no speed advantage with this system.

Figure 2 shows the system as modified to utilize a VAPC pull-switch in a figure-8 harness. The switch was wired to provide these functions with increasing excursion: off-close-open-off.

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[a] This paper was presented at the Eighth Workshop Panel on Control of Externally Powered Components of the Subcommittee on Design and Development, Committee on Prosthetics Research and Development, Mar. 31–Apr. 2, 1970, Downey, Calif.

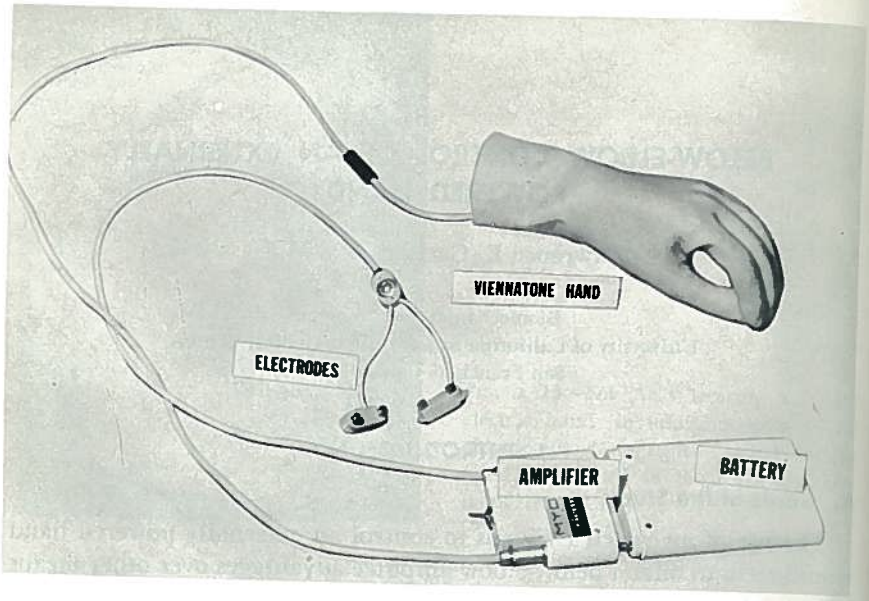

FIGURE 1.—System with EMG control.

II. PROCEDURE

A. General Procedure

Each subject was fitted with a completely new prosthesis incorporating the Viennatone hand which could be controlled either myoelectrically or with the VAPC pull-switch. After initial fitting and orientation, subject number 1 performed 30 tests (described below) with the VAPC system, while subject number 2 performed the same 30 tests using EMG control; this phase of testing took about 1 month to complete.

At this time, the two subjects were refitted and retrained for the other type of control, which took a week. The subjects also were tested with their conventional prostheses (both wore Dorrance #5 hooks) at this time in order to obtain baseline reference data. Testing at this time, rather than at the beginning of the study, insured that the subjects would be familiar with the test, so that more accurate reference data could be obtained.

The subjects then performed another 30 tests with their new systems to complete the testing program, which took another month. Comparisons could then be drawn between the two externally powered systems and the conventional system.

B. Subjects

Two unilateral male left below-elbow patients served as subjects for the study, with a third patient ready as a backup, if neeeded. Subject

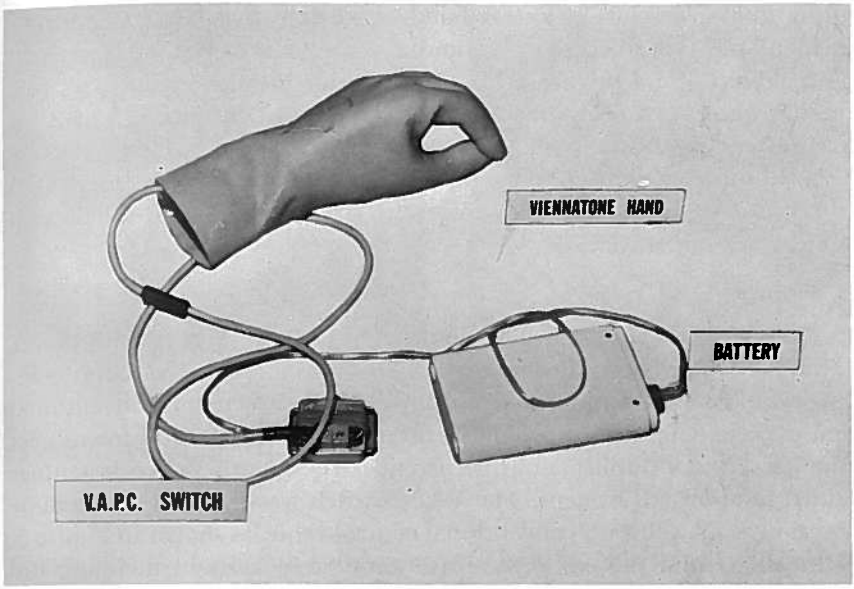

FIGURE 2.—System with VAPC switch control.

number 1 (Fig. 3) was an 18-year-old student with a wrist disarticulation due to an accident 4 years ago. He is a current wearer of both a Dorrance #5 hook and a Robin-Aids "soft" hand; he wears the latter most of the time for cosmetic reasons. The hand did not open wide enough to perform the test, so his hook was tested as his conventional device.

Subject number 2 (Fig. 4) was a 40-year-old veteran employed as a

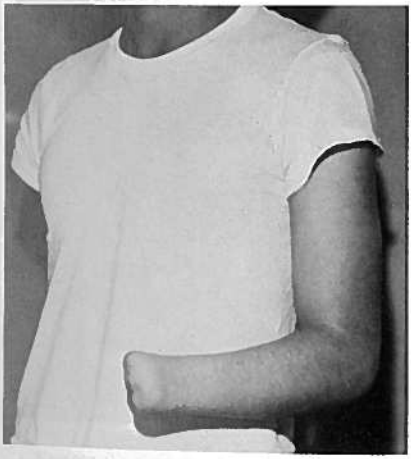

FIGURE 3.—Subject number 1.

FIGURE 4.—Subject number 2.

high school counselor; he lost his hand 4 in. below the elbow in a hunting accident in September 1969, 4 months prior to the start of the study. This subject had a private pilot's license prior to his accident, and was recently recertified using his present prosthesis, a Dorrance #5 hook in a Münster-type socket.

Both subjects were intelligent, cooperative, and highly motivated toward the study. No problems arose with scheduling, so that the backup subject was not needed.

C. Fitting

Although the sockets of both subjects' prostheses were slightly loose, the sockets were duplicated so that no new variables due to socket refitting would be introduced and a comparison between the conventional and experimental devices would be meaningful. The harness for subject number 1 was a duplicate of his current harness, with Velcro fastenings added to allow adjustment. The VAPC switch was fastened in the same location as the subject's conventional control cable, as shown in Figure 5. Since the second subject wore a Münster-type socket and therefore did not need a harness for suspension, a slightly modified harness was fabricated for the VAPC control, although the switch was located in the same place as his cable (Fig. 6).

A Viennatone MT–21A myotester (Fig. 7) was used for muscle training and EMG electrode location (Fig. 8). The extensor muscles, emanating from the lateral epicondyle of the humerus, were used to control hand opening, while the flexor muscles, originating on the medial epicondyle,

FIGURE 5.—VAPC harnessing—subject number 1.

FIGURE 6.—VAPC harnessing—subject number 2.

FIGURE 7.—Viennatone Myotester.

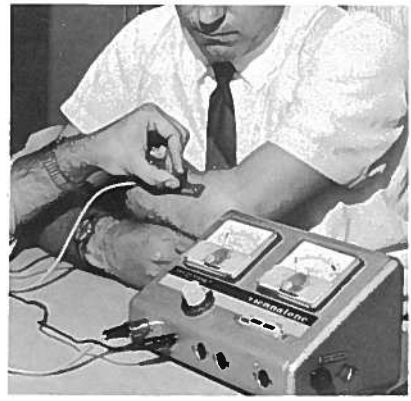

FIGURE 8.—Electrode location using Myotester.

controlled closing. Both subjects experienced a little initial difficulty in contracting the appropriate muscles, but mastered the task with very little training. They both found it helpful to flex and extend the unaffected wrist while relearning how to "flex" and "extend" the amputated side.

When the optimum electrode locations on the stump were determined, the electrode housings were fitted into the corresponding locations in the socket (Fig. 9 and 10). Small clips held the units in place, so that the electrodes could be conveniently switched between the two prostheses. The ground electrode was taped to the inside of the socket along the ulnar surface.

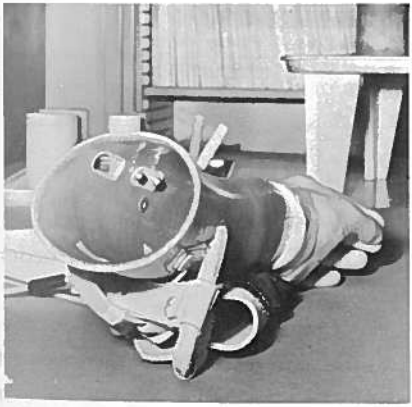

FIGURE 9.—Socket with electrodes in place —subject number 1.

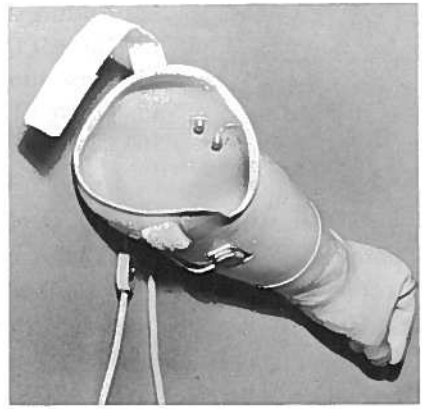

FIGURE 10.—Socket with electrodes in place—subject number 2.

D. Controls Practice

In order to control the variable of practice time, the subjects were allowed to practice with the experimental prostheses only in the laboratory. After longer periods of time had been tried, it was found that a total practice time of 5 minutes per session was quite adequate. Longer practice time resulted in more fatigue of the subjects, both physical and mental, with no advantage in improved performance. The total amount of practice time for each type of control was approximately 60 minutes.

The practice session consisted of two phases. The first consisted simply of opening and closing the hand in different positions in response to random commands by the tester, so that the amputee was unaware of what the practice sequence would be. The second phase consisted of the sequence of movements, starting with the arm fully extended at the side, shown in Table 1.

TABLE 1.—*Control Practice Exercise*

1. Open TD.
2. Flex elbow to 90°.
3. Close TD.
4. Open TD.
5. Flex elbow to 135°.
6. Close TD.
7. Extend elbow to 0°.
8. Open TD.
9. Abduct shoulder to 90°.
10. Close TD.
11. Open TD.
12. Adduct shoulder to side (0°).
13. Close TD.
14. Flex elbow to 90°.
15. Open TD.
16. Close TD.

As the testing progressed, the amputees were asked to perform these practice exercises without looking at the hand. This was done in order to place emphasis on feedback paths other than vision.

After the practice session, followed by a short rest, the subjects performed the tests, usually three per session separated by 5 minutes of rest. The subjects started out doing only two tests per session, but it turned out that three were better because they were able to get a better feel for the test.

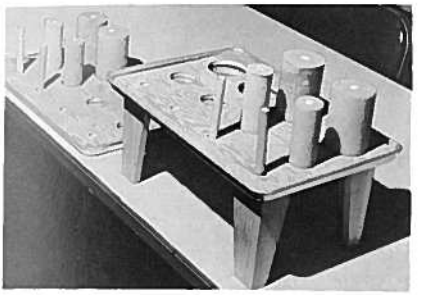

FIGURE 11.—Test arrangement.

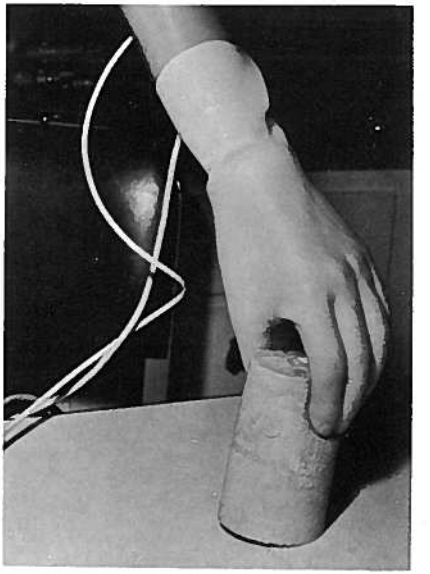

FIGURE 12.—A compression error on one of the test objects.

E. Test Procedure

The test consisted of moving 12 cylindrical objects between two 20 X 15 in. trays, as shown in Figure 11. The cylinders were all 4 in. high; there were four each with diameters of ½ in., 1½ in., and 2½ in. Half of them were made of rigid plastic, and the other half were compressible foam rubber (Fig. 12). The objects were all numbered, and had the properties shown in Table 2.

TABLE 2.—*Properties of Test Objects*

Number	Diameter	Material
1	½ in.	Incompressible
2	1½ in.	"
3	2½ in.	"
4	½ in.	Compressible
5	1½ in.	"
6	2½ in.	"
7	½ in.	Incompressible
8	1½ in.	"
9	2½ in.	"
10	½ in.	Compressible
11	1½ in.	"
12	2½ in.	"

FIGURE 13.—Grasping from the side.

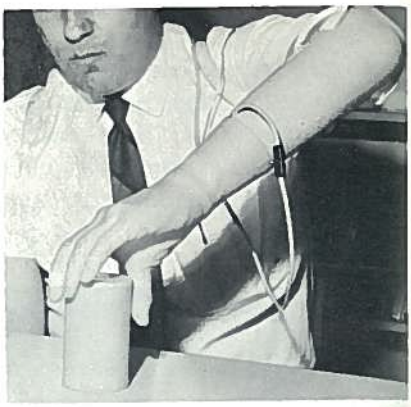

FIGURE 14.—Grasping from the top.

At the start of the test, the first six objects were placed in the lower tray, on the left, and the last six were placed in the upper tray, which was 6 in. higher. The subject grasped each object on the lower tray *in order*, and transported it to the same location on the upper tray and released it until all six had been moved. He then moved objects seven through 12 from the upper tray to the corresponding position on the lower tray. The objects were either grasped from the side (Fig. 13) or from the top (Fig. 14), but both subjects found it more convenient to grasp the objects from the top since it made it easier to avoid knocking over the other objects while performing the test (Fig. 15—18).

Prior to beginning the test program, the subjects were given the following instructions, which explain the scoring procedure:

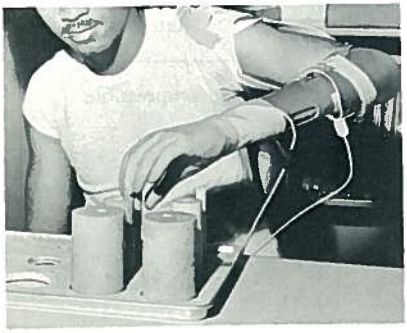

FIGURE 15.—Subject number 1 performing test (EMG control).

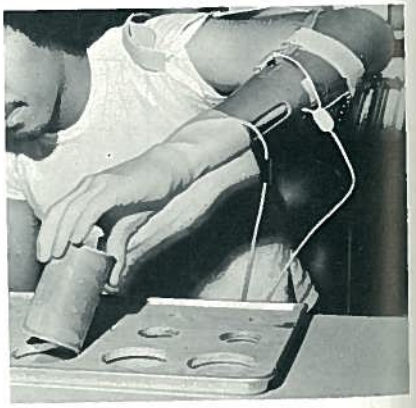

FIGURE 16.—Subject number 1 performing test (EMG control).

FIGURE 17.—Subject number 2 performing test (VAPC control).

FIGURE 18.—Subject number 2 performing test (VAPC control).

1. You are being tested on the speed of your performance on the tests and on your ability to position each of the objects without dropping them or compressing them.

2. Your time score will depend on the overall speed of your performance and on your ability to control the opening of the hand to match the size of the object being grasped. Opening too wide for an object will increase your time since you will have to wait for it to close down on an object. Not opening the hand wide enough to receive an object will require you to open it twice at the cost of additional time.

3. Half of the objects you must position are soft and easily compressible. You should grasp these objects with sufficient force to lift and transport them but *you must avoid compressing them.*

4. In addition to your score for the total time of your performance, two kinds of errors will be counted:

   a. Compression errors when you squeeze a soft object too hard.

   b. Grasp errors if you should drop or have to regrasp an object.

5. Work as rapidly as you can, but bear in mind the penalty for inaccuracy.

III. RESULTS

A. Data Processing

To facilitate handling of the data, a FORTRAN program was written to analyze the data and plot the results on a CALCOMP plotter. The raw data were punched on IBM cards and fed into a CDC 6400 computer at the University's Computer Center. Because of the scattered nature of the data (Table 3), the program smoothed the data to establish trend lines. This was done by averaging each data point with the points immediately preceding and following:

TABLE 3.—*Raw Data Values*

Subject number 1						Subject number 2					
Test time (seconds)		Number of grasp errors		Number of compr. errors		Test time (seconds)		Number of grasp errors		Number of compr. errors.	
EMG	VAPC	EMG	VAPC	EMG	VAPC	EMG	VAPC	EMG	VAPC	EMG	VAPC
119	193	1	7	1	3	144	119	1	1	3	3
75	108	2	2	0	2	280	102	7	0	2	2
89	115	2	6	1	2	180	91	2	1	0	2
60	72	0	1	1	2	102	111	0	1	0	1
58	88	1	1	0	1	112	93	3	0	0	4
53	87	1	1	0	0	82	119	0	2	0	3
51	65	0	1	0	0	102	92	1	0	0	3
54	58	1	0	0	1	90	81	0	1	0	3
54	88	1	2	0	2	90	83	1	0	0	0
56	63	1	1	0	1	77	85	0	1	0	1
51	69	1	2	0	1	67	101	0	2	0	1
48	63	0	1	0	2	71	102	0	1	0	5
68	61	3	0	1	1	70	91	0	1	0	3
63	64	1	1	1	2	63	87	0	0	0	2
45	60	0	1	1	0	67	77	0	0	0	2
49	53	0	0	0	0	60	82	0	0	0	3
48	59	1	0	0	0	65	67	0	0	0	1

45	62	0	1	0	4	63	76	0	0	0	2
46	59	1	0	0	2	121	75	1	0	1	2
51	53	1	0	1	1	67	83	1	0	0	2
46	72	1	1	0	0	73	85	0	0	2	3
42	75	0	3	0	1	73	81	0	0	0	4
44	58	0	0	0	3	87	80	0	0	0	1
50	61	1	1	0	2	68	111	1	2	0	3
44	54	2	0	0	3	67	84	1	1	0	1
44	58	0	0	0	4	99	92	0	1	3	2
39	54	1	0	0	0	72	82	0	0	0	2
45	50	1	1	0	1	74	84	0	0	1	1
44	59	0	1	0	0	63	67	0	0	0	2
40	52	0	0	0	0	58	64	0	0	0	2

$$Y_i' = (Y_{i-1} + Y_{i+1})/3 \qquad \text{for } i = 2 \text{ to } 29$$

The end points were calculated by:

$$Y_1' = (2Y_1 + Y_2)/3$$
$$Y_{30}' = (Y_{29} + 2Y_{30})/3$$

It was found by trial and error that two smoothing cycles were sufficient to generate a meaningful trend line. The smoothed data values were used in conjunction with a parabolic curve-fitting technique which fits parabolas through successive points to yield a smooth curve.

The output graphs are shown in Figures 19 through 22, which plot total test time, compression errors, and grasp errors as a function of test number for each subject with each type of control. Raw data values for EMG and VAPC control are shown as small squares and x's, respectively; the solid lines are the smoothed trend lines. The average values when the conventional hooks were used are shown as straight horizontal lines; since the average number of compression errors was zero for both subjects with their hooks, this baseline coincides with the abscissa and is not shown separately.

The program also computed the average values of the data as tabulated in Table 4 (the numbers in parentheses are averages over the last 15 tests only).

B. Quantitative Results

The results can generally be described as having two phases. The first phase is characterized by high initial values, implying poor performance, with rapid changes between tests. This effect, which may be termed the "transient phase," is an indication of the amputee learning the control method.

After a period of several tests, the second phase, or "steady state," becomes apparent. This is characterized by lower test values (i.e., better performance) with little average change from test to test, and is primarily due to inherent properties of the hand and control system such as speed of closing and geometry. For example, the test times are initially long while the subject is learning how to control the opening and closing of the hand. As he adapts to the control system and learns to optimize the hand movements (e.g., open it only as wide as necessary for each object), his time becomes limited by the speed of the hand and the speed with which he can move the objects.

1. Subject Number 1

Figure 19 (test time, subject number 1) exhibits these two phases quite markedly. The initial test times for both control methods are comparatively long, but both decrease to lower steady state values as the subject adjusts to each control system. It is difficult to compare the control systems on the basis of initial times, since the order of the test is a factor.

TABLE 4.—*Average Values of Test Results*

Control	Test time (seconds)			Number of grasp errors			Number of compression errors		
	EMG	VAPC	HOOK	EMG	VACP	HOOK	EMG	VAPC	HOOK
Subject number 1	54.0 [a](40.2)	71.1 (57.5)	40.0	.80 (.60)	1.17 (.53)	1.00	.23 (.07)	1.37 (1.40)	0
Subject number 2	90.2 (74.0)	88.2 (87.7)	83.0	.63 (.27)	.50 (.27)	1.00	.40 (.47)	2.20 (2.06)	0

[a] Values in parentheses are averages over the last 15 tests only, which represents the steady state phase of the results.

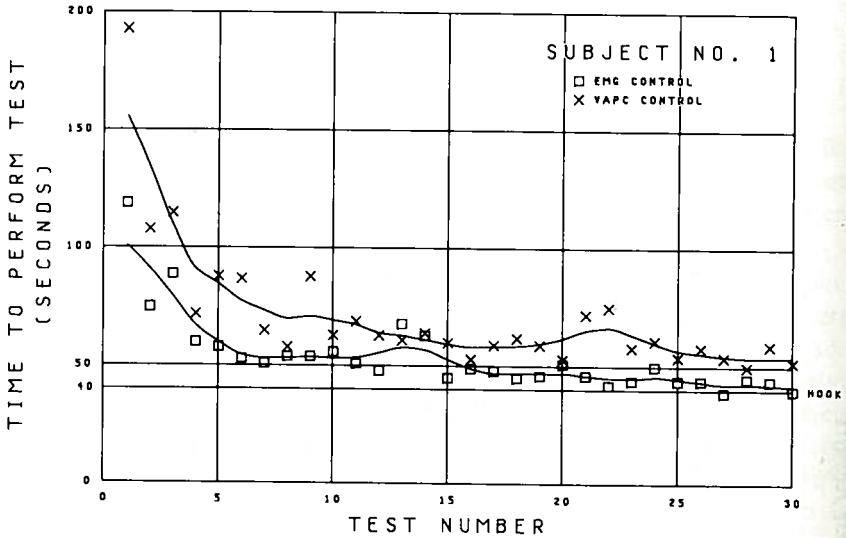

FIGURE 19.—Test time vs. test number—subject number 1.

This subject used the VAPC system first, and was not only learning this means of control, but also how to perform the test itself. It took this subject about 10 tests to reach steady state with VAPC control, while only about five tests were required with EMG control. This may or may not be significant, since the order of the test could affect the results as well.

The steady state times, however, reveal quite clearly that the EMG control allows faster performance than the VAPC control. The average time with EMG control is 54 seconds versus 71 seconds for VAPC control, but these averages include the high transient times which tend to raise the averages, and this can be misleading. The average values for the last 15 tests, which give a better indication of performance, are 46.2 seconds for EMG control versus 57.5 seconds for VAPC control. This is an indication of this subject's proficiency with EMG control; he could precisely control the amount of opening of the hand to minimize overshoot, and he could open or close the hand while moving it toward the object to be grasped. The latter activity was difficult with VAPC control because it was hard to move the prosthesis from one tray to the other without moving the shoulders and thereby changing the switch.

While test time is a measure of the speed of the test, the error scores reflect the accuracy of control. Figure 20 shows the error results for subject number 1. The two-phase nature seen in the test times is not very evident in either compression or grasp errors. However, the compression error results (top graph) distinctly show an advantage of EMG control in preventing compression errors. The subject seemed to have an excellent

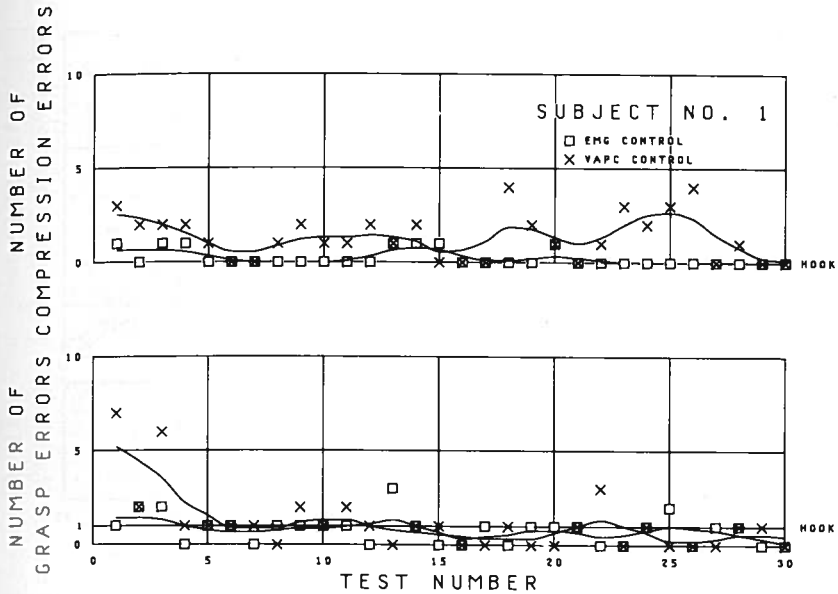

FIGURE 20.—Error scores vs. test number—subject number 1.

feel for the amount of force delivered by the hand, whereas he often tended to overshoot using the switch, resulting in squeezing the object too hard. The computed average bears out this difference: The average number of compression errors for EMG control is 0.23 versus 1.37 using VAPC control. The average number for the three tests with the hook is zero, mainly because there was not enough force available to measurably deform the four smaller soft cylinders. Therefore, the difference between EMG control and the hook average is not significant.

Grasp errors are probably more a function of the grasp characteristics of the hand and practice on the test itself rather than control type. The reason for this is that once a subject grasps an object, regardless of the type of control, he relaxes and does not activate the system until he has transported it and is ready to release it. The grasp error curve for subject number 1 (Fig. 20) exhibits this type of behavior: The curve representing VAPC control, which was the first test, exhibits a transient phase for about five tests. After that, the average curve levels off at about one error. When the subject switches to EMG control, the number of errors remains about the same, and the smoothed curves for EMG and VAPC control cross each other several times. The average number of errors is higher for VAPC control (1.17 versus 0.80) but the transient portion accounts for that, bringing both the averages below 0.6. Both control systems performed as well as or better than the subject's conventional hook.

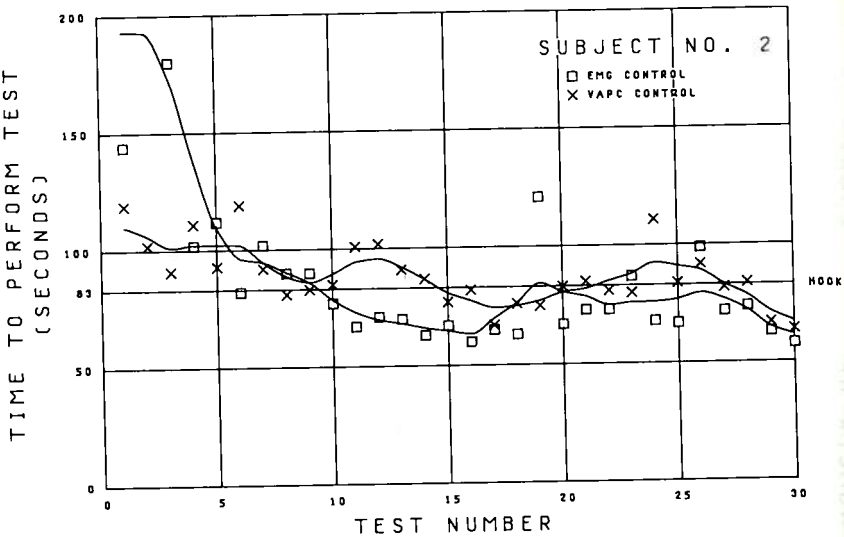

FIGURE 21.—Test time vs. test number—subject number 2.

2. Subject Number 2

The time curves for the second subject (Fig. 21) are similar to the first subject's results (Fig. 19). All of the times are slower, including the conventional average, which reflects a difference in the subjects. Subject number 1 tried to work very rapidly, constantly striving to better his time, while subject number 2 preferred to work more slowly and cautiously. This subject was tested on EMG control first, so the transient times are much longer than those when VAPC control was used, primarily due to unfamiliarity with the test. The steady state phase, however, clearly shows that the EMG times are generally faster; they are usually faster than the conventional hook average, in fact. The steady state average (the last 15 tests) for EMG control is 74.0 seconds versus 87.7 seconds for the VAPC system and 83.0 seconds with the hook.

The number of compression errors is sharply reduced with use of EMG control for this subject as well (Fig. 22). The EMG curve, representing the first test run, exhibits a short transient phase that diminishes after two or three tests, while the VAPC curve remains at a high level of error. The average number of errors clearly illustrates this difference: 0.40 for EMG versus 2.20 for VAPC.

As with subject number 1, this subject's grasp error score exhibits a transient phase for the first tests run (in this case, EMG control), but not for the second series of tests, again indicating that the type of control is not as important in affecting grasp errors as is practice on the test itself. The average score is slightly higher for the EMG tests, since they

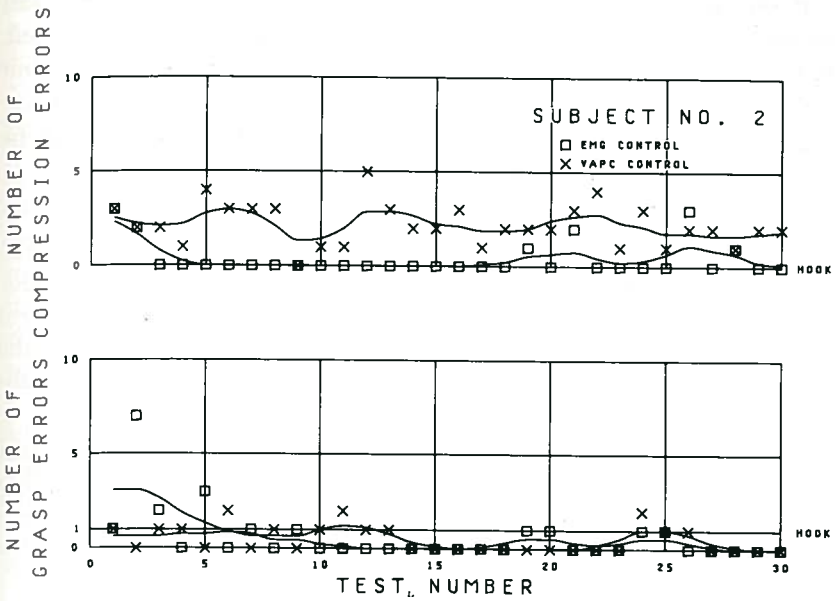

FIGURE 22.—Error scores vs. test number—subject number 2.

were the first tests, but both averages are again below the average for the conventional prosthesis.

In summarizing the results, the following can be said for both subjects: 1. EMG control was faster than VAPC control, 2. EMG control caused fewer compression errors, and 3. type of control had little effect on grasp errors. To check these conclusions, the scores from the last 25 tests were statistically analyzed at a confidence level of 98 percent, which verified that the differences in time and compression error scores were significant, but the differences in grasp error scores were not significant.

C. Patient Reactions

1. Subject Number 1

The first subject preferred the EMG system for several reasons. Mainly, he was able to achieve very fine control of the prosthesis. He could close the hand down on his own fingers without applying too much force, and he even found it possible to pick up an egg without cracking it. Since his amputation occurred 4 years ago, it took a little training to learn to contract one muscle without contracting both. After he learned to selectively contract the right muscle, however, he remarked that the control seemed very natural. In fact, he found himself trying to control his hook in the same way. He seemed to have no difficulty performing the practice exercises while drinking a cup of coffee with his right hand, a task he could not easily do with switch control.

Of the switch, he remarked that the control was too unnatural, and was very awkward in some positions, such as with the shoulder abducted. He was proficient in the test that made use of both types of control, but used a lot of motion with his opposite shoulder to control the switch.

He seemed to like the prosthesis generally, and indicated that he would buy one if he had the money.

2. Subject Number 2

This subject was also emphatic in his preference of the EMG system. His main reason was the fact that he could eliminate all forms of harnessing, since he wore a Münster-ytpe socket. He felt that the EMG control was more natural, and had no trouble in learning how to contract the proper muscles since his amputation had occurred just 5 months previously.

He also liked the hand itself, regardless of the type of control, mainly for cosmetic reasons, although there were functional reasons as well. For example, he thought the hand would provide a firmer grip on the wheel while flying. The only objection he voiced was a concern about the amount of noise it generated.

This subject was so enthusiastic about the EMG-controlled prosthesis that he wanted to buy one as soon as he could. Since he is a veteran, arrangements were made for him to keep the hand used in the test. The Biomechanics Laboratory, University of California, will perform any necessary refitting, and will retain the subject as a research patient.

D. System Performance

Most of the time, the prostheses functioned properly, but there were a few problems that developed. The VAPC switch became sticky on two occasions and did not slide smoothly. The first time, this was due to a bent actuator on one of the microswitches, and it was easily repaired. The second time, a little "STP" was applied to the sliding surfaces, which solved the friction problem that had developed.

The connector that was used to plug the VAPC switch into the battery caused a few problems. First, the pins on the connector were slightly larger than those on the EMG amplifier unit, causing the female part of the connector in the battery to spread a little each time the VAPC connector was inserted. After a few times, the connector would make contact erratically. Squeezing the small sockets together periodically solved this problem. One of the wires to this also broke once and had to be resoldered.

The EMG system functioned well with one exception: One of the wires in the electrode cable broke at the connector to the amplifier unit, necessitating disassembly of the connector and repair.

These problems were probably caused by the frequent assembly and

disassembly which the systems underwent. This was necessary because the subjects used the same hand but different control systems and sockets.

IV. CONCLUSIONS

Tests such as the ones performed in this study are somewhat limited in an absolute sense but can yield valuable information in a relative sense. The usefulness of an externally powered hand to an amputee depends on many factors such as function, cosmesis, control system, cost, and reliability; this type of test cannot provide insight into all these areas. However, but holding constant all the variables except the type of control system, definite conclusions concerning EMG versus electric pull-switch control can be drawn.

These conclusions, based both on the numerical test results and on subjective evaluation by the tester, are:

1. EMG control allows an amputee to manipulate objects faster than switch control.
2. EMG control provides more precise control of hand motion and pinch force.
3. There is no significant difference in the learning time required for the control types, and, once learned, EMG control affords more natural control of the hand.