EVALUATION OF THE HEIDELBERG PNEUMATIC PROSTHESIS

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FOREWORD

The research described in this report, *Evaluation of the Heidelberg Pneumatic Prosthesis,* by Luigi Lucaccini, Roger Wisshaupt, Hilde Groth, and John Lyman, was carried out under the technical direction of John Lyman and is part of the continuing program in upper-extremity prosthetics research.

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ABSTRACT

This paper presents the results of an engineering and performance analysis conducted on an upper-extremity prosthesis developed at the University of Heidelberg, Germany. This prosthesis provides bi-directional movement around three axes (at the elbow, wrist, and hand) and is externally powered by a portable and rechargeable CO_2 source.

Engineering tests provide data regarding the speed of movement of the various components, the forces available from these components, the mechanical reaction times of these components, the characteristics of the prosthetic control system, and a brief description of the mechanical operation of controls and components.

Performance tests were conducted on two subjects: (a) a standard above-elbow amputee, and (b) a forequarter amputee. Data from these tests include the ranges of operation of the prosthetic components achieved by the amputees, their speed in initiating the various movements of the prosthesis, their precision of motion, and their performance on a series of standardized tasks under normal and stressing conditions.

INTRODUCTION

The results of an engineering and performance assessment study of the Heidelberg Pneumatic Prosthesis conducted at the Biotechnology Laboratory, University of California at Los Angeles are given in this report. The Heidelberg Pneumatic Prosthesis represents an important milestone in the development of artificial arms since it can be considered the first practical externally powered prosthesis. Earlier attempts substituting auxiliary power for conventional muscle power led only to construction of several prototype models, as for example the IBM electric arm or to a limited number of individual units as in the case of the French electric hand.

The Heidelberg prosthesis can be used as a hybrid system with conventional and pneumatically driven functions or as a complete externally powered system. This flexibility makes it useful for amputees at all levels of disability, although the greatest rehabilitative value of the prosthesis will be for the severely handicapped. For these patients, satisfactory substitution of lost functions is hardly possible with conventional body-powered systems and an external energy source is expected to aid in reducing effort and fatigue during operation.

The pneumatic arm provides the same functions as conventional prostheses but in addition permits active wrist rotation, adding to its utility.

The relatively wide acceptance of the pneumatic prosthesis in Europe and the interest expressed in this country were the prime reasons for conducting a controlled laboratory study and assessing its functional and engineering characteristics. Similar studies have been conducted on other externally powered devices such as the AIPR Pneumatic Prosthesis, the French electric hand, the Yugoslav electronic hand, and the Northwestern University electric elbow.

Various phases of this assessment study have been in progress since 1961 when this prosthesis was first obtained from the University of Heidelberg. Delays were imposed by several unforeseen events. On two occasions the arm was returned to Germany, once for replacement of the elbow bellows and again for an overhaul of the control valves. All replacement parts had to be obtained from the University of Heidelberg since no parts were commercially available. Waiting periods and experimental "downtimes" were therefore very long. Performance testing was completed late in the spring of 1964 and was followed by the engineering tests.

The study follows the general procedure outlined by Groth, Lyman, and Kaiser (1963), and is based on the "semi-case study" approach. Several phases of the evaluation have drawn heavily on earlier work in the area of prosthetic evaluation. Specifically to be mentioned in this regard are studies by Blaschke, Gottlieb, Jampol, and Taylor (1949), Gottlieb and Lyman (1951), Gottlieb, Santschi, and Lyman (1953), and Kay and Peizer (1958); and papers by Fishman (1954) and Groth and Lyman (1956).

The report is divided into three parts. In Section I, results of the engineering tests are presented along with a physical description of the Heidelberg Prosthesis (hereafter also referred to as the experimental arm). Section II contains the results of performance tests obtained on two amputee subjects using the experimental arm along with similar data wherever applicable for one of the subjects using a conventional American above-elbow prosthetic arm. Conclusions and recommendations regarding the experimental arm are presented in Section III.

I. ENGINEERING EVALUATION

A. System Description

1. Physical Configuration

The complete Heidelberg prothetic arm has the following three basic components which form the active system: (1) the upper arm, (2) the lower arm, (3) the terminal device (TD). The upper and lower arm shells are fabricated of conventional plastic materials.

The configuration used in this study was chosen to be representative of a variety of options available for various amputation levels and various user occupation groups. Comprehensive surveys of these options have been provided by Marquardt (1963) and Marquardt and Haefner (1957).

a. Upper Arm. No active components used in the operation of the powered articulations are contained in the upper arm. It is terminated distally by an end plate with holes arranged for the mounting of the lower portion of the arm.

b. Lower Arm. This part is connected to the upper arm by means of a threaded pin located proximally in the upper end of the elbow mechanism. Figure 1 illustrates the lower arm and terminal device. Flexion and extension functions are provided by the elbow through the inflating and exhausting of a bellows. The elbow locking mechanism which consists of a bellows, locking pin, and spring is located inside the lower arm adjacent to the elbow mechanism. The elbow unit and elbow locking unit are illustrated in Figure 2. Figure 3 illustrates the wrist rotation unit which operates through the combined action of a bellows and return spring. Next to the wrist rotation unit but not shown is the wrist locking mechanism which operates in a manner similar to the elbow locking unit.

c. Terminal Device. A sculptured wooden hand is connected to the lower arm wrist unit with an axial shaft. The articulated thumb closing toward the index finger is activated by a bellows and spring inside the hand permitting the thumb to be locked at any desired position. The distal ends of the thumb, index finger, and second finger are equipped with small rubber pads to aid prehension (Fig. 4).

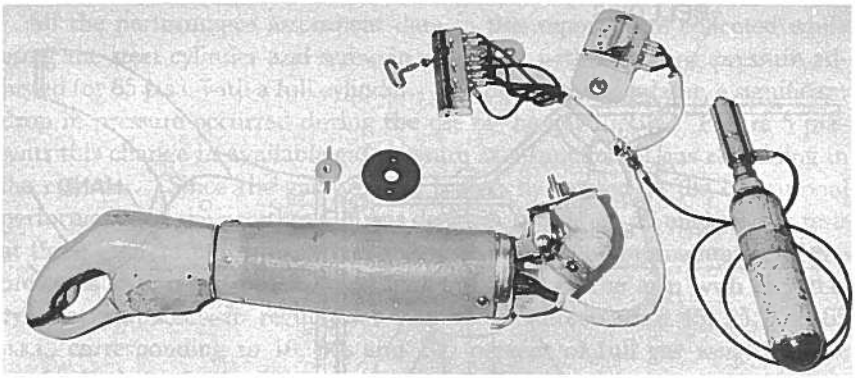


FIGURE 1. Heidelberg Pneumatic Prosthesis. Photograph includes elbow bellows, lower arm, terminal device, gas bottle and screw-in regulator, 7-position control valve, 4-position control valve, washer, and wing nut.

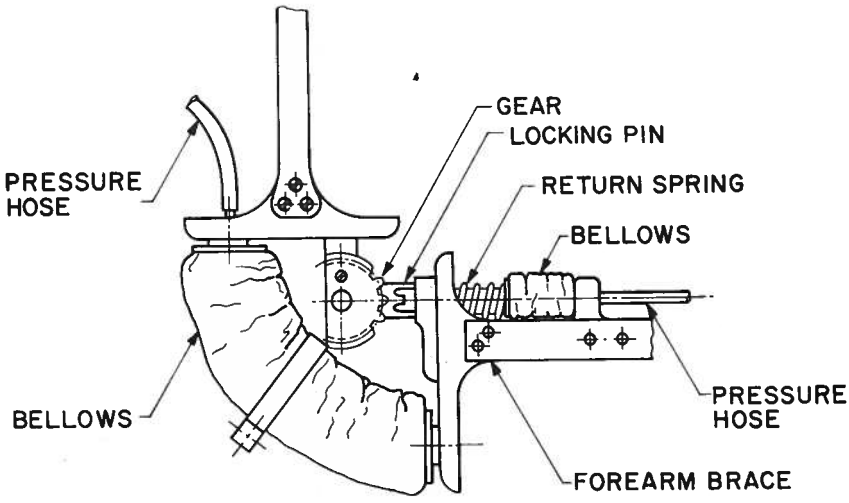


FIGURE 2. Elbow unit.

2. *Power Source and Linkage*

The Heidelberg arm is gas powered and designed to be operated from a portable compressed CO_2 source, a small pressure cylinder filled with liquid CO_2, and connected to a regulator adjusting the operating pressure. The portable cylinder is recharged by connecting it to a large CO_2 tank using a special valve and reduction fitting obtained commercially. Problems arising for the amputee from this procedure will be discussed in Section I.B.4.d.

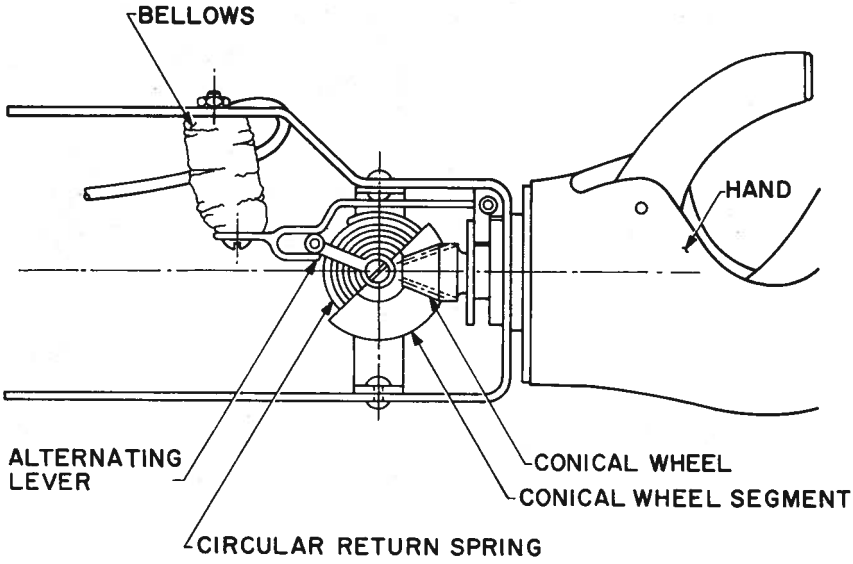


FIGURE 3. Wrist unit.

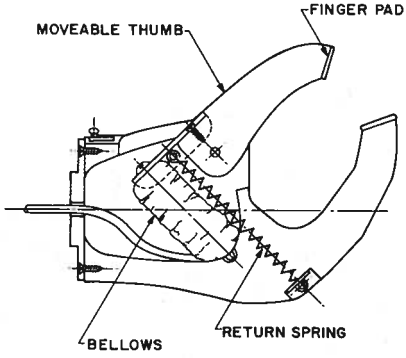


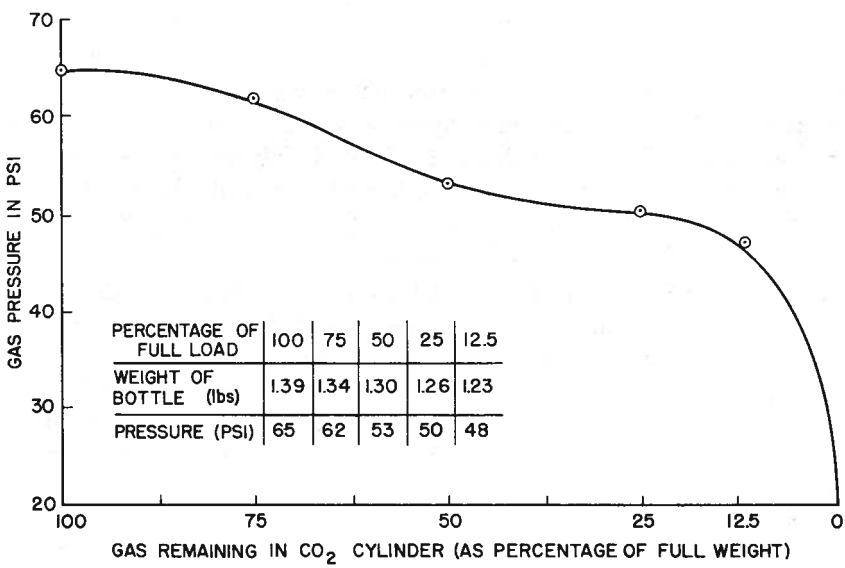
FIGURE 4. Pneumatic hand.

The German cylinder supplied with the arm had a built-in regulator; however, it was made of aluminum and did not meet the United States standards for high pressure gas containers. It was replaced by an equivalent size steel cylinder with a screw-in regulator that was commercially available. The weight of the empty steel cylinder with regulator was 1.22 lb. as compared to 0.46 lb. for the original aluminum device. The capacity of the steel cylinder was 0.17 lb., whereas the capacity of the aluminum cylinder was estimated at 0.26 lb. (taking into account the volume difference). As a consequence, the gas represented 12.2 percent of the total weight in the case of the steel cylinder versus 36.1 percent for the aluminum cylinder.

All the performance assessment data in this report were collected while using the steel cylinder and screw-in regulator, with operating pressure adjusted for 65 p.s.i. with a full cylinder. In spite of the regulator, a significant drop in pressure occurred during the use of the gas supply. Figure 5 presents this change in available gas pressure as a function of gas remaining in the cylinder. Since the gas pressure is directly related to the operational performance of the prosthesis, it was decided to conduct all engineering tests at three discrete pressures. These were selected to be representative of the pressures that could be expected in normal use of the arm with the steel cylinder and screw-in regulator. The values chosen were 45, 55, and 65 p.s.i., corresponding to 10, 60, and 100 percent of full gas weight in the steel cylinder (cf. Fig. 5).

The arm was found to operate equally well from a large laboratory CO_2 tank equipped with an adequate regulator or from a standard laboratory compressed air supply with regulator. Tests of the elbow mechanism showed that at 65 p.s.i. there was no significant difference in the operation of the arm when either CO_2 or compressed air was used. Compressed air was chosen for engineering testing for convenience, repeatability, and availability of a good quality regulator.

The linkage from power source to control valves and from control valves to functional prosthetic parts was a small diameter rubber tubing (0.04 in. ID). This small tubing size serves also to damp the operation of the arm. The importance of this damping function was demonstrated by connecting the power source directly to the bellows.



PERCENTAGE OF FULL LOAD	100	75	50	25	12.5
WEIGHT OF BOTTLE (lbs)	1.39	1.34	1.30	1.26	1.23
PRESSURE (PSI)	65	62	53	50	48

FIGURE 5. Change in gas pressure with depletion of power supply.

3. Control System

Prosthesis control is achieved by the use of a set of on-off valves. Two valves, at least, are necessary for antagonistic functions, such as prehension, motion A and release, motion B. One valve connects the powerline to the bellows, permitting the inflation necessary for motion A when opened. A second valve exhausts the bellows by opening it to the atmosphere, thus allowing the reverse movement, motion B, of the prosthetic component by return spring or gravity as in the case of elbow flexion. Other valves are concerned with locking and unlocking functions. Construction of the valves is based on the use of ball-type pressure greasers modified for this purpose. Activation of the individual valves within a control is achieved by a multiple sector camshaft or by successive sections on a lever. The operation of the cam and valve complex is described in Section I.C.

B. Basic Mechanical Characteristics

1. Available Ranges of Motion

Antagonist movements of the arm receive power only for one motion, and the opposite motion is passive. Passive movement is produced either by the action of a spring compressed in the active phase or by gravity as in the case of elbow movement. Active or passive power control, pressure of the power supply, and external load will determine the operating characteristics for each function. The experimentally determined operating characteristics should be represented by a three-dimensional surface whose coordinate axes would be operating pressure, time, and angular deflection of displacement. Such a diagram would have to be constructed for each condition of external load. However, a representation of this kind would be too complex to be of practical value and a more limited approach was used. For each load condition, chosen to be representative of the range the arm can handle, a set of recordings was made showing displacement as a function of time at the three pressures. Using these curves and the diagram of pressure as a function of gas remaining in the bottle (Fig. 5), one may determine the performance characteristics of any component of the arm over the range of available pressure.

a. Elbow Range. The elbow has 10 locking positions about 9 deg. apart from each other, providing a range of motion of 81 deg. from upper to lower locking positions. It is possible to move the arm beyond the extreme locking position and extend this range slightly. The elbow locking mechanism was disconnected during testing of range of motion. Results of these tests are illustrated in Figures 6 and 7. A zero reference position was arbitrarily chosen as the position of the elbow in full extension with a load of 0.625 lb. at 65 p.s.i. The zero reference corresponded to an angle of 20 deg. with the vertical. The mounting of the forearm and application of loads was identical to that described in Section I.B.2.a. Ranges of motion

under the various loading and pressure combinations are presented in Table 1 in terms of this arbitrary reference point. A significant decrease in range occurred either when pressure was reduced or load increased.

TABLE 1.—*Range of Elbow Unit, Loaded and Unloaded, for Three Gas Pressures*

Gas pressure (p.s.i.)	No load	0.625 lb.	1.25 lb.	2.00 lb.
45	+4/+91	0/+82	−2/+74	−2/+62
55	+4/+94	0/+86	−2/+79	−2/+69
65	+4/+96	0/+90	−2/+83	−2/+74

NOTE.—All values are in degrees.

b. Wrist Range. The wrist unit has 18 locking positions, 12 deg. apart from each other. The no-load range extends about 3 deg. on each side of the extreme locking positions. A constant torque loading was not considered representative of the normal loading conditions that would occur during use by amputees. Thus, to investigate the functional adequacy of the wrist unit the forearm was kept at a position of 90 deg. with regard to the upper arm, and two aluminum cylinders (1.5 in. diameter, 4 in. long, 0.75 lb.; 1.5 in. diameter, 8 in. long, 1.49 lb.) were used as loads. These cylinders were held in the terminal device so that the center of gravity of the cylinder coincided with the axis of rotation of the wrist mechanism. Size and weight of the large bar were experimentally determined so as to render operation of the wrist impossible for supination under the lowest operating pressure (45 p.s.i.). The zero reference point was defined as the position of the wrist in supination at 65 p.s.i. with no load. Experimentally determined values for wrist rotation range of motion are presented graphically in Figures 8 and 9. These results are summarized in Table 2. It should be noted in Table 2 that the range obtained at 45 p.s.i. with 1.49 lb. load was determined only for pronation since supination was not possible in this case. It can be seen from Table 2 that range of wrist motion was not altered appreciably over these combinations of load and pressure employed in testing.

TABLE 2.—*Range of Wrist Unit, Loaded and Unloaded, for Three Gas Pressures*

Gas pressure	No load	0.745 lb.	1.49 lb.
45	0/+210	0/+210	−5/+205
55	0/+210	0/+210	−5/+205
65	0/+215	0/+210	−7/+203

NOTE.—All values are in degrees.

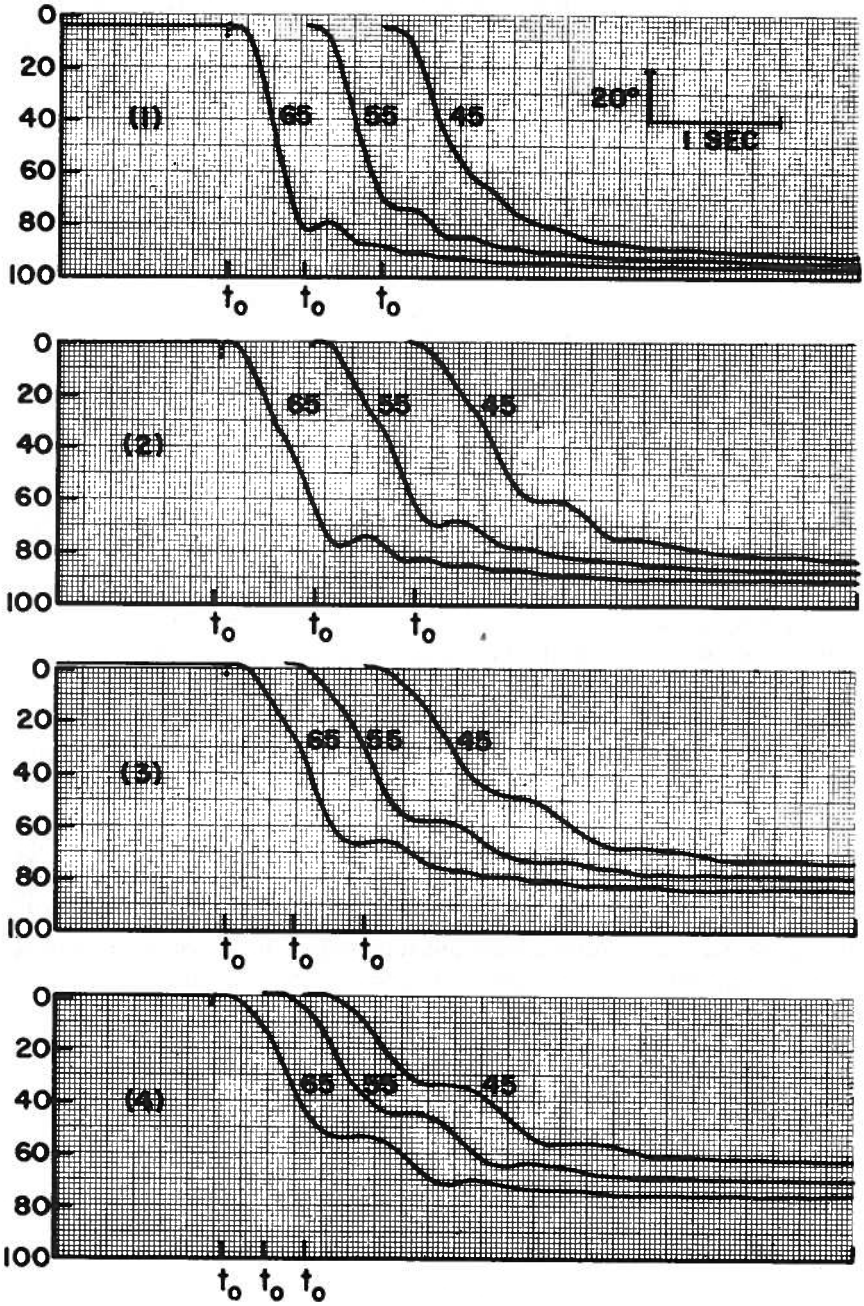


FIGURE 6. Flexion curves for elbow unit. Curves for gas pressures of 65, 55, and 45 p.s.i. are superimposed for (1) no load, (2) 0.625-lb. load, (3) 1.25-lb. load, and (4) 2.50-lb. load.

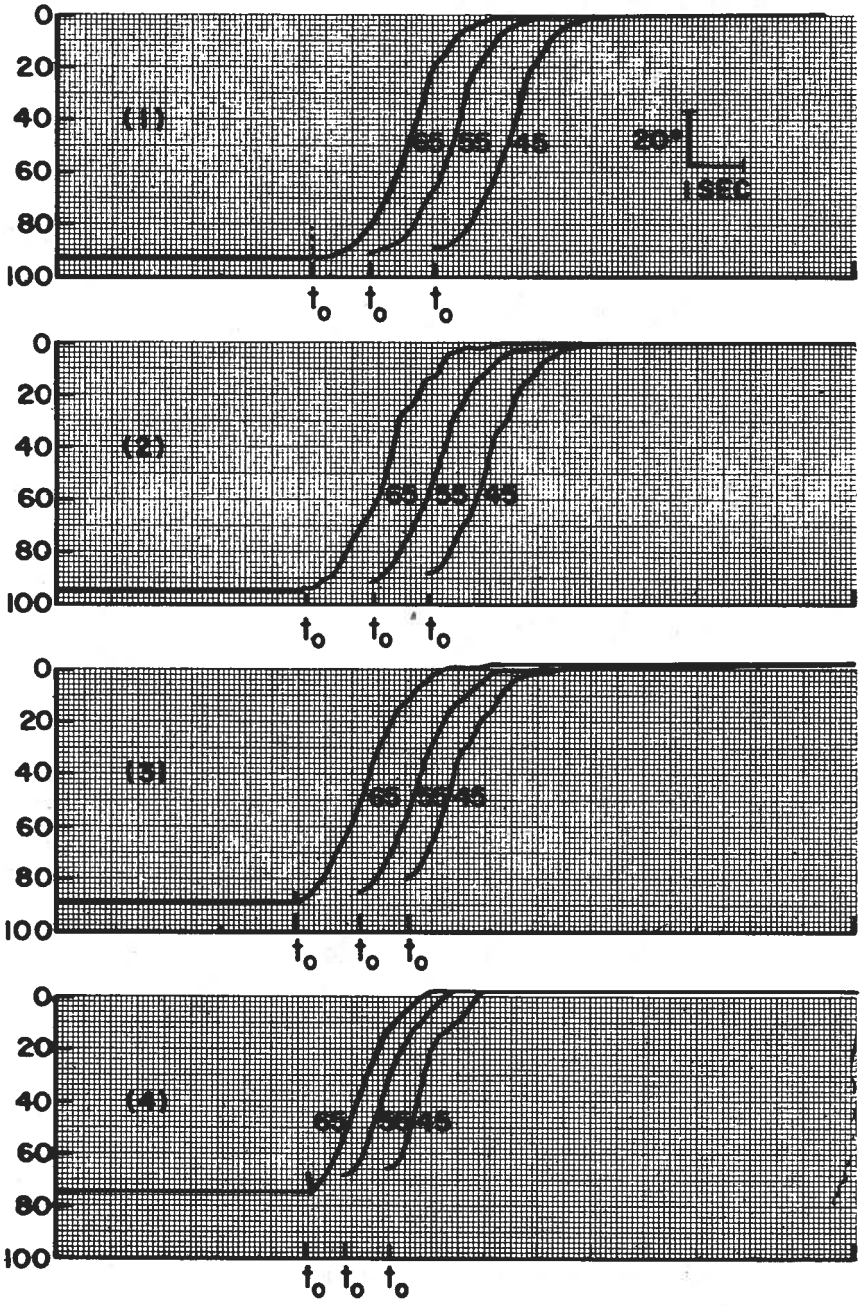


FIGURE 7. Extension curves for elbow unit. Curves for gas pressures of 65, 55, and 45 p.s.i. are superimposed for (1) no load, (2) 0.625-lb. load, (3) 1.25-lb. load, and (4) 2.50-lb. load.

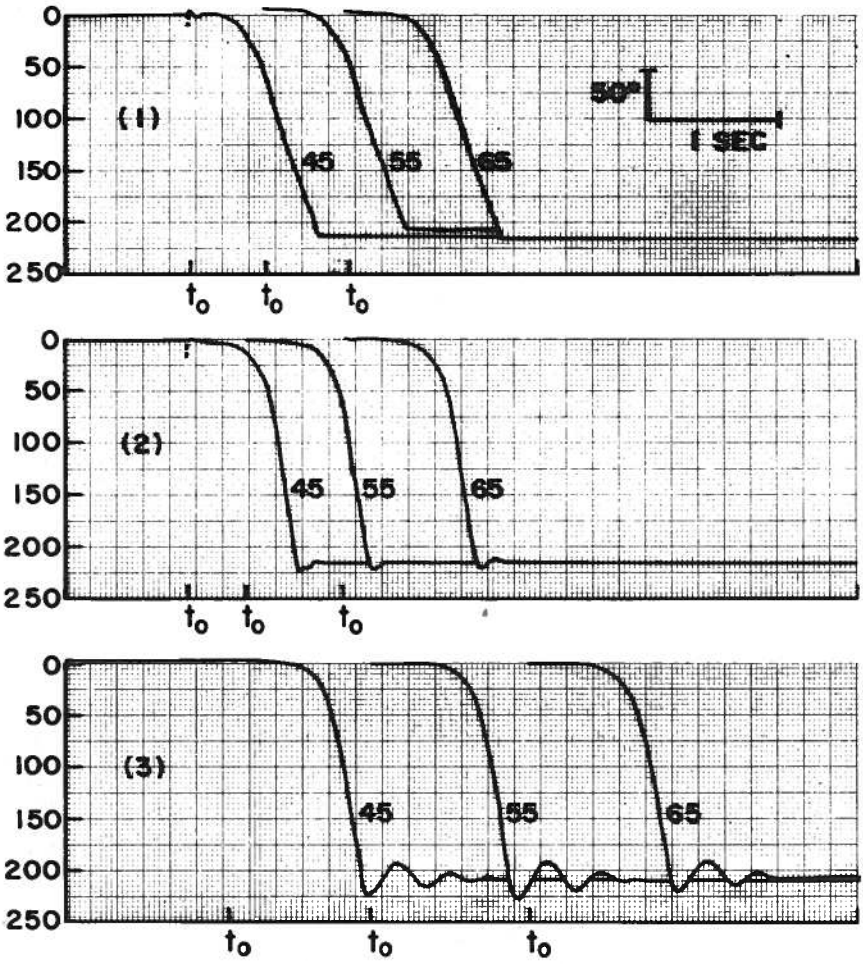


FIGURE 8. Pronation curves for wrist unit. Curves for gas pressures of 65, 55, and 45 p.s.i. are superimposed for (1) no load, (2) 0.745-lb. load, and (3) 1.49-lb. load.

c. Terminal Device Range. The terminal device has no fixed locking positions but can be locked by friction anywhere along its range of motion. There was no readily apparent technique for simulating a variable load on this unit, nor was the practical application of such a condition apparent; therefore, the operation of the terminal device was investigated without loading. In all cases a maximum range of motion of 45 deg. deflection was obtained except for closing at 55 and 65 p.s.i. which showed an additional degree of deflection. This was due to the compression of the rubber pads on the thumb and finger which disappeared when the valve was closed. The curves for this test are shown in Figures 10 and 11.

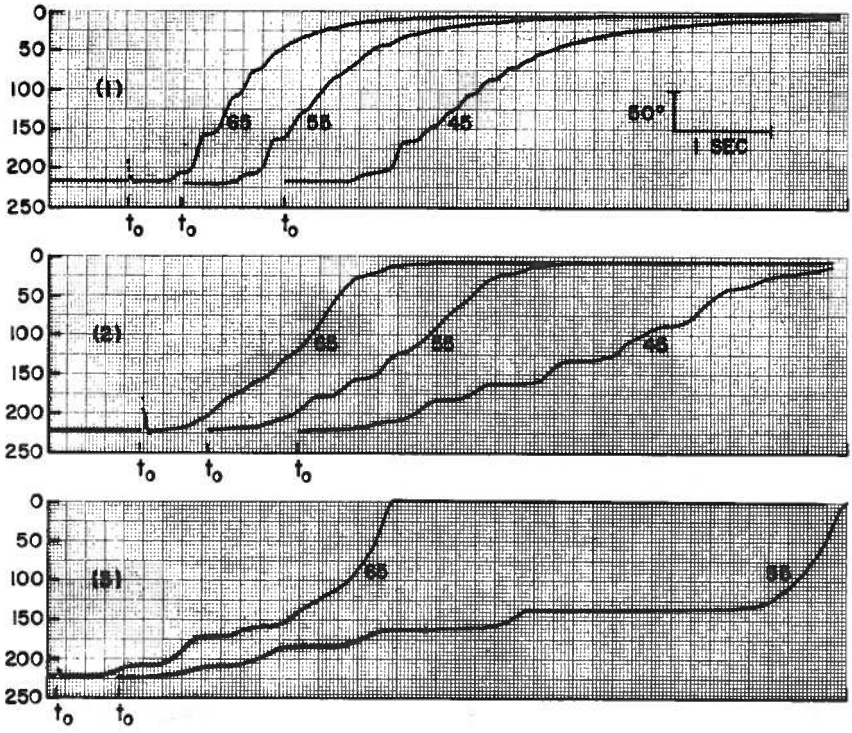


FIGURE 9. Supination curves for wrist unit. Curves for gas pressures of 65, 55, and 45 p.s.i. are superimposed for (1) no load, (2) 0.745-lb. load, and (3) 1.49-lb. load. No movement of wrist occurred with 1.49-lb. load at 45 p.s.i. gas pressure.

2. *Available Forces*

a. Stalling Force of Elbow. The prosthesis with upper arm removed was mounted at the proximal end of the elbow mechanism to a horizontal mounting plate. Forces were applied to a point on the terminal device at 14.5 in. from the axis of elbow rotation. The forces always acted in the vertical direction and were experimentally increased until elbow flexion was prevented upon application of power to the arm. Four measurement positions were chosen. These were the extreme lower (0 deg.) and upper (90 deg.) positions of the elbow, and two intermediate positions at about 30 deg. and 60 deg. The zero reference was the same as described in Section I.B.1.a, 20 deg. from the vertical. Figure 12 presents stalling force of the elbow unit as a function of gas pressure and angle of flexion. These data are summarized in Table 3.

Since the extension movement of the arm is essentially a passive function achieved by exhausting of the elbow bellows, the resulting force is the vertical component of the weight of the forearm plus the weight of the

terminal device and any external load. The same force application point and flexion angles as for the flexion test were used to measure the extension force of the arm. These forces were found to be 0.50, 0.60, 0.70, and 0.75 lb. for test angles 0, 30, 60, and 90 deg. respectively.

TABLE 3.—*Maximum Weight Lifted by Elbow Unit for Three Gas Pressures*

Gas pressure (p.s.i.)	Position of elbow			
	0°	30°	60°	90°
45	6.80	3.90	2.10	1.05
55	8.30	4.75	2.60	1.35
65	10.00	6.45	3.10	1.65

NOTE.—All values are in pounds.

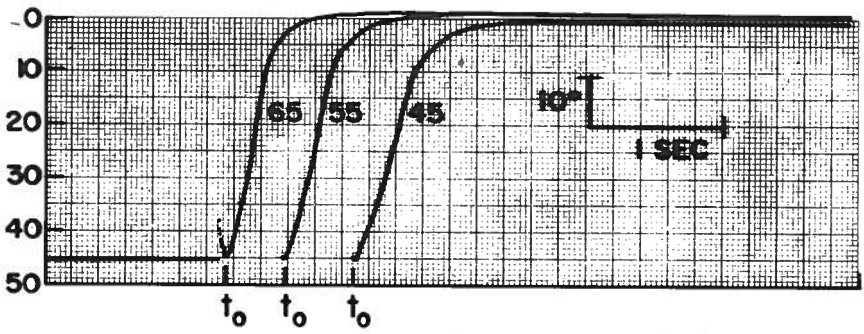


FIGURE 10. Closing curves for terminal device. Curves for gas pressures of 65, 55, and 45 p.s.i. are superimposed.

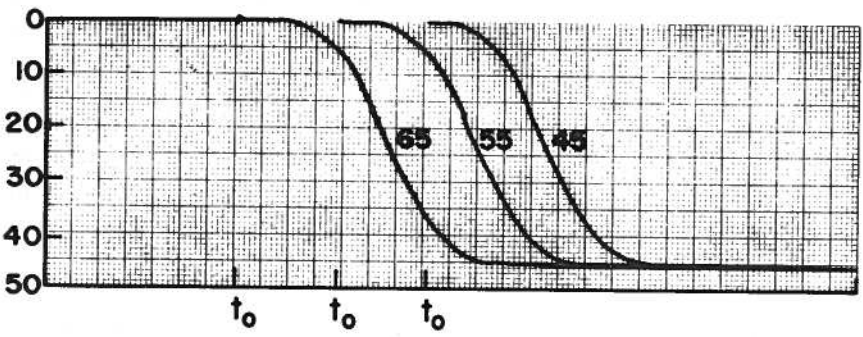


FIGURE 11. Opening curves for terminal device. Curves for gas pressures of 65, 55, and 45 p.s.i. are superimposed.

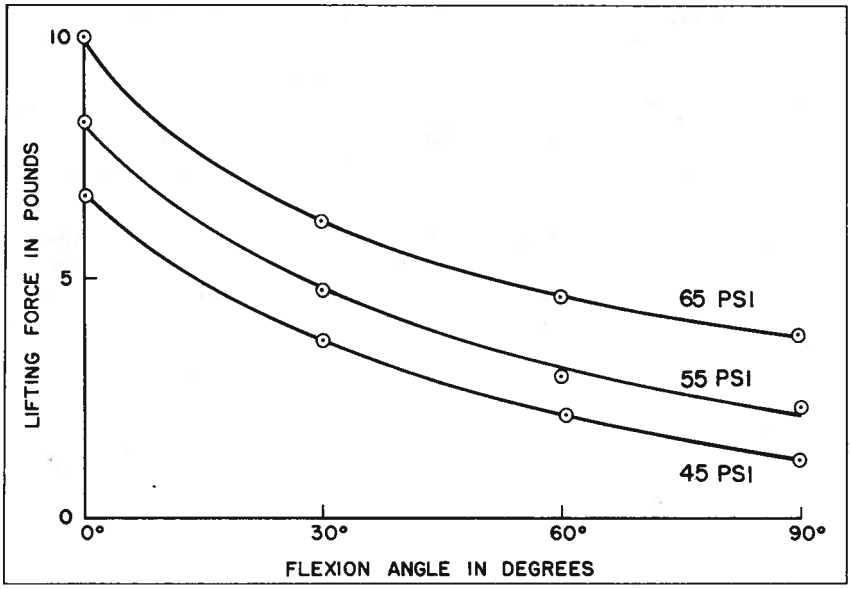


FIGURE 12. Stalling force of elbow unit as a function of flexion angle.

b. Stalling Force of Wrist. These values were determined by applying a stalling torque to the wrist unit through a 4-in. lever of negligible weight attached to the terminal device. The angular zero reference point was defined as the position of the hand in supination at 65 p.s.i. with no load. Stalling torques were determined for both directions at five test positions: 0, 60, 120, 180, and 210 deg. (from full supination to full pronation). The results of these tests are presented in Figures 13 and 14, and are summarized in Table 4. Inspection of these results shows that pronation is far more powerful than supination, and the pronation force is highest in the center of the range of wrist motion while the supination force increases linearly from 0 deg. to 210 deg.

c. Terminal Device Prehension Force. Prehension force was measured with a force indicator adjusted to one of four widths: 0.525, 1.00, 1.45, and 1.95 in. Results were obtained at these openings for the three gas pressures described previously. Figure 15 illustrates these results, which are also summarized in Table 5.

TABLE 4.—*Maximum Forces of Wrist Unit for Three Gas Pressures*

Gas pressure (p.s.i.)	Position of wrist				
	0°	30°	90°	150°	210°
Pronation:					
45	0. 80	0. 85	1. 10	1. 00	0. 90
55	1. 10	1. 25	1. 30	1. 40	0. 90
65	1. 25	1. 80	1. 75	1. 60	1. 10
Supination:					
45	0. 25	0. 30	0. 40	0. 55	0. 75
55	0. 25	0. 27	0. 35	0. 50	0. 65
65	0. 25	0. 25	0. 30	0. 45	0. 55

NOTE.—Forces are in pounds. Torques can be obtained by multiplying by 4 (inches) to give values in inch-pounds.

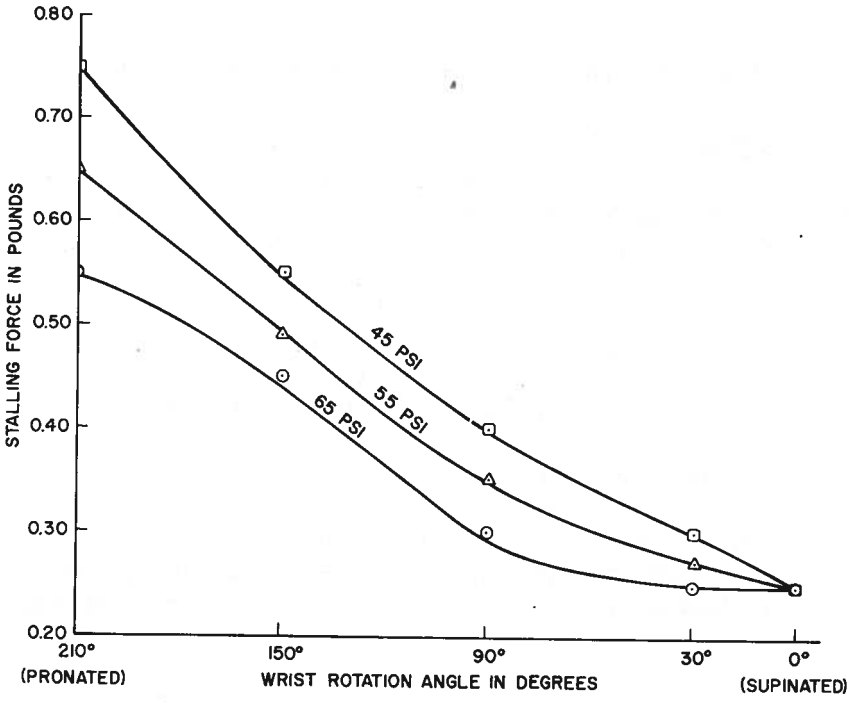


FIGURE 13. Stalling force of wrist unit (supination).

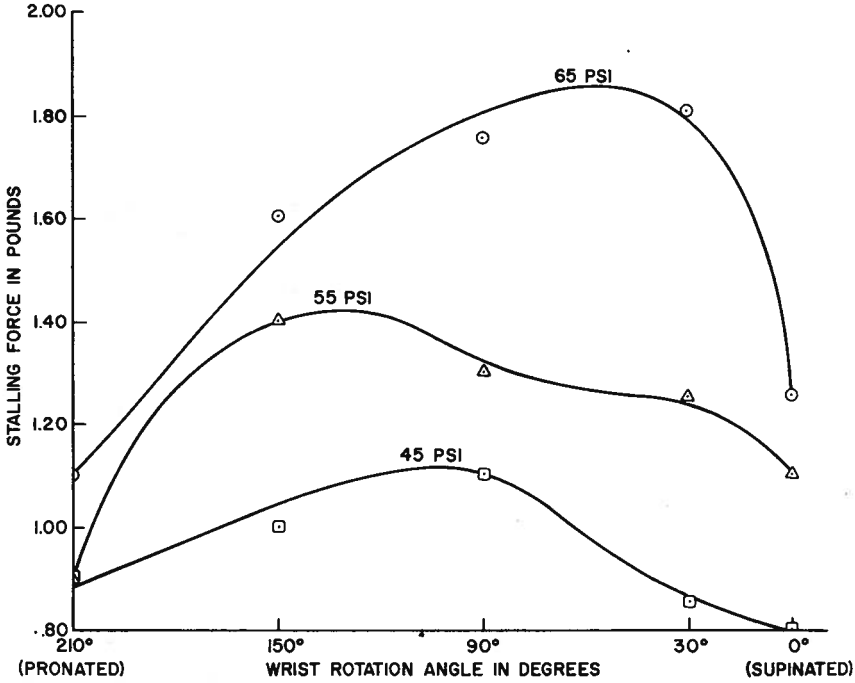


FIGURE 14. Stalling force of wrist unit (pronation).

TABLE 5.—*Terminal Device Prehension Force for Three Gas Pressures*

Gas pressure (p.s.i.)	Terminal device opening			
	0.52 in.	1.00 in.	1.45 in.	1.95 in.
45	8.4	9.5	11.8	15.0
55	13.1	13.5	14.0	17.5
65	15.6	17.8	18.5	22.0

NOTE.—All values are in pounds.

3. *Mechanical Time Lags and Velocities*

In this section the movement durations determined by the mechanical systems of the arm are discussed. "Time zero" is defined as the instant at which gas pressure was applied to the respective motor device or the instant at which the same unit was open for exhaustion of gas to the atmospere. The time intervals necessary for manipulation of control valves and the effect of locking mechanisms were neglected in this phase of testing. Separation of unlocking from activation of the motor unit would be tedious.

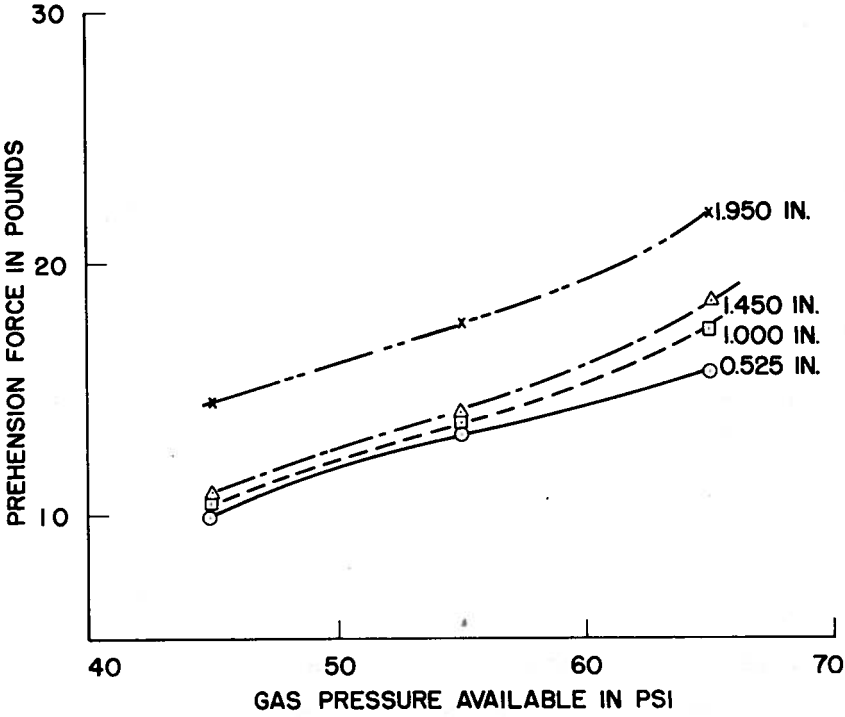


FIGURE 15. Terminal device prehension force as a function of gas pressure and size of opening.

Also, the activation of the control valves depends not only on the design of the valves but also on the amputee's method of activation. Thus a "standard" method of activation is a matter of choice, and inclusion of such a method would only introduce irrelevant variability into these measurements. In these tests the normal control valve was bypassed by keeping it open to the desired function, and an electromagnetic valve was inserted in series with the control valve. This valve was opened by a switch which also provided a signal used to mark "time zero" on the data records. The delay introduced by the time constant of the valve was about 10 msec. and was neglected. Movements of the various prosthetic units were measured by coupling a precision potentiometer to the respective joint and displaying voltage changes on an oscillograph calibrated to give full span deflection for the total movement range. Figures 6, 7, 8, 9, 10, and 11 present recordings of deflection as a function of time for each component under the various load and pressure conditions described earlier. The following values have been determined from these records:

(a) Reaction time—Defined as the time required to obtain a deflection corresponding to 2 mm. of movement of the recording pen.

(b) Operation Time—Defined as the time required to obtain 80 percent of the total deflection of the available range of motion.

(c) Average Velocity—Defined as the ratio of 80 percent of full motion to operation time.

a. Reaction Time. Results of these tests are presented in Table 6. In general, time lags increased for powered movements as load was increased or as available pressure to the unit decreased. The reverse was true for passively operated antagonist movements except for the wrist unit.

b. Average Velocity. Results of these tests are presented in Tables 7, 8, and 9. Again increased load or decreased operating pressure enhanced passive movement velocities, but slowed active movements.

4. Trouble Points

a. Elbow Unit. Occasionally, the elbow locking mechanism would not disengage and permit flexion. This was found to be the result of jamming of the locking pin in its bushing. From excessive wear a small spur had developed on the front of the pin which jammed the locking pin on retraction.

b. Terminal Device. The finger pads became loose frequently during testing and had to be reglued. They also became quite worn and small pieces of the pads broke off at the edges.

c. Wrist Unit. No particular mechanical problems occurred during operation of the wrist mechanism.

d. Power Supply and Linkage. During normal operation the pneumatic lines became clogged at the nozzles of the control valve and prevented the operation of some functions of the arm. Although this was not particularly difficult to repair, it required a knowledge of the specific linkages to each function and the ability to remove and replace the connectors that secured the tubing to the valve nozzle. Such maintenance would be quite difficult for an amputee but would not be expected to occur frequently with a clean CO_2 supply.

Filling and changing of the portable CO_2 source was another trouble point. Closing and opening of the valve at the neck of the CO_2 bottle and removal and replacement of the screw-in regulator would be tedious with the use of only one hand without the aid of special holding devices. This criticism applies only to United States commercial devices which were used and with which other American users may have to contend.

During the engineering testing, the pneumatic lines broke frequently under pressure. Substitution of a polyethylene tubing should avoid this problem which was due to deterioration of the rubber tubing, possibly caused by atmospheric smog.

e. Control System. One of the ball-type pressure greasers used in the seven-position control valve became worn and sometimes jammed on release of the control cable. This problem became more frequent after the second

TABLE 6.—*Mechanical Time Lags of Prosthetic Movements, Loaded and Unloaded*

Loads	Gas pressure (p.s.i.)		
	45	55	65
	Flexion		
No Load:	192	176	168
0.62 lb.	200	184	172
1.25 lb.	228	220	188
2.00 lb.	312	280	260
	Extension		
No Load:	520	530	750
0.62 lb.	350	380	420
1.25 lb.	280	300	320
2.00 lb.	220	250	280
	Pronation		
No Load:	380	480	520
0.75 lb.	440	540	600
1.49 lb.	600	600	580
	Supination		
No Load:	820	608	512
0.75 lb.	1040	680	520
1.49 lb.	—[a]	768	660
	T.D. closing		
No Load	108	88	80
	T.D. opening		
No Load	360	460	580

NOTE.—All values are in milliseconds.

[a] No movement.

TABLE 7.—*Average Velocities of Elbow Unit, Loaded and Unloaded*

Load and pressure	Flexion			Extension		
	Operation time[a]	Deflection[b]	Velocity[c]	Operation	Deflection	Velocity
No Load:						
45[d]	772	65	84.2	1480	67	45.3
55	704	70	99.4	1590	68	42.8
65	344	72	209.3	1700	70	41.2
0.625 lb.:						
45	1120	62	55.4	1500	67	44.7
55	736	65	88.3	1570	68	43.3
65	588	68	115.6	1780	71	39.9
1.25 lb.:						
45	1352	57	42.2	1320	58	43.9
55	1180	60	50.8	1400	64	45.7
65	1112	64	57.6	1580	68	43.0
2.00 lb.:						
45	1128	37	32.8	880	50	56.8
55	1200	52	43.3	1060	52	49.1
65	1160	56	48.3	1220	57	46.7

[a] Values are in milliseconds.
[b] Values are in degrees.
[c] Values are in degrees per second.
[d] Values are in pounds per square inch.

month of testing. It was temporarily relieved by repeated pulling of the control chain until the position of the worn spot was moved from the area of contact with the cam.

C. Basic Control Characteristics

1. Control Valve Function

Operation of the arm is determined by two control valve units: (a) a wrist control valve, and (b) a terminal device and elbow control valve. The wrist control valve is a four-valve, four-position control. The action of these valves is as follows:

Valve 1: Inflates wrist lock chamber, pushing wrist locking rod into appropriate wrist locking hole, locking wrist.

Valve 2: Exhausts wrist lock chamber, allowing spring-loaded locking rod to retract, unlocking wrist.

Valve 3: Inflates wrist supination bellows, supinating wrist.

Valve 4: Exhausts wrist supination bellows, allowing spring-loaded bevel gear to pronate wrist.

The sequence of operations of the wrist control valve is shown in Table 10.

TABLE 8.—*Average Velocities of Wrist Unit, Loaded and Unloaded*

Load and pressure	Pronation			Supination		
	Operation time[a]	Deflection[b]	Velocity[c]	Operation time	Deflection	Velocity
No Load:						
45[d]	500	159	318.0	1930	158	81.9
55	480	159	331.3	1337	158	118.1
65	520	160	307.7	1058	160	151.2
0.75 lb.:						
45	328	159	484.8	3240	158	48.8
55	332	159	478.9	2040	158	77.5
65	340	159	467.6	1530	160	104.6
1.49 lb.:						
45	336	158	470.2	—[e]	—	—
55	346	158	456.6	6412	185	28.9
65	425	155	364.7	2620	185	71.4

[a] Values are in milliseconds.
[b] Values are in degrees.
[c] Values are in degrees per second.
[d] Values are in pounds per square inch.
[e] No movement.

TABLE 9.—*Average Velocities of Terminal Device*

Gas pressure (p.s.i.)	Closing			Opening		
	Operation time[a]	Deflection[b]	Velocity[c]	Operation time	Deflection	Velocity
45	404	34	84.2	680	34	50.0
55	332	35	105.4	780	34	43.6
65	280	35	125.0	700	35	48.6

[a] Values are in milliseconds.
[b] Values are in degrees.
[c] Values are in degrees per second.

TABLE 10.—*Flow Diagram for Four-Position Control Valve*

Step	Function	Valve			
		1	2	3	4
0	Rest				
1	Wrist Lock	•			
2	Release Wrist Lock		•		
3	Pronation		•		•
4	Supination		•	•	

NOTE.—Open valves are indicated by a dot.

The terminal device and elbow control unit is a six-valve, seven-position control. The action of these valves is as follows:

Valve 1: Inflates thumb adduction bellows, closing thumb.

Valve 2: Exhausts thumb adduction bellows, allowing spring to open thumb.

Valve 3: Inflates elbow lock bellows, pushing locking pin into gear of elbow mechanism, locking elbow.

Valve 4: Exhausts elbow lock bellows, allowing spring-loaded locking pin to retract, unlocking elbow.

Valve 5: Inflates elbow flexion bellows, flexing elbow.

Valve 6: Exhausts elbow flexion bellows, allowing extension of forearm by force of gravity.

The sequence of operations of the terminal device and elbow control valve is shown in Table 11.

TABLE 11.—*Flow Diagram for Seven-Position Control Valve*

Step	Function	Valve					
		1	2	3	4	5	6
0	Rest						
1	Thumb adduction	•					
2	Thumb abduction		•				
3	Thumb adduction	•					
4	Thumb adduction, elbow lock	•		•			
5	Release elbow lock				•		
6	Release elbow lock, extend				•		•
7	Flex elbow				•	•	

NOTE.—Open valves are indicated by a dot.

In Tables 10 and 11, a zero or rest position is noted for each valve. These are completely inactive settings to which the unit returns when the amputee relaxes tension in the control straps.

The particular sequence of valve operations and choice of functions for each valve has been carefully chosen by the designer. One example of an important design decision is the repetition of hand closing on both sides of the hand opening control position (see Table 11). This arrangement has three advantages: (1) if the valve is accidentally activated from the position of rest, hand closing is a less dangerous function to be activated than hand opening, especially when an object is being transported. (2) When returning to the position of rest, passing through the closing position (step 1) last (before rest) counteracts the slight opening that occurs during travel through the hand opening control position (step 2). (3) Having a second position for hand closing (step 3 as well as step 1) permits activation of hand closing directly after elbow activation without passing through the position for hand opening. With this arrangement, the chances of accidentally opening the hand and/or dropping an object are reduced.

Other decisions about the sequence of operations of each valve and the assignment of functions to the two controls units were made by the designer after careful observation of a number of different arrangements. The rationale for the final design has been described in detail by the designer (Marquardt and Haefner, 1957).

2. Control Valve Displacements and Forces

The displacement of the control chain required to advance the seven-position control valve through one step was about 0.15 in., except for step 4 which immediately followed step 3. The forces necessary to achieve these displacements ranged from a 3.5-lb. force required to advance to step 1 to a 6.0-lb. force required to advance to step 7.

The displacement of the control lever required to advance the four-position control valve through one step varied from 0.09 to 0.20 in. The forces necessary to achieve these displacements ranged from 0.9 lb. at step 1 to 2.0 lb. at step 4.

II. PERFORMANCE EVALUATION

A. Subjects

Two subjects were chosen to wear the experimental arm for performance testing. Table 12 describes the subjects. Subject 1 was a unilateral right standard above-elbow amputee, and Subject 2 a unilateral right forequarter amputee, both in good health. Subject 1 is a regular wearer of conventional prostheses and is quite proficient in their use. Unfortunately, it was not possible to obtain the services of a forequarter amputee who was also a regular wearer.

The subjects were chosen in order to represent the more severely handicapped amputee population, for whom prosthetic replacement of lost function by externally powered devices is of greatest importance. Figures 16, 17, 18, and 19 illustrate the degree of amputation of each subject.

Ideally, an evaluation should be based on a comparison of performance between an experimental and a conventional prosthesis as worn by the same amputee. Such a comparison was possible only for the standard above-elbow subject. Performance of the forequarter amputee was evaluated also in terms of data obtained from the above-elbow subject. It should be emphasized that such a cross-subject comparison of functional regain is not desirable but was dictated by necessity.

B. Prosthetic Systems

1. Prosthetic Fitting

All socket fabrications and fittings of the experimental arm were performed by Carl Sumida, C.P., of the Child Amputee Prosthetics Project, University of California at Los Angeles. The socket of the conventional arm worn for testing by the above-elbow amputee was fabricated by Woodrow Yamaka, C.P., of Alpha Orthopedic Appliances, Los Angeles, California. Mr. Yamaka has serviced this amputee periodically for several years.

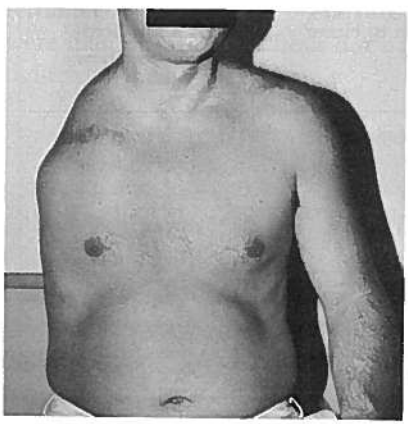


FIGURE 16. Forequarter amputee (front view).

TABLE 12.—*Description of Subjects*

Subject data	Subject No. 1	Subject No. 2
Sex	Male	Male
Age	47	26
Height	5′9½″	6′2″
Weight	180 lb.	180 lb.
Occupation	Draftsman, architectural field supervisor.	Student
General health	Good, with exception of heart attack 3 years ago which requires avoidance of strenuous activity.	Good
Attitude	Good	Good
Intelligence	Above average	Above average
Amputation	Unilateral right standard above-elbow.	Unilateral right forequarter.
Stump measurements	5½″ from acromion to end of stump.	None
Length of upper left arm	12″ from acromion to elbow center.	12½″ from acromion to elbow center.
Length of lower left arm	10½″ from elbow center to wrist.	11″ from elbow center to wrist.
Cause of amputation	Traumatic (industrial accident)	Surgical (malignant growth).
Age at amputation	21	23
Present prosthesis	Conventional Hosmer internal elbow, VO hook, figure 8 harness.	Has been fitted for a CO_2 powered Sierra.
Use of present prosthesis	Regular use during job and leisure activities.	None
Experience	Has worn prostheses since 1942; connected with prosthetic testing and training programs since 1950.	Inexperienced

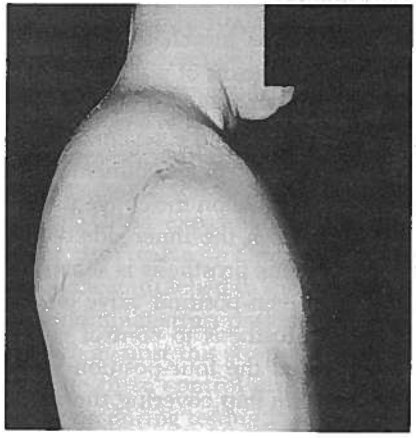


FIGURE 17. Forequarter amputee (side view).

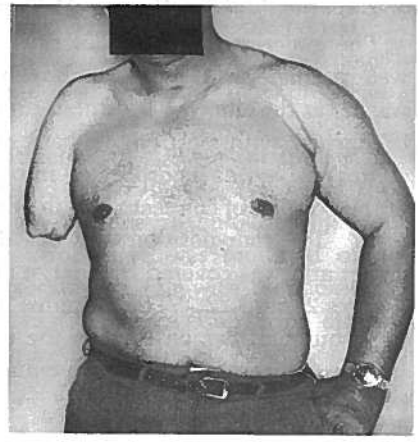


FIGURE 18. Standard above-elbow amputee (front view).

2. *Conventional Prosthesis*

The prosthesis worn by the above-elbow subject consists of a conventional Hosmer internal elbow turntable, a Sierra Model B wrist flexion unit, and a Northrop-Sierra two-load, heavy-duty VO hook with specially canted fingers. The elbow unit is mounted in a standard above-elbow double-wall plastic laminated socket. A "figure 8" harness supports the prosthesis, with the standard dual control arrangement for elbow flexion, elbow locking, and terminal device opening. The prosthesis is shown in Figure 20. No changes were made to this prosthesis during testing besides minor readjustments in tightening the harness straps.

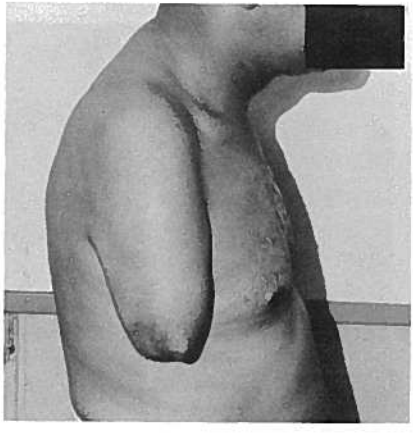


FIGURE 19. Standard above-elbow amputee (side view).

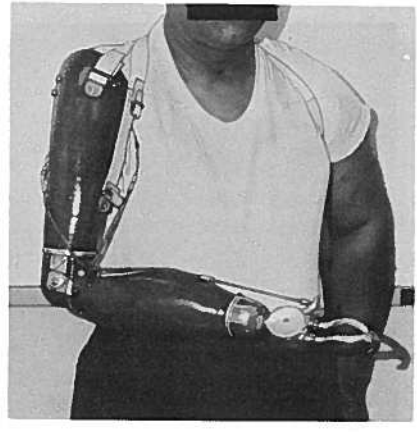


FIGURE 20. Standard above-elbow amputee with conventional prosthesis.

3. Experimental Prosthesis—Above-Elbow Amputee

The experimental arm described in Section 1 was attached to a lightweight, single-wall, standard above-elbow socket by means of a wingnut and washer at the elbow. Prosthesis support was provided by a modified "figure 8" harness with elastic cross-back strap. The chain of the seven-position control valve was incorporated into the harnessing control attachment strap at the position of connection to the Bowden control cable on the conventional arm. The four-position control valve was located on the inner side of the socket and was covered by a large plastic flap. This prosthesis is shown in Figures 21 and 22. The amputee operated the seven-position valve by the same humeral flexion used in the conventional prosthesis to control elbow flexion and terminal device opening. He operated the four-position valve by humeral adduction, creating pressure against the flap covering the valve lever.

The wingnut at the elbow allowed manual adjustment of the angle of inward rotation of the elbow in a similar fashion to that obtainable in a conventional prosthesis with elbow turntable.

Two modifications were made to this prosthesis during the initial training period. First, a cross-back strap was added to the "figure 8" harness to improve stability of the fitting. Second, the location of the four-position valve was moved from under the frontal harness support strap to its present location (see Fig. 21). This was done to improve separation of control motions of the two valves, since in the initial location the subject was not able to achieve independent control of each valve. No further changes were made during testing.

4. Experimental Prosthesis—Forequarter Amputee

The experimental arm was attached to a conventional forequarter single-wall plastic laminated socket by the wingnut and washer arrangement de-

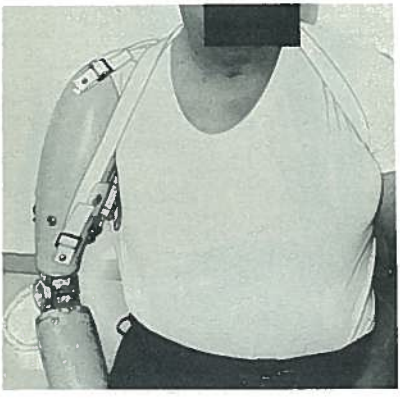


FIGURE 21. Standard above-elbow amputee with pneumatic arm (front view).

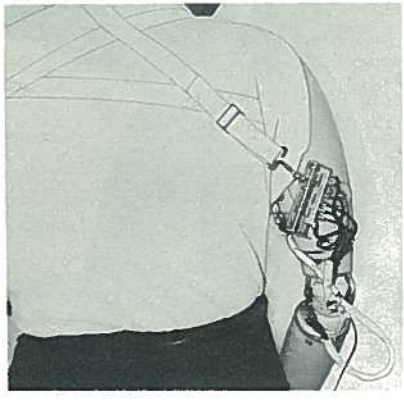


FIGURE 22. Standard above-elbow amputee with pneumatic arm (rear view).

scribed previously. A turntable at the shoulder of the socket permitted manual adjustment of the angle of humeral flexion. The wingnut arrangement permitted manual adjustment of the degree of inward cant of the forearm at the elbow.

The seven-position control valve was attached to the rear of the socket and was connected to a strap passing around the body to the front of the socket. Chest expansion against this strap was used to pull the chain of the control valve. The four-position control valve was mounted on a plastic sheet attached to the bottom of the socket on a line with the shoulder. An abdominal strap passed over the lever of this valve. Expansion of the stomach against this strap was used to depress this lever. Figures 23 and 24 illustrate these control arrangements. No changes were made to this configuration during testing.

C. Training

Training in the use of the experimental arm was conducted in two phases. In the first phase, the amputee practiced simple motions under the supervision of laboratory personnel. Each amputee was trained for about 16 hours in weekly sessions of two to four hours over a five-week period. This training consisted of initial familiarization with controls, then of simple drills for the separate functions of the arm, and finally of complex activities such as grasp and transport of a number of objects of different geometric shapes.

At this time, evaluation measurements for isolated movements were recorded. The amputees were sufficiently proficient to operate the arm in complex activities, but required additional practice for consistent performance. Therefore, training continued in its second phase during the period of testing of isolated motion. At the beginning of a day's testing,

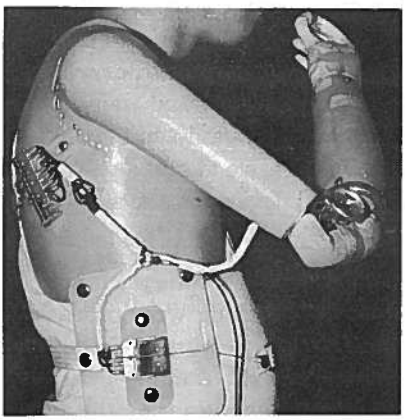


FIGURE 23. Forequarter amputee with pneumatic arm (side view).

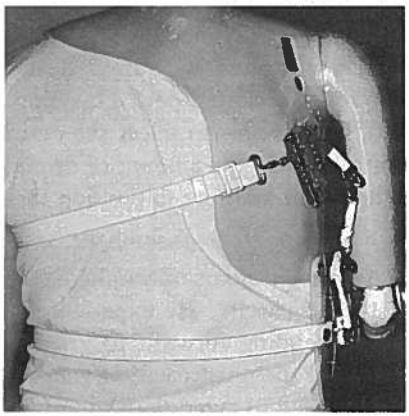


FIGURE 24. Forequarter amputee with pneumatic arm (rear view).

the amputee was allowed a warmup period of 15–30 min. in which he practiced various complex actions.

At the time evaluation measurements of performance tests of coordinated activity were initiated, the daily warmup period was reduced to about 10 min. and toward the end of the investigation to about 5 min.

In general, the forequarter amputee learned to operate the experimental arm at a faster rate than the above-elbow amputee. Three possible factors may have contributed to this difference:

(1) The forequarter amputee was much younger than the above-elbow amputee and better able to endure sustained training than the above-elbow amputee who had to avoid over-exertion because of a pre-existing heart condition.

(2) The control arrangement for the forequarter prosthesis was independent of the position of the articulated units of the arm, thus permitting a more positive and stable control operation.

(3) Since the above-elbow amputee was a very experienced wearer, he had more difficulty in mastering the control arrangement of the experimental arm due to conflict with habit patterns previously established with the conventional prosthesis.

Specific comments regarding progress in training for each amputee are as follows:

1. Above-Elbow Amputee

Separation of wrist and hand functions was not possible with the wrist control valve located under the frontal harness support strap. With this arrangement, inadvertent opening and closing of the terminal device occurred during operation of the wrist. For this reason the location of the wrist control valve was changed as described in Section I.B.2.b.

After 12 hours of training, the subject was able to operate the seven-position valve reliably, initiating the desired functions with few errors. Separation from wrist functions was good. However, he was not able to position the elbow accurately during flexion or extension, nor regulate closely the amount of terminal device opening. By the end of the formal training period, he was able to select the desired wrist movement easily, but could not control closely the amount of pronation movement. He also had particular difficulty in learning to position the open terminal device for a secure grasp.

2. Forequarter Amputee

After eight hours of training, this subject was able to separate the functions of the arm well. He experienced difficulty in controlling wrist pronation. When bending forward to grasp an object at table height, he frequently activated the wrist rotation valve, but by the end of the training period he had learned to avoid the abdominal expansion which was causing this problem. He experienced slight difficulty in learning to position the terminal device for grasp.

D. Performance Tests

1. Range of Motion

a. Objective. To measure the range over which the amputee can effectively operate the prosthesis.

b. Procedure. The amputee was instructed to position his prosthesis as if for use at each of the following positions:

(1) the mouth
(2) the breast pocket
(3) 90 deg. flexion of the elbow
(4) the entire arm perpendicular to chest
(5) the perineum
(6) the anus

The range of wrist motion and terminal device opening was measured at each position.

c. Apparatus. Terminal device opening was measured with a caliper between the centers of the finger pads of thumb and forefinger of the experimental arm and between the inner edges of the hook of the conventional arm. Wrist and elbow rotation angles were measured with clear plastic goniometers, attached directly to the prosthesis and aligned with the axis of rotation of the wrist and elbow.

d. Sensitivity. The caliper was graduated in increments of 0.025 in. All measurements of terminal device opening were repeated and showed little variation. Movements of the wrist and elbow were measured in degrees of rotation, taken visually by referring to a standard point on the forearm or humerus to the goniometer. These measurements were repeatable within one degree.

e. Results. Elbow flexion ranges were found to be the following:

(1) Above-elbow amputee—Conventional arm: 10 deg. to 135 deg. for a total of 125 deg.
(2) Both amputees—Experimental arm: 24 deg. to 118 deg. for a total of 94 deg.

All measurements were taken with the vertical plane as the zero reference point.

The terminal device openings and wrist rotation ranges obtained by the amputees at each standard elbow position are indicated in Table 13. These values are expressed as percentages of the maximum ranges that can be obtained from manual manipulation of the controls. These maximum ranges are the following:

(1) Terminal device—Conventional arm: 3.25 in.
(2) Terminal device—Experimental arm: 2.28 in.
(3) Wrist rotation—Experimental arm: 210 deg.

f. Comments. Terminal device opening for the experimental arm was measured while the terminal device opening valve was held open to avoid

TABLE 13.—*Percentage of Maximum Function Obtained with Each Prosthesis at Six Standard Elbow Positions*

Location	Standard AE conventional arm		Standard AE experimental arm		Forequarter experimental arm		Minimum terminal device opening recommended[a]
	Terminal device opening	Wrist rotation	Terminal device opening	Wrist rotation	Terminal device opening	Wrist rotation	
Mouth	75	.....	100	100	100	100	50
Breast pocket	87	.....	100	100	100	100	50
90° flexion	100	.....	100	100	100	100	100
Perpendicular to chest	100	.....	100	0	100	100	50
Perineum	100	.....	100	100	100	100	50
Anus	48	.....	0	0	100	100	50

Note.—All values are in percents.

[a] Santschi, 1958.

locking. This was necessary in order to achieve maximum opening, since an attempt to lock the terminal device when fully opened always resulted in a small amount of closure. This closure resulted from unavoidable travel through step 1 of the seven-position valve on return to the locked or resting position of the valve. For similar reasons wrist rotation range was measured with the four-position valve in active rather than locked positions. All measurements were made with a newly filled CO_2 cylinder to avoid reduction of the range due to reduced operating pressure.

Table 13 shows clearly that the amputees were unable to achieve intermediate control capabilities for the wrist and hand functions of the above-elbow experimental arm. Either the amputee was able to control these functions over their entire range at a particular elbow position or he was not able to operate them at all. For the conventional arm, terminal device range of motion was restricted when the arm was positioned at certain body areas. This resulted from a reduction in the amount of remaining travel in the control cable.

The forequarter amputee was able to achieve full wrist and terminal device operation with the experimental arm at all elbow positions tested. The standard above-elbow subject was not able to control the wrist at two test positions nor the terminal device at one of these. However, in the case of the wrist, this was simply a result of loss of contact between the wrist control valve lever and the side of the body when the arm was moved away from the body. For the terminal device, loss of function when the arm was positioned behind the back reflects a slackening of the harness control strap which actuates the seven-position valve. The results of the forequarter amputee make it clear that a control arrangement which is independent of the location of the prosthesis and harness would correct this loss of function.

The range of elbow flexion of the experimental arm is limited compared to that of the conventional arm, especially in regard to the upper limit of flexion. Besides being reduced to 75 percent of the range of the conventional arm, the experimental arm falls 17 deg. short of the 135 deg. upper limit attained with the conventional arm. The forequarter amputee was able to compensate partly for this lack by passive adjustment of the shoulder joint of his socket. This was not always a satisfactory solution since the forearm actually projected past the face and required turning and bending of the neck to reach the terminal device with the head. The standard above-elbow subject was able to reach his head only while bending his neck forward and with additional humeral stump flexion beyond that necessary to position the seven-position control valve in step 7 of the control. In addition, the standard above-elbow amputee was not able to operate the terminal device in close proximity to the head because this required sufficient relaxation of humeral stump flexion to allow the seven-position valve to fall from the

flexion control position to the terminal device control positions, thereby allowing the arm to move down from the face. Again, a control system arrangement independent of the position of the prosthesis would correct this loss of function.

In summary, the experimental arm was superior to the conventional arm in terms of range of wrist and terminal device function. Control valve operation was not restricted by arm position, assuming independence of control linkage, as was control cable travel in the conventional arm. The wide range of active wrist rotation provided more flexibility than did the passive wrist cant feature (3 settings) of the conventional arm. Also, the ability to manipulate elbow and wrist with the terminal device locked in any position of its range of opening was an improvement over the VO hook which returns to its initial state when the elbow is unlocked. Although the terminal device of the experimental arm has only three-fourths the range of opening of the conventional hook (2.3 in. versus 3.1 in.), this did not prove to be as limiting as the reduction in elbow range.

2. *Speed Tests*

a. Objective. To obtain a measure of the speed with which an amputee can initiate the motion of each of the functions of his prosthesis.

b. Procedure. All testing was done with the amputee standing in front of a visual display giving the necessary command words, as for example "flex," "extend," etc. The experimenter was able to illuminate any one of these commands by the operation of a switch which was concealed from the amputee. The amputee was instructed to watch the visual display and to perform the indicated command with his prosthesis as soon as possible after it was illuminated. Reaction time was measured simply as the difference in time between onset of illumination of the command word and initiation of the desired prosthetic movement.

Two types of reaction time scores were derived, *simple* and *complex*. In the simple situation the amputee was told which command would be presented before the trial began. In the complex situation he was given no advance information as to which command word would be presented. Twenty simple reaction time trials were presented for each function of each arm. Twenty complex trials were also presented, with the order of presentation varied according to a random schedule. Before each trial the amputee was given the verbal preparatory signal "ready," with a foreperiod that ranged from 1.0 to 2.0 seconds.

Errors or improper selections of function were recorded as a second performance measure on complex RT trials.

With the experimental arm, the amputee started each trial with the prosthesis locked at the center of the range of movement of each function. This method permitted movement of any component of the prosthesis in either direction to occur and be recorded on every trial. With the conventional

arm, the elbow was held at 90 deg., unlocked with the hook closed. All six movements of the experimental arm (flexion, extension, pronation, supination, opening, closing) were tested; three movements of the conventional arm (flexion, extension, opening) were tested.

Occasional "blank" trials on which no signal light was presented, although the subject was given a preparatory signal, were inserted into the testing schedule to discourage the subject from anticipating the command light. Anticipation was not a problem, apparently, since neither subject responded in the absence of the actual command light.

c. Apparatus. Movement around each joint of the prosthesis under test was monitored by attachment of rotary precision potentiometers to each joint (see Section II.D.3.c.). Each potentiometer was part of a circuit that provided a voltage analog to degrees or inches of movement around the joint. Movements and command presentations were recorded on four channels of an eight-channel oscillograph (Offner, Type R).

d. Sensitivity. Reaction time scores were computed from the speed of recording paper travel (25 mm./sec.). Data records were read to the nearest 0.25 mm. or 0.01 sec. Slight corrections were necessary for pen misalignment between recording channels.

e. Results. Both simple and complex reaction times for each prosthetic function are presented in Figure 25 for each amputee-prosthesis combination. These data are summarized respectively in Tables 14 and 15. Table 16 presents the errors (initiation of wrong movement) that occurred on complex reaction time trials with the experimental arm averaged over both amputees. Errors are classified by type for each prosthetic movement tested. Note that in some cases, the percentage of errors summed horizontally across the table is greater than 100 percent. This is due to the occurrence of more than one error on some trials.

TABLE 14.—*Simple Reaction Time Means and Standard Deviations*

Movement	Standard AE conventional arm	Standard AE experimental arm	Forequarter experimental arm
Flexion	0.31±0.03	1.19±0.16	0.57±0.29
Extension	0.36±0.05	1.03±0.19	0.71±0.19
TD Opening	0.63±0.07	1.37±0.22	0.60±0.23
TD Closing	.....	1.00±0.19	0.37±0.13
Pronation	.....	0.97±0.33	0.49±0.10
Supination	.....	0.96±0.28	0.58±0.10

NOTE.—All values are in seconds.

TABLE 15.—*Complex Reaction Time Means and Standard Deviations*

Movement	Standard AE conventional arm	Standard AE experimental arm	Forequarter experimental arm
Flexion	0.64±0.14	1.29±0.27	1.16±0.26
Extension	0.64±0.12	1.74±0.18	1.97±0.13
Opening	0.86±0.12	1.98±0.46	1.48±0.19
Closing	.....	1.39±0.40	1.21±0.23
Pronation	.....	1.19±0.23	1.08±0.17
Supination	.....	1.52±0.33	1.84±0.24

NOTE.—All values are in seconds.

f. Comments. Simple reaction time scores were found to be lowest for the above-elbow subject with the conventional arm. Scores for the forequarter amputee on some items were almost as low. Reaction times for the above-elbow subject with the experimental arm were nearly twice as slow as his own peformance with the conventional arm.

Average complex reaction time scores were about equal for the two subjects with the experimental arm and were a 100 percent increase over those of the above-elbow subject with the conventional prosthesis.

The slightly longer reaction times found for terminal device opening with the conventional arm reflect that this was a two-step process requiring locking of the elbow before opening of the hook. The elbow was unlocked in both simple and complex reaction time trials at the start of each trial.

With the experimental arm, complex reaction times showed about the same relative pattern for the six movements of the prosthesis for both subjects. Extension, opening, and supination were all slower to be initiated than flexion, closing, and pronation. In view of the similarity of complex reaction times found with this prosthesis for both subjects, it is hard to explain the large difference found between them in simple reaction time scores, both in terms of absolute values and in terms of relative distribution over the various prosthetic movements.

Since complex reaction time scores showed good agreement for both subjects with the experimental arm, they probably reflect better the ability to initiate prosthetic movement than does the simple reaction time situation. There is no question that the standard above-elbow subject is much faster to initiate movement with the conventional arm than either subject with the experimental arm. In part, the difference found (about 0.70 seconds) reflects the difference in the number of choice alternatives with the two prostheses, six movements for the experimental versus three for the conventional. However, this value cannot be completely accounted for by the increased task complexity since the increased number of alternatives would only be expected to add 200 to 300 msec. to the complex reaction time scores (Woodworth & Schlosberg, 1954).

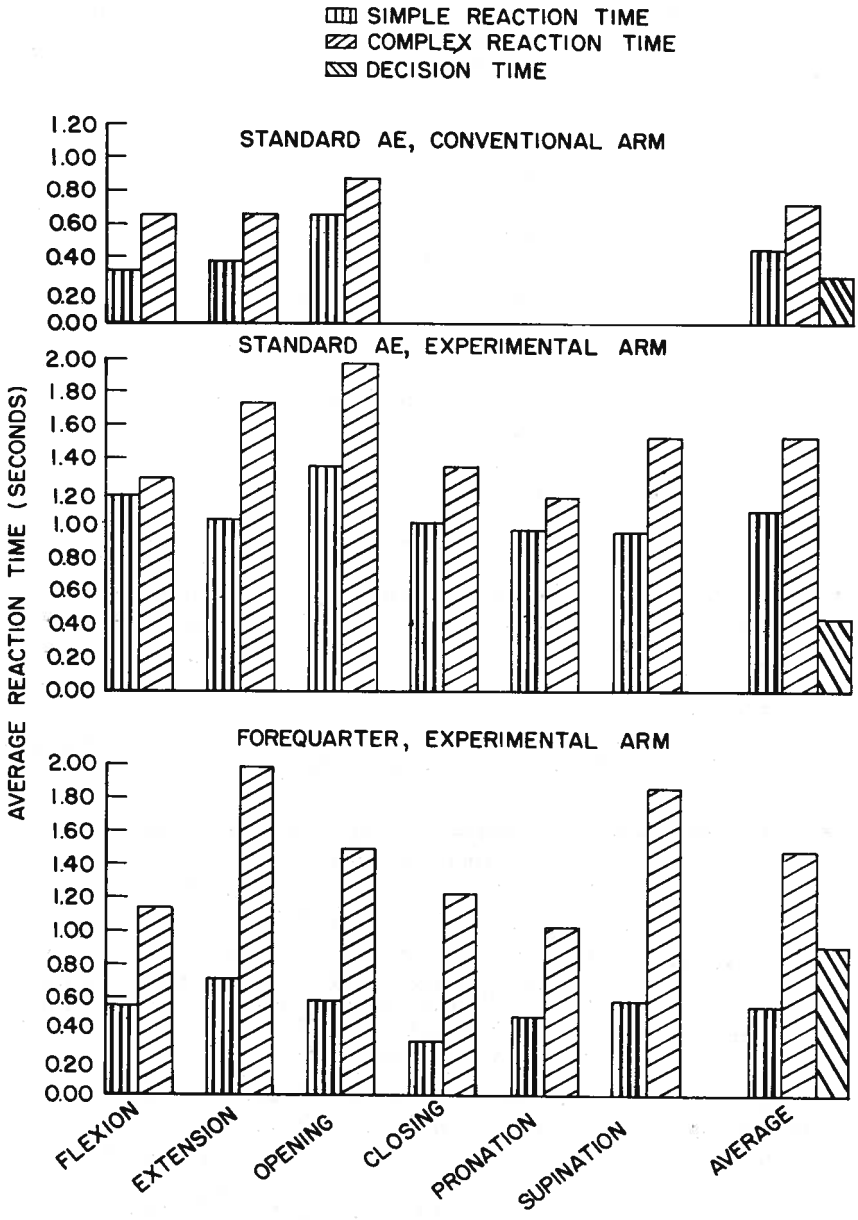


FIGURE 25. Average reaction time scores.

An analysis of the errors on the complex reaction time trials with the experimental arm showed that only eight specific error types occurred for both amputees. These are reported in Table 16. Four of these errors, three closing errors and one pronation error, occurred with very high probability

on trials of the particular function under test. In most cases they were not errors in the true sense. Rather, they reflect the fact that for each control valve there was one position (step 1 on the seven-position valve, and step 3 on the four-position valve) for which it was almost impossible to avoid some unwanted movement during travel through these positions to reach positions farther along the control sequence.

Four error types represent a true confusion in the selection of prosthetic function. These are the following:

(1) Extension instead of flexion (27.5 percent)
(2) Flexion instead of extension (12.5 percent)
(3) Pronation instead of closing (10.0 percent)
(4) Closing instead of supination (32.5 percent)

The first two errors represent confusion between control positions on the same valve while the last two represent activation of the wrong valve entirely. Comparison with errors made with the conventional arm (10 percent extension errors on flexion trials and 20 percent flexion errors on extension trials) shows that these errors are not excessive.

In summary, although error rates between conventional and experimental arms were similar, initiation of movement with the experimental arm was twice as slow as with the conventional arm in the complex reaction time situation.

3. Precision of Motion

a. Objective. To obtain a measure of the precision with which an amputee can operate each of the functions of his prosthesis.

TABLE 16.—*Percentage of Errors (Initiation of Wrong Movement) Occurring on Complex Reaction Time Trials*

Movement	Type of Error					
	Flexion	Extension	TD opening	TD closing	Pronation	Supination
Flexion	——	* 27.5	2.5	* 92.5	2.5	0
Extension	* 12.5	——	0	* 95.0	0	0
TD Opening	0	0	——	* 85.0	2.5	0
TD Closing	0	0	2.5	——	* 10.0	0
Pronation	0	2.5	0	2.5	——	0
Supination	2.5	5.0	0	* 32.5	* 85.0	——

* Denotes error made by both amputees.

b. Procedure. Three functions were tested for the experimental arm (elbow, wrist, and terminal device movement) and two functions for the conventional prosthesis (elbow and terminal device movement). The

amputee was instructed to lock his prosthesis at one of the two extreme positions of the function to be tested. Upon command, the amputee attempted to position and lock the arm at a position indicated by a visual pointer that was adjustable along the plane of movement of the function being tested. After completing a trial, the subject returned his prosthesis to the starting position and the visual indicator was also returned to its zero position before being reset for the next test position. The subject was instructed to work at a normal pace and to match the test position as accurately as possible. Five minute rest periods were taken after every five or ten trials.

For the elbow, five test positions in its range of motion were chosen. Four of these positions, the same for conventional and experimental arms, corresponded to locking positions of the experimental arm; the fifth represented a point close to the upper limit of flexion. Similarly, five test positions in the range of wrist rotation were chosen; these also were locking positions. For the terminal device which has no specific locking positions along its range of motion in either prosthesis, four widths of opening were chosen.

A series of 40 trials was performed at each test position of each prosthetic function. Twenty of these trials were performed with the prosthetic component starting at one end of its range of motion and 20 were done with it starting from the other end. Testing of terminal device opening with the conventional prosthesis was the only exception. Since the hook used does not lock open, only 20 trials were performed at each test position with this component, all starting from the completely closed position. The order of presentation of these test positions was randomized for each prosthetic function tested. All testing was completed on one function before beginning the next.

c. Apparatus. The clear plastic goniometers used to measure range of motion were employed in these tests to indicate to the amputee the test positions to be matched. These goniometers acted as visual indicators for elbow and wrist rotation. For terminal device opening, a simple device consisting of two large metal pins mounted on a metal base was used. The distance between the pins could be adjusted manually to indicate the desired amount of terminal device opening.

Movement around each of the three joints of the experimental arm (and the two joints of the conventional arm) was monitored by attachment of a precision potentiometer to the particular joint and members in question. The potentiometer was part of a circuit that provided a voltage analog to degrees or inches of movement. In this manner, every movement around a joint could be sensed and recorded as it occurred in time. A two-channel inkwriting oscillograph (Offner, Type RS) was used to record the voltage across the potentiometers.

Visual inspection of data records permitted measurement of several criterion scores for each trial. Among these were:

(1) time to completion
(2) number of extra movements
(3) size of each extra movement in degrees or inches

d. Sensitivity. The recording system was calibrated before testing began on each function using a goniometer or a caliper to compare the actual physical position or the prosthetic component to its position as displayed on the oscillogram. Calibration procedures were repeated midway during testing and again at the end of testing. Spot checks were made at every rest period. A correction table for nonlinearity in the recording system was developed from each calibration and used in data reduction.

Time scores were computed from speed of recording paper travel. They were accurate to about 0.1 seconds. Degrees of rotation or inches of movement were read to the nearest 0.25 mm. with an accuracy of about 0.25 mm. (±1 degree of rotation or ±0.05 in.). The number of excess movements or readjustments was derived simply by counting each discrete rise or fall in voltage in a data record.

e. Results. The results of precision of motion tests for each function of the experimental and conventional prostheses are presented graphically in Figure 26. These data are summarized in Table 17. In these graphs, a separate curve is presented for each arm-amputee combination. The

TABLE 17.—*Precision of Motion Test Means and Standard Deviations*

Test position	Standard AE conventional arm	Standard AE experimental arm	Forequarter experimental arm
Elbow:			
39°	1.9±1.2	16.5±16.8	10.1± 6.4
75°	2.7±1.5	16.7±10.0	13.9± 6.0
93°	2.1±1.0	6.8± 4.2	7.4± 4.4
111°	2.1±1.1	7.5± 5.8	3.5± 2.2
117°	2.1±0.6	.....	4.8± 1.3
Wrist:			
81°P	.....	26.4±26.7	13.0±15.9
47°P	.....	13.4±15.3	3.5± 2.1
0°	.....	22.7±24.1	6.2± 4.9
48°S	.....	13.4±11.0	2.8± 1.3
84°S	.....	6.3± 3.6	3.1± 1.4
Terminal Device:			
0.3 in.	4.0±6.6	8.9± 7.8	7.5± 8.7
0.8 in.	5.3±7.4	11.4± 6.2	10.2±10.1
1.4 in.	4.9±5.6	14.7± 5.3	11.2± 9.0
2.2 in.	3.3±2.9	17.0±18.1	6.1± 7.2

NOTE.—All values are in seconds.

dependent variable is the total time taken to reach the desired test position and it is graphed as a function of the test position to be assumed. Test positions for each prosthetic function are spaced along the abscissa of each graph so that they correspond to the actual spatial separation of test positions along a linear scale.

Most data points represent the average of 40 trials as earlier noted, combining trials from both initial starting positions for each test position of each function.

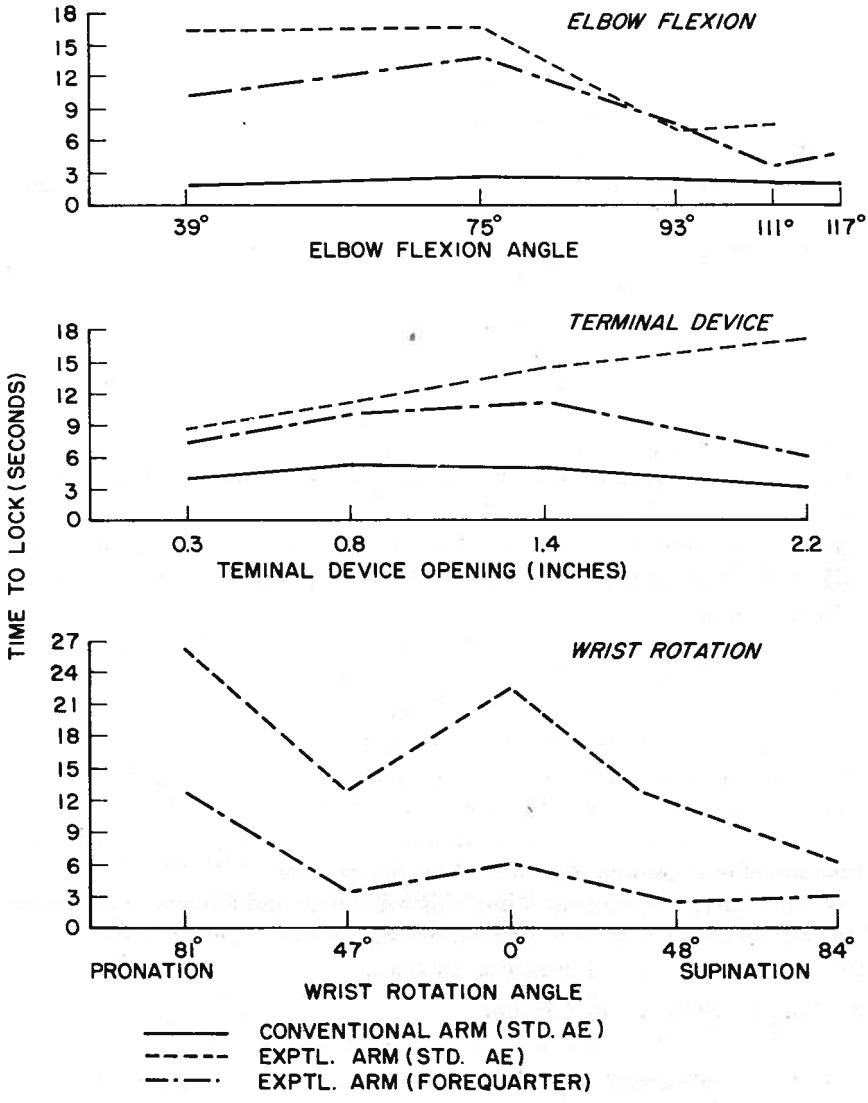


FIGURE 26. Precision of motion for experimental and conventional prostheses.

f. Comments. Although data were gathered for other dependent variables in addition to time taken to reach test position, these data will not be presented in any detail. It should be noted that the number of readjustments taken was found to parallel time scores closely for each function. To obtain a rough approximation of the average number of readjustments taken to reach a test position with the experimental arm, it is only necessary to multiply the time score in seconds by a factor of either 1.0, 0.5, or 0.33 for wrist, elbow, and terminal device, respectively.

For both wrist and elbow movements of the experimental arm, no final error measure was possible since fixed locking positions were chosen for testing these functions. Results for the terminal devices were good, with final error within ±0.1 in. with both prostheses.

The following two facts are evident upon inspection of Figure 26:

(1) On all functions for which a comparison between the two prostheses is possible, precision of motion is far superior with the conventional arm.

(2) Precision of motion scores are relatively flat over the range of motion of each function with the conventional arm, while this is never the case with the experimental arm.

Performance with the experimental arm is somewhat better for the forequarter amputee than for the above-elbow amputee. However, their curves follow the same pattern over the range of test positions of each function.

Originally, it was planned to treat precision of motion data separately for each function with respect to the starting position of the prosthesis, or the initial direction of movement. For example, data for wrist rotation trials starting from full supination of the wrist would have been presented separately from the data for those trials on which the amputee started from a fully pronated position. The hypothesis was that as the distance of the test position increased from the starting position of the prosthetic component, accuracy would increase because the amputee would have more time in which to release the control valve and lock the prosthesis. However, since such a large number of readjustments occurred on most trials with the experimental arm, starting position could not have had any practical significance. Inspection of the data in regard to initial starting position revealed no such relationship, and data for each function are thus presented only as a function of test position, regardless of starting position.

In summary, the practical ability of being able to position rapidly and hold any component in a specific position accurately was found to be quite poor for both amputees using the experimental arm.

4. Analysis of Coordinated Motion

a. Objective. To assess the adequacy of the prosthesis as an integrated, articulated unit capable of performing complex tasks, and to assess the degree of independence an amputee can achieve with it on everyday tasks.

b. Procedure. Fifteen simple tasks were chosen as representatives of the more difficult activities an amputee might perform in daily life. Each amputee performed these tasks under the observation of laboratory personnel. In order to obtain an objective rating of his performance, time and error scores were recorded by the observer for each perfomance trial. Subjective estimates of performance were also recorded as supplemental data.

Specifically, the amputee, wearing the particular prosthesis to be tested, was instructed in the method of task performance. He then practiced the task until in the judgment of the observer and the amputee he had reached a fairly stable level of performance. The amputee then began a series of 50 trials on the task. Total completion time and number of errors (regrasping, excess motions, dropping of objects) were recorded for every trial as well as any incidental observations. Five minute rest periods were taken after every five or ten trials (depending on task difficulty) or sooner if requested by the amputee.

If at any time during testing the amputee was able to complete five successive trials within a range of 0.5 seconds (for trials requiring less than 15 seconds to complete) or within 1.0 seconds (for tasks over 15 seconds in duration), testing was stopped for that task. Although the amputee was aware of this time criterion, he was instructed that good performance rather than speed per se was desired.

Timing began at the instant the amputee was told to begin the task and was stopped when he had returned the prosthesis to the initial position after completing the task. All trials began and ended with the amputee at one of two standard starting positions, one standing and one sitting.

After the series of performance trials on each task, the amputee was asked to indicate his rating of the task as performed by him with the prosthesis on a 10-point scale which ranged from "excellent" to "unacceptable—physical damage." This scale is presented in Table 18.

The tasks as performed are listed below with task elements indicated sequentially.

Standing Start Position

Stand erect with arms relaxed at sides, feet positioned 45 deg. apart, terminal device closed.

Sitting Start Position

Sit erect, arms against the body, elbows level with the table and forearms resting on table edge at about the middle of the forearm, terminal device closed.

Standard Tasks

(1) Sharpening Pencil (Pencil I)

Standing start position—grasp wooden pencil lying flat on table in terminal device—insert pencil into sharpener—turn sharpener handle three times with

sound hand—remove pencil from sharpener—return to table top and release—return to start.

(2) Pencil to Pocket (Pencil II)

Standing start position—grasp pencil on table top with terminal device—transport pencil to opposite side breast pocket—insert pencil in pocket and release—return to start.

(3) Drinking Soup

Sitting start position—grasp spoon from table with sound hand—insert spoon in terminal device—dip spoonful of soup with terminal device—raise spoon to mouth and drink—return spoon to table top and release—return to start.

(4) Coffee Cup Drinking

Sitting start position—cup two-thirds full—grasp cup handle with terminal

TABLE 18.—*Amputee Task Rating Scale*

Subject Name _____

Prosthesis _____ Date _____ Task _____ Experimenter _____

Operational condition	Adjective rating	Description	Numerical rating
Normal operation	Satisfactory	Excellent	1
		Good	2
		Satisfactory with mildly unpleasant characteristics	3
Emergency operation	Unsatisfactory	Acceptable with unpleasant characteristics	4
		Unacceptable for normal operation	5
		Acceptable for emergency performance only	6
No operation	Unacceptable	Unacceptable even for emergency use	7
		Unacceptable—dangerous	8
		Unacceptable—uncontrollable	9
	Catastrophic	Unacceptable—physical damage	10

device—raise cup to mouth and drink—return cup to table and release—return to start.

(5) Water Glass Drinking

Sitting start position—glass two-thirds full—grasp glass in terminal device—raise glass to mouth and drink—return glass to table and release—return to start.

(6) Hanger Task

Standing start position—grasp wooden hanger on table top in terminal device—raise hanger from table top and transport 10 feet to clothes tree—hang hanger on clothes tree and release—return to start.

(7) Briefcase Transport

Standing start position—bend body down and grasp handle of briefcase which is sitting upright on floor—straighten up body and walk 10 feet to table, raising briefcase to table top height—lift briefcase onto table and release—return to start.

(8) Answer Telephone

Sitting start position—grasp phone receiver in sound hand—place receiver in terminal device—raise receiver to ear, holding for five seconds while writing with sound hand—release receiver at ear into sound hand—replace receiver on cradle with sound hand while returning prosthesis to start position.

(9) Open and Close Door

Standing start position—grasp knob of door in terminal device—rotate knob until unlocked—pull door open to 90 deg. and release—close door with strong push from prosthesis—return to start.

(10) Remove and Replace Jar Lid

Standing start position—grasp jar lid in terminal device and lift jar from table top—rotate jar in sound hand to unscrew from lid—rotate jar back into lid to tighten—replace jar on table with terminal device and release—return to start.

(11) Zip and Unzip Trouser Fly

Standing start position—use sound hand to position zipper tab for grasp—grasp tab with terminal device—pull tab down with prosthesis to unzip—pull tab up with prosthesis and release—flatten tab with sound hand—return to start.

(12) Grasp and Light Cigarette

Standing start position—grasp cigarette in opposite side breast pocket with terminal device—raise cigarette to mouth and insert—release cigarette and extend prosthesis to about 90 deg. flexion—place matchbook in terminal device with sound hand—simulate striking of match with sound hand—return to start.

(13) Remove and Replace Bill in Wallet

Standing start position—remove wallet from pocket with sound hand—

hold wallet open with sound hand—grasp and remove bill from wallet with terminal device—place bill on table and release—grasp different bill on table with terminal device—insert bill in wallet and release—replace wallet in pocket with sound hand—return to start.

(14) Signature Task

The purpose of this task was to determine whether the amputee could write his name legibly using the prosthesis. No time or error scores were taken since quality of performance was the only concern. The amputee merely wrote his name 50 times with pencil and paper while seated at a table.

(15) Table Setting

The amputee was required to prepare a standard table setting using a plate, a bowl, a cup and saucer, and four pieces of silverware. The items were located in the center of a table, two feet from the edge. The amputee bent forward and grasped each item separately, placing it at the proper place in the marked outline of a place setting at the table edge. The instructions for this task emphasized speed more than quality of performance. The purpose was to obtain a measure of performance with the prosthesis under stressing circumstances. Time and error scores were taken for each of 25 trials on this task, with rest periods after every five trials. Only one practice trial was allowed before testing began.

c. Apparatus. The equipment used in the standard sequence tasks is given in the task descriptions. A stopwatch graduated in tenths of a second was used for time measurements. Errors were counted visually by the observer and recorded with the time scores immediately after each trial.

Testing was done in a closed, well-lighted laboratory room. Both amputees used identical equipment for all tasks including the table and an adjustable stool (for seated tasks).

d. Sensitivity. Stopwatch readings were recorded to the nearest tenth of a second. A slight systematic error may have been introduced by differences in method of timing between observers and in the difference between reaction times of each observer; however, every effort was made to standardize these measurements.

Since evaluation of the severity of an error is complex and at best arbitrary, it was decided to count any discrete movement in excess of those necessary to complete the task as an error. Thus regrasps, dropped objects, interrupted motions and the like were weighted equally and tallied as one error for each occurrence. In general, the same observer graded the performance of one amputee over the entire series of 50 trials on a task. In a few cases, where testing was conducted for more than one day, a different observer was used on the second day. Inspection of these data showed no significant difference in error or time scores between observers, indicating good agreement in individual criteria.

e. Results. Overall performance on the first 13 standard tasks described

in Section II.D.4.b. for each amputee-prosthesis system is illustrated in Figure 27. The six curves illustrate both average errors and average completion times on these tasks for 10 trial blocks over the 50 trials. It should be noted that not all data points represent an average based on 130 individual scores (13 tasks X 10 trials/task) since some tasks were halted before 50 trials if the amputee reached the criterion for stable performance.

Table 19 presents a breakdown of results for each of the thirteen standard tasks as performed by each amputee-arm system. Included in this table are the following values:

(a) Best performance time—expressed either as criterion time for trials halted before 50th trial or as the average of the last five errorless trials.

(b) Total errors made during testing on each task.

(c) Total trials completed for each task.

(d) Average errors per trial for each task.

(e) Whether or not amputee reached time criterion on the task.

(f) The amputee's rating of his performance on the task.

Time and error scores for the table set tasks are presented in Figure 29. These curves represent performance by each amputee-arm system averaged over successive blocks of five trials.

On the signature task both amputees were able to produce a legible signature after some practice. The standard above-elbow subject performed better with the conventional arm than with the experimental arm, but after 50 trials he had improved the quality of his signature to nearly the same level with the latter prosthesis. The forequarter amputee was only able to produce a signature of fair quality after 50 trials.

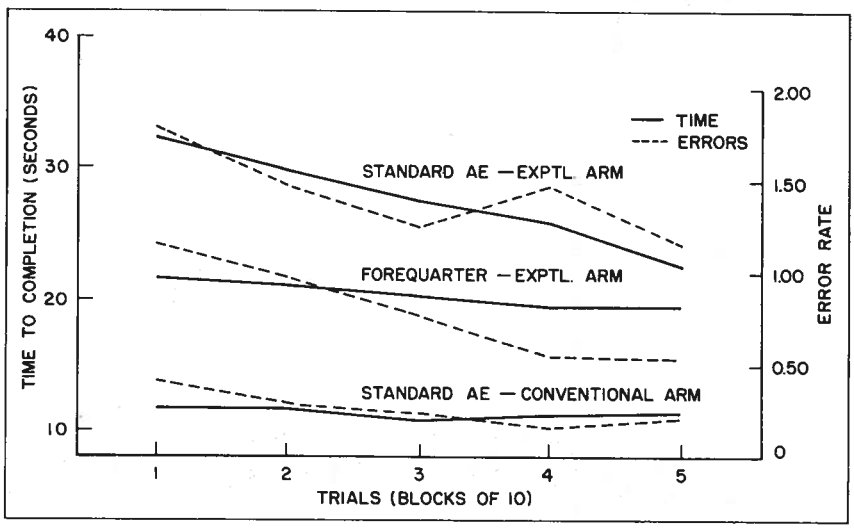


FIGURE 27. Performance on 13 standard tasks.

TABLE 19.—*Summary of Performance on Standard Tasks*

Task	Best time (sec.)	Total errors	Total trials	Average error	Was criterion reached?	Amputee rating of task[a]
Standard AE conventional arm:						
Pencil I	9.8	0	22	0.00	yes	2
Pencil II	6.1	12	50	0.24	no	2
Soup	8.5	5	28	0.18	yes	2
Coffee Cup	15.1	16	50	0.32	no	6
Glass	12.0	16	50	0.32	no	5
Hanger	5.5	5	32	0.16	yes	2
Briefcase	6.2	18	50	0.36	no	2
Telephone	15.7	16	50	0.32	no	2
Door	8.0	3	45	0.07	no	5
Jar	17.5	29	50	0.58	no	5
Zipper	9.1	20	34	0.59	no	5
Cigarette	10.5	9	29	0.31	yes	6
Billfold	13.1	9	50	0.18	no	3
Standard AE experimental arm:						
Pencil I	12.8	49	50	0.98	no	2
Pencil II	14.9	79	50	1.58	no	3
Soup	22.9	106	50	2.12	no	4
Coffee Cup	17.7	38	50	0.76	no	6
Glass	22.5	23	21	1.10	yes	2

Hanger	14.5	23	50	0.46	no	2
Briefcase	17.1	35	50	0.70	no	3
Telephone	21.9	37	50	0.74	no	2
Door	25.0	52	50	1.04	no	3
Jar	20.3	40	50	0.80	no	7
Zipper	25.4	128	50	2.56	no	9
Cigarette	19.3	153	50	3.06	no	6
Billfold	32.6	123	50	2.46	no	2
Forequarter experimental arm:						
Pencil I	15.5	21	19	1.11	yes	1
Pencil II	12.1	21	37	0.57	yes	2
Soup	13.0	18	50	0.36	no	8
Coffee Cup	19.8	41	50	0.82	no	10
Glass	28.8	36	50	0.72	no	6
Hanger	13.6	47	50	0.94	no	1
Briefcase	18.2	43	50	0.86	no	3
Telephone	24.5	17	18	0.94	yes	2
Door	16.5	26	50	0.52	no	3
Jar	18.0	25	50	0.50	no	4
Zipper [b]	.....	.....	.....	.....	.....	.....
Cigarette	16.4	96	50	1.92	no	4
Billfold	17.3	41	50	0.82	no	1

[a] See Table 18 for explanation of rating values.
[b] Subject was unable to complete task.

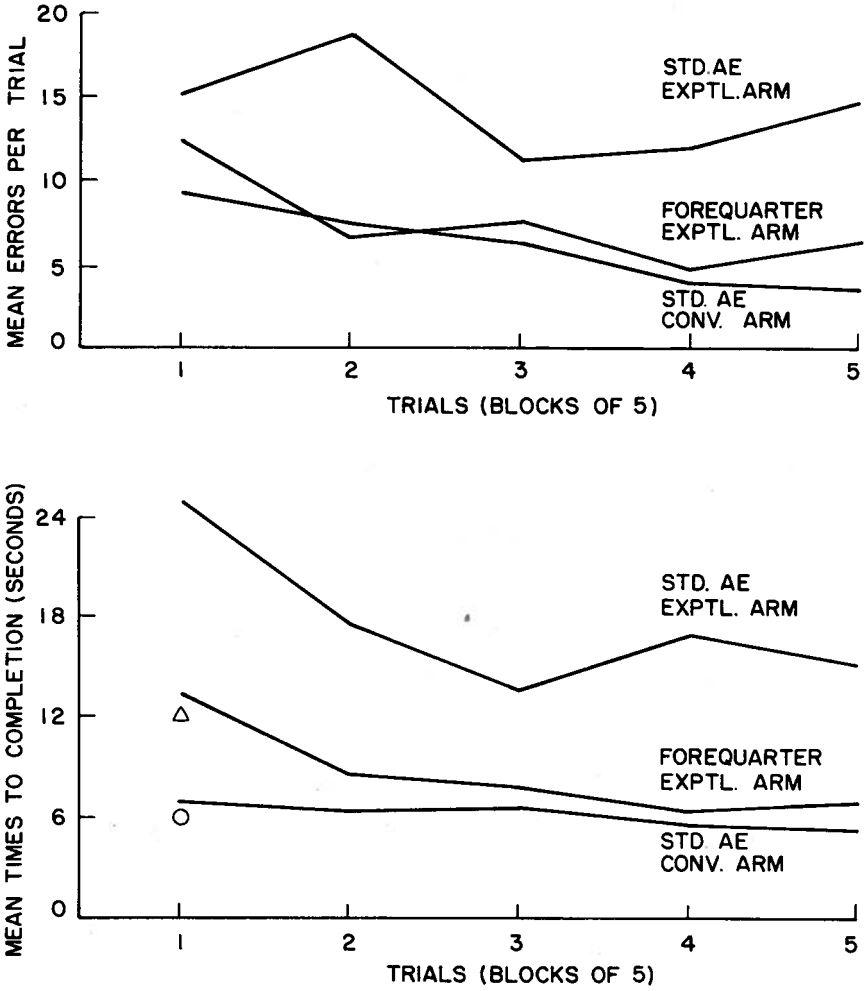


FIGURE 28. Performance on table set task.

△ 1st trial average of above-elbow amputees, VO hook (from Groth and Lyman, 1957).

○ 1st trial average of 5 above-elbow amputees, VO hook, adjusted for difference in number of task objects.

f. Comments. The order of testing for each amputee progressed from the simpler standard sequence tasks to the more complex. Depending on the initial reaction of the amputee to a task and his success with it in the pre-test training period, some tasks were not performed in order but were deferred until later testing. For this reason, and also because these tasks cannot be equated in terms of difficulty, it is not meaningful to display performance data here as a function of task test order.

Performance on the 13 standard sequence tasks by the standard above-elbow subject using the conventional prosthesis was good throughout testing both in terms of average errors and average completion times. Since this subject was quite proficient in the use of this prosthesis, little learning would be expected. Slight evidence of learning is given by the small reduction in error scores which occurred for him. No change was observed in average time taken for task completion.

With the experimental arm, both subjects were considerably slower and committed more errors, the forequarter amputee showing a better overall level of performance. The standard above-elbow subject improved both in time and error scores while the forequarter amputee improved only in error scores.

Performance on the table setting task presented a somewhat similar picture. In this task, in which no practice was allowed and in which subject instructions emphasized speed of performance, the same rank order of proficiency of arm-amputee systems resulted as for the 13 standard tasks. Again the performance of the above-elbow amputee with the conventional prosthesis was much better than with the experimental arm. Performance by the forequarter amputee with the experimental arm was intermediate between the two, but was much closer to the level of the standard above-elbow with the conventional arm than it was for the 13 standard tasks.

In general, error scores on the table-setting task were greater than on the 13 standard tasks, while time scores were superior. This would be expected considering the nature of the tasks and instructions. Also, more evidence of learning was found on the table-setting task, undoubtedly because pre-test practice was limited.

Scores with the conventional arm on the table-setting task are comparable to those obtained in another study (Groth & Lyman, 1957) using five unilateral above-elbow amputees with a VO hook. The average of their scores (one trial per subject) is higher than that obtained here for the standard above-elbow subject on the first five trials. When their scores are corrected for the difference in number of task objects involved, however (11 rather than 8), their times agree well with those obtained here (Fig. 28).

It is apparent that on the tasks described, performance with the experimental arm on the average is inferior to the conventional arm in terms of time and error scores. It is difficult to generalize regarding the superiority of one prosthesis over the other because of the difficulties of intra-individual comparison noted earlier (Section II.C.), and because of the difference in effective training periods for the two prostheses. The above-elbow amputee has been wearing the conventional prosthesis daily for over ten years. Total effective training on the experimental arm, including pre-task practice period and use during testing, is only of the order of 75 to 100 hours for each amputee. Nevertheless, considering the level of skill represented by these training periods, any further improvement in the use of the experimental

arm would be expected only after much additional training and use of the arm.

E. Specific Operational Problems Encountered During Testing

During the entire evaluation procedure a daily log was kept of informal observations. Specific problems encountered by the amputee during use of the experimental arm were derived from this log. They are grouped in the following sections according to the particular component of the prosthesis involved.

1. Elbow Unit

Speed of movement of the forearm over the lower range of flexion is too fast to permit precise control of its movements. Upon reaching about 100 deg. flexion the elbow exhibits a jerking movement and then slowly creeps over the remainder of the range. This movement can be seen in the curves of Figure 6. Apparently the physical configuration of the bellows within its support is responsible for an abrupt restriction in bellows expansion. Past the point of jerking the precision of motion is improved due to the reduction in speed. The reduction is so great, however, as to annoy the amputee. The jerking motion that occurs at 100 deg. also makes transport of liquids in open vessels difficult.

The elbow locking mechanism did not always provide a secure lock. In some instances the amputee was able to "lock" the arm at a position midway between two actual locking positions. This was due to a friction lock achieved by jamming of the locking pin against the gear mechanism of the elbow. When a load was applied to the forearm, such as in grasping a coffee cup, it was sufficient to depress the forearm enough to allow the pin to mesh with the gear, which it did with a loud thump. This was more of an annoyance than an actual hindrance in task performance.

A complaint often voiced during those tasks which involved motion at the face regarded a reduction of the upper flexion limit which occurred with reduction of gas pressure from the portable CO_2 source. While this reduction was only of the order of 5 deg. it was critical in view of the already severely limited upper range of elbow motion. This problem was compounded by the addition of a load (cf. Table 1).

Frequently on extension the amputee's motion was interrupted. This was mainly a problem with the standard above-elbow subject. It was due to a failure to maintain the proper tension in the control cable, thus permitting the control valve to slip backwards in the sequence of control positions, away from the position of extension (step 6).

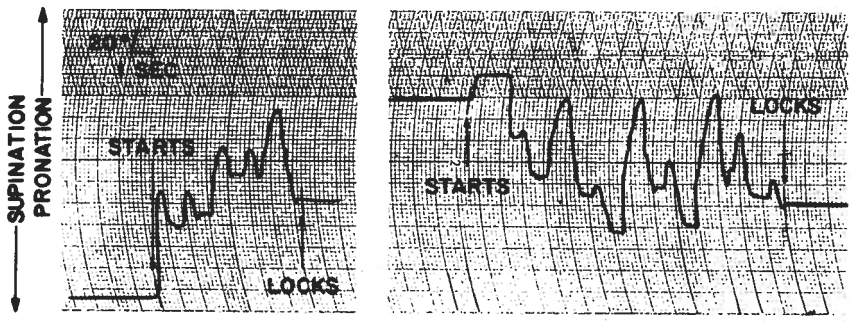
2. Wrist Unit

The wrist unit was by far the most difficult unit to control. Pronation speed was faster than supination, but both movements were apparently faster than could be easily controlled. Whenever possible in the standard

sequence tasks the amputees preferred to work out the optimum wrist rotation setting during the training period for the task and leave the wrist set at that position during the task performance. Only on the three tasks on which wrist activity could not be avoided did they rotate the wrist during the task.

Figure 29 illustrates the difficulty in controlling the wrist unit which was observed in precision of motion testing. The cost in time of using this unit was so high as to discourage the amputees from its use.

On initiation of supination movements the wrist exhibited what we termed a "pronation jerk," or movement of the wrist in the pronation direction before supination could begin. This artifact is illustrated in part (b) of Figure 29. It is caused by pronation spring's action upon unlocking of the wrist. This artifact was not critical in performance of the standard sequence tasks as performed here, but is an obviously undesirable feature of the wrist operation since it represents a built-in inadvertent movement of as much as 20 deg.



(a) Pronation trial. (b) Supination trial.

FIGURE 29. Samples of data of precision of motion tests with wrist unit.

In (a) amputee attempts to reach and lock at a test position 95 deg. away from starting position (extreme supination). In (b) amputee attempts to reach the same test position starting from opposite end of range of motion (extreme pronation). In both cases note large number of movements made, wide range of movement, and total time taken to reach lock (7 seconds and 14 seconds).

Pronation movements contribute more to performance variability with wrist unit than do supination movements. Most large errors are "overshoots" of test position on pronation. Also note in (b) that at start of trial there is an artifactual pronation movement as amputee unlocks wrist to initiate supination. This artifact occurred on nearly all supination trials.

3. *Terminal Device*

The terminal device was considered too bulky and clumsy by our amputees. Its size prevented its use in areas such as pockets, small purses, etc. It could not be used in close proximity to other objects since during grasp or release of one object often another was disturbed (for example, in the table-

setting task in which utensils must be placed close together). Another frequent complaint related to size of the hand was that it frequently blocked the line of sight from amputee to object, depending on the orientation of the hand. Thus, information regarding approach to grasp and secureness of grasp was restricted.

The non-padded third finger adjacent to the two padded fingers protruded past the finger pads on the padded fingers and interfered with the grasp of small objects on the table top. For instance, a wooden pencil could only be grasped at the end rather than in the middle, if lying on a flat surface.

The amount of terminal device opening was a problem in two situations. In grasp of a round door knob, the opening was barely sufficient to permit grasp and then only in an awkward fashion. The available opening did not permit grasp at all of the standard cylindrical drinking glass. For our tests, we were forced to use a small (2-in. diameter) juice-type glass. Another solution would have been that of the Heidelberg training programs—use of a stemmed wine glass. A third solution, grasping the rim of the glass as is done by some hook wearers, was not feasible since the bulkiness of the hand prevented the amputee from bringing his mouth to the rim of the glass.

The orientation of the finger tip surfaces did not permit a secure grasp of a number of curved geometric shapes during training and testing. For example, the telephone receiver had to be jammed into the opening between the fingers in order to achieve a secure grasp.

Grasp of small, smooth metal objects such as the zipper tab was not secure and they often slipped from between the finger pads. Larger objects were grasped more securely.

III. SUMMARY AND RECOMMENDATIONS

A. Review of Subject Performance

Considering performance with the experimental prosthesis in comparison with the conventional prosthesis, we can summarize our findings as follows:

(1) Range of available motion was not substantially improved with the experimental prosthesis in spite of the addition of a new function (wrist rotation). Both range of flexion and of terminal device opening were noticeably less than those achievable with the conventional prosthesis.

(2) Initiation of movement with the experimental arm (complex reaction time studies) was much slower than with the conventional prosthesis. This result reflects several factors, including pneumatic time lags, the increased complexity of the control motions, and the greater number of choice alternatives.

(3) Precision of motion achieved with the various functions of the experi-

mental prosthesis was much poorer than with the conventional prosthesis, wherever a comparison was possible.

(4) Performance on a series of standardized tasks was much slower and showed more errors with the experimental prosthesis than the conventional. Similar results were obtained on a more difficult task conducted under the stress of a speed test.

Again we would like to emphasize the limitations of our conclusions. The comparison statements are based mainly on the results of performance tests of the standard above-elbow amputee, using performance with the conventional prosthesis as a baseline for comparison. In general, results of the forequarter amputee were found to parallel those of the standard above-elbow subject with the experimental arm, though they were somewhat better. As noted earlier, differences between subjects make inter-individual comparison difficult. Such differences here included level of amputation, control motions, age, physical condition, and previous prosthetic experience. Therefore, we can only consider the results obtained with the forequarter amputee as supportive data. His data would be best evaluated in terms of his own performance on another prosthesis.

The very limited nature of our sample as well as the high variability of performance obtained obviates the use of traditional statistical significance tests. Nevertheless, the levels of performance reported here represent a substantial investment in training time and experience and they can be considered as a reasonable representation of the performance obtainable with the experimental prosthesis.

This is not to imply that further improvement is not possible. On the contrary, the data of Figure 27 indicate that some learning was still occurring and that a complete performance asymptote had not been reached on the series of standard everyday tasks. However, a significant improvement in performance would only be expected after much additional training. The informal reports of Marquardt and Haefner (1957) regarding their training procedures seem to substantiate this point.

B. Operational Safety

Two points should be considered in regard to safety of the experimental prosthesis. First, the portable aluminum CO_2 source (German) does not meet United States standards of safety and there have been informal reports of explosions occurring during recharging. No such difficulty occurred with the steel cylinder used in this evaluation.

Second, the inability of the amputees to achieve positive and precise control of the prosthesis, coupled with the changes in operating speed which occur upon loading of the various components (pronation is an excellent example) made the arm unpredictable in some situations. One example is the refusal of the forequarter amputee to activate the wrist unit when

holding an object near the face. He developed this attitude after striking himself in the face more than once with a spoon during performance tests.

C. Functional Cosmesis

Regarding cosmesis, little direct attention was given to this aspect of the evaluation. In general, informal observations of amputee opinions indicate that their major concern was with the functional shortcomings of the experimental arm. Specific complaints concerned the jerky motions of wrist and elbow already noted. Also mentioned were the filling and exhausting noises occurring with stop and start of movement. These were judged to be more than loud enough to attract attention to the wearer.

D. Prosthesis Acceptance

The reactions of both subjects to the experimental prosthesis can be described as mixed. For the forequarter amputee this prosthesis represented a definite regain of functions lost to him after amputation. However, this was his first experience with a prosthesis that provided any appreciable motion. He frequently expressed feelings of frustration regarding his inability to achieve positive control and regarding the limited elbow range.

The standard above-elbow subject was less enthusiastic regarding the experimental arm initially, but expressed the feeling that with long term training and practice he would eventually reach an acceptable level of performance. Nevertheless, he expressed feelings of frustration and disappointment during use. His comparison basis was his own conventional prosthesis.

E. Initial Cost and Maintenance Cost

Although the Heidelberg Arm has been available to a limited number of European amputees for several years, it is not yet in production in this country and therefore generally unavailable to American users. Our latest information from the United States manufacturer, the Otto Bock Co. of Minneapolis, indicates that this prosthesis will be sold in the near future, but accurate cost estimates are not yet available. Maintenance costs can only be determined after the United States model is in use or is subjected to prolonged field testing. Our experience with the German model indicates that maintenance costs could be fairly high, depending, of course, upon the quality of components in the American model.

F. Systems Reliability

Repairs and maintenance necessary on the experimental prosthesis have been mentioned in various sections of this report. They will be reviewed here briefly as follows:

(1) Wear of the elbow bellows resulted in rupture of this component twice. Once the unit was replaced by the German developer; the

second occurrence was treated at the University of California at Los Angeles by use of a rubber patch.

(2) A ball-type pressure greaser in the 7-position control valve became worn and frequently jammed the operation of the valve.

(3) Clogging of pneumatic lines was a frequent event at the area of the control valve nozzles, requiring disassembly of the linkages. This problem may have been due to the use of a laboratory compressed air supply and might not occur if CO_2 is the sole power source.

(4) The terminal device finger pads became worn, requiring regluing a number of times.

(5) The rubber tubing broke during testing. Examination revealed the development of numerous small cracks probably due to atmospheric smog effects.

Expected downtime with the experimental arm during normal operation would be considerable in light of our experiences. Since the particular model of the arm tested here is of 1958 or 1959 vintage, there may have been recent improvements to design and especially to quality of components to increase reliability of the prosthesis. Nevertheless the prosthesis tested here was a production model, not a prototype or test model, and the difficulties reported, as well as a number of unreported minor incidents, would be expected in normal operation over a period of three to six months. Maintenance would be difficult in most cases for the amputee himself and the prosthesis would require professional care.

We should mention for comparison purposes that no serious mechanical problems occurred with the conventional prosthesis which was used under the same conditions of testing by the standard above-elbow amputee. This subject also used this prosthesis concurrently in his daily routine. Replacement was made to the terminal device fingers due to normal wear of the neoprene linings.

G. Recommendations

The following suggestions are made with regard to functional deficiencies of the experimental prosthesis as revealed in the evaluation testing. The emphasis here is on gross functional improvements rather than upon specific, detailed mechanical modifications or on other mechanisms for their implementation.

(1) The upper flexion range of the elbow unit should be increased to 135 deg. so as to permit activity in the face region with a minimum involvement of "body english."

(2) Maximum terminal device opening should be increased by an inch or more to increase the range of objects that may be grasped.

(3) Replacement of the terminal device by a hook would be desirable to

increase maneuverability in approach and grasp, and to increase the flexibility and variety of grasp orientations.

(4) Another approach to improving grasp, while retaining the present terminal device, would be to streamline hand and fingers, to increase size of opening, and to line with rubber the inner surfaces of thumb and fingers. In this way, objects could be grasped within the hand rather than at the fingertips only.

(5) Speed of movement and available force should be more nearly constant over the range of each movement and equal for both directions of movement. The extreme difference in pronation and supination speeds is an example.

(6) Movements should be smoother and positive at all times in the intended direction. The "creep" in the elbow unit at the upper flexion range, the jerky motion of supination, and the brief pronation movement occurring at the initiation of supination should all be eliminated.

(7) In addition to being slow, supination is a very weak movement. The forces available should be increased.

(8) Increased speed of initiation of each function would be desirable, since on the average it took over one second to initiate movement even in the simple reaction time situation.

(9) Precision of operation of the elbow and wrist would be improved by allowing locking to occur anywhere along the range of motion rather than only at fixed positions. Even more important in this regard would be a reduction in time of operation of the locking system. The "hunting" motion observed in our precision of motion tests result both from the necessity of finding a fixed locking position and of activating the locking system while the unit moves past the locking position. The amputee either had to initiate locking before reaching the locking point (thus "leading" the arm), or try to overshoot just enough so that the lock would be operating just as the unit returned past the locking point.

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