ELECTROCUTANEOUS FEEDBACK FOR ARTIFICIAL LIMBS
SUMMARY PROGRESS REPORT
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INTRODUCTION

Since February 1, 1974, the UCLA Biotechnology Laboratory has been researching "Electrocutaneous Feedback for Artificial Limbs." The objective of this research has been to investigate the effectiveness of supplying electrocutaneous sensory feedback as an aid to the patient in controlling upper-limb prostheses and orthoses. The following eight-task research program is in progress:

1. Design and development of several different electrocutaneous sensory feedback systems.
2. Basic research studies of electrocutaneous stimulation parameters including:
   - methods of encoding sensory feedback parameters: single and multiple electrodes,
   - comparison of bipolar and monopolar stimulation,
   - study of the importance of a reference signal to feedback effectiveness,
   - investigation of undesired interaction between myoelectric control and electrocutaneous feedback when used simultaneously in an arm prosthesis,

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aPrimary support for this research was provided by the National Institutes of Health, Grant No. GM-21430, with supplemental support from both the Veterans Administration and the Social Rehabilitation Service. Powered components, both standard and modified, were supplied by the Veterans Administration Prosthetics Center. Their assistance in our research is hereby gratefully acknowledged.
determination of performance degradation resulting from interruption of sensory feedback when a prosthesis is temporarily stationary,
• effects of varying single electrode material and geometry parameters.

3. Investigation of the effectiveness of various supplemental electrocutaneous feedback signals for prostheses and orthoses.
4. Clinical evaluations of prototype electrocutaneous sensory feedback systems for prostheses and orthoses.
5. Refinement and clinical evaluation of harness-mounted proportional controllers/electrocutaneous feedback systems for use with commercially available switch-controlled electric hands and elbows.
6. Design and evaluation of a prosthesis control harness for use by non-amputees to assist them in conducting research and development for artificial limbs.
7. Determination of the feasibility of a proportionally controlled linear power assist device for artificial limbs.
8. Development of a four degree of freedom microcomputer-aided prosthesis with electrocutaneous feedback.

Guidelines for designing electrocutaneous sensory feedback systems for upper-limb prostheses and orthoses are being established, and information for related applications in other areas provided. The feasibility and utility of prosthetic-orthotic devices with electrocutaneous feedback is being ascertained through careful experimental evaluation on amputees and neuromuscularly handicapped individuals.

The following subsections describe progress on each of the eight tasks. Related work by others has been reported elsewhere (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 13, 14, 15, 16).

1. DESIGN AND DEVELOPMENT OF SEVERAL DIFFERENT ELECTROCU TANEOUS FEEDBACK SYSTEMS

Three different sensory feedback systems are being developed. During the first half of 1974, a two degree of freedom (hand and elbow) proportionally controlled, externally energized prosthesis with grasp-force and hand-opening feedback was assembled to facilitate the clinical evaluation of electrocutaneous sensory feedback (Fig. 1 and 2). Proportional control was achieved by using servo amplifiers controlled by harness-mounted potentiometers (Fig. 3) and a control logic circuit. Variation in grasp force and hand position (opening), sensed by transducers mounted in the hands (Fig. 4 and 5) controlled the pulse width and pulse repetition rate of a stimulator (Fig. 6) which delivered constant current pulses to the stump of the
amputee by means of a single concentric silver electrode (Fig. 7). Performance data for this prosthesis are reported in the Task 4 and Task 5 progress section. The prosthesis is more fully described by Prior and Lyman elsewhere (11, 12).

**FIGURE 1.**—Experimental two-degree-of-freedom, proportionally controlled, externally energized arm prosthesis with sensory feedback: a. assembled view, b. pictorial representation.

**FIGURE 2.**—Subject wearing the two-degree-of-freedom, proportionally controlled, externally energized arm prosthesis with sensory feedback. The cosmetic glove and upper arm cover have been removed for these photographs: a. side view, b. back view.
In July 1975, development began on a myoelectrically controlled hand with electrocutaneous sensory feedback of grasp force and hand opening (Fig. 8 and 9). An improved version of the stimulator shown in Figure 6, is being used, and two electrodes, identical to that shown in Figure 7, press against the patient’s forearm. Various coding schemes can be selected by means of a 16 pin dual inline package (DIP) plug on the electronics circuit board. The hand is a standard VA/NU myoelectric hand (Fidelity Electronics, Ltd.) with strain gages and hand-opening potentiometer installed by VAPC (Fig. 9).

Finally, a conventional cable-operated above-elbow prosthesis has been assembled (Fig. 10). Work on installation of an add-on sensory feedback system to the prosthesis is in progress. Position feedback potentiometers will be added to both the hook and the elbow, and strain gages placed in the cable or on the hook. Stimulator circuitry similar to that of Figure 6 will be used.

2. BASIC RESEARCH STUDIES OF ELECTROCUTANEOUS STIMULATION PARAMETERS

Work has begun on three basic studies of electrocutaneous parameters relevant to the design of sensory feedback systems for prostheses and orthoses. Progress is described in the next four subsections.

A. Methods of Encoding Sensory Feedback Parameters: Single and Multiple Electrodes

The analog information output from a sensor can be encoded in a variety of ways before being applied to the skin. To date, monopolar
FIGURE 4.—Special VAPC electric hand with sensory feedback: a. top view, b. bottom view.
Figure 5.—Modification of the Otto Bock System Electro Hand to provide grasp-force and hand-opening sensory feedback; a. original hand mandrel, b. modified hand mandrel.
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Figure 6.—Schematic diagram of the electrocutaneous stimulator contained in the experimental prosthesis.

Pulse stimulation using the following parameters appears to be optimum from both an information transfer as well as a comfort standpoint:

1. variations in pulse repetition rate from 1 to 40 pps, with 1 to 15 pps being preferred when discrimination of pulse repetition rate is required;

2. variations in pulse width from 10 to approximately 200 μsec; and

3. variations in electrode current from 1 to 7 mA.

Coding one parameter using simple monopolar pulses and a single electrode can be achieved by varying pulse repetition rate, pulse width, or pulse amplitude (Fig. 11a, b, and c). Over the ranges indicated in the Figure, two parameters can be encoded, and variations
in pulse width can be perceived separately from variations in pulse repetition rate (Fig. 11d). The same is true with variations of pulse amplitude and pulse repetition rate (Fig. 11e), but simultaneous changes in pulse amplitude and pulse width cannot normally be distinguished (Fig. 11f).

If monopolar pulses are gated in bursts, more coding possibilities emerge (Fig. 12).

If multiple electrodes are used, more elaborate approaches become feasible: coding each parameter with a separate electrode (Fig. 13a), activating one of several electrodes depending upon the output from a sensing transducer (Fig. 13b), firing electrodes in sequence with one of them accentuated (Fig. 13c), using two electrodes in conjunction with intensity or time delayed localization of stimuli (Fig. 13d and e), and using several electrodes arranged semicircularly around a central reference electrode (Fig. 13f). In this last approach, every pulse from the pulse generator is felt at the central electrode. After each pulse is presented at the central electrode, a short time delay occurs, followed by a pulse felt at one of the electrodes on the semicircle.

As of 31 July 1975, work has been concentrated primarily on assembling the necessary hardware. At present, apparatus is complete to allow coding signals as shown in Figure 11a, b, and d, Figure 12a, b, d (3), and Figure 13a. Simple modifications are planned to facilitate encoding signals as illustrated in Figure 11c and e and Figure 12c and d (2). James Duncan, an M.S. candidate, and Andrew Szeto, a Ph. D. candidate, have constructed apparatus to evaluate coding signals, as suggested in Figure 13b, d, e, and f. Mr. Szeto will
FIGURE 8.—Block diagram of the myoelectrically controlled hand with electrocutaneous feedback of grasp force and hand opening.
FIGURE 9.—Photograph of the partially completed myoelectrically controlled hand with electrocutaneous feedback of grasp force and hand opening: a. top view, b. bottom view. The special myoelectric hand with mounted strain gages and feedback potentiometer was supplied by the Veterans Administration Prosthetics Center.
use the apparatus (Fig. 14 and 15) in a series of studies starting in August 1975. No work has yet begun on implementing the methods of coding parameters depicted in Figure 12d (1) or Figure 13c. Pilot studies have been conducted using the coding methods suggested in Figure 11a, b, and d and Figure 13a. In addition, the approach of Figure 11d was used in the first experimental prosthesis described in Task 1. Pilot experiments have indicated that all of these approaches are feasible and can support the necessary information transfer. Which approach is optimum, however, has not yet been established; the next logical step in our research is to accurately compare the various coding possibilities using accepted psychophysical methodology in carefully conducted experimental designs.

B. Comparison of Bipolar and Monopolar Stimulation

The purpose of this study is to determine how much pain reduction is achieved by using bipolar pulse quantal stimulation, as opposed to simple monopolar pulse stimulation. A monopolar pulse stimulator (Fig. 16) and a bipolar pulse quantal stimulator (Fig. 17), controlled by an electrocutaneous stimulation controller (under development), will be used in the study. Specific details of the experimental design are not finalized, but it will employ accepted psychophysical methodology to answer the following questions:

- How much pain reduction is achieved by the use of bipolar pulse quantal stimulation, as opposed to simple monopolar pulse stimulation?
- How do dynamic range and information transfer rates compare for these two types of stimulation?
Is bipolar pulse quantal stimulation an optimum choice and, if so, under what conditions (considering such factors as cost, type of patient, expected functional improvement, and amount of pain)?
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**Figure 12.**—Coding with gated monopolar pulses and a single electrode: a. variation of burst repetition rate, b. variation of burst duration, c. variation of burst amplitude, d. suggestions for varying two parameters at a single electrode, and e. coding schemes which are not recommended.

C. Investigation of Undesired Interaction Between Myoelectric Control and Electrocutaneous Feedback When Used Simultaneously in an Arm Prosthesis

Present day myoelectrically controlled hands suffer from a reduced amount of sensory feedback available to the patient as compared with even the small amount of feedback available in conventional cable-operated prostheses. When grasping objects with a myoelectrically controlled hand, visual feedback is the dominant mode. Electrocutaneous sensory feedback from the hand can be expected to improve function, but unfortunately another problem arises with the use of simultaneous myoelectric control and electro-
FIGURE 13.—Coding with monopolar pulses and multiple electrodes: a. coding each parameter with a separate electrode, b. activating one of several electrodes depending upon the output from a sensing transducer, c. firing electrodes in sequence with one of them accentuated, d. time-delayed localization of stimuli, e. intensity localization of stimuli, and f. firing one of several electrodes arranged around a central reference electrode.

cutaneous feedback—interaction between the two. To date, this problem has not been adequately investigated, though some research has been done. Kaplan (13) and Rohland (14, 15) employed separate electrode sites for control and stimulation and various filtering schemes as a solution to the interaction problem. Scott (16) describes the use of time sharing and gain control principles to enable a myoelectric control unit and a sensory feedback stimulator to function from a common set of electrodes. Carl Mason of the Bioengineering Research Service, VAPC, in a private communication said he is investigating modifications of the VA/NU hand EMG amplifier circuits to achieve: 1. rapid recovery from input overload transients from the stimulator and 2. filtering of stimulator frequency components.
FIGURE 14.—The apparatus for spatially encoding a single sensory feedback parameter using multiple electrode displays.

FIGURE 15.—Apparatus for encoding sensory feedback signals using monopolar pulses and multiple electrodes—block diagram.
FIGURE 16.—Laboratory-type version of the monopolar pulse electrocutaneous stimulator model MPES-L1.

FIGURE 17.—Laboratory-type bipolar pulse electrocutaneous quantal stimulator model BPEQS-L1.
In our research at the Biotechnology Laboratory, we have used a different approach to the interaction problem. During the summer of 1974, the apparatus of Figure 18 was assembled with which we were able to investigate the consequences of floating and common ground connections. Figure 18d shows some typical data obtained using the apparatus. We concluded that floating grounds reduced interference to the point where adequate EMG control appeared possible. Precise reasons for this reduction are being investigated; a simple ground loop in the common electrode connection does not appear to be the cause.

The apparatus shown in Figure 18b is not clinically practical for the following reasons: In current clinical practice, dry metal stainless steel electrodes are normally installed in the prosthesis socket. Floating electrodes attached by double-sided adhesive collars and electrode gels would add to hardware inconvenience and could be too difficult for patients to handle. Additionally, myoelectric hands already purchased by patients do not possess amplifiers of the same quality as the amplifier employed in the experimental apparatus, and while existing electric hands could be modified, it would be desirable to avoid such changes if possible.

In consideration of these limitations, the EMG amplifier of Figure 18e has been modified (Fig. 19) to include electronics from a VA/NU myoelectric hand, and stainless steel myoelectric electrodes used in place of the floating electrodes. Preliminary results indicate that interaction can be kept low enough for proper operation, using the stainless steel electrodes and the VA/NU electronics, only if separate myoelectric amplifier and stimulator grounds are maintained. The design for the second prosthesis described in Section 1 is based on these preliminary results.

D. Other Research Studies of Electrocutaneous Stimulation Parameters

No progress has occurred on the following research studies during the progress report period: 1. Study of the importance of a reference signal to feedback effectiveness; 2. determination of performance degradation resulting from interruption of sensory feedback when a prosthesis is temporarily stationary, and 3. effects of varying single electrode material and geometry parameters.

3. INVESTIGATION OF THE EFFECTIVENESS OF VARIOUS SUPPLEMENTAL ELECTROCUTANEOUS SENSORY FEEDBACK SIGNALS FOR PROSTHESES AND ORTHOSES

Pilot studies (see Sections 4 and 5) have indicated that grasp-force and terminal-device-opening information are very useful to the
FLOATING GROUNDS

OUTER FLOATING ELECTRODES WITH ELECTRODE GEL

STIMULATING ELECTRODE: SILVER

BIOPOTENTIAL ELECTRODES:
FLOATING ELECTRODES WITH ELECTRODE GEL

INNER ELECTRODE
OUTER ELECTRODE
ANNULAR SPACING

STIMULATING ELECTRODE: SILVER

STIMULATOR
COMMON GROUNDS

EMG AMPLIFIER
+ GND -

CHART RECORDER
FIGURE 18.—Apparatus used to investigate undesired interaction between myoelectric control and electrocutaneous feedback when used simultaneously: a. photographs of Philip A. Case demonstrating the experimental setup, b. block diagram of the apparatus when connected for floating grounds, c. block diagram of the apparatus when connected for common grounds, d. some typical data, and e. the myoelectric amplifier.
amputee. A preliminary evaluation of elbow flexion-extension sensory feedback information is in the planning stages. Future studies may consider other sensory feedback signals such as wrist position, humeral rotation, limb loading, and fingertip temperature.

4. CLINICAL EVALUATIONS OF PROTOTYPE ELECTROCUTANEOUS SENSORY FEEDBACK SIGNALS FOR PROSTHESSES AND ORTHOSES; and
5. REFINEMENT AND CLINICAL EVALUATION OF HARNESS MOUNTED
PROPORTIONAL CONTROLLERS/ELECTROCUTANEOUS FEEDBACK
PACKAGES FOR USE WITH COMMERCIALLY AVAILABLE SWITCH
CONTROLLED ELECTRIC HANDS AND ELBOWS

A pilot evaluation of the performance of the first prosthesis
described in Section 1 was performed. In a block manipulation task
(Fig. 20), the subject's best times were 14 seconds with his normal
right arm, 40 seconds with his own cable-operated prosthesis, and
50 seconds using the new experimental prosthesis. The patient was
not fully trained, and it is probable that significant negative learning
transfer was present. For these reasons, it is estimated that a 5 to 10
second improvement in his score could reasonably be expected
without further modification of the prosthesis. In addition, a special
high speed elbow motor which will reduce the elbow motor trans-
versal time by nearly a factor of 2 will be incorporated in place of
the present VAPC elbow motor (see Fig. 20b). This is expected to
reduce the experimental prosthesis time in this task to a level sub-
stantially below that for a conventional cable-operated prosthesis
(Table 1).

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Best score, time in seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal right arm</td>
<td>14</td>
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<tr>
<td>Patient's own conventional cable AE prosthesis (worn on a daily basis)</td>
<td>40</td>
</tr>
<tr>
<td>Experimental prosthesis—best measured time as of 12/31/74</td>
<td>50</td>
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<tr>
<td>Projected scores when fully trained:</td>
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<tr>
<td>Without further modification of the experimental prosthesis</td>
<td>40 to 45</td>
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<tr>
<td>After the addition of the high speed elbow motor</td>
<td>32.5 to 37.5</td>
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In tests of the effectiveness of grasp-force sensory feedback, the
subject was asked to duplicate a grasp on a pinch meter without
vision after first establishing a reference grasp while looking at the
meter (Fig. 21). Results of the first testing session are shown in
Table 2a. The patient was able to duplicate the reference grasp more
STEP 15 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 16 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 17 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 18 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 19 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 20 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 21 - BLOCK AT SIDE, ELBOW EXTENDED

STEP 22 - BLOCK AT 2

STEP 23 - BLOCK AT 2

STEP 24 - BLOCK AT 2

STEP 25 - BLOCK AT 2

STEP 26 - BLOCK AT 2

STEP 27 - BLOCK AT 2

STEP 28 - BLOCK AT 2

STEP 29 - BLOCK AT 2

STEP 30 - BLOCK AT 2

STEP 31 - BLOCK AT 2

STEP 32 - BLOCK AT 2
### ELBOW MOTOR TRAVEL TIME BUDGET

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<th>Description of Transition</th>
<th>Present Step</th>
<th>Next Step</th>
<th>% Travel</th>
<th>Normal Arm (Timed)</th>
<th>Conventional Cable Operated Prosthesis (Estimated Range)</th>
<th>Standard VAPC Elbow</th>
<th>Special High Speed Elbow Unit</th>
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<td>2</td>
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<td>25</td>
<td>100</td>
<td></td>
<td></td>
<td>.2 - .3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Includes 5 to 7 seconds, 5 to 7 seconds includes control motions and start and stop times.

3 to 4.5 seconds includes neither control motion nor start and stop times.

15 to 22.5 seconds includes control motions and start and stop times.

7.5 to 11.5 seconds includes neither control motion nor start and stop times.

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**Figure 20.** Details of the block manipulation task: a. photo collage of 25 steps in the task, b. elbow motor travel time budget.
FIGURE 21.—Test used to evaluate the effectiveness of grasp-force sensory feedback: 
a. subject establishing a reference grasp while looking at the pinch meter, b. subject at-
ttempting to duplicate the reference grasp while he is prevented from viewing the pinch 
meter by the experimenter.
accurately with his own cable-operated prosthesis than with his
normal right hand. However, the range for the cable-operated
prosthesis was only from 0 to 4 lb, as compared to the 0 to 15 lb
range tested for the normal right hand. The table also shows that
the experimental prosthesis with sensory feedback offered improve-
ment over the prosthesis without sensory feedback. Results of
the second session (Table 2b), using the VAPC hand and position control
of hand motion, also show improvement. The poor score for duplica-
tion of a 3 lb pinch was due to the difficulty of controlling pinch
force with a position feedback controller. Improvement is expected

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Test Pinch, lb (range tested)</th>
<th>Ability to duplicate, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal right hand</td>
<td>0-15</td>
<td>±2</td>
</tr>
<tr>
<td>Patient's own conventional cable-operated prosthesis (worn on a daily basis)</td>
<td>0-4</td>
<td>± .75</td>
</tr>
<tr>
<td>Experimental prosthesis using the Otto Bock hand, rate controlled with timed stroke reset zone and without rapid reset, conductive elastomer pressure transducer mounted on thumb pad, and hand position sensory feedback (10 to 160 pps)</td>
<td>0-15</td>
<td>± 5</td>
</tr>
<tr>
<td>With grasp force PWM sensory feedback</td>
<td>0-15</td>
<td>± 5</td>
</tr>
<tr>
<td>Without grasp force PWM sensory feedback</td>
<td>0-15</td>
<td>± 15 (no ability to duplicate was apparent)</td>
</tr>
<tr>
<td>Experimental prosthesis using the special VAPC hand, position controlled with rapid reset, strain gage pressure transducer mounted on hand mandrel, and hand position sensory feedback (1 to 15 pps)</td>
<td>3</td>
<td>3½ to 9½</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5 to 6½</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>5.75 average</td>
</tr>
<tr>
<td></td>
<td>8.125 average</td>
<td>6¼ to 14</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10 to 11¼</td>
</tr>
<tr>
<td></td>
<td>10.94 average</td>
<td>27</td>
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</table>
when a combination position and force feedback controller is tested further.

In another test to evaluate hand opening (position) sensory feedback, the patient was required to determine which of four sizes of blocks he was grasping (Fig. 22). The results obtained are shown in Figure 23. Part (a) of this table shows that for the first testing session the percent of correct responses for the experimental prosthesis with sensory feedback was greater than without feedback; however, the experimental prosthesis did not approach the 100 percent correct response score for the normal right hand. In the second testing session, the subject’s own conventional cable-operated prosthesis was tested, as was the VAPC hand. A correct score of 77.5 percent was obtained for the VAPC hand with feedback. The subject always was able to identify correctly Blocks I and II, and only once mistook Block III for Block II; however, he had difficulty distinguishing between Blocks III and IV. It is estimated that further refinements of the pulse repetition rate versus hand-opening relationship will boost the percent score to above the 90 percent level.

Throughout testing, hardware problems were experienced. In the first testing sessions, the Otto Bock electric hand stalled several times when closing, and the feedback transducers did not produce consistently the same outputs for identical inputs.

In the last session in the second group, the elbow turntable slipped, the VAPC hand breakaway (a safety device composed of a pivot in the base of the thumb member which automatically gave away when grasp force exceeded a certain value) kept breaking away, and the front shoulder strap proportional control potentiometer mounting screws came loose. By the time these problems were corrected so that the block manipulation test could be run, the subject was exhausted, and the batteries nearly discharged. Despite these conditions, he achieved his best scores during this session. Thus, there is some justification to believe that test scores will improve still further in future tests.

6. DESIGN AND EVALUATION OF A PROSTHESIS CONTROL HARNESS FOR USE BY NON-AMPUTEES TO ASSIST THEM IN CONDUCTING RESEARCH AND DEVELOPMENT OF ARTIFICIAL LIMBS

A prosthesis control harness which allows researchers to wear artificial limbs outboard of their own intact limb is being fabricated (Fig. 24). The harness will enable researchers to experience feedback sensations and control problems similar (though not identical) to those encountered by the amputee. The control harness is being
FIGURE 22.—Test used to evaluate hand position sensory feedback. The subject was required to state which of four widths of blocks he was grasping while prevented from seeing the blocks by a partition.

built to allow us to better interpret the patient’s statements about the strengths and weaknesses of the first experimental prosthesis described in Section 1.

7. DETERMINATION OF THE FEASIBILITY OF A PROPORTIONALLY CONTROLLED LINEAR POWER ASSIST DEVICE FOR CONVENTIONAL CABLE-OPERATED ABOVE-ELBOW PROSTHESSES

On February 27, 1974, a patent disclosure (Prior and Scott) was made describing a proportionally controlled linear power assist device for conventional cable-operated above-elbow prostheses (Fig. 25 and 26). The new device is estimated to allow as many as 5,000 above-elbow and shoulder-disarticulation conventional cable wearing patients in the United States to markedly improve their functional capabilities. It is anticipated that the incorporation of sensory feedback into such a power assisted above-elbow prosthesis would greatly improve function. More details of this device are reported elsewhere in this issue of the Bulletin of Prosthetics Research (17).
**TEST CONDITIONS**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Correct Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal right hand.</td>
<td>100</td>
</tr>
<tr>
<td>Experimental prosthesis using the Otto Bock hand, rate controlled with timed stroke reset zone and without rapid reset and conductive elastomer pressure transducer mounted on thumb pad (defeated)</td>
<td></td>
</tr>
<tr>
<td>(a) starting with hand open</td>
<td>52.5</td>
</tr>
<tr>
<td>starting with hand closed</td>
<td>60</td>
</tr>
<tr>
<td>without sensory feedback</td>
<td>30</td>
</tr>
<tr>
<td>Experimental prosthesis using the Otto Bock hand, rate controlled with timed stroke reset zone and without rapid reset, and strain gauge mandrel mounted grasp force transducer (12-11-74)</td>
<td></td>
</tr>
<tr>
<td>with hand position sensory feedback, 40 pps closed to 3.125 pps wide open</td>
<td>62.5</td>
</tr>
<tr>
<td>starting with hand open</td>
<td></td>
</tr>
<tr>
<td>starting with hand closed</td>
<td>50</td>
</tr>
<tr>
<td>patient's own conventional cable operated prosthesis (12-11-74 and 12-28-74)</td>
<td>62.5</td>
</tr>
<tr>
<td>very tiring</td>
<td></td>
</tr>
<tr>
<td>experimental prosthesis using the special VAPC hand with strain gauge mandrel mounted grasp force transducer (operating during tests with feedback)</td>
<td></td>
</tr>
<tr>
<td>position controlled with rapid reset</td>
<td></td>
</tr>
<tr>
<td>with hand position sensory feedback (1 pps closed to 15 pps wide open) (12-31-74)</td>
<td>77.5</td>
</tr>
<tr>
<td>without sensory feedback (12-31-74)</td>
<td>57.5</td>
</tr>
<tr>
<td>position and force controlled with rapid reset and without sensory feedback</td>
<td>42.5</td>
</tr>
<tr>
<td>not tested</td>
<td></td>
</tr>
</tbody>
</table>

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**FIGURE 23**

8. DEVELOPMENT OF A FOUR-DEGREE-OF-FREEDOM MICROCOMPUTER-AIDED PROSTHESIS WITH ELECTROCUTANEOUS SENSORY FEEDBACK

This task involves the integration of four functional subsystems, developed earlier by the UCLA Biotechnology Laboratory, into an experimental four-degree-of-freedom microcomputer-aided prosthesis with electrocutaneous sensory feedback.
FIGURE 24.—Prosthetic control harness which allows researchers to wear artificial limbs outboard of their own intact limb.

FIGURE 25.—Proportionally controlled linear power assist device for conventional cable-operated above-elbow prostheses: assembled pictorial view.
These four functional subsystems are:

1. a four-degree-of-freedom externally energized arm using standard and modified standard components;
2. several alternative sensory feedback systems;
3. several alternative computer-aided control techniques and,
in particular, two myoelectric pattern recognition and control approaches;
4. electronic circuitry suitable for self-contained (battery operated) computer-aided prosthetic/orthotic applications, including
   a. micro power myoelectric amplifiers,
   b. proportional control systems, and
   c. interface circuitry (A/D and D/A converters, analog multiplexers, etc.).

The selection of a suitable microprocessing system is complicated by the fact that developments are occurring so rapidly that a new selection procedure may be necessary when the specific system is purchased. Present plans are to purchase a CMOS microprocessor development system.

Based on results and information obtained during the progress report period, a preliminary design for the computer-aided prosthesis has been completed. The block diagram of the proposed system (Fig. 27) shows that the prosthesis would contain four externally energized powered components: a hand, a wrist, an elbow, and a
humeral rotator. The elbow would be a standard VAPC powered elbow modified for high speed operation. The hand would be the special VAPC electric hand with sensory feedback shown in Figure 4. The humeral rotator would be of the type fashioned in our laboratory (Fig. 28), and the wrist rotator is still being reviewed. Under consideration for the wrist rotator are a modified Northwestern University wrist rotator (Fig. 29), the new Otto Bock wrist rotator (when it becomes commercially available), or one of the units we have fabricated in our laboratory.

Figure 26 reveals that certain features of the proposed prosthesis would insure a minimal level of function for the patient. The most important factor is that the patient would have simultaneous direct control over his hand and elbow at all times. Control of prehension

**FIGURE 28.—Humeral rotators made from modified VAPC elbow motors.**
FIGURE 29.—Modified Northwestern University Model III wrist rotator: a. side view, b. end view. A feedback potentiometer will later be installed in one of the locations from which motors were removed. In the other location, an electromagnetic brake may be added.

would be separate from the other powered components of the prosthesis, and would use a proportional controller inserted in the control attachment strap similar to that used in the first prosthesis described in Section 1. In addition, the output of this controller would be processed by the computer to aid in decision making. The hand would contain an electrotaneous feedback system similar to those described in Section 1, and would sense grasp force and hand opening.
Control of the elbow would be myoelectric, probably with a pair of electrodes located on the triceps to control extension of the elbow, and another pair on the biceps to control elbow flexion. The elbow servo motor would always be under direct control of these electrodes; however, the output from the elbow myoelectric amplifiers would also be processed by the computer. Approximately 6 to 10 additional sets of electrodes would be placed at various regions on the body, including the scapular region and the deltoid region, depending upon where the best signals were obtained. All of the outputs from these electrodes would be processed by myoelectric signal conditioners, then analog multiplexed, digitized, and finally processed by the microprocessor.

The following additional information would also be provided to the microprocessor.

1. The output of a limb loading transducer (most likely a strain gage) mounted in the forearm member just distal to the elbow, and
2. The outputs from a two-degree-of-freedom shoulder goniometer built into the prosthesis shell and attached to the harness to provide a reference signal which is related to the position of the amputee’s shoulder.

The electrocutaneous feedback system of the prosthesis would contain, in addition to grasp-force and hand-opening information, feedback of wrist and elbow position, wrist and humeral rotator future states, and possibly limb loading force.

When operating the prosthesis, the patient would use control motions for grasp in a manner analogous to those used when controlling a conventional cable-operated prosthesis. The hand controller and hand servo amplifier would probably operate in a position and force servo feedback mode. The elbow servo amplifier would respond as a rate system, that is, the speed of the elbow would be proportional to the myoelectric output signals. The microprocessor would have control over only the humeral rotator and the wrist rotator, though it would monitor all the signals previously discussed. The processor, using pattern recognition algorithms of the type developed by our laboratory, would make decisions which would control the humeral and wrist rotator motors to provide coordinated motion. Provisions for manual operation of the humeral and wrist rotators, possibly using the same control actions as are currently used by amputees to operate passive turntables and rotators, would be considered.

A design aim has been to attempt to ensure a reasonable level of functional performance from the prototype clinical system by maintaining as much simplicity as possible so as to be consistent with available software capability and hardware technology. We recognize that such an approach is a compromise and that we have
ignored much of the inherent complexity of a natural arm which must eventually be considered if a sophisticated prosthesis is to be achieved. The proposed design is an interim one with which we have attempted to maximize prosthetic function while still maintaining current technical feasibility.

REFERENCES