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New Approaches for the Control of Powered Prostheses Particularly by High-Level Amputees[a]

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INTRODUCTION

Electric prostheses were first tested many years ago (1,2,13,15) but are still being improved (10). Commercially available hands (Otto Bock, Fidelity Electronics/VA-NU, Viennatone) are primarily intended for below-elbow amputees and are controlled myoelectrically using the electrical signals produced by muscles such as the long wrist extensors and flexors, parts of which generally remain after amputation. More recently, Otto Bock has introduced an electric wrist which has found good acceptance but more limited application. The wrist is intended to be operated by amputees with an amputation at the mid-forearm level, who have enough residual pronation and supination to operate a rotary microswitch supported between the inner and outer shells of the prosthesis. The inner shell is divided so that the distal portion can rotate with respect to the proximal portion which is fixed to the outer shell. Amputees with longer residual limbs have no room for a microswitch and wrist motor in the prosthesis, but they can be fitted so that their natural pronation and supination turns the hand directly.

Higher-level amputees (short below-elbow amputees and above-elbow amputees) have generally not been able to benefit from powered wrist rotation because of the lack of suitable methods for controlling the motor reliably. Wrist rotation to position an electric hand is important for a unilateral amputee and essential for a bilateral amputee, if the prosthesis is going to be fully functional (16). Methods for reliably controlling several degrees of freedom would probably increase substantially the rate of acceptance of powered artificial limbs.

Although approximately 15,000 electric hands have been produced worldwide since World War II (personal communication, Jack Hendrickson, Otto Bock Inc., Minneapolis, Minn.), this number represents only a few percent of the more than 100,000 arm amputees estimated to be in the U.S. alone (5). Only a few percent of the amputees fitted with an electric hand have also received an electric wrist, based on the total production of these units (Jack Hendrickson, personal communication).

Reasons which are often cited for the relatively slow acceptance of these technical advances include increased cost, occasional problems with reliability and servicing, and a lack of prosthetists trained to fit and maintain powered prostheses. However, these problems can and must be overcome where powered prostheses offer a severely disabled individual improved control over his environment and dignity as an individual. Dr.H. Schmidl has shown that these problems can be overcome. More than 2,500 amputees have been fitted in his Institute, I.N.A.I.L., in Budrio (Bologna), Italy (personal communication, 1978).

Our group in Edmonton has been particularly interested in methods for

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[a] Support for the research and clinical application described here came from the Medical Research Council of Canada, University of Alberta Hospital Research Fund, War Amputations of Canada, Medical Services Research Foundation of Alberta, and related private foundations.

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improving the control of powered prostheses by high-level amputees (short below-elbow amputees and above). In the last 3 years, 30 electrically-powered prostheses were fitted at various levels by Edmonton prosthetists (Table 1). Although the numbers are relatively small,acceptance has been good. The vast majority of the amputees wear the powered prosthesis in preference to a cable-driven hook or no prosthesis (many of the amputees had rejected conventional prostheses which were previously fitted). The acceptance of the powered prostheses (and the function of amputees in doing objectively measured tasks with the prostheses compared to amputees wearing conventional prostheses) will be described in a later publication. All amputees fitted with powered prostheses to-date had previously tried conventional prostheses for periods of months or years.

This paper will concentrate on three specific amputees to illustrate some of the novel techniques we have developed for providing control of several degrees of freedom. Our approach has involved groups of individuals, as indicated by the affiliations of the authors. Specialized knowledge has been utilized from prosthetics, occupational therapy, various medical specialties, basic science, and engineering fields. Constant feedback and interaction within this group has been essential to our success.

TABLE 1 [a]

Length of Stump	No. of Limbs Fitted with Electric: Hand	Wrist	Elbow
Below-Elbow			
Long to wrist-disarticulation	6	1	
Mid-forearm	4	4	
Short	9	5	
Above-Elbow			
Long to medium	7	4	3
Short to forequarter amputees	4	4	4
Total	30	18	7

[a] Twenty-eight amputees have been fitted (including two bilaterally) with one or more electrical components depending on the length of their stump and other factors. Amputees not fitted with an electric wrist utilized either natural pronation and supination or a passive Otto Bock unit with several click positions. Amputees not fitted with an electric elbow utilized a conventional cable-operated elbow.No electric hooks were used in this study.

PROSTHETIC PROGRAM

Amputees are either referred, or have sought out individuals in the group after hearing about the program. A medical and prosthetic history is taken and they are assessed for surface EMG muscle sites (using a myotester, Otto Bock, 757 M5) and for other possible switch or contact points to control a prosthesis. Some preprosthetic training is done with the myotester by an occupational therapist, to improve signal levels, separation, and reliability of intended myoelectric control sites. In difficult cases, a temporary prosthesis is made with plaster to determine whether an amputee can function appropriately with myoelectric or other forms of control. This preprosthetic period lasts at most a few days and the amputee is seen generally as an outpatient. Following the preprosthetic assessment, a plan is worked out in discussion among members of the group,the Amputee Clinic of the University Hospital, and the amputee. Referring doctors are informed of the plan as well as the approximate cost and duration of the required treatment. (Note: prosthetic costs are not generally covered by government-supported programs, except for particular groups such as veterans or workers' compensation cases, but various insurance and other groups may cover part or all of the costs.)

The prosthetist then prepares the artificial limb using the standard techniques recommended by various training programs for myoelectric prostheses (Otto Bock, New York University) with some modifications which will be described later. All components used are commercially available from Otto Bock [d] (electric hand, wrist), Variety Village [e] (electric elbow) and Leaf Electronics [f] (several electronic modules developed locally). Once the prosthesis is completed, the patient returns for fitting and training. This usually requires about 1 to 2 weeks for below-elbow amputees, and 2 to 3 weeks for higher-level amputees, particularly if independent control of several degrees of freedom (hand, wrist, elbow) is required.

Postprosthetic training is done by an occupational therapist and consists of the following three phases:

1. **A checkout drill**. The amputee is observed to see if he is able to operate each degree of freedom reliably and independently in a variety of body positions. This is best done in several short sessions over a period of a few days, since the muscles involved may fatigue readily, particularly if they have not been used for many years. Various adjustments to the prosthesis and to the settings of the electrical components may be carried out during this period to optimize the range of motion available to the amputee and the ease and reliability of his function.

2. **Simulation of basic tasks** — This phase involves grasp and release of various sized objects, simulated eating (without the psychological components that would be introduced, for example, by a full cup of hot coffee), and dressing tasks including doing and undoing buttons, buckles and zippers.

3. **Coordination and incorporation into activities of daily life** — This phase involves various real-life activities, depending on the requirements of the amputee. When amputation occurred congenitally or in early life, the amputee may be taught to do two-handed tasks he has never done before. Similarly, tasks involving both limbs are emphasized with bilateral amputees, and coordination between the artificial and

[d] Otto Bock Orthopedic Industries, Duderstadt, Federal Republic of Germany

[e] Variety Village Electro-Limb Production Centre, 3701 Danforth Avenue, Toronto, Ontario, Canada MIN 2G2

[f] Leaf Electronics, 11804-124 Street, Edmonton, Alberta, Canada T5L OM3.

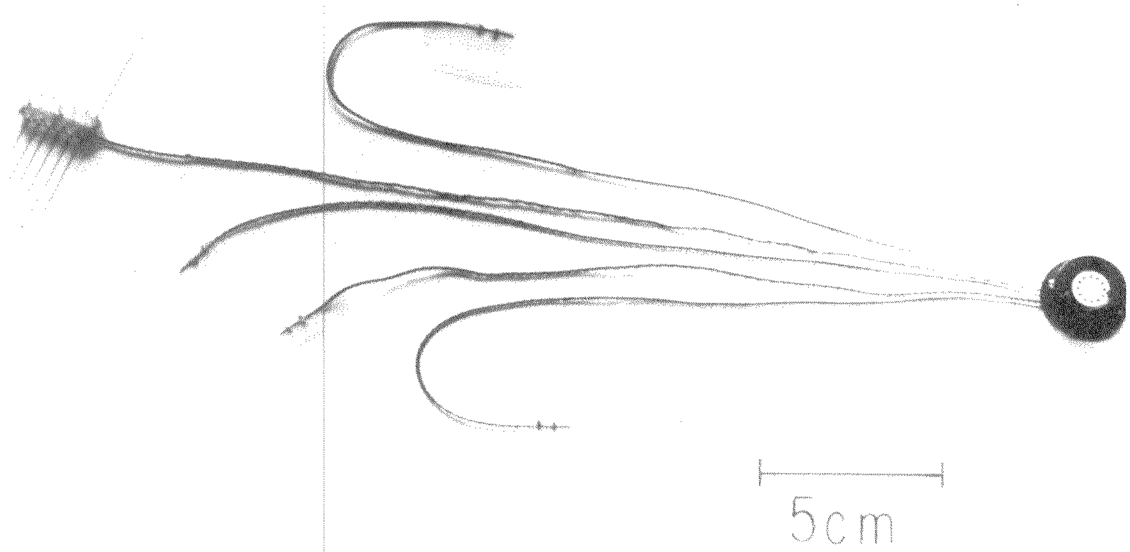

FIGURE 1.
Device for implantation in a short below-elbow amputee. It contains EMG probes for four muscles, a nerve cuff, and a percutaneous connector.

natural limbs in a unilateral amputee. Progress is measured at the Amputee Clinic of the University Hospital by physiatrists, prosthetists and therapists before training is completed.

Finally, an evaluation is carried out some months after fitting (or sooner if the amputee is having some difficulty). This session involves standard objective tests (which will be described elsewhere) and a questionnaire on the amputee's reaction to and use of his prosthesis. Evaluation is performed by an occupational therapist who has not previously been involved in the treatment, in order to obtain an impartial assessment.

The results of a valuable but non-standard experimental procedure will be presented first, and more standardized current clinical procedures will follow.

RESULTS

The results will be organized around three cases which illustrate different approaches to fitting higher-level amputees with powered prostheses. The relative merits of each approach will be discussed later.

CASE 1

Mr. H.S. (a 63-year-old in good general health) sustained a left below-elbow amputation as a result of a World War II injury. The residual limb had a well-healed, non-adherent, painless scar without evidence of neuromata. The proximal portion of extensor carpi radialis brevis and longus muscles were present and strong. Flexor carpi ulnaris and flexor carpi radialis were small and weak. He had minimal pronation and supination of the residual limb. The range of motion of the elbow was normal. Needle EMG examination by Dr. R. G. Lee indicated that portions of pronator teres and the supinator muscles were available and functional.

He had worn various prostheses since amputation, particularly a cosmetic conventional "working hand" which was difficult for him to use. In 1974, before there was a program in Edmonton, he went to Minneapolis to be fitted with an Otto Bock hand. With practice he learned to use the hand in most body positions with fair reliability and was very pleased with it. However, prosthetic fitting of the short residual limb with good skin contact was difficult. Since good skin contact was required for myoelectric operation, a sock could not be used, resulting in moderate to severe skin maceration and erythema from the required intimate fit of the socket.

With the normal methods available in 1977 there did not seem to be any possibility of his operating an electric wrist rotator, which he wished to do because of his hobbies of carpentry and furniture refinishing. However, techniques had by then been developed for chronically recording electrical signals from nerves and muscles in mammals (22,25). Although the pronator and supinator muscles were functional, no surface EMG sites were available for tapping these control sources because of their position and depth within the arm. We offered the amputee the possibility of using implanted electrodes for wrist control, pointing out that it would be one of the first operations of its kind in the world (see Tucker and Peteleski (26) for a description of an implant in one muscle of one patient). We showed him our results from animal experiments as well, to provide him with as much information as possible. He discussed the matter with his family and decided to proceed with the operation.

Implanted Device.

A device (Fig.1) was constructed by Dr. J.A. Hoffer and implanted by Dr. L.A. Davis, an orthopedic surgeon who has been involved with related animal experiments for several years (6). It contained four EMG probes, each with two electrodes spaced 5 mm apart and exposed for a length of 3 mm, where they emerged from a 0.5 mm thick Silastic ® sheet (Dow-Corning 500-5)[g]. The device also contained a Silastic nerve cuff (length = 23 mm; i.d. = 3.4 mm; Dow-Corning 601-335) with three internal electrodes and an external ground electrode for the length of the cuff. Sutures were attached to the longitudinally slit cuff to aid in opening and closing it.

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[g] Dow-Corning Corp.,Midland, MI 48640.

We have previously described (7, 22, 25) the number and arrangement of electrodes which maximize the sensitivity to the neural signals in the presence of unwanted signals from muscles and external sources.

All electrodes were nine-stranded platinum-iridium wires (Medwire Co.), which were coiled around Dacron suture threads to form strong, flexible cables. Each wire had a Teflon® insulation (o.d. = 0.125 mm) and the cables were further enclosed in a Silastic tube which was filled with medical grade Silastic adhesive (Dow-Corning #891). The cables led to a percutaneous connector (Fig. 1) with a 12-pin socket in its core (o.d. = 10 mm; Augat Inc., Attleboro, MA.). Each wire was bared and soldered to the socket. Soldered connections were covered with epoxy (Epon 812) and coated with Silastic. The skin connector was made of Pyrolite® carbon (General Atomic[h]) and had a flange of 25 mm external diameter with 12 holes placed around the rim to allow subcutaneous connective tissue to invade and stabilize the connector in the skin (21). The height of the connector was 10 mm, so that the upper portion with the 12-pin socket emerged through the skin for connection to a prosthesis.

All materials likely to come in contact with body fluids were known to be biocompatible and had been used individually in animal experiments and in clinical applications for several years. The device and the operative procedures were approved by the Ethics Committee of the University of Alberta Hospital prior to human implantation.

Surgical Procedure

The operative procedure took place in October 1977 and lasted 5½hours. The four EMG probes (Fig. 1) were individually sutured onto the fascia over the bellies of the long wrist extensors and flexors, pronator teres and supinator muscles. During the procedure the leads were connected to a stimulator so that the electrodes could be placed as close to the motor points as possible. Four EMG probes were included to provide independent, separate sites for myoelectric control of four functions: hand opening (wrist extensors), hand closing (wrist flexors), and wrist rotation in the two directions (pronator and supinator). EMG probes were implanted on the muscles which were accessible from the surface (wrist extensors and flexors) to improve the size, stability and separation of the electrical signals. Since all electrodes were implanted, the amputee could use a stump sock postoperatively to avoid skin irritation.

The nerve cuff was implanted around a portion of the ulnar nerve distal to the last functional motor branch (flexor carpi ulnaris). The neuroma was clearly seen during the operation and no connection from the nerve to the skin was observed. The nerve (distal to this branch) and the neuroma were dissected free of surrounding tissues. The nerve cuff was included to test the feasibility and practicality of using graded stimulation of the amputated nerve to provide sensory feedback of grip strength from the electric hand. Several groups have tried electrical stimulation of skin (e.g.,9, 11, 17, 19) or of nerves with implanted electrodes (e.g. 4, 14, 27) but the number of amputees tested has been small. The nerve cuff was also designed to test the feasibility of using motor signals generated in ligated nerves for neuroelectric control of powered prostheses in the future. The nerve cuff was provided with a longitudinal slit which could be opened by pulling on attacted suture threads (Fig. 1). Once the cuff was in place, the threads were tied to provide good mechanical closure around the nerve, and to insulate it electrically from surrounding muscles (7, 25).

Incisions were made in the cubital fossa and just distal to the elbow for implantation of the EMG probes and nerve cuff. A small circular incision was also made on the lateral surface of the upper arm between the flexor and extensor compartments. The upper portion of the skin connector was pushed through this circular incision and sutured in place with a purse-string suture, but the perforated flange remained in subcutaneous tissue.

Training

The amputee was up and about the day following the operation and was anxious to see what signals he could generate in the laboratory. Following the operation he came once or twice a week for training, until the postoperative edema subsided and the residual limb assumed its final shape. No postoperative problems were encountered and the skin healed well around the skin connector (Fig. 2). Recording and training involved connecting the percutaneous socket via a flexible cable to two myotesters (Otto Bock) with connectors modified for this purpose. This arrangement provided four meters for observing the four EMG signals required to control a hand and a wrist.

The amputee had no difficulty in activating the desired muscles, some of which had not been required in functional activities for over 30 years. Signals observed on the meters of the myotesters ranged from 40 μV on the wrist flexors to well over 100 μV on the wrist extensors. The limit of the meter is 100 μV so the maximal signals from several sites could not be measured in this way. The actual values were not pursued further since 100 μV is already several times what is normally required to operate a myoelectric device.

The impedance of the implanted electrodes measured only 1-2 kΩ at 1 kHz and was constant over time. In comparison, the impedance of surface electrodes is one-to-two orders of magnitude higher, and it varies with temperature, moisture content of the skin, mechanical pressure, and other factors. The low, steady impedance of implanted electrodes provided much better rejection of outside interference (3) and stability in operating a powered prosthesis under a variety of external conditions, including proximity to power tools and electrical equipment. The steady impedance values also indicate that the electrodes had remained stable and that connective tissue growth had not been excessive (23).

Initially, the amputee had some difficulty in isolating each of the four signals, although this improved with practice. The degree of "crosstalk" recorded on one meter while another muscle was being activated was variable from session to session. The crosstalk did not arise from placement of electrodes, since one nerve (e.g., the ulnar) could be stimulated maximally with surface electrodes evoking large compound potentials from electrodes on the muscles innervated (e.g., 200 μV) — and virtually no signals on other EMG electrodes (<10 μV). The crosstalk was presumably due to coactivation of several muscles

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General Atomic Co., Medical Products Div., San Diego, CA.

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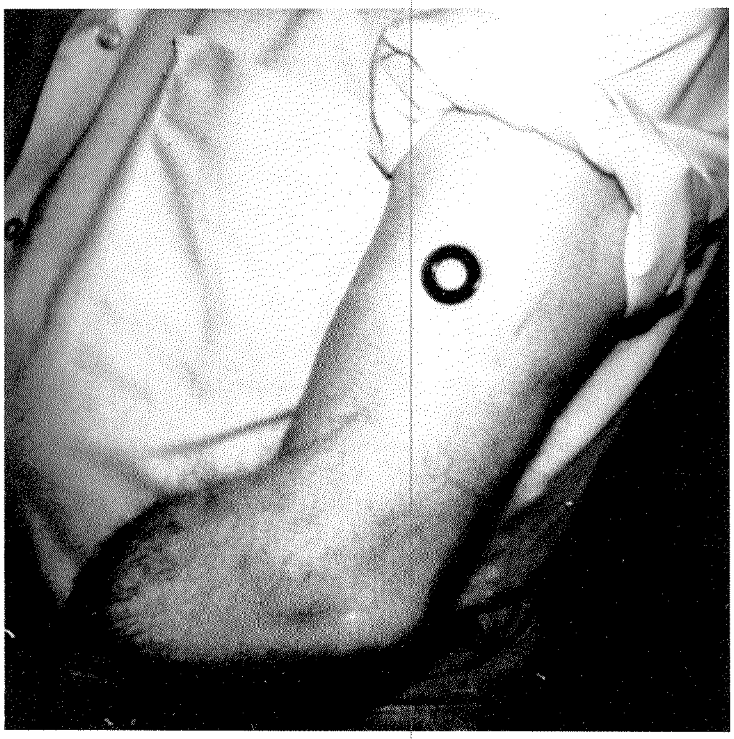

FIGURE 2—A

FIGURE 2—B

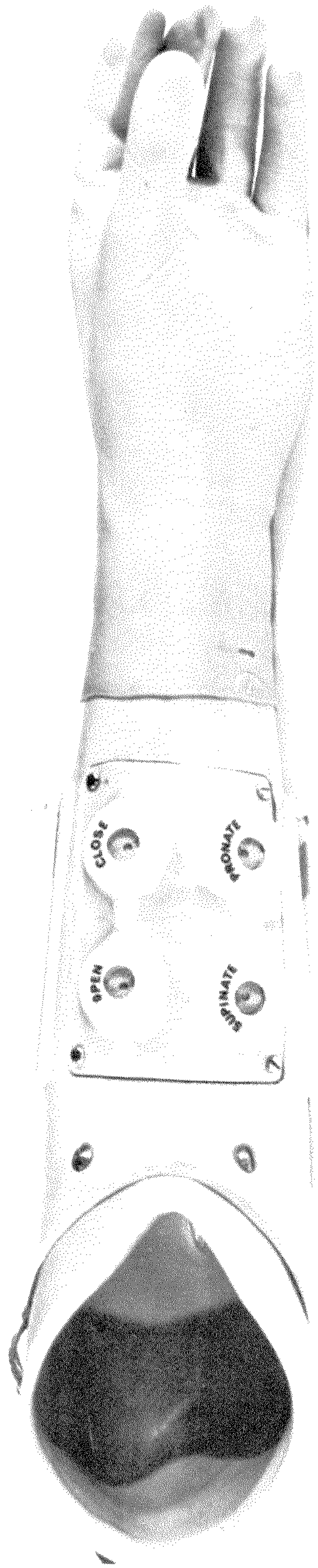

FIGURE 2—C

Figure 2-A: short below-elbow amputee (Case 1) showing the residual limb after surgical implantation of the device. Figure 2-B: Prosthesis and the cable leading to the percutaneous connector. Figure 2-C: a closer view of the prosthesis seen in Figure 2-B.

by the brain. Some of the muscles are often used in combination, so activating one muscle in total isolation from all others may be a somewhat unnatural task. Nonetheless, each muscle could be activated so that the signal on its own meter was two or three times that produced on any other meter. This ratio was more than sufficient to allow amplifier thresholds to be set to avoid interaction in operating the prosthesis.

The amputee also practiced operating an electric hand and wrist on a bench-mounted system before his prosthesis was finished.

The prosthesis was completed and fitted to the amputee in January 1978. It contained (Fig. 2C) a 6-V Otto Bock electric hand (Type 8E17) and wrist, together with four ordinary Type 13E27-G Otto Bock myoelectrode amplifiers. Since the wrist rotator was not designed for myoelectric sources, Mr. D. Charles developed a power control and logic module (PCL-1)—this and other modules (Fig. 3) which will be described are available from Leaf Electronics Ltd., and are compatible with all commercially available hands, wrists, and elbows tested to date. The module permits myoelectric and other types of control (see below) of a wide variety of 6-V or 12-V powered devices, and also allows one of the two inputs (e.g., the more important or the weaker one) to have priority over the other, if they occur simultaneously.

The amputee used the prosthesis in many aspects of daily life until November 1978. With time, skin retraction occurred around the skin connector. After thinning and necrosis of subcutaneous tissue, the flange of the skin connector worked its way through the skin on one side. (Possible reasons for this breakdown will be discussed later.) A small amount of serous fluid (a few drops per day) had been observed during most of the time the skin connector was in place and this drainage increased somewhat as skin breakdown occurred. However, at no time was there clinical evidence of deep infection. Bacteriological tests indicated the presence only of Staphylococcus epidermidis. The connector was easily removed under local anaesthesia by cutting the cables and the skin was sutured shut. The electrodes and portions of the cable are still implanted, and may be attached at a later date either to another skin connector or to a telemetry device to transmit the signals through the skin. In the meantime, the amputee is evaluating "tristate" control (see below) to allow him to control the wrist unit, which he has become accustomed to and enjoys using.

During the year that he had implanted electrodes, a fully functional sensory feedback system was not built into his prosthesis, but a number of tests were made. The ulnar nerve could be stimulated through its cuff electrode with single pulses (e.g., 6 V for 10 μs) or steady rates, at levels and durations far less than those required for direct activation of muscle. The amputee reported that the sensation evoked by stimulation was localized to the ulnar aspect of his phantom limb in a region covering his ring and small fingers, which is an area normally innervated by this nerve. Thus, some sensory nerve fibers survived over 30 years in the ligated nerve and retained their central connections. The amputee's subjective impression appeared to fuse at quite low rates (10–20 stimuli/s) and faded at higher rates of stimulation, suggesting some atrophy of the nerves. Whether regular activation would have improved the state of the nerve is an interesting but unanswered question. Voluntary signals or

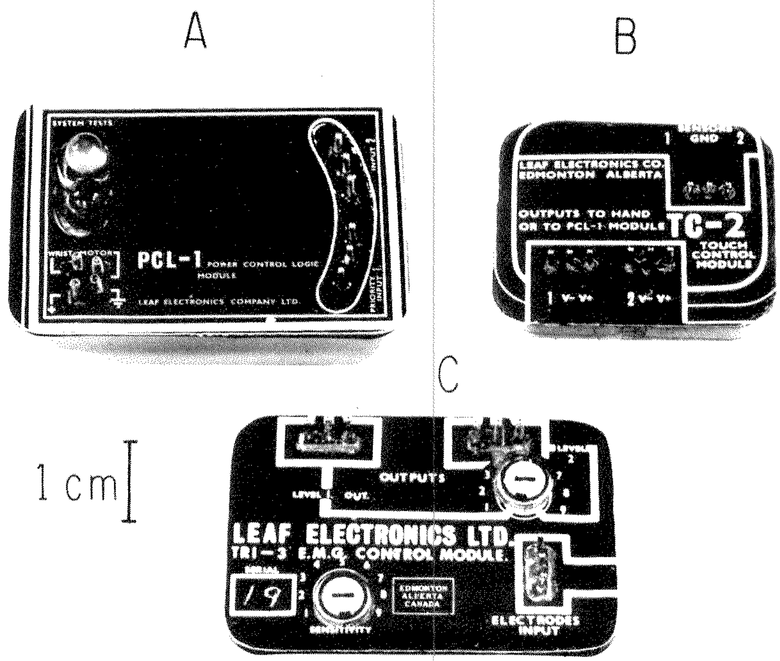

FIGURE 3
Modules containing (A) power, control and logic circuitry for use with electric wrists and elbows (PCL-1); (B) touch control (TC-2); and (C) tristate myoelectric control (TRI-3). Further details of the functions of these modules are given in the text, and full information is available from Leaf Electronics (address given on page 52)

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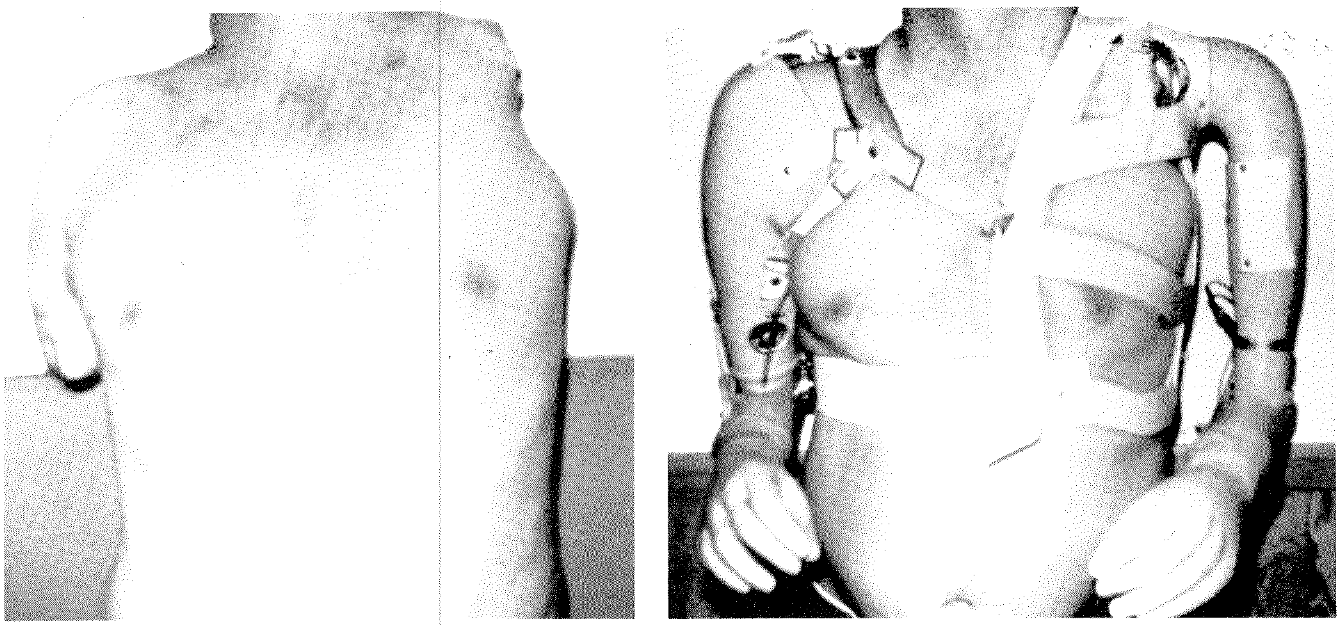

FIGURE 4
A bilateral amputee (M.C.) with an above-elbow amputation on the right side and a partial forequarter amputation on the left, before, and after fitting. The components used on each side are described in the text.

evoked signals (from stimulating the ulnar nerve at the elbow) could not be recorded reliably from the cuff, again implying atrophy of the nerve. However, we cannot rule out possible effects of trauma during surgery or the relation of the cuff to the nerve. Nonetheless, signals can be recorded from similar nerve cuffs on freshly ligated nerves in experimental animals for more than a year following ligation (24).

Case 2

Mr. M.C. (34 years old) had a right above-elbow amputation at a mid-humeral level and a partial forequarter amputation on the left side, with retention of the majority of the scapula, but with large areas of skin grafting (Fig. 4.). The amputations resulted from a farm accident involving a hay baler in September 1976. He was initially fitted with a prosthesis having a cable-controlled elbow and hook on the right side. His left side was not fitted at that time, since the high level and bilateral nature of the amputation would not have permitted useful function to be achieved by conventional means.

When the amputee was referred to us early in 1978, a surface EMG examination revealed that he did not have any of the biceps muscle remaining on the right side but did have suitable signals from the triceps and from a small portion of the coracobrachialis muscles. To fit his right side myoelectrically, three joints (elbow, wrist, and hand) had to be controlled with only two suitable muscle sites. Dr. H. Schmidl, who has the most experience with fitting high-level amputees myoelectrically, suggested that a cable-driven elbow be retained. A Hosmer outside-locking elbow was suggested, with a mechanical excursion multiplier to reduce the excursion of shoulder movements needed to operate the conventional elbow. The reduced excursion is useful in preventing interaction between elbow function and the EMG signals used to control more distal joints. Furthermore, Dr.Schmidl kindly provided us with a circuit (referred to in 16) which permits a small EMG signal to control one movement and a larger EMG signal to activate a relay for control of a second movement. Circuits for using one muscle to control two movements have also been developed independently by others (20, 3).

With the two muscles available on the right side of this amputee, control of four movements is possible; e.g., closing and opening a hand (from low and high levels of contraction in coracobrachialis) and pronation and supination of the wrist (from low and high levels of contraction in triceps). The amputee was trained in the use of these muscles to operate such a prosthesis.He uses this hybrid prosthesis, with a cable-driven elbow with excursion multiplier and mechanical elbow lock (Hosmer E-400) but myoelectric hand and wrist, for nearly all activities. He has worked as a supervisor on a crew applying asphalt to roads, driven a tractor, and done related jobs in his farming community. He is currently employed by the Alberta Department of Agriculture.The amputee reports tht the multiple-level control is now virtually automatic—except in crisis situations where his initial reaction may be incorrect. He must then consciously think of the correct level of muscle activation to produce an appropriate movement.

His left side was initially fitted with a non-functional prosthesis for cosmetic purposes and for balancing the weight on the two sides of the body to prevent scoliosis. More recently (November 1978) he returned and was fitted with an electric elbow, wrist, and hand on his left side, using a combination of tristate myoelectric and touch control. The new tristate module (TRI-3; Leaf Electronics) is activated by the medial portion of deltoid muscle and is used to close and open a myoelectric hand. The amputee had reported a small amount of electrical interference, which affected the right side when he was near unusually strong power sources. The left side (fitted with the recently developed modules) is not affected by this interference, although the gain is higher (since the EMG signal levels are less than half those available on the right side). Nor is there crosstalk when he moves what remains of his left shoulder to touch metal contacts on the prosthesis (details in Case 3 below) which control elbow and wrist movements.

After receiving further training for bilateral function, the amputee returned home and experienced no major prosthetic problems. However, while working outdoors for long periods of time in the cold Canadian winter, a skin-grafted area touching metal contacts froze without the amputee knowing it and caused some skin breakdown. This prevented him from using the left prosthesis for the rest of the winter, although he continued to function well with the right. The skin has since healed and he is able to use both prostheses on a daily basis.

Case 3

Mr. M.O.C. (38 years old) had a right unilateral amputation just below the shoulder in July 1977 (Fig. 5). The amputation was in this case also the result of a farm accident involving a hay baler, which also caused burns. Because of the extensive skin grafts required, the range of motion of the amputee's short residual limb is limited. He was fitted conventionally shortly after the accident, but the prosthesis had to be controlled by his sound side because of his limited range of motion. Nonetheless, the amputee wore his prosthesis on a regular basis and continued to operate his farm independently. He was referred to us and we began treatment in October 1978, after his crop had been harvested.

The skin grafts prevented reliable recording of myoelectric signals, because of the high electrical resistance and the small size of the signals that filtered through the grafts. We were also concerned about breakdown of the grafted area if mechanical pressure switches were used. Previously, in treating a phocomelic teenager who was unable to operate mechanical switches, Mr. D. Charles had developed a system of "touch control" using module TC-2 from Leaf Electronics (Fig. 3B). Touch control allows a voluntary motion to place skin as a high-impedance conductor bridging between a selected metallic contact and conductive foam mounted at several points in the socket. Contact completes a metal-skin-foam circuit which produces a switching action through logic elements in the module. The module is designed to operate with any skin contacts, even those of very high resistance (up to $2 \times 10^7\ \Omega$) and biologically negligible currents

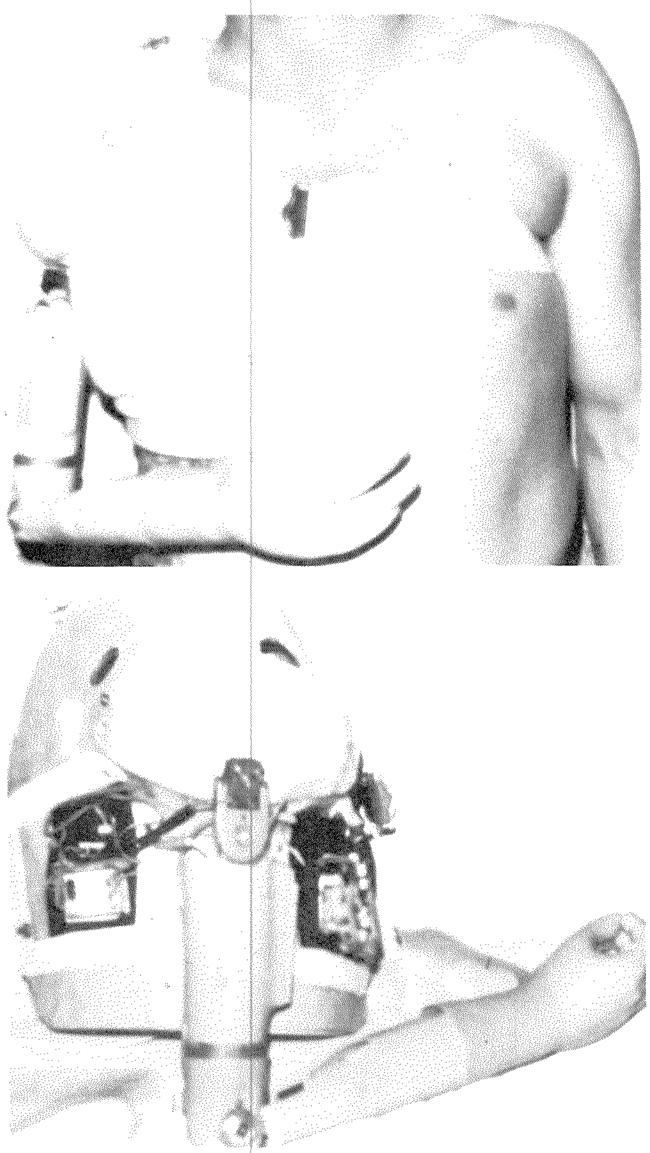

FIGURE 5
A very short above-elbow amputee (Case 3) with his prosthesis, containing an electric hand, wrist, and elbow all operated by touch control using shoulder movements. The weight of the prosthesis is distributed over a large area because of the extensive skin grafts, and the modules are attached to the body of the prosthesis. In the side view, a cover which fits over the modules has been removed to show their locations.

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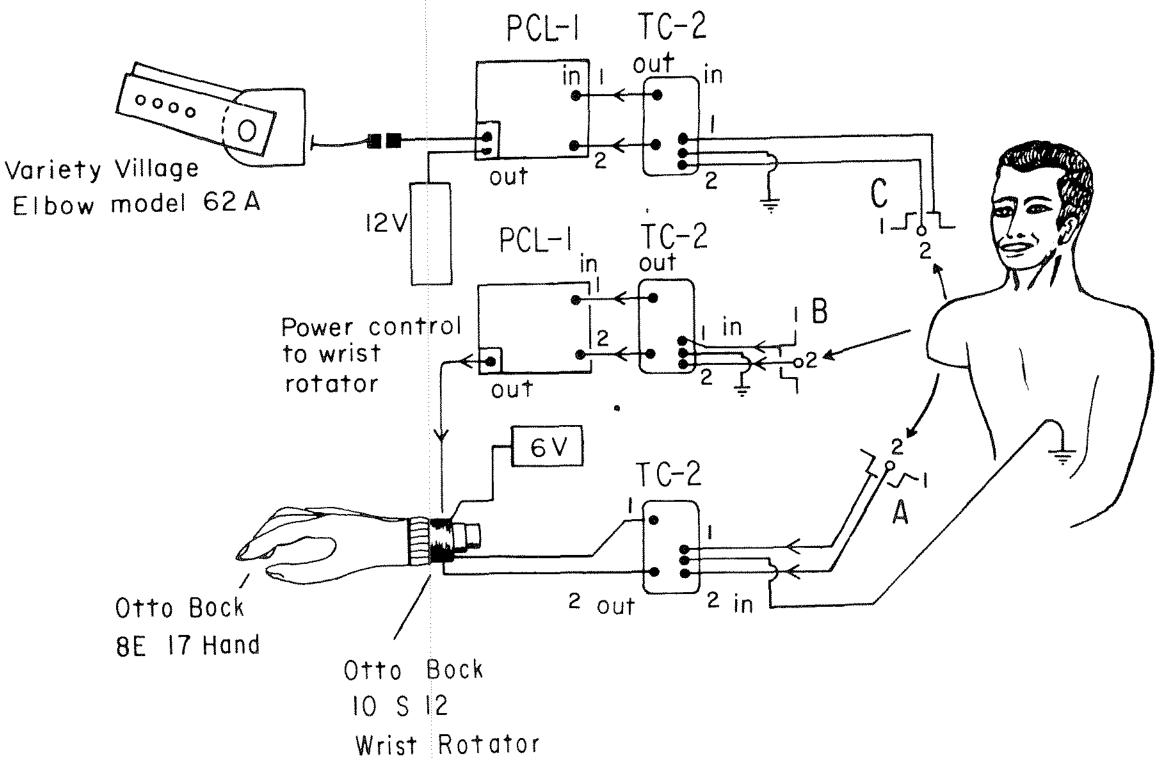

FIGURE 6
Schematic diagram of the wiring of components used for the amputee illustrated in Figure 5 (Case 3).

At A the hand is shown operated by protraction of the humerus (forward movement). The skin contacts non-priority first; thus, when priority is touched (the skin being stretched and indented a bit to do so) the previous input is cancelled. Note that it is up to the prosthetist to decide which function he wishes to connect to which inputs. "Open" and "close" inputs are interchangeable on the Bock hand. If, on withdrawal slowly of the shoulder from the electrodes the non-priority is the last to leave the skin—and if that is connected to "close"—then the hand will not drop an acquired object.)

At B the wrist is shown operated by abduction of the humerus (away from the body). The skin contacts #2 (non-priority) first to pronate the wrist, and with further motion contacts #1 (priority) to supinate the wrist. With no contact the wrist does not move.

At C the elbow is shown operated by retraction of the humerus (backward movement). The skin contacts #2 (non-priority) first to flex the elbow and with further motion contacts #1 (priority) to extend the elbow. With no contact the elbow does not move.

(less than 1 nA) and is therefore suitable even for thick skin-grafted areas—or for patients with heart pacemakers.

The amputee could reliably protract, retract and abduct the remnant of the humerus at the scapulo-humeral joint. Yet he needed to control two movements each around three joints: elbow, wrist and hand. Again, we decided to have one movement control two functions by building concentric electrical contacts into his prosthesis (Fig.6). The central circular contact protrudes so that it is touched first (contact No. 2 in Fig. 6). The other contact of the pair is in the form of an annulus and is insulated from the central contact. The outer contact is given priority (#1) in the PCL-1 modules so that touching this contact overrides the effect of contact 2. Touching the outer (annulus) contact results from the natural compliance of the skin as the pressure increases. (Conductive foam is also built into the prosthesis at several places around the rim to serve as a comfortable, reliable ground connection.) Thus, a small protraction can be used to close an electric hand, with further forward movement opening the hand: the other connections and modules required to control the rest of the six functions are shown diagramatically in Figure 6.

Note that the same modules function for controlling a 12-V elbow as for a 6-V or 12-V hand and/or wrist. All these modules interconnect with each other and with the overall system, using standard cables such as the 13E48 and 13E50 from Otto Bock. (The 6-V Otto Bock system is used whenever possible because the 12-V system will probably be discontinued in the future.) If an electric elbow is used,two battery packs are required: both fit into the above-elbow section of the prosthesis. The 12-V battery remains inside the prosthesis while the interchangeable 6-V battery snaps into a recess on the outside of the prosthesis. The prosthesis for this amputee covered a fairly large area — (i) to stabilize the prosthesis on the body, and (ii) to spread the weight over a large area and prevent breakdown of the skin graft. The modules were easily mounted on the prosthesis (Fig.5B). The amputee was trained to use the prosthesis and could reliably touch the contacts. He has minimal cutaneous sensation in the grafted area, but retains proprioceptive sensation of humeral position. However, the amputee sometimes touched contacts inadvertently while performing gross movements, or as a result of movement triggered by phantom pain, which he experienced.

Because the skin grafts held the humerus firmly against the body, a surgical release and further skin grafting were recently performed (January 1979). This procedure increased his range of motion and has alleviated the problem of phantom pain. Moving the contacts further from his body (to utilize his greater range of motion) has greatly increased his abiliity to use this prosthesis reliably.

DISCUSSION

These three examples illustrate the techniques which have been developed and applied in Edmonton to a larger number of amputees (Table 1). The three cases chosen are of interest because of their complexity, but are not unique except for the fact that only one surgical implantation has been done to date. From our overall experience, a systematic approach to treating various levels of amputation has been developed which is summarized in Table 2. The treatment of patients with wrist disarticulation or long forearm amputations typically utilizes an electric hand and natural pronation and supination of the wrist. For mid-forearm amputations, a wrist motor is added. This can be controlled by a microswitch, as described in the Introduction, in line with recommendations from the manufacturer (Otto Bock). For short below-elbow amputees, several options are available. Otto Bock recommends use of the myoelectric hand alone, but we have developed methods compatible with Otto Bock components which permit the amputee to benefit from use of an electric wrist rotator in addition to an electric hand.

The implanted device described for the first patient has a number of potential advantages. The signals from electrodes implanted on muscles are larger, more selective, and more stable from day to day than those obtained from surface EMG sites. Surgical implantation of electrodes was successful in providing the amputee with a range of control and movement greater, at the time, than could have been offered in any other way. Eventual breakdown of the skin, which necessitated removal of the connector, was attributed to tilting of the connector rather than to any infection. This problem might be avoided in future implants by a different arrangement of cables around the connector to distribute the torques during movement more uniformly, or by using more-flexible materials. However, the percutaneous connector is the weakest link of this design, so we are investigating the use of telemetry and other systems to eliminate problems associated with the skin connector completely (4, 26).

The stability of the signals and the total absence of lead breakage are encouraging for further development of implanted electrodes.

TABLE 2
Scheme for fitting upper-limb amputees with powered artificial limbs depending on the length of residual limb remaining.

BELOW-ELBOW AMPUTEES
1. **Wrist disarticulation:** myoelectric hand plus natural pronation and supination.
2. **Mid-forearm:** myoelectric hand and electric wrist (switch operated by residual pronation and supination).
3. **Short:** a) myoelectric hand alone;
   b) plus implanted electrodes for myoelectric wrist; or
   c) tristate control for myoelectric hand and wrist.

ABOVE-ELBOW AMPUTEES
1. **Long-to-medium:** cable-controlled conventional elbow plus myoelectric control (biceps, triceps) or neuroelectric (?) control of hand, wrist.
2. **Short-to-partial forequarter:** electric elbow, hand and wrist (if possible) using myoelectric control (shoulder muscles) and/or touch control (shoulder movements).

"Tristate Control"

The use of "tristate" control for short below-elbow amputees has many advantages and does not require surgical procedures. Tristate control involves training an amputee to control two different functions by grading the amplitude of EMG signals from a single site. The small module, TRI-3 (Fig.3C), permits convenient interchangeability and requires no modification to the Otto Bock hand or wrist. Thus, a choice of functions can be implemented easily. For example, a low level of EMG from the wrist flexors might be used to close a hand, and a higher level to open the hand. Then, a low level of EMG signals from the wrist extensor is used to rotate the wrist in one direction, while a higher level rotates the wrist in the opposite direction.

Alternatively, high levels of EMG signals from both sites can be used to control the hand while smaller levels from the same sites control the wrist. This alternative does not involve extensive relearning for an amputee who has previously worn an electric hand without an electric wrist, since the same muscles continue to operate the hand. It also takes advantage of the natural anatomical relation of the muscles, since pronator teres is close to the wrist flexors. When amputees were asked to try to turn their wrist, enough EMG was often generated to activate the low level of a TRI-3 module. Similarly, supinator lies deep to the wrist extensors, and attempts to supinate the wrist have often generated sufficient EMG to activate the low level of another TRI-3 module. When given the choice, the three short-below-elbow amputees tested to date have favored this alternative approach.

Since the components are all compatible, various alternatives can be tried in a single session, simply by exchanging plugs—no soldering or knowledge of electronics is required and the tests can be done without complex equipment or procedures. When trying various alternatives,we have been surprised to find that the TRI-3 module will often give reliable control of two functions from sites where control of even one movement had been thought to be unlikely. Thus, we recommend thorough testing with tristate or other types of control from the surface of the body, before considering surgical procedures. Implantation of electrodes offers possibilities of neuroelectric, as well as myoelectric, control and of providing several modalities of sensory feedback by stimulating different nerve fiber populations (27). However, more experience is required before the relative roles of invasive and non-invasive techniques can be determined.

With long above-elbow amputees, a cable-controlled conventional elbow is recommended at the present time, due to the limited number of control sites. Many amputees can function more quickly and with greater power than they would obtain from commercially available electric elbows, and the mechanical linkage of the cable-controlled elbow provides useful proprioceptive feedback of elbow motion, position, and loading. This view may change with more sophisticated methods of signal processing (see, for example, 28) or new developments in electric elbows (e.g., 8). However, available muscles should not be wasted as they are in a conventional prosthesis. Remaining portions of biceps and triceps or related muscles can be used myoelectrically to control an electric hand and wrist using tristate control. A future possibility (indicated by a question mark in Table 2 since it has not yet been attempted) would be to record signals from the ends of the severed nerves of wrist muscles, at a point where they normally separate from the main nerve trunks above the elbow.

With a short above-elbow amputation or a shoulder disarticulation, an electric elbow is required, in addition to an electric hand and generally a wrist rotator. The importance and usefulness of the wrist rotator to the amputee should not be underestimated. The extra function it provides is well worth the additional skill and time its implementation requires. As illustrated in Results, a combination of myoelectric control (either shoulder muscles and/or touch control with shoulder movements) can be used. Mechanical switches have also proved useful for short above-elbow amputees (1), and for congenital amputees where a digit or two is present, often above the elbow (12, 18). These digits can generally be moved, but sometimes not with enough force to reliably operate a microswitch; touch control is required under those circumstances, and it is useful whenever a microswitch might otherwise be used. Touch control has the advantage that it eliminates all breakable moving parts.

The range of methods described, and the ease of interchangeability based on the use of compatible modular components, are of significant value to the severely disabled upper limb amputee.

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REFERENCES

1. Alderson, Samuel W.: The Electric Arm (Chap. 13). In Human Limbs and their Substitutes, Paul E. Klopsteg, Philip D. Wilson, et al., Hafner Publishing Co., New York, 359-408,1968.
2. Battye, C.K., A. Nightingale, and J. Whillis: The Use of Myoelectric Currents in the Operation of Prostheses. J. Bone and Jt. Surg., 37-B(3):506-510, August 1955.
3. Childress, Dudley S., and John N. Billock: Self-Containment and Self-Suspension of Externally Powered Prostheses for the Forearm. Bull. Prosth. Res., BPR 10-14:4-21, Fall 1970
4. Clippinger, Frank W., Roger Avery, and Bert R. Titus: A Sensory Feedback System for an Upper-Limb Amputation Prosthesis. Bull. Prosth. Res., BPR 10-22:247-258, Fall 1974.
5. Committee on Prosthetics Research and Development: Rehabilitation Engineering: A Plan for Continued Progress. Nat. Acad. Sci., Washington, D.C., April 1971.
6. Davis, L.A., Tessa Gordon, Joaquin-Andres Hoffer, Jack Jhamandas, and Richard B. Stein: Compound Action Potentials Recorded from Mammalian Peripheral Nerves Following Ligation and Resuturing. J. Physiol., 285:543-559, 1978.
7. Hoffer, Joaquin-Andres: Long-Term Peripheral Nerve Activity During Behaviour in the Rabbit: The Control of Locomotion. Ph.D.. Thesis, Johns Hopkins Univ., No. 76-8530, University Microfilms, Ann Arbor, Mich. 1975.
8. Jacobsen, Stephen C., Robert B. Jerard, and David Krutti: Development and Control of the Utah Arm. Proc. 5th Int. Symp. on External Control of Human Extremities: Dubrovnik, Yugoslavia, 1975.
9. Kato, Ichiro, Shugo Yamakawa, Kiyoshi Ichikawa,and Masayuki M. Sano: Multi-Functional Myoelectric Hand Prosthesis with Pressure Sensory Feedback System — WASEDA Hand — 4P. Advances in External Control of Human Extremities. Proc. 3rd Int. Symp. on External Control of Human Extremities: Dubrovnik, Yugoslavia, August 25-30, 1969. Edited by Momcilo M. Gavrilovic and A. Bennett Wilson, Jr., Belgrade, Yugoslavia: Yugoslav Committee for Electronics and Automation (ETAN), 155-170, 1970.
10. Kato, Ichiro: Trends in Powered Upper Limb Prostheses. Prosth. Orthot. Int., 2(2):64-68, August 1978.
11. Mann, Robert W.: Prosthesis Control and Feedback Via Noninvasive Skin and Invasive Peripheral Nerve Techniques. In Neural Organization and Its Relevance to Prosthetics, edited by William S. Fields and Lewis A. Leavitt. Intercontinental Medical Book Corp.: New York, 177-190, 1973.
12. Neff, G.: Prosthetics Principles in Bilateral Shoulder Disarticulation or Bilateral Amelia. Prosth. Orth. Int., 2(3):143-147, December 1978.
13. Reiter, Reinhold: A New Electrohand (Eine Neue Elektrokunsthand). Grenzgebiete der Medizin, 1(4):133-135, 1948.
14. Reswick, James B., et al.: Sensory Feedback Prosthesis Using Intraneural Electrodes. Proc. 5th Int. Symp. on External Control of Human Extremities. Dubrovnik, Yugoslavia, 1975.
15. Schlesinger, G.: Der Mechanische Aufbau der Kunstlichen Glieder. In Ersatglieder und Arbeitshilfen, Springer Verlag: 407-410, Berlin 1919.
16. Schmidl, Hannes: The INAIL—CECA Prostheses. Orth. Prosth., 27(1):6-12, March 1973.
17. Schmidl, Hannes: The Importance of Information Feedback in Prostheses for the Upper Limbs. Prosth. Orth. Int., 1(1):21-24, April 1977.
18. Schmidl, Hannes: The I.N.A.I.L. Experience Fitting Upper-Limb Dysmelia Patients with Myoelectric Control. Bull. Prosth. Res., BPR 10-27:17-42, Spring 1977.
19. Brittain, Robert H.: Development of a System to Provide Sensory Feedback of Pinch Force from a Prosthetic Hand. in Sensory Feedback in a Myoelectric Prosthesis, edited by Robert H. Brittain and Robert N. Scott. University of New Brunswick, Bio-Engineering Institute, Fredericton, New Brunswick, Canada, Prog. Rep. 15:3-12, February 1978.
20. Pauga, J.E. and Robert N. Scott: Clinical Evaluation of UNB 3-

State Myoelectric Control. Univ. New Brunswick Bio-Engineering Inst., Prog. Rep. No. 16: Fredericton, New Brunswick, Canada, September 1978.

21. Stanitski, Carl L. and Mooney, Vert: Osseus Attachment to Vitreous Carbons. Materials and Design Considerations for the Attachment of Prostheses to the Musculo-Skeletal System. J. Biomed. Mater. Res. (Biomed. Mat. Symp.4):97-108, 1973

22. Stein, Richard B., Dean Charles, L. Davis, Jack Jhamandas, A. Mannard, and T.R. Nichols: Principles Underlying New Methods for Chronic Neural Recording. Can. J. Neurol. Sci., 2:235-244, 1975.

23. Stein, Richard B., Dean Charles, Tessa Gordon, Joaquin-Andres Hoffer, and Jack Jhamandas: Impedance Properties of Metal Electrodes for Chronic Recording from Mammalian Nerves. I.E.E.E. Trans. Biomed. Engng., BME 25(6):532-537, Nov. 1978.

24. Stein, Richard B., Joaquin-Andres Hoffer, Tessa Gordon, L.A. Davis, and Dean Charles: Long-Term Recordings from Cat Peripheral Nerves During Degeneration and Regeneration: Implications for Human Repair and Prosthetics. In Nerve Repair: Its Clinical and Experimental Basis, edited by D.L. Jewett and H.R. McCarroll. C.V. Mosby: St. Louis, 1980.

25. Stein, Richard B., T.R. Nichols, Jack Jhamandas, L.Davis, and Dean Charles: Stable Long-Term Recordings from Cat Peripheral Nerves. Brain Res.,128:21-38, 1977.

26. Tucker, F.R., and N. Peteleski: Myoelectronic Telemetry Implant for Myoelectric Control of a Powered Prosthesis. Can. Elec. Eng. J., 2(4):3-7, 1977.

27. Walker, Cedric F., Gregory R. Lockhead, David R. Markle, and James H. McElhaney: Parameters of Stimulation and Perception in an Artificial Sensory Feedback System. J. Bioeng., 1(3):251-260, August 1977.

28. Wirta, Roy W., Donald R. Taylor, and F. Ray Finley: Pattern-Recognition Arm Prosthesis: A Historical Perspective — A Final Report. Bull. Prosth. Res., BPR 10-30:8-35, Fall 1978.