PERSPECTIVES ON THE USE OF EXTERNAL POWER IN UPPER-EXTREMITY PROSTHESES

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We have previously reported our progress in developing an electrically powered elbow and an electrically powered hand (BPR 10–11, 12). Throughout the course of this design and development program we have constantly considered the problems that might be encountered in fitting patients in an effort to anticipate and overcome them. Although each may be used individually, both the VAPC hand and elbow (BPR 10–12) are electrically compatible and designed for control by special switches which are considered part of the electrical component constellation. In general, a strategy of modularity has been employed to permit either or both components to be installed in existing prostheses by replacing the conventional components and by inserting the control switches in the conventional harness. Employing these components in the construction of a new prosthesis does not require a higher order of prosthetic technology than that for conventional components. The development of these components has advanced to the stage where we have fitted them to several patients who have been wearing VAPC hands and elbows in varying combinations for periods of up to 1 year. Our experiences in fitting externally powered components developed elsewhere go back approximately 3 years.

Despite our attention to and anticipation of problems to be encountered in fitting patients with these components, our actual experiences took several surprising turns. The prosthetic treatment of three patients, in particular, illustrates the sometimes serendipitous influence of clinical experience on design and development. Each of these cases had previously worn conventional prostheses. All three were employed in regular, full-time jobs or full-time school programs and had never

previously participated as pilot wearers or subjects in studies of experimental components.

The initial case in this series was a 24-year-old veteran of the Vietnam era who lost his right arm above the elbow in 1968, leaving him with a stump extending approximately 2 in. below the acromion. When first seen he wore a conventional prosthesis with standard above-elbow socket, Hosmer elbow and spring assist, Dorrance hook, and saddle-type above-elbow harness. Occasionally he wore a passive cosmetic hand. He operated his elbow lock by shoulder extension and depression. Elbow flexion and terminal device operation were controlled by shoulder flexion and scapular abduction.

He was refitted with a new prosthesis incorporating the VAPC electric elbow operated by a pull switch in accordance with the basic design concept underlying the use of the VAPC elbow (Fig. 1). The control switch was inserted in the control attachment strap and he operated the elbow by employing the same control motion—shoulder flexion—that he used to operate the terminal device. A pull of a few ounces and an excursion of ⅛ in. extended the elbow; applying a few more ounces of force and an additional ⅛ in. of excursion flexed the elbow; continuing the pull, bottomed out the switch and transmitted force through his cable system to his terminal device (Dorrance 555 hook) in the conventional manner.

After being fitted with this system, the patient underwent a training program aimed at achieving mastery of the control elements of the system. Approximately 6 hours were spent in two training sessions of

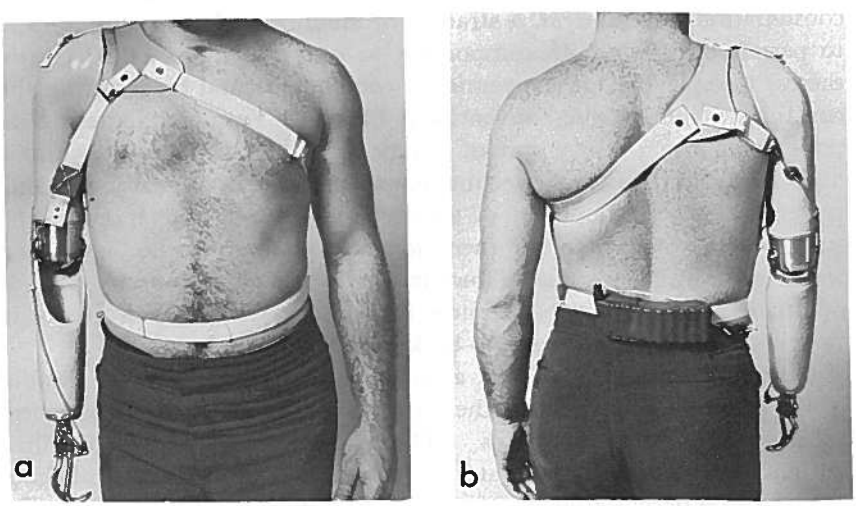

FIGURE 1.—(a) New prosthesis incorporating the VAPC electric elbow, operated by electric pull switch; (b) posterior view showing the battery pack (A) and harness control system for conventional terminal device.

3 hours each. At the end of this period his performance level was deemed adequate and he was instructed to continue the controls training drills at home before a mirror and to employ the arm as fully as possible in practical activities during his daily life. He wore the arm in this configuration for approximately 7 months. However, as a full time student in a drafting course he found it difficult to avoid inadvertent operation of the electric elbow. He was required to spend several hours at a tilted drafting board and in this position the slight displacement of the cable was sufficient to actuate the elbow. For all other activities during the day he used the arm with the electric elbow. In general, the patient said he was quite pleased with the performance of the electric elbow and elected to continue wearing it.

The patient summed up his reaction to use of the arm over a period of 7 months by saying "If you could get rid of the noise and give me a smaller and lighter battery pack, the arm would be great." These comments led us to bring the patient into the laboratory for a review and analysis of the overall effectiveness of the VAPC elbow, a process leading to the identification of both positive and negative features. On the positive side it was clear that the patient's performance effectiveness was markedly improved by the large reduction in the excursion and force required to flex the elbow. The relatively small forces and excursions required by the VAPC elbow enabled him to operate his conventional terminal device more effectively away from his body at the level of the shoulders. Also contributing to increased facility was the elimination of the elbow locking requirement since the VAPC electric elbow locks and unlocks automatically. On the negative side he found the elbow "noisy" and the battery pack "heavy" at 16.5 oz. Our analysis of his performance and experiences indicated that the external wire between the elbow and the battery pack was inconvenient and subject to damage. We also noted, particularly during the early period of wear, some difficulty in distinguishing between the switch position for flexing and that for extending the elbow.

It was difficult to evaluate the significance of the patient's comments about the noise generated by the elbow. The VAPC elbow and every other electric elbow are, of course, noisier than the conventional Hosmer elbow which is practically noiseless. But since the patient's only frame of reference as to the degree of noisiness was based on his subjective comparison with the noiseless Hosmer elbow, it was difficult to determine whether the elbow was in fact "too noisy." One obvious solution to the problem of noise is the use of high precision gears, bushings, and bearings. Coupled with sealed or fluid dampened motors, high precision components can be expected to operate at relatively low noise levels but their costs are high. One of the fundamental requirements underlying the initial design of the VAPC elbow was that its cost

should not substantially (more than twice) exceed the cost of the conventional elbow. The commercial cost of the VAPC elbow is expected to be less than twice the cost of the conventional Hosmer elbow. We calculate that redesigning the unit with high precision components and a quieter motor would more than quadruple the cost of the unit. Since this particular patient did not feel that the noise produced by the unit was of sufficient magnitude to consider discarding it, we ignored the problem of noise for the time being.

In considering the problem of battery weight it was determined that the patient had been charging the batteries once a day and that he had never depleted the charge in a day's use sufficiently to interfere with elbow function. One obvious approach to this problem therefore was simply to reduce the capacity of each cell in the battery in order to reduce overall weight. The original battery pack at 16.5 oz. was rectangular in shape and measured 1⅛ in. x 2 in. x 6 in. It furnished 500 mah. at 24 volts. By halving the number of cells and packaging them in a flatter, more flexible container (Fig. 2) overall weight was reduced. This new power pack weighed 10.0 oz. and measured ½ in x 3 in. x 8 in., a relatively flat configuration. It furnished 225 mah. at 24 volts. The patient found the reduced capacity of the smaller package entirely adequate for his daily needs. Although he felt that the problem of excessive weight was significantly reduced, if not eliminated, he found that the battery pack, mounted on the body either on the back, abdomen, or side interfered with certain activities. The problem then became one of location of the battery pack and of the cabling between it and the elbow. The solution which emerged is shown in Figure 3. By using different configurations of battery cells with the same capacity as the new power pack, we were able to install the complete power source *inside* the prosthesis, eliminating the external electric cabling and the need to carry the battery pack on the body. This unit weighed 9.8 oz. and measured 2 in. x 2 in.

FIGURE 2.—Internal arrangement of the flat battery pack (B) using nickel cadmium batteries.

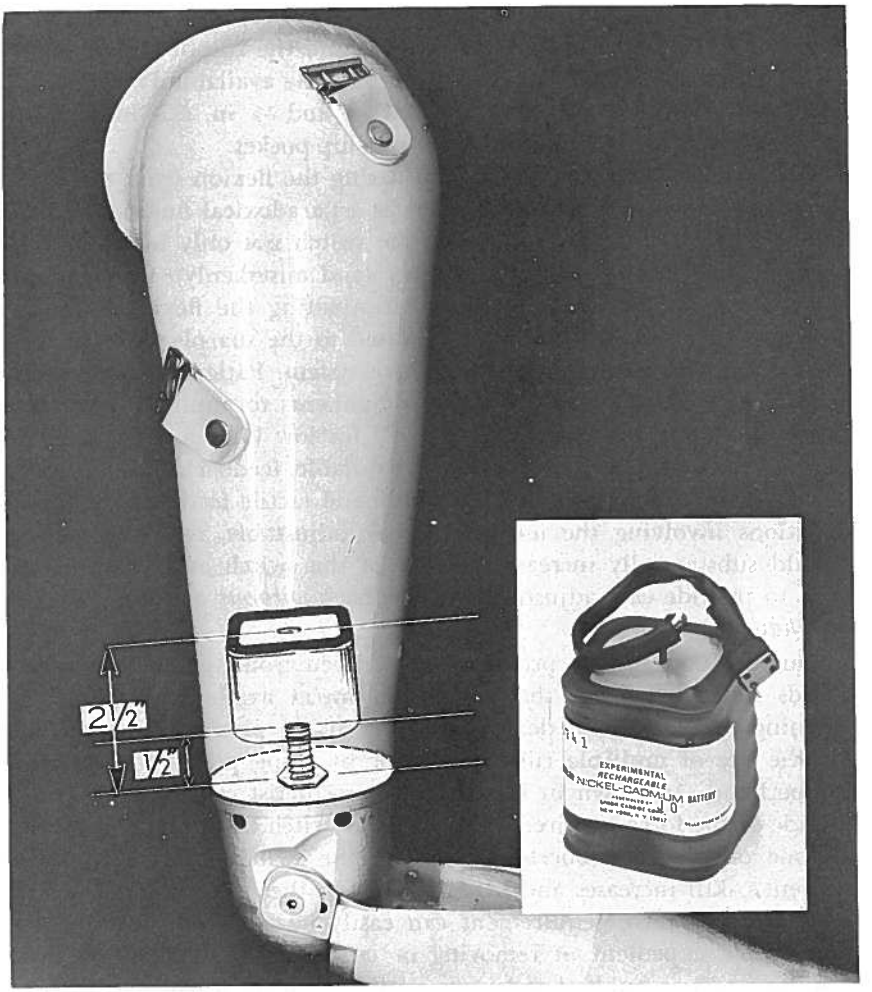

FIGURE 3.—Illustration showing battery pack and internal location utilizing the available space below the stump.

x 2 in. It also furnished 225 mah. at 24 volts. Since the VAPC elbow is identical in external dimensions to the Hosmer elbow, we found that it was possible to package the entire power source within the humeral section of the prosthesis *provided there was at least 2½ in. of space between the end of the stump and the top of the turntable.*

The patient's response to this change was highly positive. He found it "lighter and more convenient." We have, therefore, designed two alternative power packs for VAPC electrical components. Power Pack A is the internally mounted unit described above which is designed for

patients with standard or shorter above-elbow stumps with approximately 2½ in. between their distal ends and the top of the turntable. For patients with longer stumps, we have made available Power Pack B which is a flat, flexible package (10.0 oz. and ½ in. x 3 in. x 8 in.) designed to be worn on a waistbelt or in a hip pocket.

The patient's difficulty in discriminating the flexion from the extension positions in the control switch was a paradoxical finding. We had deliberately and carefully designed the switch not only for the advantages of minimum excursion, but also (and mistakenly) for minimum force. The patient's difficulty in discriminating the flexion/extension operating positions was finally attributed to the sharply reduced force feedback furnished by such a low force system. Patients receive useful information from the resistance of components to applied forces. In a sense, therefore, we had "overdesigned" for low force and had thereby severely compromised the normally available feedback. There are of course many options to provide audible and tactile feedback. But those solutions involving the use of internal, adjustable, resistance springs would substantially increase the cost of the switch and make it difficult to provide easy adjustment of feedback *without getting inside the mechanism.*

Our solution to this problem was derived from the use of rubberbands used to control the prehension forces available in voluntary opening hooks. A great deal of adjustability in pinch force is possible by the use of multiple rubberbands or by using portions of a single rubberband. As shown in Figure 4 the prosthetist can adjust the magnitude of the force required to actuate the switch by applying a portion of one or several rubberbands *outside* the switch. Moreover, as the patient's skill increases and his sensitivity to the position of the switch increases, the force requirement can easily be adjusted downward by the simple expedient of removing or cutting rubberbands. With the addition of two rubberbands, our patient quickly learned to discriminate between the flexion and extension positions of the switch. He found that the quality of his control over the elbow was significantly improved by this addition.

After 7 months of wear, the patient was fitted with the VAPC pull-switch-operated electric hand (BPR 10–12). The entire system was installed as shown in Figure 5. The harness and control system was still modeled on the conventional in that the control switch mounted in the control attachment strap was used to open and close the hand. Flexion and extension of the elbow were controlled by another VAPC switch mounted in the otherwise conventional elbow lock control strap. The system, therefore, is essentially an electrical analog of the conventional above-elbow harness and control system. Small forces and short range flexion motions at the shoulder, respectively, close and open the

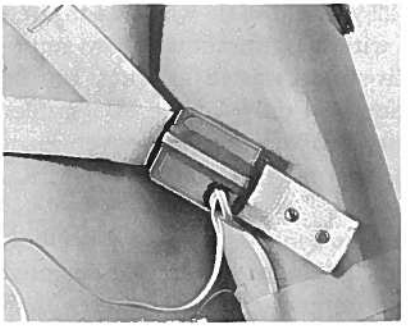

FIGURE 4.—Rubberbands used to adjust the magnitude of force required to actuate the switch.

hand. Abduction and/or extension of the shoulder extends and flexes the elbow; locking in any position is automatic. The patient, therefore, employs essentially the same body control motions he uses to control his completely conventional prosthesis. However, instead of using a rather crude movement like abduction/extension of the shoulder only to lock and unlock the elbow, this motion now produces flexion and extension of the elbow. Moreover, during the period of 3 months of wear *the internally mounted Power Pack A was found to have sufficient capacity to operate both components.* In general, the patient is quite pleased with the operation of the entire system including powered elbow and powered terminal device. He has "good" control over the prosthesis and he expressed a desire to continue to wear it on a routine basis. Retraining in controlling both the powered elbow and powered terminal device was accomplished quite easily

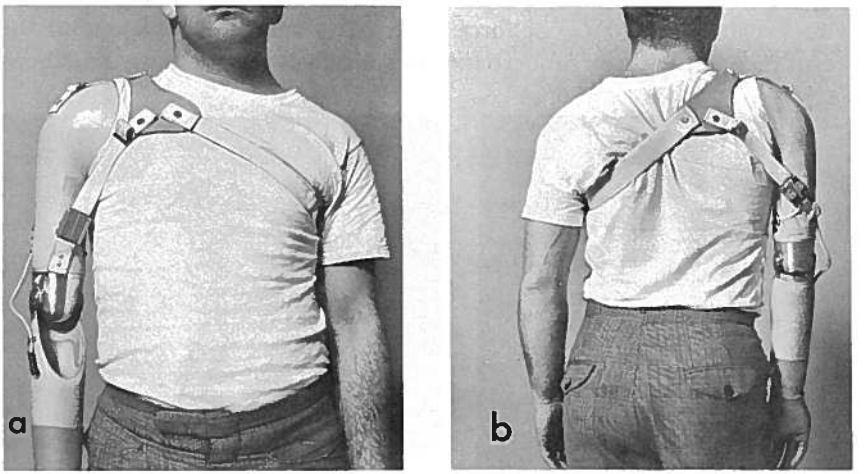

FIGURE 5.—Complete VAPC externally powered system: (a) anterior view showing elbow and anterior switch; (b) posterior view showing installation of the in-line switch for terminal-device control and terminal device (hand).

The second case in this series was a 22-year-old male who was injured in a motorcycle accident, leaving him with a right, above-elbow amputation and a fused shoulder joint. His stump was 12 in. long, and he was left with 15 deg. of shoulder flexion and only a trace of shoulder abduction and extension. When first seen he wore a conventional prosthesis with standard above-elbow socket, Hosmer elbow, APRL hook, and above-elbow Figure-8 harness.

Because of the limitation of shoulder motion, he operated his elbow by pulling the elbow control cable with his sound hand. He operated his terminal device by abduction of the opposite scapula rather than by the flexion of the shoulder of the amputated side.

Due to the low order of function available to this patient with his conventional prosthesis, he presented a challenging case for the application of external power. He was refitted with a new above-elbow socket and a VAPC electric elbow controlled by a pull switch mounted in a nonelastic front support strap (Fig. 6). His terminal device, an APRL hook, was controlled by a conventional cable in a standard above-elbow harness. With the severely limited shoulder flexion available, he was still constrained to operate the terminal device by scapular abduction of the sound side. The elbow control switch was mounted on the front support strap in an effort to use the slight residual shoulder motions to operate the elbow and to eliminate the involvement of the sound arm.

During the initial training sessions after fitting, the patient had great difficulty in operating his APRL hook without inadvertently operating the elbow.

The APRL hook was replaced with a Dorrance 88X hook with three rubberbands (Fig. 7). The force required to open the hook against the resistance of the three rubberbands was insufficient to actuate the elbow.

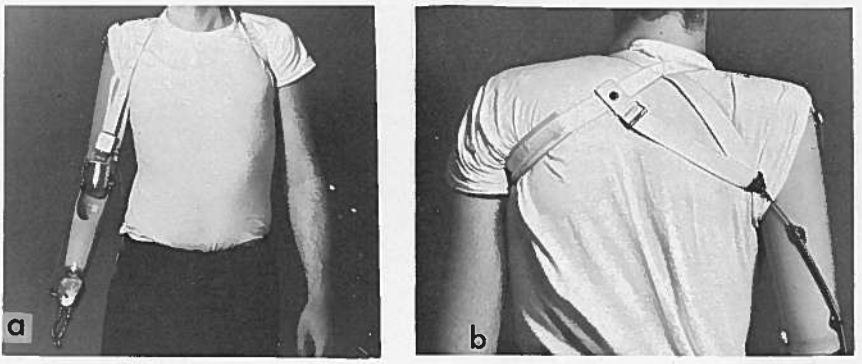

FIGURE 6.—(a) New prosthesis incorporating the VAPC electric elbow operated by electric pull switch; (b) posterior view showing harness configuration for body-powered terminal-device (APRL hook) operation.

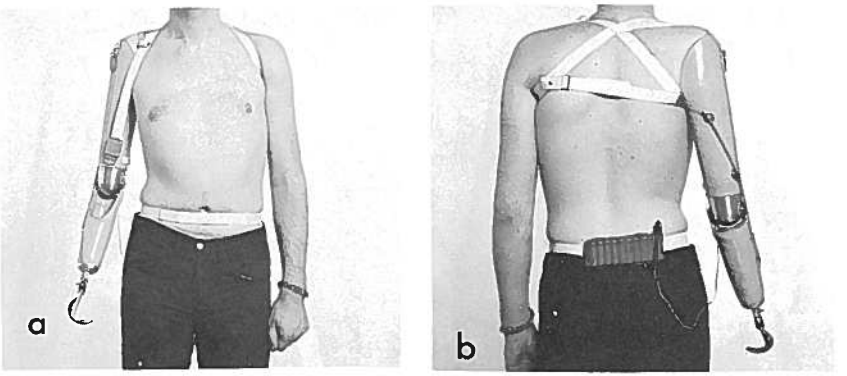

FIGURE 7.— (a) Prosthesis after replacing APRL hook with a Dorrance 88X hook; (b) posterior view showing location of battery pack and harness and cable configuration.

The patient has been wearing this prosthesis for approximately 10 months. He wears it every day, all week, at home, and at his job. During the first 6 months of this period he was employed as an elevator operator in a large hotel which required him to wear a uniform including a tight jacket. He found that the battery pack mounted on a belt around his waist was quite uncomfortable under the tight jacket. Since his stump was too long to permit installation of Power Pack A (internal), nothing could be done about this particular problem at the time. However, the patient was promoted to a new job at which he could wear conventional clothing, a circumstance which sharply reduced the problem. The patient's performance has been markedly improved by eliminating the need to operate his elbow lock manually. His own reactions are in general quite positive.

After 10 months of experience with the VAPC elbow, the patient was furnished the VAPC electric hand in place of his Dorrance 88X hook. As shown in Figure 8 the harness and control system is relatively unchanged except for the insertion of the VAPC pull switch in a control attachment strap to control the hand. Flexion and extension of the elbow are controlled by a switch installed in a nonelastic front support strap as previously fitted. The hand is controlled by a switch installed in the control attachment strap and activated by scapular abduction of the sound side. However, the force and excursion were reduced significantly in comparison to the conventional terminal device. With only limited shoulder motion available, adjustment of the switches was critical.

He has been wearing the new components for approximately 4 months and his reactions are quite positive. He wears the prosthesis every day, all day, and wishes to continue wearing it. He did, however, comment negatively on the slow rate of closure of the hand.

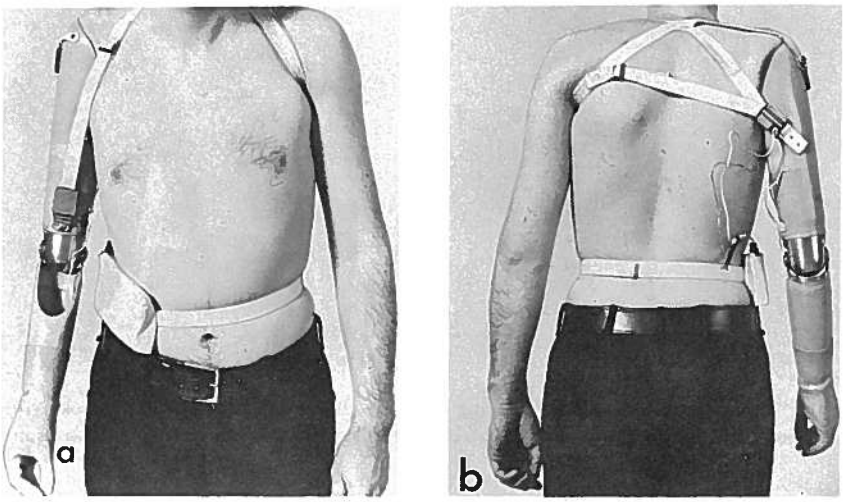

FIGURE 8.—(a) Complete VAPC externally powered system, elbow, terminal device (hand), switch, and battery pack B; (b) posterior view showing the installation of the in-line switch for terminal-device control.

Our experience with this patient has brought to light the potentially valuable application of externally powered elbows for patients with limited motion or strength of the shoulder on the amputated side.

The third case in this group is a rare bird, being a bilateral below elbow who, prior to being fitted with powered components, wore APRL hands bilaterally. He was a 30-year-old veteran of the Korean War

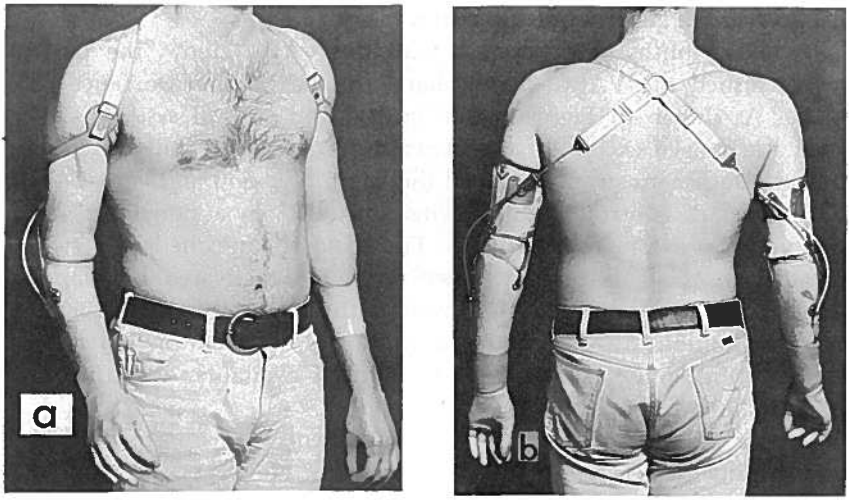

FIGURE 9.—(a) Conventional below-elbow prostheses with body-powered terminal devices (APRL hands); (b) posterior view showing harness and cable configuration.

with a short (4½ in.) right stump and a wrist disarticulation on the left side. When first seen he had been wearing bilateral below-elbow prostheses with APRL hands, conventional bilateral below-elbow harness, and flexible hinges (Fig. 9). He has been continuously employed until recently when he enrolled as a full-time student in a Business Administration program. He was considered an active, skillful user of prostheses.

This patient was not fitted with VAPC components. He was initially fitted on his right dominant side with a myoelectrically controlled Viennatone hand which he wore for a period of approximately 1 year (Fig. 10). His initial and subsequent reactions were highly positive. He frequently reported that he had far better control over his myoelectrically controlled hand than he did over the previously worn APRL hand on the right side. The patient registered two negative reactions. He noted that the Viennatone hand was "noisy" but certainly not to a degree that would lead him to discard it in favor of the noiseless APRL hand. He also felt that the amplifier and battery pack were bulky. But again "on balance," he preferred the Viennatone to his previous APRL.

Treating this patient was a relatively new experience for us in that we know of no other comparable case in which bilateral below-elbow amputees use mechanical hands bilaterally; the use of a combination consisting of a myoelectrically controlled hand and a mechanically controlled hand for a period of a year is new in our experience. We have previously registered our doubts about the utility of myoelectrically controlled hands for unilateral below-elbow amputees (BPR 10–10, 11, 12), and we have seen little to change our view. Our experience with this case has taught us that this position with respect to bilateral

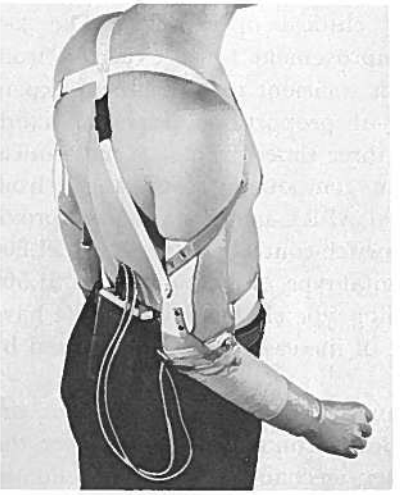

FIGURE 10.—Viennatone myoelectric hand fitted to right stump. The electronic circuitry and batteries are housed in same pack and worn around the waist.

below-elbow amputees may not be tenable. In standard tests of performance (BPR 10–7) the patient's skill was slightly superior with the myoelectrically controlled hand in that he committed fewer errors and his performance was slightly faster, perhaps indicating the value of eliminating the shoulder flexion control movement on the side fitted with the electric hand.

The bilateral application of external power, while not virgin territory (BPR 10–6), is a relatively unexplored area for us, particularly as regards bilateral below elbows and bilateral above elbows where other mechanical options have been successfully used. For this reason and at the patient's request, we are in the process of fitting him bilaterally with electric hands. Developing a sensible rationale for this procedure introduces several new perspectives. In this connection the question of economy provides some interesting insights. To fit a bilateral below-elbow amputee with two commercially available electric hands requires a minimum expenditure of approximately $6,500, *if the VAPC switch-controlled hands are used.* The use of two myoelectrically controlled Viennatone hands of the non-proportional or digital type, would cost approximately $1,200 for the hands, amplifiers, and battery packs. The use of proportionally controlled Viennatone hands would raise the cost to approximately $1,500 for the hands alone. These figures closely approximate prices quoted by commercial sources. The patient was initially fitted with two APRL hands at the approximate cost of $500. During the evaluation he expressed a strong preference for the myoelectrically controlled Viennatone hand over the essentially similar switch-controlled VAPC hand. In preliminary trials he felt his control of the myoelectric hand was better. While there are obvious advantages in going ahead with the fitting of the patient bilaterally in our laboratory, we must at the same time bear in mind the practical considerations in everyday clinical operations. The key question of course, is whether the improvement to be expected from two myoelectrically controlled hands is sufficient to warrant an expenditure of $1,200 as against $500, or—if proportional types of hands were considered—the cost of $1,500 or three times the cost of mechanical hands. The incremental increase in component costs ranges from approximately $500 for two mechanical APRL hands through approximately $500 for two VAPC electric-switch-controlled hands to $1,200 for two myoelectrically controlled digital-type electric hands to $1,500 for two myoelectrically controlled analog-type electric hands. We have no way of knowing whether the curve of increasing costs is matched by a curve of increasing function.

Looking at these questions from another view, it appears that the principal advantage of the myoelectrically controlled devices over the pull-switch-controlled devices, in either mechanical or electric hands,

is that the patient is not required to use shoulder flexion to operate the terminal device. From this standpoint a question arises as to the significance of eliminating for bilateral below elbows the shoulder motion normally required to operate the terminal device, and whether tripling or increasing the cost six times is warranted to eliminate it.

We have also considered the matter of accessory hardware. Two APRL hands involve only the common Bowden cable control system. Use of the pull-switch-controlled VAPC hands involves a single battery pack to operate both components and two switches. Two myoelectrically controlled hands either of the digital- or analog-type require, in addition, two battery packs, two sets of electrodes, and two amplifiers. A new perspective is generated in which we have to consider "trading off" whatever improvement in function is possible from the use of two myoelectric hands against the additional weight and bulk to be carried by the patient.

In this particular case, we have a bilateral below-elbow amputee with one short below-elbow stump and one wrist-disarticulation stump. All commercially available electric hands are designed with their power cables exiting through the hand attachment stud. The conventional procedure in fitting the wrist disarticulation leaves no room for the cable to pass internally through the stud and into the distal end of the socket. One solution is to increase the length of the prosthesis to provide room. Another is to modify the hand to permit the cable to exist somewhere on the dorsum with the consequent disadvantage of an external cable near the distal end of the prosthesis. Although these problems are significant, they do not preclude the fitting of wrist-disarticulation stumps.

We are presently engaged in evaluating the patient's reactions and his performance in the use of two myoelectrically controlled electric hands. We anticipate this experience will improve our understanding of some of the problems that may occur in clinical practice.

Design and development of externally powered components for upper-extremity prostheses have in general been centered on the engineering details of electric elbows and hands. Design engineers have focused their efforts on the selection of materials, gears, motors, and switches, sometimes ignoring easily anticipated problems in fitting patients in ordinary clinical practice. During the development stages, "quick and dirty" evaluations on experienced pilot wearers fitted in the laboratory failed to identify problems associated with continuous routine wear by "non-professional" patients. Because of our dual responsibilities for both design and development and for patient care, we attempted to anticipate these problems from the very outset. Nevertheless, when the VAPC elbow and the VAPC hand were developed sufficiently for us to consider commercial production and we fitted

"non-professional" patients, unexpected problems arose. The three experiences described above have significantly altered the perspective in which we view the fitting of below-elbow amputees with externally powered components.

While it is difficult to understand the need for the unilateral below-elbow amputee to be fitted with a powered hand, several significant advantages may accrue to the bilateral below-elbow amputee fitted with powered hands. But the selection of the powered system to be used must be weighed against the wide range of costs of these components and against the number, bulk, and weight of the accessory components required with particular types of powered hands.

The unanticipated reactions of a fairly routine type of short above-elbow case led to significant design changes in our system. Our preoccupation with the elbow and hand functions *per se* lulled us into false confidence about the acceptability of our power pack to patients. The objection of a patient to the weight, bulk, and exposed wires of a system forced us to redesign the power pack which led to great improvement. Our system now has two power options available—Power Pack A for shoulder disarticulations and standard or shorter above-elbow stumps, and Power Pack B, a relatively light, flexible power source for patients with long stumps. Power Pack A is completely contained within the humeral section, eliminating exposed wires and externally carried batteries. Moreover, the capacity of the system is adequate for operating the two compatible components, VAPC elbow and hand.

We also saw the potential value of our electric elbow for patients with extremely limited ranges of joint motion.

The development of the VAPC electric hand and elbow is advanced to the point where we are negotiating for commercial production of approximately 100 elbows and a smaller number of hands. We will initiate with the Research and Development Division of the Prosthetic and Sensory Aids Service an extensive clinical test program through which we intend to fit over 100 relatively new veteran amputees of the Vietnam era. The information fed back to this Center will aid us in defining prescription requirements and in understanding the real utility of externally powered devices.