TECHNICAL NOTES

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Metacarpal Phalangeal Joint-Driven Index Finger Prosthesis[a]

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Background

The patient for whom this prosthesis was developed had sustained an industrial accident (bandsaw) that resulted in the amputation of the four fingers of the right hand at about the level of the distal end of the proximal phalangeal segments. The surgical closure and revision left the patient with the stumps as pictured in Figure 1 and Figure 2. He retained substantially full range of motion of all the metocarpal phalangeal (M.P.) joints. He could hold handles but could not perform heavy tasks. He retained a cumbersome form of lateral prehension of the thumb against the residual index finger which disallowed manipulation of small objects.

Significant to the development of this prototype prosthesis was the fact that the patient was highly motivated to be fitted with a functional prosthetic restoration, was himself interested in mechanics, and was not too concerned with cosmetics per se.

Description

The actual prototype prosthesis as pictured in Figure 3 and Figure 4 can be described as an MP joint driven, quadricentric proximal interphalangeal (P.I.P.) joint, index finger prosthesis. The medial external control rod mechanically links the M.P. and P.I.P. joints of the prosthesis.

Figure 5 shows the patient's hand with the prosthesis in full extension. Figure 6 shows moderate closure, and Figure 7 pictures functional apposition between the thumb and the forefinger of the prosthesis.

It can be seen from Figures 7 and 8 that there has been an improvement in the patient's functional prehension over that potentially available in the condition shown in Figure 2.

Figure 9 pictures the volar wrist passage of the simple attachment strap and the distal stainless steel (SS) index finger stump ring. From Figure 9 one can also note the design and course of the SS wire that makes up the proximal edge of the open socket of the prosthesis. This proximal border wire follows the anatomical crease of the volar surface of the index finger, and prevents an undesirable piston action between the stump and the prosthesis as the M.P. joint drives and controls the P.I.P. joint. The tender

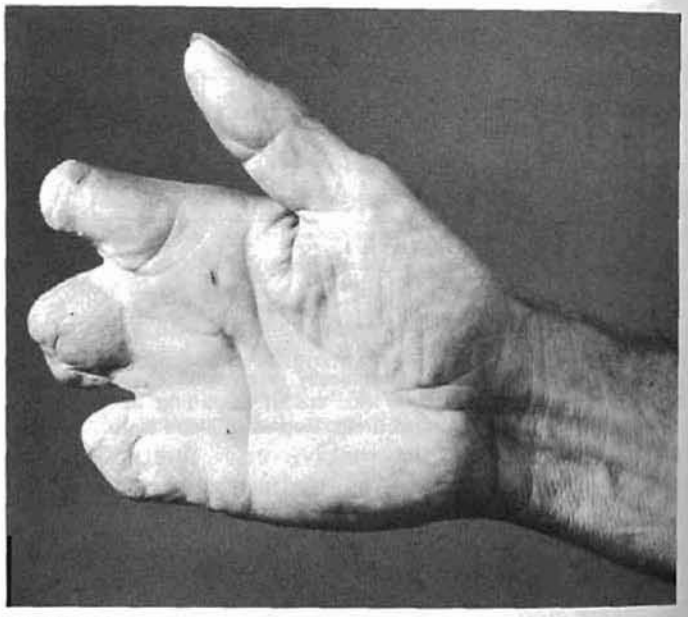


FIGURE 1.
Palmar view of patient's right hand, showing surgical closure and revision.

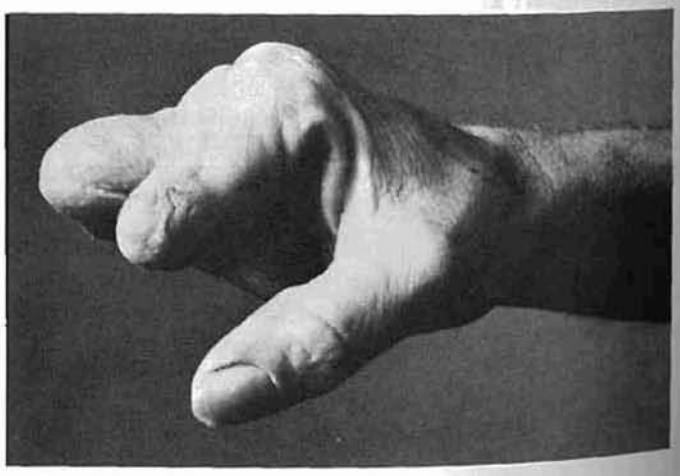


FIGURE 2.—Side view of patient's hand.

[a]Developed by the author while Senior Lecturer, Cumberland College of Health Sciences, Sydney, Australia, through Technical Aids for the Disabled (T.A.D.), a voluntary agency.

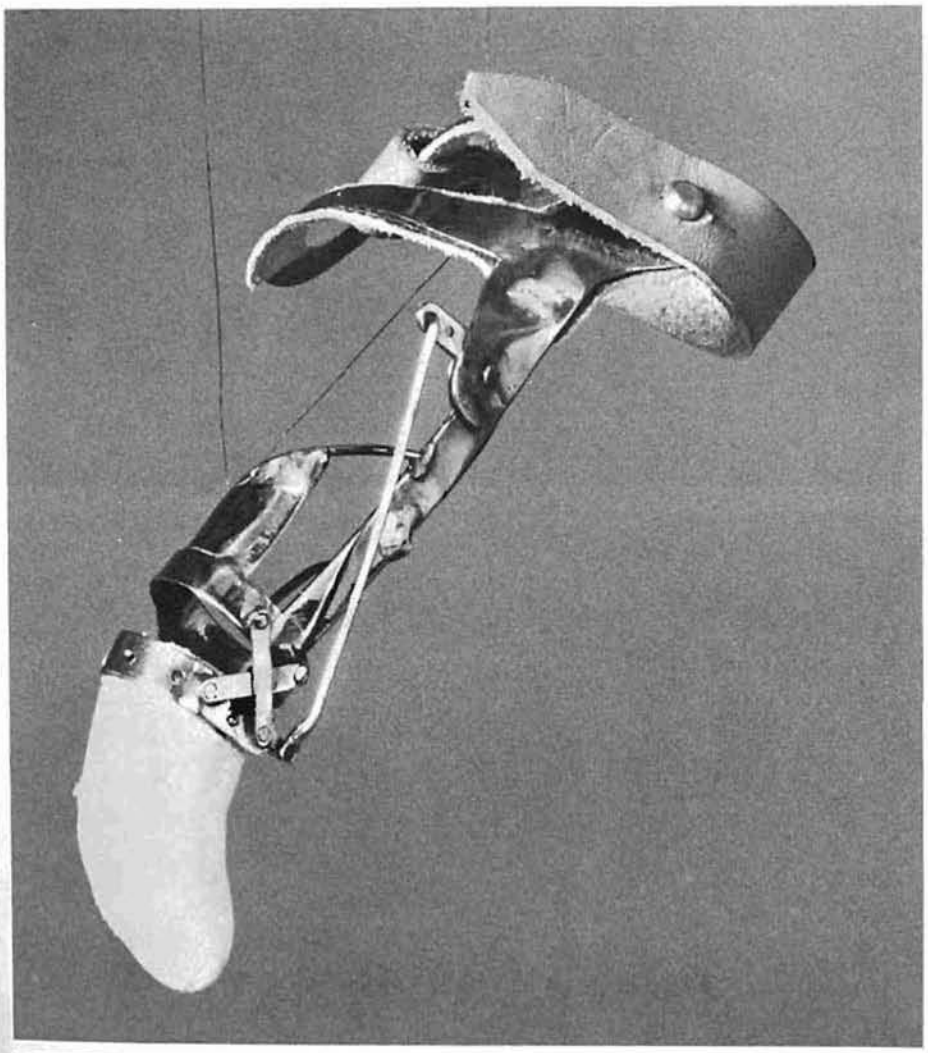
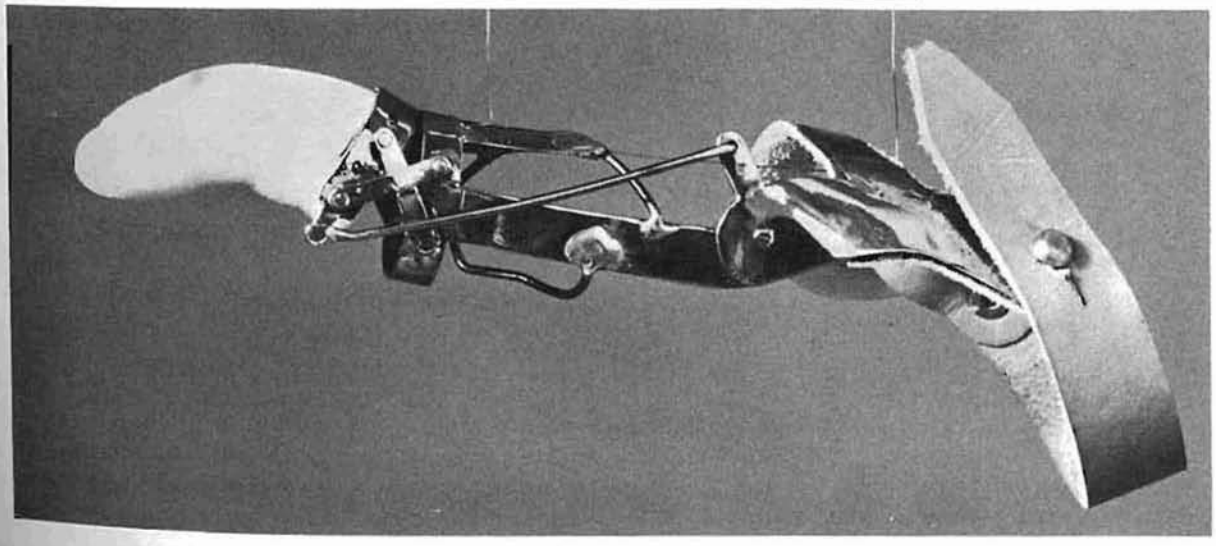


FIGURE 3.
Prototype prosthesis in closure position.

FIGURE 4.
Prototype prosthesis in full extension.



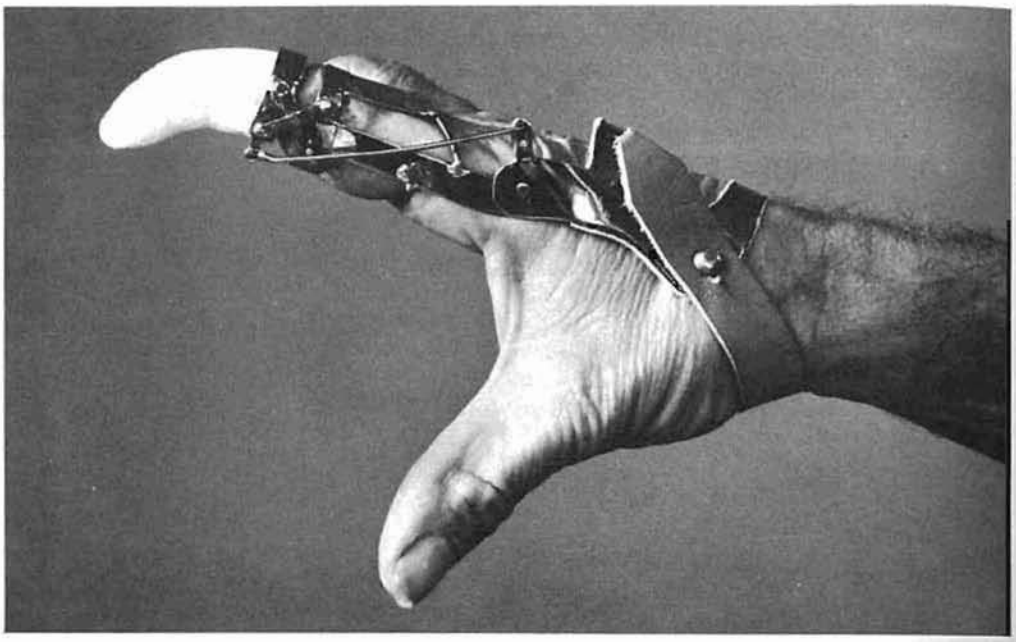


FIGURE 5.
Patient's hand with prosthesis in full extension.

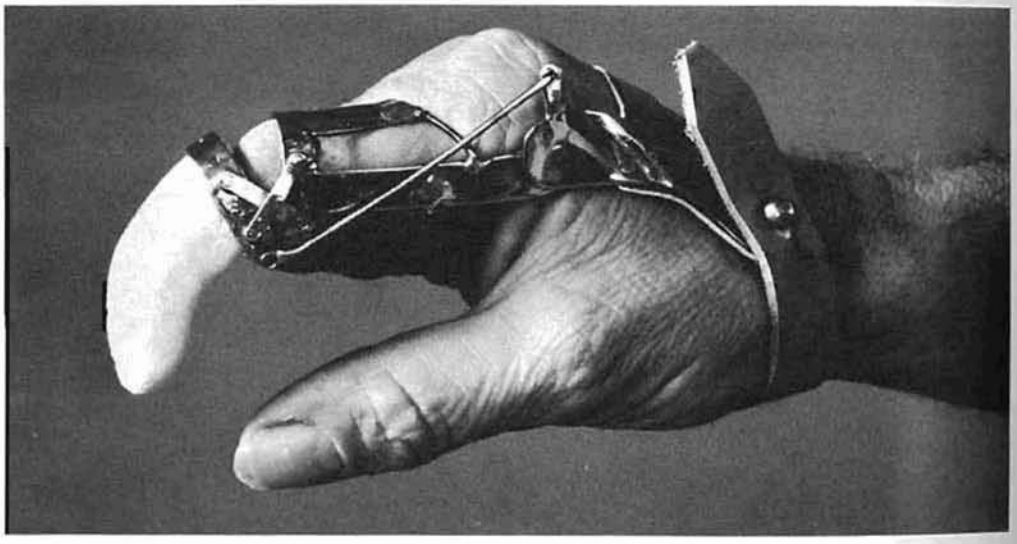


FIGURE 6.
Patient's hand with moderate closure of prosthesis.

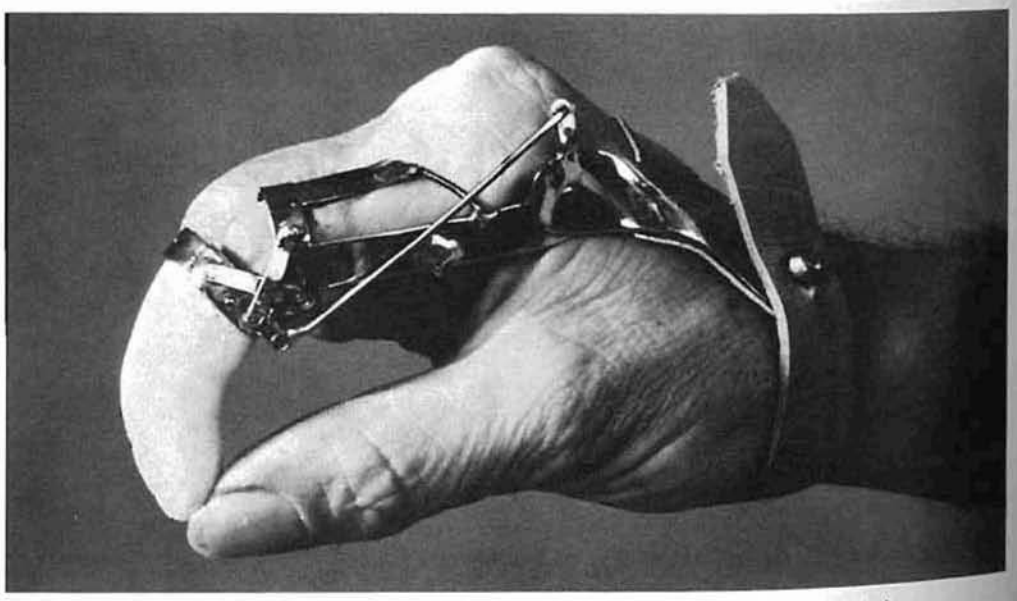


FIGURE 7.
Patient's hand showing functional apposition between thumb and the forefinger of the prosthesis.

scar tissue between the residual portions of the index and the middle finger made very careful fitting necessary at this point.

Fabrication—A precise negative cast of the amputated hand and wrist was formed of Dow Corning Silastomer, providing details of skin wrinkles and finger prints. A plaster male model was then cast.

Stainless steel and silver solder were used for all metal components of this prototype because they allowed a design that was strong, light in weight, and durable. No effort was made to alter the color of the polished SS surfaces, but the distal finger segment was painted and approximately color-matched to the patient's hand.

The distal finger segment was fabricated from Orthoplast[b] which demonstrated some resilience as well as adequate rigidity. This segment was cast in a position of 35° flexion from a negative mold that was taken from the patient's left hand. It had anatomical details such as finger nail and interphalangeal creases.

Training and Function—Since the functional use and activation of the prosthesis followed normal hand function, the patient immediately was able to demonstrate facility in use without training. He has been cautioned not to dip the thermoplastic finger in hot water. He was followed closely for six weeks and later occasionally by correspondence. He wore the device routinely all day.

The patient was able to use the remaining thumb effectively against the prosthetic index finger to operate a slide fastener, manipulate a paper clip or a button, pick up a glass, grasp a handle, or control an artist's paint-brush. He was tested satisfactorily though informally on some of the standard tests used by occupational therapists. Gripping force (not measured) was relatively weak because of the unfavorable mechanical advantage of the crossed four-bar linkage, which aimed primarily at attaining normal range of motion of the fingertip.

The residual portions of the other fingers have substantially normal ranges of motion. They assist in stabilizing handles against the palm.

Special Design Considerations—As can be seen in Figures 5, 6, and 7, the proximal end of the Orthoplast finger segment is concave and caps over the end of the residual proximal phalanx—although it never actually touches it. As the quadricentric joint is activated, this concave surface glides near the tip of the residual phalanx to present a functional and cosmetic articulation.

The chassis or anchor point of the prosthesis is a 3 oz. leather-lined frame that is contoured to fit over the dorsum of the hand. It is held securely in place with a single wrist strap.

[b]Orthoplast is the trademark of Johnson and Johnson for a synthetic balata thermoplastic material which softens below the boiling point of water.

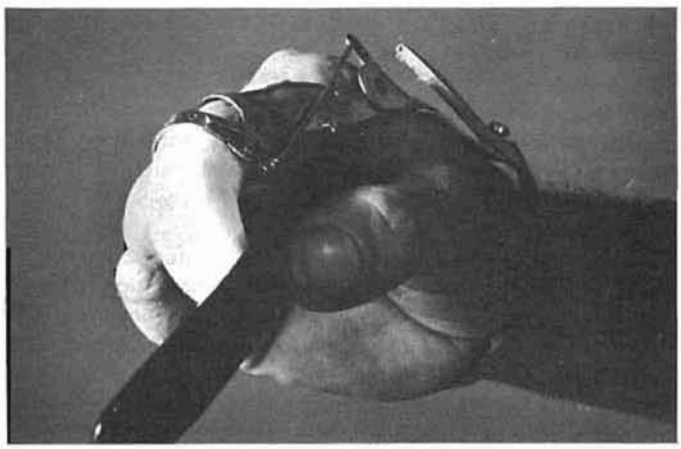


FIGURE 8.
Patient's hand grasping comb between thumb and the forefinger of the prosthesis.

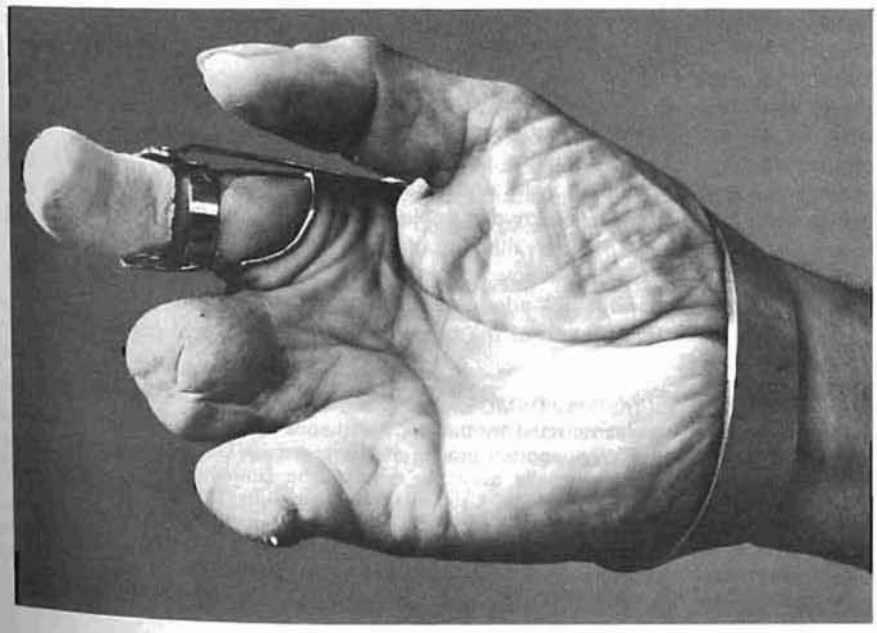


FIGURE 9.
Palmar view of patient's hand, showing volar wrist passage of the strap and the index finger stump ring.

VA / USMC Electric Hand with Below-Elbow Cineplasty[a]

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Cineplasty, the surgical creation of a means for direct muscular control of a prosthesis, was proposed as skin-covered tendon loops by Vanghetti (1). Independently (at the suggestion of a distinguished Swiss turbine engineer, Stodola,) the German surgeon, Sauerbruch, developed skin-lined tunnels through muscle bellies (2,3). The cineplasty concept seems to have enjoyed waves of enthusiasm (particularly in wartime) and then languished in relative obscurity (4).

The history, indications, contra-indications, surgical technique, and training methods, as well the basic muscle physiology and the design of cineplastic prostheses, are well presented in the classic report entitled "Human Limbs and Their Substitutes" (5–7). The chapter on techniques emphasizes the modifications of the original Sauerbruch technique which were suggested by his colleague Lebsche. These technical suggestions included the use of an intact muscle in the segment proximal to the amputation (i.e., biceps in case of below-elbow amputation) the release of the distal insertion of that muscle, large tunnel diameter, and rotation of the skin tube so that the suture line was not under pressure.

Although relatively common at a few centers 25 years ago[c], biceps cineplasty for below-elbow amputation is now an uncommon and rarely performed surgical procedure. The reasons for the decline of this procedure have included difficulty with surgical technique, a large number of surgical failures and / or inadequate patient selection, and the relatively poor performance of the original prosthetic devices developed for this type of amputation.

Most of the limited number of amputees treated with biceps cineplasty for below-elbow amputation seen in our clinic have abandoned their cineplasty prosthesis and switched to conventional prosthetic control utilizing hook, cable, and biscapular abduction or humeral flexion for activation of the terminal device. The sophistication and functional capability of current electric and myoelectric prostheses would appear to have value for patients with satisfactory biceps cineplasty below-elbow amputations. This report does not suggest that biceps cineplasty be considered as a definitive treatment of new below-elbow amputees, but does suggest a new method of fitting existing biceps cineplasty below-elbow amputees with electric hand (Fig. 1) (a possibility suggested for investigation in ref. 5) rather than standard voluntary closing terminal devices.

This report describes the fabrication of a below-elbow cineplasty electric hand prosthesis which has the following advantages compared to conventional prosthetic devices:

1. Ease of fabrication with existing conventional components.
2. Positive hand prehension control.
3. Modular design of the prosthesis for ease of component replacement, maintenance, and repair.

Materials and Methods

C.H. is a 45-year-old male right-below-elbow amputee, a service-connected Korean Conflict veteran. This patient had not recently been an active prosthetic arm user, although he had made many attempts in the past to be functional, both with conventional scapular abduction cable-controlled devices and with biceps-cineplasty-controlled devices. This patient was self-referred to our Amputation Rehabilitation Program in an attempt to see what new types of prosthetic devices might be available to him. After analysis of the patient and currently available prosthetic components, a VA / USMC electric hand (12-volt)[d] below-elbow cineplasty-controlled prosthesis was constructed and fitted to this patient with great success (Fig. 1). This patient feels quite strongly that utilization of the electric hand has provided him with increased function compared to standard hooks and has given him the ability to perform tasks which were impossible with the hook. In addition, the patient is quite pleased with the cosmetic nature of the prosthesis. At the present time, this patient has once again become a continuous prosthesis wearer and uses his prosthesis daily as an employee in the maintenance service at the Tucson VA Medical Center.

The components required for the fabrication of a below-elbow-cineplasty controlled electric hand include the following:

1. Below-elbow biceps cineplasty kit with pin, yoke, and cables;
2. A 12-volt VA / USMC hand with trip-switch, battery, charger, and connectors;
3. Standard prosthetic below-elbow arm components including wrist units, ball receivers, ball terminals for ball receivers, Bowden cable housing, retainers, and baseplates.
4. The availability of standard shop lamination facilities.

Below-elbow stump length is crucial for fitting the electric hand, since adequate space is required in the distal forearm for location of the battery pack and electrical connections in

[a] Supported in part by the Veterans Administration.

[b] Address reprint requests to: J.M. Malone, M.D., Department of Surgery, A.H.S.C., University of Arizona, Tucson, AZ 85724.

[c] Heckathorn and Childress (8) report finding only two potential subjects in "a thorough search" of the Chicago area in 1979. Of these, one could not be used as a subject because of prolonged disuse of the biceps, but the other, a 48-year-old veteran of the Korean Conflict who underwent the procedure in 1954 following wrist disarticulation of the dominant right hand, showed excellent acceptance of the cineplasty and participated in the authors' studies of relationships between surface EMG and muscle function.

[d] The VA / USMC electric hand is an adaptation of a Viennatone electric hand by the VA Prosthetics Center (now VAREC) through a VA-supported project at Northwestern University. The hand was commercially available through the United States Manufacturing Co., Pasadena, California, the distributor. While this paper was in press the authors were advised that requests for information and product literature on the hand should now be directed to the manufacturer, Fidelity Electronics, Ltd., 8800 N.W. 36th St., Miami, Florida 83138.

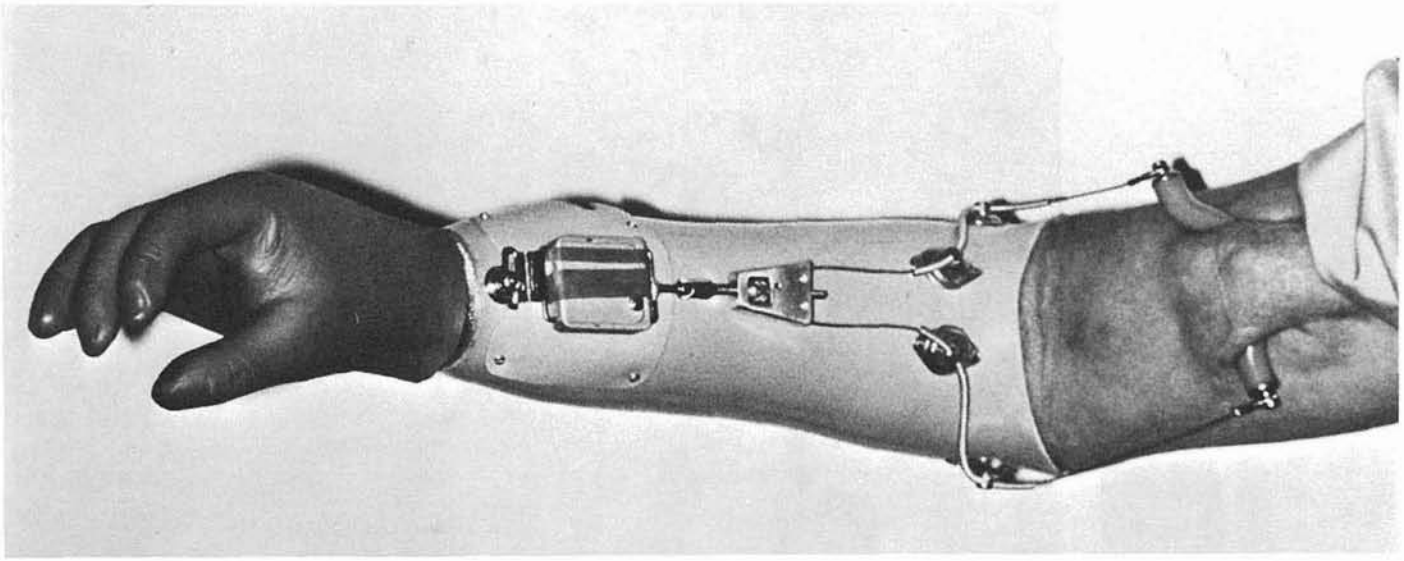

FIGURE 1—Self-contained, self-suspended below-elbow cineplasty prosthesis with VA / USMC electric hand adapted to operation with trip-switch control from the biceps cineplasty tunnel. The battery pack and electrical connections are enclosed in the distal forearm. (Because the biceps tendon was detached at the time of cineplasty operation, the anterior socket brim did not need the usual tendon notch cutout.)

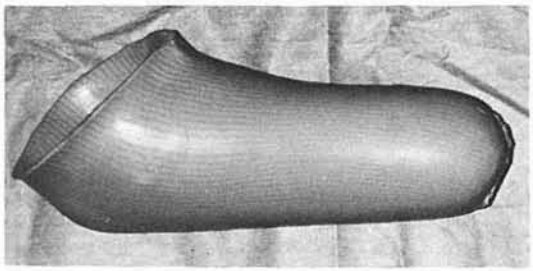

FIGURE 2.
Standard plastic laminate socket for a self-suspending below-elbow socket.

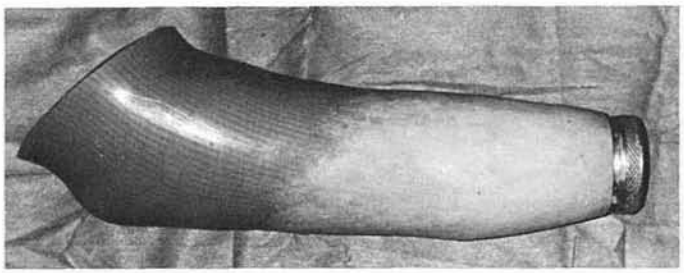

FIGURE 3.
Wax buildup of the below-elbow prosthesis to allow space for distal battery placement as well as attachment of the wrist unit with prosthetic alignment, length, and cosmesis provided as needed.

order to preserve the advantages of a self-contained and self-suspended prosthesis. The space requirement (forearm shortening) is approximately 2½ inches.

Standard shop procedures are utilized for casting and lamination of a self-suspending below-elbow socket (Fig. 2). After the socket has been checked and modified as needed, it must be extended with wax (to be melted out after lamination) in order to allow for distal battery pack placement and electrical connections. Any type of wrist unit appropriate for the individual patient may be used. The wrist unit is attached to the wax buildup extension, with the desired prosthetic alignment, length, and cosmetic shaping (Fig. 3). A lamination is then applied over the socket. When this first lamination has set, a second lamination, separated by a PVA bag, is then applied. After the second lamination is removed from the first lamination, a window the approximate size of the battery pack and wire connectors is cut out of the anterior distal forearm of the first lamination. A conforming cover, somewhat larger than the window, is made from the second lamination. The first lamination is placed in the oven for wax meltout. After wax meltout, the prosthesis is ready for assembly (Fig. 4).

The VA / USMC trip-switches have a metal "hook" or flat loop for harness strap attachment on each end. On the end farther from the battery / hand leadwire (4-wire cable) the strap hook is removed from the switch by loosening the retaining Allen setscrews. The strap hook is then silver-soldered to a ball receiver and replaced on the trip-switch (Fig. 4). This ball receiver will eventually be used for attachment to the ball on the cineplasty yoke adjustment pin (so that length control of the cineplasty cable unit is possible). A slide buckle hook, preferably the width of the strap hook on the trip-switch, is then placed on the anterior distal portion of the prosthesis, distal to the battery compartment window, and secured in place with machine screws (6 / 32). The battery compartment window cover, cut out from the second lamination, is notched distally to allow passage of the battery / hand 4-wire cable into the distal forearm battery compartment section (Fig. 5). The slide buckle mounted on the distal forearm will not only receive the trip-switch (battery / hand lead end) strap hook (and hold the trip-switch in place), but will also allow easy removal of

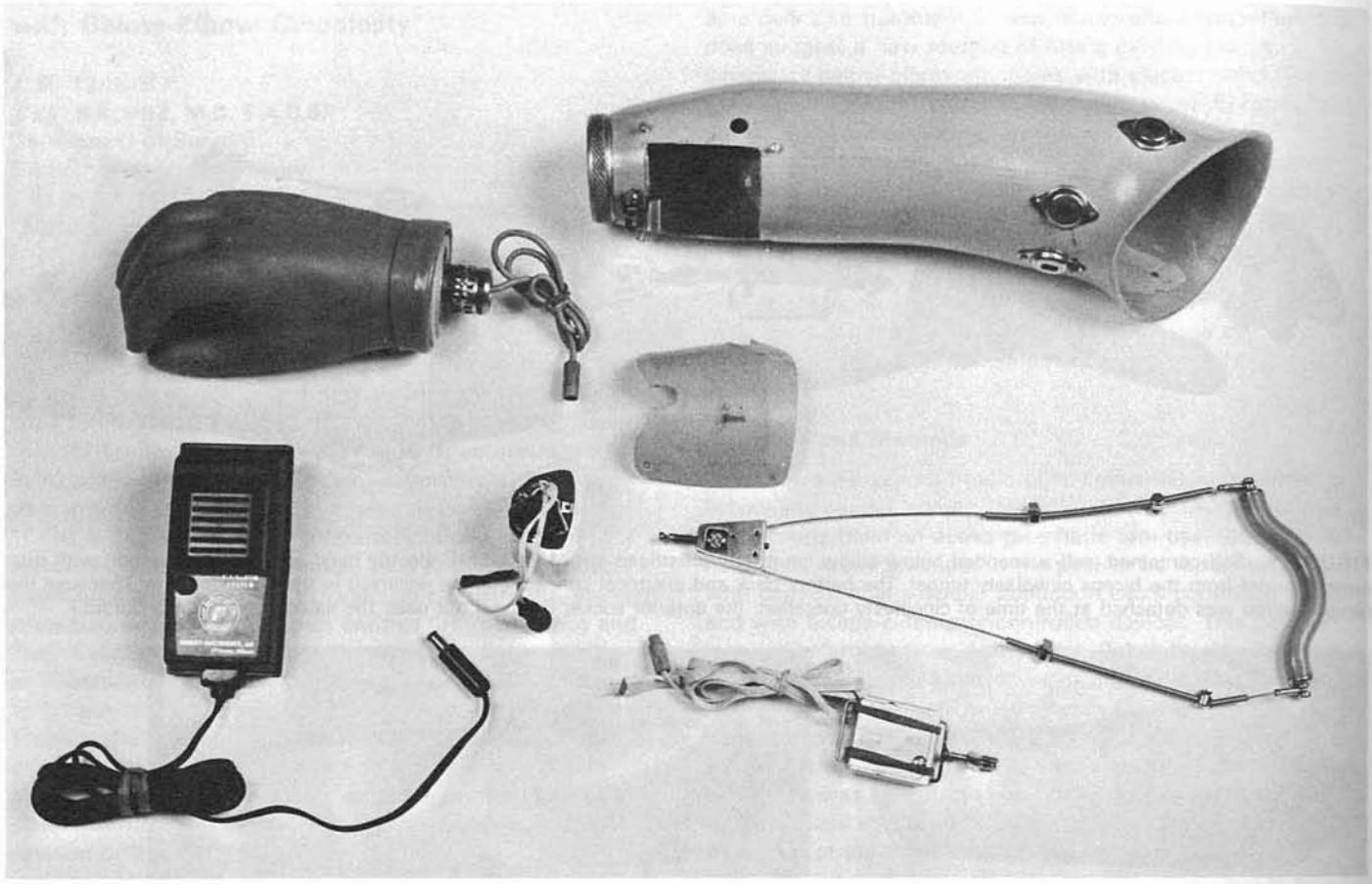

FIGURE 4.
Electric and prosthetic parts prior to prosthesis assembly. The battery compartment window is large enough to accommodate the battery and electrical connectors. The hand's electrical cable can be seen coming out of the center of the F-M wrist disconnect stud.

the trip-switch for prosthesis maintenance and repair, as well as rapid access to the battery compartment.

The electric hand is connected to the wrist unit and the hand power cable with plug is run through the wrist unit into the battery compartment. The battery pack is placed into the distal forearm. The battery plug lead from the trip-switch is connected to the battery pack and the electric hand control cable is connected to the appropriate hand cable from the trip-switch. The battery, lead wires and all electrical connections easily fit in the battery compartment section. The laminated door for the battery compartment is then placed under the trip-switch and secured in place by small self-tapping screws (Fig. 5). The charger post for the battery pack is secured to the prosthesis after drilling appropriate mounting holes (lateral side of prosthesis in battery compartment area). All electrical connections are then checked and the hand is tested.

Once satisfactory hand operation (opening and closing) is achieved, the prosthesis is ready for cable hookup and individual modification. Retainer baseplates are secured to the prosthesis in positions which will allow vertical alignment of the cineplasty yoke adjustment pin to the trip-switch ball receiver unit (Figs. 1,5). The patient dons the prosthesis and places the cineplasty pin in the biceps tunnel to allow cable connection. The cineplasty cables are attached to the cineplasty pin and passed through the Bowden housing, and appropriate cable length to the cineplesty yoke is determined. Correct cineplasty cable length **must** allow for cable length adjustments[e] by use of the cineplasty yoke adjustment pin. The ball on the adjustable pin of the cineplasty yoke is then inserted into the ball receiver on the trip-switch (Fig. 5). The patient is now asked to flex his biceps so that cable travel and trip-switch excursion can be analyzed further and appropriate final adjustments for cable length and / or cineplasty yoke pin length can be made in order to achieve maximum hand function (Fig. 6).

Discussion of Prosthetic Results

This patient rapidly adapted to this prosthesis and surprisingly, he displayed effective control of hand prehension. Hand prehension control was achieved by

[e] To set for correct resting length of the muscle.

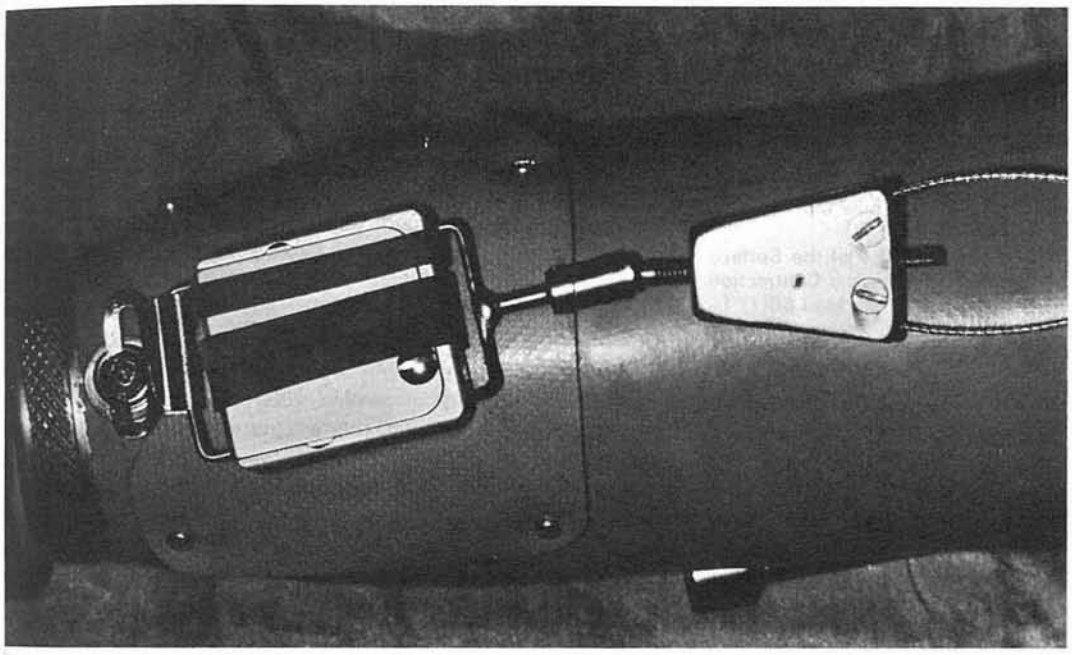

FIGURE 5.
Close-up of the distal forearm of the prosthesis showing the relationship between the trip-switch cineplasty yoke and the battery compartment window cover. The four-part cable from the trip-switch passes through a notch in the battery compartment cover into the battery compartment. The battery charging post mounts laterally below the battery compartment window.

opening the hand to full position and then intermittently tripping the switch on and off in rapid sequence to close the hand until the desired prehension force was achieved. Our patient seemed to learn rapidly how much hand closure corresponded to specific grip strength. The dexterity available to the patient with those maneuvers allowed him the ability to pick up an egg without cracking it or to close the hand with full force achieving between 25–40 pounds of distal tip prehension force. When questioned carefully, our patient suggested that his prehension control was a combination of visual clues from the hand as well as proprioceptive feedback through the biceps cineplasty. The cosmetic value of the electric hand, the positive control of hand prehension through the biceps cineplasty unit, and the increased functional range of the electric hand allowed this patient a natural appearance with increased function which was not possible with standard voluntary opening or closing cable devices.

FIGURE 6.
Final adjustments of cable length and cable function. Cineplasty control permits greater independence of shoulder motion and terminal device position is obtained with the harness control.

Conclusion

This type of prosthetic design offers a biceps cineplasty patient the opportunity to use electrical prosthetic components in order to achieve increased function and cosmesis. This patient demonstrates a design technique that is effective for fitting existing biceps cineplasty patients: this technique adds another specific type of prosthetic device to the armamentarium for the treatment of upper-extremity amputation patients.

We are now in the process of modifying our present design to allow utilization of both electric and myoelectric terminal devices ■

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Adaptation of the VA / USMC Electric Hand to the Liberty Mutual Myoelectric Boston Elbow for Above-Elbow Amputees[a]

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Many prosthetists, surgeons, and physical therapists think of upper-extremity function almost exclusively in terms of the human hand. Now, it is true that the human hand is an incredible functional device which cannot at present be mechanically or electronically duplicated, but if the hand cannot be put in the correct position to accomplish a specific task, its intricate and delicate functions are severely impaired. Much the same limitation applies to prosthetic terminal devices: externally powered hands may, potentially, offer significant improvement in function compared to standard cable control of a hook or other terminal device, but inability to place the terminal prosthetic device (either a hook or hand) in precisely the correct position for a specific function decreases the efficiency of the terminal unit.

Compared to standard harness-controlled elbow flexion systems with elbow lock, the Liberty Mutual myoelectric elbow (Boston elbow), which is a proportionally controlled electrically powered elbow, potentially has improved functional benefit due to increased control of elbow position and more accurate placement of a terminal prosthetic device. The "standard" Boston elbow was constructed to be utilized with a standard Hosmer-Dorrance hook controlled with biscapular abduction or figure 8 harness and humeral flexion (we prefer the latter harnessing approach). Since externally powered terminal devices may increase both function and cosmesis for above-elbow upper-extremity amputee patients, we have adapted the Boston elbow for use with either the VA / USMC 12-volt electric hand[c] or any of several Hosmer-Dorrance voluntary opening hooks. In addition, this adaptation of the VA / USMC electric hand with the Boston elbow has been done in a manner that allows rapid hand / hook interchange for those specific times when a hook may be desirable as compared to the hand unit. The above-elbow amputee patient fitted with a Boston myoelectric elbow with proportional control and a VA / USMC electric hand represents, we feel, a significant step forward in patient function, control, and cosmesis compared to a standard conventional hook and cable prosthetic arm. The purpose of this report is to describe the adaptation of the Liberty Mutual Boston myoelectric elbow for the VA / USMC electric hand and for rapid hand / hook interchange (Fig. 1).

Materials and Methods

The adaptation of the Boston elbow for the 12-volt VA / USMC electric hand is a relatively simple procedure. The above-elbow amputation residual limb must be short enough to allow 2¼ inches of room (for a separate hand battery pack unit) between the elbow turntable and the distal end of the socket. Location of the hand battery pack above the elbow turntable rather than on the forearm reduces the leverage of the forearm and the power requirement for elbow flexion, thus improving elbow battery life. Our own preference, in several patients in whom there was excessive humeral length, was to perform above-elbow revisions in order to allow fitting of the Boston elbow with electric hand, yet retain adequately long humeral length for good prosthesis control.

The electric leadwire from the 12-volt VA / USMC hand must be removed from the center of the screw attachment unit (where it was originally placed to simplify wrist rotation) and placed in an external position to facilitate hand / hook interchangeability. This change in leadwire location is accomplished by removing the hand attachment plate, notching it with a file on the anterior medial edge of the plate (for wire clearance), and then placing the plate with the wire pathway as shown in Figure 2. As shown in both Figure 1 and 2, we prefer use of the Fletcher-Motis disconnect unit for both the

[a] Supported in part by the Veterans Administration and Liberty Mutual Insurance Co. (Research Div.).

[b] Address reprint requests to: J.M. Malone, M.D., Department of Surgery, A.H.S.C., University of Arizona, Tucson, AZ 85724.

[c] The VA / USMC electric hand is an adaptation of a Viennatone electric hand by the VA Prosthetics Center (now VAREC) through a VA-supported project at Northwestern University. The hand was commercially available through the United States Manufacturing Co., Pasadena, California, the distributor. While this paper was in press the authors were advised that requests for information and product literature on the hand should now be directed to the manufacturer, Fidelity Electronics, Ltd., 8800 N.W. 36th St., Miami, Florida 83138.

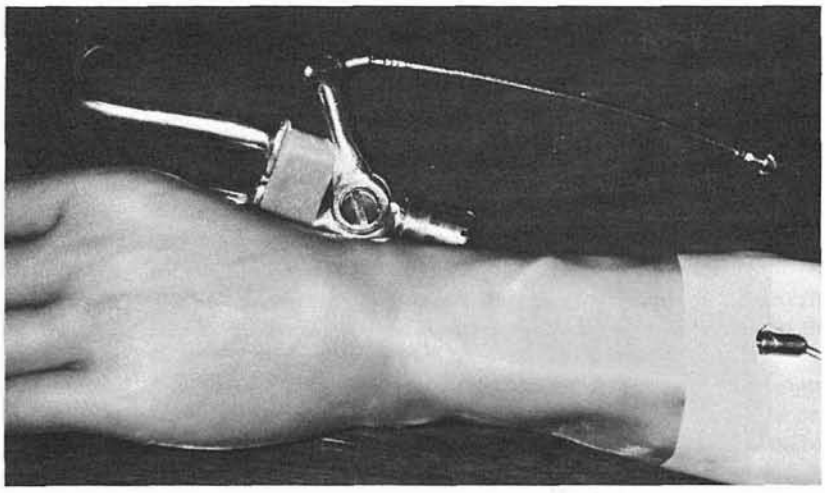


FIGURE 1.
This is a photographic representation of our concept of rapid hand / hook interchange. Pictured are a conventional Hosmer-Dorrance voluntary opening hook with adapter cable placed beside a VA / USMC 12-volt electric hand attached to a Liberty Mutual myoelectric elbow. Both terminal devices utilize a Fletcher-Motis disconnect unit.

hook and hand, in order to enhance their rapid interchangeability.

The electric hand trip-switch unit (the side with the 4-wire battery / hand cable) must be mounted on the anterior forearm frame as close to the wrist as possible through the utilization of a slide buckle hook which is secured to the forearm frame (6/32 screws) as shown in Figure 3. The slide buckle arrangement should be angled at approximately 20 deg to the lateral aspect of the forearm in order to allow direct alignment with the Bowden cable. This slide buckle arrangement with trip-switch allows rapid trip-switch removal for switch repair or arm disassembly. The more proximal strap bar on the trip-switch (side opposite the 4-wire cable) is removed by loosening the two Allen retaining screws and a ball receiver is silversoldered to the strap bar (Fig.3). The strap bar is then replaced on the trip-switch.

The VA / USMC hand is then attached to the wrist unit leaving the electrical leadwire exposed in the anterior medial position. The battery power plug with two wires and the hand connector 2-wire cables are pulled apart (thus splitting part of the 4-wire cable) (Fig.4), thus allowing the hand connector cable to remain close to the hand at the wrist unit and the

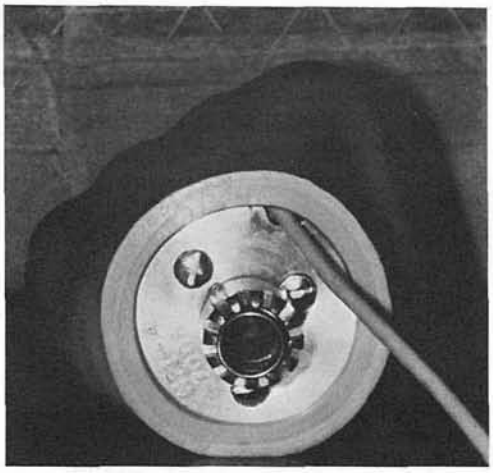


FIGURE 2. A rear end view of the VA / USMC electric hand demonstrates the relocated position of the leadwire from its original central location to its present anterior medial location. Notice the notch in the hand baseplate unit to avoid wire damage with hand mounting, dismounting and rotation.

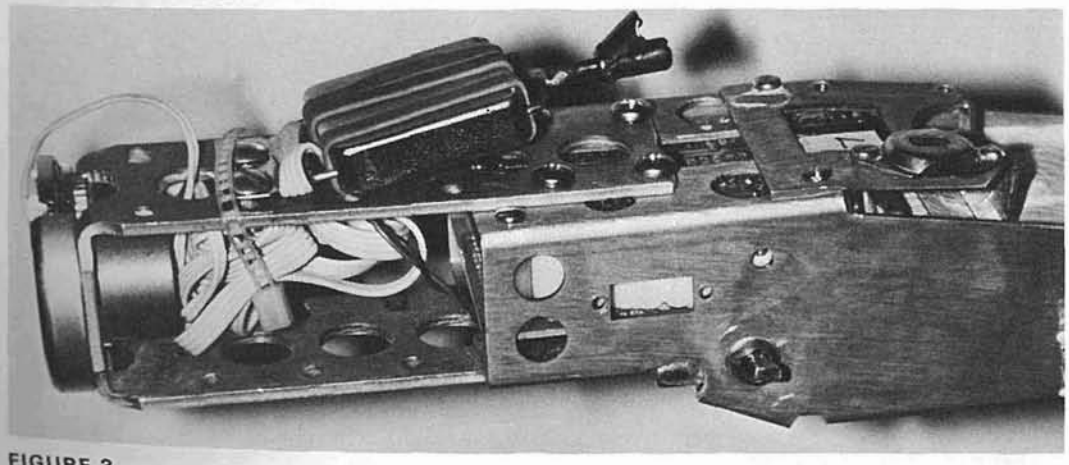


FIGURE 3.
The trip-switch unit is mounted as distally on the forearm as possible. It is angled approximately 20 degrees to the lateral aspect of the arm for accurate Bowden cable alignment. Note that the side of the trip-switch with the 4-wire battery / hand cable is secured to the distal forearm with a slide buckle hook. The more proximal strap bar on the trip-switch is removed, silver-soldered to a ball receiver and re-attached.

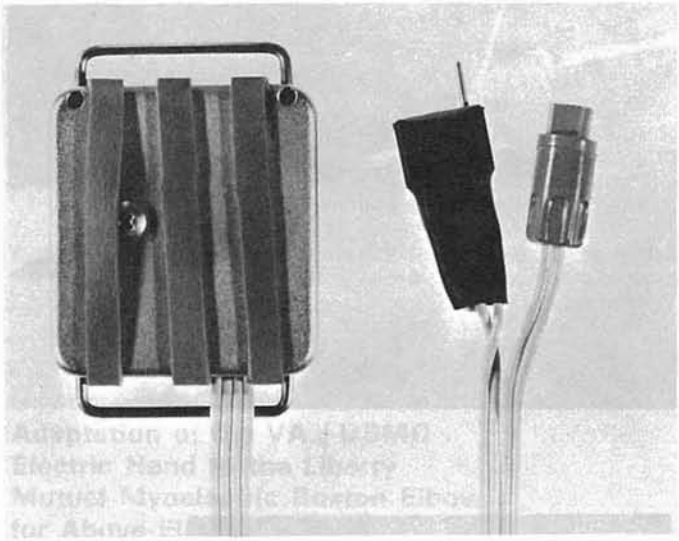


FIGURE 4.
A 4-wire cable emerges from the distal end of the trip-switch. At its opposite end, the cable is split to allow one 2-wire portion to proceed distally to connect with the hand, and the other 2-wire cable to reach the battery pack located above the turntable.

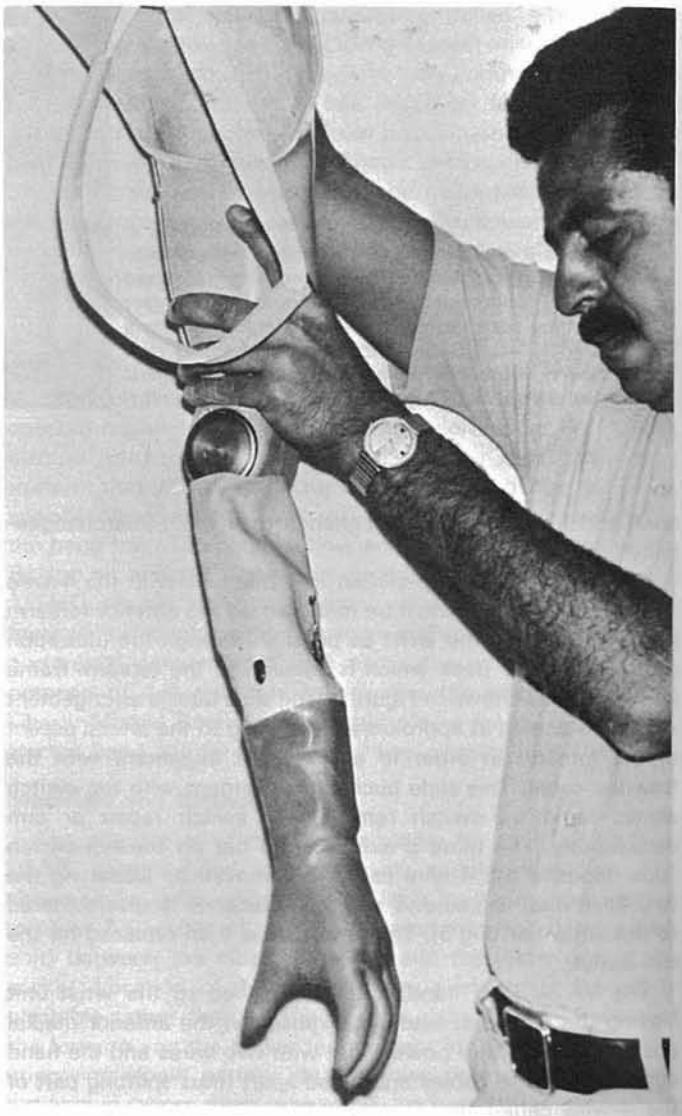


FIGURE 6.
When a cosmetic glove is placed over the VA / USMC electric hand, the power cable lead to the hand is hidden. Notice the Bowden cable trip-switch attachment.

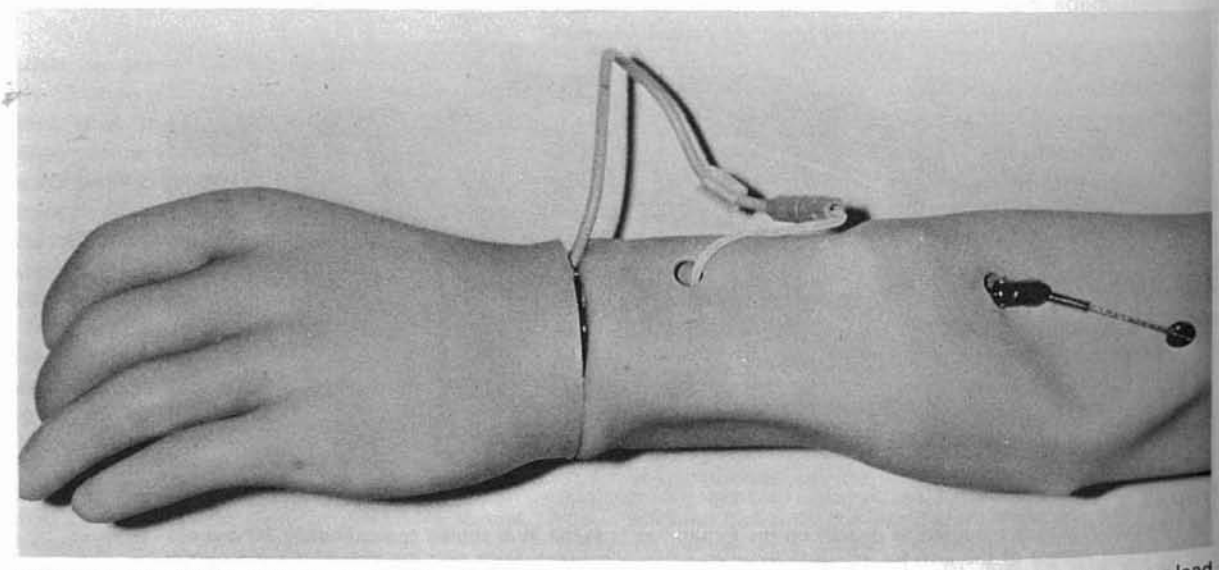


FIGURE 5. The VA / USMC electric hand is attached to the forearm of the Boston elbow. Notice the hand cable power lead connection and the ball receiver Bowden cable connection.

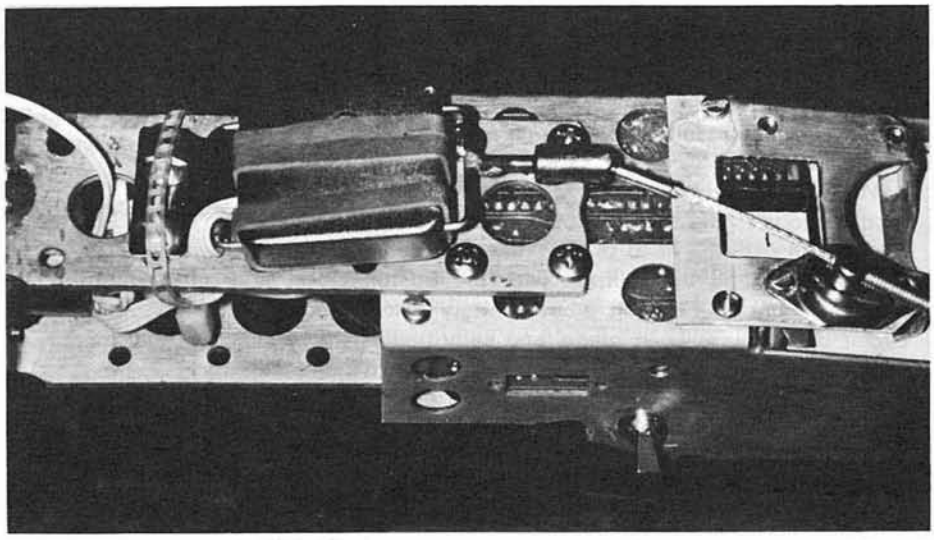
battery power wire to reach the battery unit, which will be placed above the elbow turntable in the socket portion of the prosthesis. The residual 4-wire cable and hand cable from the trip-switch are rolled into the forearm frame and secured with a simple plastic fastener or loop of tape as shown in Figure 3. The battery power cable must travel under the retainer base-plate on the forearm and pass under the elbow unit to a posterior hole in the socket just above the turntable where the hand battery pack will be located. The hand battery pack unit and associated wire leads are easily accessible through a laminated window unit placed in the humeral portion of the prosthesis containing the socket.

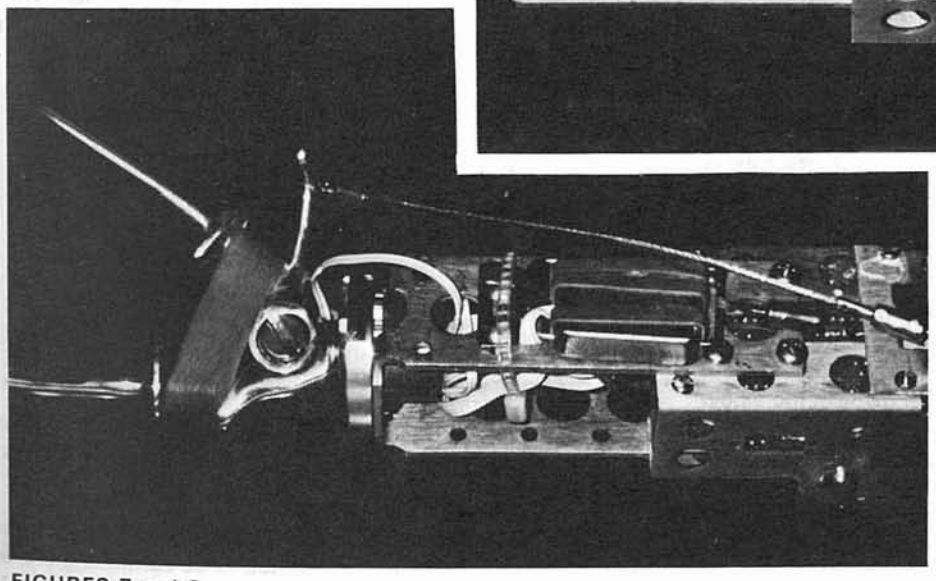
The elbow must have a leather sleeve glued to the posterior distal side allowing the battery cable to travel on flexion, extension, and elbow rotation. This leather covering over the battery cable is a very important step in the fabrication process in order to avoid battery cable impingement during elbow motion.

The electric hand is now disconnected from the forearm and removed. The cosmetic foam forearm cover is placed over the forearm and a hole is made in the distal forearm cover so that the hand switch wire can be pulled externally (Fig. 5). Another hole is made on the anterior side of the forearm cover at the level of the ball receiver to allow connection to the Bowden cable (Fig. 5). The electric hand is now replaced and its power cable connected. A cosmetic hand glove is donned. When the cosmetic glove is rolled up over the wrist unit, it will cover the lead connector cable (Fig. 6).

In order to achieve hand removal for hook use, the patient rolls back the cosmetic glove, disconnects the hand cable and removes the hand. The hook is then attached to the forearm. The Bowden cable is removed from the ball receiver on the trip-switch (Fig. 7) and connected to an adapter cable which is part of the hook, thus achieving a hook / electric hand interchange (Fig. 1, 8).

The power plug for the hand battery charger unit is attached





FIGURES 7 and 8.
Hand / hook interchange is accomplished by removing the hand from the forearm, disconnecting the hand lead plug, disconnecting the cable from the ball receiver on the trip-switch unit, connecting the hook to the forearm and attaching the adapter cable from the hook to the Bowden cable (Figure 8.) (An interposition cable (Fig. 1) is an integral part of our standard hook. This interposition cable bridges the hook and the more proximally placed Bowden cable.)

to a leather circle on the posterior aspect of the socket just above the turntable. This leather circle is separate from the previously mentioned leather cover for the battery leadwire cable.

With this modified prosthesis, humeral flexion (figure 8 harness) for hook opening serves the same mechanism for trip-switch excursion with hand use; however, the patients do require some practice with the hand unit, since the biscapular range of motion for elbow flexion plus hook opening with a Bowden cable can be as much as 3 inches, whereas complete trip-switch travel is less than one inch. In addition, we have modified the standard 5-position trip-switch to a 4-position switch, so that full switch opening results in hand opening rather than neutral (no function). This latter modification is extremely important in order to achieve full control of hand function.

For hand-use-only with the Boston elbow unit (and no hook adaptation) the Bowden cable control can be removed entirely, the trip-switch can be mounted on the posterior aspect of the humeral section of the prosthesis, and the switch can be triggered by direct attachment to a harnessing strap rather than through a Bowden cable mechanism.

The adaptation as thus described with two battery packs allows extended elbow and hand function. Elbow function is approximately 8–10 hours from one battery charge and a quick charge (85 percent of capacity) can be accomplished in 10 minutes. Hand function is approximately 12 hours on a single charge—however, full hand recharge takes approximately 12–18 hours.

We are currently in the process of evaluating several more modifications to the Boston elbow which will allow either the 12-volt VA / USMC hand or the 12-volt Otto Bock electric / myoelectric hand to be fitted with the Boston elbow and powered from the 12-volt elbow battery pack. Changes in circuit design have been made, and early preliminary results suggest that prolonged (10–12 hours) elbow and hand function may be accomplished with this improved prosthesis, thereby obviating the need for a separate hand battery pack unit and thus simplifying the entire process of the fitting of an externally powered hand to a Boston elbow with or without the modifications to allow electric hand / hook interchangeability.

These more recent modifications in design and adaptability of components are part of our effort to construct a prosthesis for above-elbow amputees which uses one powered elbow, either switch or myocontrolled, which is interchangeable with existing externally powered or conventional prosthetic devices—and with the whole system powered by one battery proximally placed to increase elbow flexion efficiency, decrease forearm leverage, and increase battery life. At the present time, we have constructed a Liberty Mutual myoelectric elbow prosthesis which meets all of these requirements and is interchangeable with most of the externally powered terminal devices that are currently available. After further testing and refinement of this design process, we will be redefining the entire technique discussed in this present technical report.

Conclusion

Adaptation of the VA / USMC electric hand to the Liberty Mutual Boston myoelectric elbow is extremely simple and results, we feel, in improved patient function. The additional adaptation which allows electric hand / hook interchange gives the patient function and cosmesis and allows the patient individual adaptability for use of whichever terminal device may provide the patient maximum function. We feel that these adaptations allow us to have greater flexibility in fitting above-elbow amputee patients and in meeting their specific prosthetic needs ■

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Simple Living Aids for the Arthritic Patient

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Introduction

Assistive devices for patients with limb deficiencies (e.g., amputation, paraplegia, hemiparesis, severe arthritis) fall into two distinct categories, physiological and environmental. The physiological design concept is directed toward modifying the structure or function of the patient's physiology to provide some functional regain, as is done by limb prostheses (1,2,3,4), electrical stimulation of paralyzed limbs (5,6,7), tactile and kinesthetic feedback (8,9,10,11), etc. The environmental design concept is based on environmental modification and technical aids providing the effect of functional regain with or without augmenting the patient's limb functionality.

A classic reference by Lowman and Klinger (12) describing technical aids and self-help devices is no longer in print,

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[b] Ms. Feder has left the Home Secure project to take another position, but Home Secure is reported to be continuing under another director.

During the period described in this technical note, Home Secure was supported by the Area Agency on Aging, by the Councilman of the Fifth District of the City of Los Angeles, and by the Jewish Family Service of Los Angeles.

but a smaller version (13) has been prepared by Ms. Klinger for the Arthritis Foundation. Hale (14) has prepared a recent book covering the gamut of technical aids for many disabilities, with special attention to those useful in England. A variety of aids are described in the magazine "Accent on Living" (15) and in various catalogs. The Green Pages (16) is a compendium of sources (manufacturers or distributors).

A few examples of technical aids are eating devices (17), telephone systems (18), working accessories (18), cooking and personal hygiene devices (6), etc. The recent emphasis on standards for barrier-free environments (19) has been widely publicized.

While both design philosophies are equally effective for amputee, spinal-cord-injured and stroke patients, the second design concept is typically more effective for the arthritic patient. Such patients possess the physiological structure; function, however, is very limited. Current therapeutic measures center on alleviating the pain and increasing the range of movement; complete functional regain is not evident, especially with the elderly.

This note will report several living aids provided to arthritic patients, particularly the elderly, that resulted in satisfactory functional regain.

Methods

The objective of the project was to make it possible for arthritic patients to conduct daily tasks satisfactorily by moderate modification of their living arrangements. The modifications were selected to include primarily "off the shelf" items requiring as little development as possible. (No items that required any kind of research were considered.) It was also decided to consider only items that could be installed easily by a technician or craftsman such as a plumber or electrician (but not a graduate engineer) and that required very little or no maintenance; certainly no requirement for sophisticated maintenance procedures was allowed. Low cost was also a primary consideration.

Personal hygiene

Soap—A serious problem facing many arthritic patients is hand-washing. Most patients could not flex the hand enough to grab a bar of soap, or generate sufficient force to keep it in the hand. Such difficulties prevented many patients from maintaining clean hands and they often required the assistance of a relative or a friend for such functions.

A simple solution was found in a liquid soap dispenser attached over the bathroom sink. A flat hand was sufficient to press the outlet to obtain the soap, and the washing function could proceed with little need for hand flexion. Even a small dispenser contains enough soap for approximately 60 uses, and it can be occasionally refilled by a relative or a neighbor.

Several such dispensers are available with variations in soap volume and price. A good quality dispenser costs in the range of $4–$12, so it is reasonably inexpensive considering the extent of the functional regain provided.

Faucet—A similar problem was encountered during the hand-washing function: most faucet knobs are too small and round, again requiring extreme finger flexion as well as

EDITOR'S NOTE

Many of the papers published in the Bulletin describe relatively complex mechanical or electronic equipment. Such devices may be useful for improving the lives of disabled persons, but the necessary research, development, and evaluation require many years, and development and manufacture in moderate quantity are both likely to be expensive. One must always keep in mind the possibilities for simple aids, and be alert to see where modifications of common commercially available items may serve immediately at a small fraction of the cost of a special device.

There is, of course, a long (and in large part unrecorded) history of environmental modifications, tools, and technical aids: ramps and stairs instead of cliffs or ladders, chairs with arms instead of benches or stools, handrails, insulated or enlarged handles, pliers for heavy work but tweezers for fine tasks, etc. For several decades the International Committee on Technical Aids, Housing, and Transportation (ICTA) of Rehabilitation International has been particularly active on a more formal basis in collecting and disseminating, on a world-wide basis, information about a wide range of aids. Therapists in many countries have effectively helped their individual patients with simple devices.

There is no doubt that the headlong pace of the semiconductor revolution has unlocked an enormous range of hitherto unthinkable possiblities in rehabilitative technology. Further advances in polymers, fiber optics, etc., will probably compound those opportunities. However, students of fashion, history, and human nature will agree that we will surely often find ourselves struggling to apply a microprocessor where a piece of Velcro or a length of Bowden wire might more reliably do more at almost no cost.

As for applying existing simple objects in new ways to solve old problems, we like to think of Picasso and his inspired juxtaposition of a bicycle seat and handlebars. The vivid image of a ram's head that resulted stares at you from the pages of art history texts, a landmark in the development of visual imagery. The receptivity, intuition, and insight of a Picasso serve to remind us that genuine sophistication and the elegant solution (in science as in art) is likely to be expressed in surprising simplicity.

The writer of this paper is familiar to regular BPR readers as author or co-author of a number of articles and technical notes on prosthetics research and development. His interest in uncovering solutions at a cost level light-years below that of an advanced device employing current technical capabilities is interesting and even, perhaps, provocative.

Editor

generation of a large gripping force—both of which the patient is incapable of providing.

In order to utilize the small forces of which the patients are capable, a faucet knob with a long lever arm was selected. Such a long lever arm compensates for the small force available to provide the necessary torque to turn the knob. No finger flexion is required; the patient can apply the force with a normally-open hand, a forearm, etc.

Several such levers are available; some of them are fancy and expensive. A simple but functional unit costs $3–$5 and can be installed easily in a few minutes.

Bathroom floor—Because of the sloppy washing movements of such patients, some water eventually falls upon the bathroom floor, rendering it dangerously slippery, particularly in view of the weakness of the lower limbs. Many accidents have occurred, some of them fatal.

In order to increase the foot-floor contact under wet conditions, a friction tape was used. Several strips of such tape were attached to the floor near the sink and the tub. The tape thickness is several millimeters, so the top surface stays well above the puddles as well as providing the necessary friction for stable and balanced walking in the dangerous area. The cost, several dollars for a medium size bathroom, is minimal.

Handrails and grab bars—Often, when arising from sitting on the toilet, standing up is difficult due to the weakness of the lower limbs. An existing solution is the well-known grab bar strategically attached to the wall near the toilet. A combination of forces from the upper and lower limbs is normally sufficient to allow the patient to stand up. Such devices are already in use in bathrooms near toilets or tubs and will not be further elaborated here. The ANSI Standard (19) provides numerous examples, as well as standards for handrails on steps and ramps.

Appliances

Light switches—Several of the common table-top lamps are equipped with a small turn switch for the control of the light. Such switches require wrist or shoulder rotation, extreme finger flexion, and fine force regulation on the part of the patient, creating a complex task out of the simple function of light control. The same problem is also evident in the control of television sets.

A simple procedure to overcome such problems is the installation of a large pushbutton switch on the electrical wire of the appliance with the appropriate extension cord. The pushbutton switch is of the type that turns the current "on" with one push and "off" with the next. No finger flexion is required, and the function could be performed with either the fingertips or the palm or side of the open hand. The extension cord is cut to the appropriate length to allow the switch to be placed on the table top or on the top of the television set.

Extension cords could be purchased for $2–3 and the pushbutton switch costs about the same. Installation, again, is simple and fast.

Mobility aids

Grocery shopping aids—Grocery shopping is a major problem for the elderly arthritic patient. In our study, most such patients shopped at a store located 2–3 city blocks from their residence in a mid-city area with a large proportion of elderly residents. Walking is the common means of transportation. Two distinct difficulties are encountered; carrying the heavy grocery bag, and finding sitting or resting facilities enroute. The heavy grocery bag could not be carried at all by the patients with weak upper limbs. Sitting for rest purposes was often necessary two or three times along the route due to weakness of the lower limbs.

Many elderly patients use a carrying cart for the grocery bag. Such a two-wheel cart, with rubber tips on two additional legs, is made of lightweight aluminum. In order to provide the sitting-resting function, such a cart was modified by equipping it with a flat top surface hinged to the frame. When sitting is desired, the cart is parked upright, on the two wheels and two legs, and the top is lowered to provide a sitting surface. This modification is currently being considered for development and production. Utilizing existing carts, the cost for modification is minimal and within the guidelines of the project, when a sturdy cart with appropriate height of basket brim is selected.

Procedures

The project is conducted by Home Secure, located in the Fifth District of Los Angeles. Home Secure employs, on a part-time basis, semi-retired persons whose backgrounds are related to hardware, such as machinists, electricians, etc. The residents of the district are familiar with the services of Home Secure from previous services provided to them. The staff members (primarily social workers), while visiting elderly residents, compiled lists of problems; these were grouped into categories. The consultant would select those (usually about 40 percent) which could be undertaken immediately. The part-time employees are regularly sent to install the required living aids in the homes of the elderly requesting such services. Funding for Home Secure and for this project was provided by the Area Agency on Aging (AAA), the Councilman of the Fifth District of the City of Los Angeles, and the Jewish Family Service of Los Angeles. Some local hardware stores, becoming interested, provided items at wholesale.

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Methodology Devised for a Program to Improve Efficiency and Reduce Risks for Wheelchair Locomotion [a]

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ABSTRACT—The purpose of this paper is to present methodology specifically designed for objective study of problems associated with physiological stresses of manual wheelchair use. Excessive metabolic and cardiopulmonary stresses for everyday tasks could hinder rehabilitative efforts and be hazardous for certain patients. Sources of stress include: the relatively small musculature used for propulsion; architectural barriers; low levels of physical fitness; and inefficient wheelchair design. We propose that in order to reduce these stresses, quantitative data related to their mechanisms need to be derived. Therefore, we are conducting studies in the following areas;

1. Quantitation of metabolic, cardiovascular and pulmonary stresses of operating manual wheelchairs over various terrains;
2. Evaluation of physical fitness of wheelchair-dependent patients;
3. Improvement of physical fitness of wheelchair-dependent patients; and
4. Evaluation of the efficiency of various wheelchair designs.

This research to date has provided further understanding of problems related to wheelchair confinement and demonstrated techniques to alleviate them. In this way, wheelchair locomotion could become less stressful and thus contribute to a higher level of rehabilitation.

Introduction

Wheelchairs are frequently prescribed for patients with debilitating injuries and illnesses. As an alternative to walking, the physical stresses involved in operating a manual wheelchair are often underestimated by those who have never used one. Recent research indicates that manual wheelchair locomotion may elicit significant muscular, metabolic, cardiovascular and pulmonary stresses (1,2,3,4). These stresses may hinder rehabilitative efforts and impose risks upon certain patients, especially older individuals and those with impaired cardiovascular and / or pulmonary function (4,5).

Several factors which apparently contribute to the stressfulness of wheelchair locomotion include:

1. limited physical work capacity of the upper body musculature;
2. nature of the patient's disability;
3. improper operation of the wheelchair;
4. unnecessary architectural barriers;
5. deficient physical fitness of patients; and
6. inefficient design of wheelchairs.

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In reviewing the literature, however, little objective data are available concerning these factors. To enhance rehabilitation, such data seem important for recognition and elimination of architectural barriers to wheelchair use; for more objective prescription of wheelchairs; improvement of wheelchair user fitness, and for improvement in wheelchair design.

Therefore, the overall objectives of this project are to:

1. Develop instrumentation and methods to quantitate metabolic, cardiovascular and pulmonary stresses of operating manual wheelchairs over various terrains;
2. Develop instrumentation and methods for objective evaluation of the physical fitness of wheelchair-dependent patients;
3. Develop instrumentation and design exercise programs to improve the physical fitness of wheelchair-dependent patients; and
4. Develop instrumentation and methods to objectively evaluate the efficiency of various wheelchair designs.

The purpose of this paper is to present the methodology and protocols specifically designed to achieve these objectives.

Materials and Methods

Subjects—Aspects of this research project involve both wheelchair-dependent (WD) patients and able-bodied subjects. The majority of these subjects are male and female volunteers from the Dayton Veterans Administration Medical Center and Wright State University. The WD subjects' disabilities are primarily lower body in nature. Prior to testing, each subject is familiarized with test procedures and instrumentation, and informed of the purpose of the particular study, the extent of their participation, any known risks, and their right to terminate participation at will without penalty. Each subject signs an informed-consent form as an expression of understanding. The protocol and procedures of this research project have been approved by the Medical Human Subjects Review Committee of Wright State University.

Research Facilities—To conduct this comprehensive project two complementary laboratories were developed, the Physiology Research Laboratory at the Dayton Veterans Administration Medical Center and the Laboratory of Applied Physiology at the Wright State University School of Medicine. A major portion of "in-field" testing has been conducted at Wright State University, which has an underground tunnel system connecting all buildings. This tunnel system provides various terrains (cement, tile, carpet and ramps) and offers all-year-round weather protection. Ambient temperature and relative humidity are maintained at a fairly constant 20°C and 50 percent, respectively.

Physiological Variables—Where appropriate, the following physiological variables are determined.

Metabolic and Pulmonary Stresses. Oxygen uptake ($\dot{V}O_2$, liters · min^{-1} STPD), carbon dioxide output ($\dot{V}CO_2$, liters · min^{-1} STPD), pulmonary ventilation ($\dot{V}E$, liters · min^{-1} BTPS), respiratory exchange ratio (R, $\dot{V}CO_2 \cdot \dot{V}O_2^{-1}$) and ventilatory equivalent of oxygen ($\dot{V}E \cdot \dot{V}O_2^{-1}$) are determined by open circuit spirometry (6,7,8). For most studies, subjects breathe via a two-way breathing valve (Collins "J") and expired gases are collected over a specific time period in a Douglas bag. Oxygen and carbon dioxide concentrations are then determined by an electrochemical O_2 analyzer (Applied Electrochemistry S–3A) and an infrared CO_2 analyzer (Beckman LB–2). Both analyzers are calibrated before and during testing with room air and reference gases of known O_2 and CO_2 concentrations. Expiratory gas volume is measured by a dry gas meter (Parkinson-Cowan CD–4) which has been modified for digital readout (9), and calibrated against a 120-liter Tissot gasometer.

Net locomotive energy cost (NLEC, net kcal·kg^{-1}·km^{-1}) is derived from the following computation (8):

$$NLEC = (E\text{-}e)\ (Wt \cdot D)^{-1}$$

where:
E = gross caloric output in kcal
e = resting caloric output in kcal
Wt = subject's weight in kg
D = distance traveled in km

Caloric outputs for substrates utilized are determined from $\dot{V}O_2$ and R values. NLEC provides an index to express the relative energy cost (corrected for resting metabolism and body weight) per kilometer of distance travelled. It is inversely related to the efficiency of locomotion—the lower the NLEC the higher the efficiency, and vice versa.

Cardiovascular Stresses. The electrocardiogram is recorded via direct leads (Electronics for Medicine VR-6) during data collection in the laboratory, or via radiotelemetry (10) during in-field data collection. Heart rate is continuously monitored during all studies by a portable cardiotachometer (Gedco CT–2). Arterial blood pressure (systolic and diastolic) is obtained from a stabilized arm with a sphygmomanometer by auscultation. Cardiac output, ventricular stroke volume and arteriovenous oxygen difference are determined non-invasively by either CO_2 rebreathing (11) or impedance cardiography (12) techniques.

Specialized Instrumentation—To perform many of this project's studies, specialized instrumentation had to be designed and constructed.

In-Field Instrumentation. Figure 1 illustrates instrumentation which is used for in-field data collection of basic metabolic ($\dot{V}O_2$, $\dot{V}CO_2$, R) and cardiopulmonary (HR, $\dot{V}E$) variables (8). To set and maintain locomotive velocity, a pace cart (Figure 1A) is pushed by a technician directly in front of the test subject in the wheelchair (Figure 1B). This cart, which was adapted from a wheelchair, was equipped with an electronic speedometer, odometer and timer. Another technician, wearing a Plexiglas board on which data collection instrumentation was mounted (Figure 1C) is seen following the test subject. This portable instrumentation consists of a 60-liter Douglas bag, 3-way valve, cardiotachometer, and timer.

To quantitate power output requirements for manual wheelchair locomotion under a variety of conditions, an electronic system which utilizes wheelchair pushing force measurements[a] was designed and constructed (13). With

a See "Appendix" for author's comments on converting his metric nomenclature into SI terms.

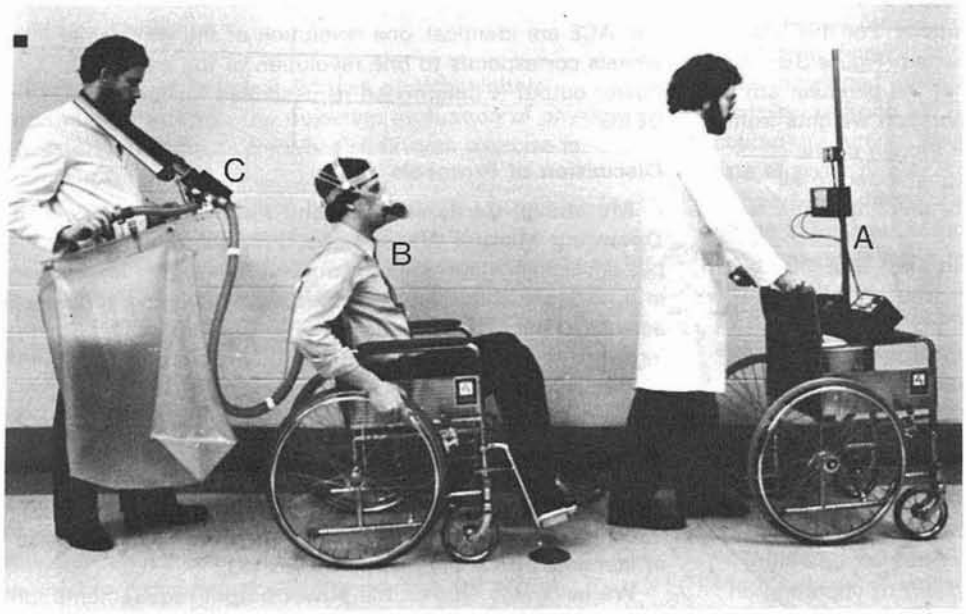

FIGURE 1.
Instrumentation used for in-field data collection of metabolic and cardiopulmonary variables. (A) pace cart, (B) subject, (C) data collection instrumentation.

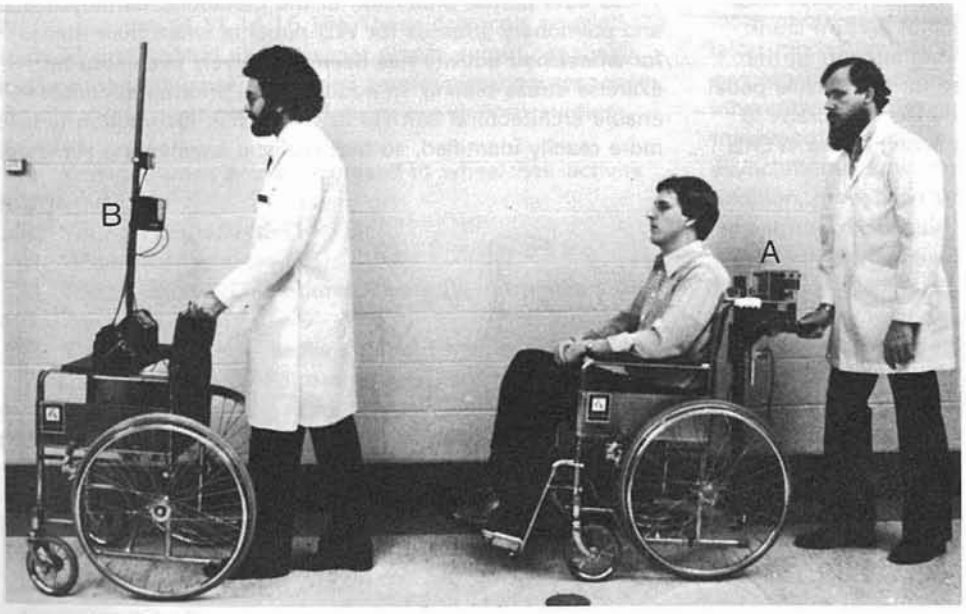

FIGURE 2.
Data collection of average wheelchair pushing force. (A) straingage bridge transducer and electronic integrator, (B) pace cart.

this system (Figure 2), power output (kpm · min^{-1}) to propel a manual wheelchair is calculated from the average force (kp) necessary to push a wheelchair and its occupant multiplied by the propulsion velocity (m · min^{-1}). Average pushing force is obtained by a strain-gauge bridge transducer and an electronic integrator mounted on the back of a wheelchair (Figure 2A). Wheelchair velocity is obtained by the abovementioned pace cart (Figure 2B).

Laboratory Instrumentation. For the laboratory determination of physiological responses to wheelchair activity, a stationary wheelchair ergometer (WERG) was designed and constructed (6,14). This instrument, which is illustrated in Figure 3, allows the precise setting and maintenance of power output (PO) to simulate actual wheelchair operation under various conditions. Therefore, it may be used for fitness evaluation tests (4,14), exercise training (4,15,16) and comparative wheelchair-bicycle locomotive stress studies (4,6,17). This WERG is basically an extension of the popular Monark bicycle ergometer (BERG). Wheelchair wheels were mounted on a solid steel axle which was supported by low-friction ball bearings. A chain and sprockets coupled this axle to the flywheel of the BERG. Standard gearing of the Monark was retained so that each wheelchair wheel revolution corresponded to one bicycle pedal revolution. During each rotation, the flywheel "travels" 6 meters. An electronic speedometer (Figure 3A) is observed by subjects to maintain the desired wheelchair wheel (and flywheel) velocity. An electronic wheel revolution counter (odometer) and stopwatch allow precise monitoring of the distance "traveled" over a period of time. The standard flywheel friction belt was used, but because of the relatively low braking forces required for the WERG, the measuring

scale was modified to increase its sensitivity. For this, the pendular arm was lightened and lengthened (Figure 3B). An expanded scale (Figure 3C) at the end of the pendular arm is appropriately calibrated by hanging calibration weights from the friction belt. To account for internal friction of the ergometer, a constant force of 0.035 kp is added to all braking force readings. Power output for this ergometer is calculated as follows:

$$PO\ (kpm \cdot min^{-1}) = \text{braking force (kp)} \times \text{flywheel velocity } (m \cdot min^{-1}).$$

Arm cranking is also a useful mode of exercise for WD patients. Figure 4 illustrates a combination wheelchair-arm crank ergometer (WERG-ACE) which permits the precise setting and maintenance of power output for both wheelchair and arm crank exercise (11,18). This instrument, therefore, enables either mode of arm exercise to be used for stress testing and training of WD patients. In addition, it facilitates studies which compare physiological stresses for operating the conventional handrim propulsion system to operating an arm crank propulsion system at identical power output levels. The WERG-ACE is similar in design to the above described WERG-BERG. The primary difference is that an arm crank assembly, which was inserted into the seat support of the Monark bicycle ergometer, is substituted for the bicycle pedal assembly. A chain and sprockets coupled the arm crank to the flywheel of the Monark. Since the gearing of the WERG and ACE are identical, one revolution of the wheelchair wheels corresponds to one revolution of the arm crank. Power output is determined as described for the WERG-BERG.

Discussion of Protocols

Metabolic, Cardiovascular and Pulmonary Stresses of Operating Manual Wheelchairs Over Various Terrains. To put physiological stresses for manual wheelchair locomotion in a more understandable perspective, we compared this arm activity to more familiar modes of locomotion which use the legs. For this, we studied metabolic, cardiovascular and pulmonary stresses for:

1. Wheelchair locomotion and walking on a hard, smooth level surface at the same velocities (4);
2. Wheelchair locomotion and walking on level tiled and carpeted surfaces at the same velocity (8); and
3. Wheelchair ergometer and bicycle ergometer exercise at identical power output levels (4,6,17).

We have also studied the power output requirements for operating manual wheelchairs over various terrains (13,19). These data permit prediction of the metabolic, cardiovascular and pulmonary stresses for WD patients when their fitness for wheelchair activity has been objectively evaluated by exercise stress testing. In addition, this information could enable architectural barriers to wheelchair locomotion to be more readily identified, so that realistic engineering standards

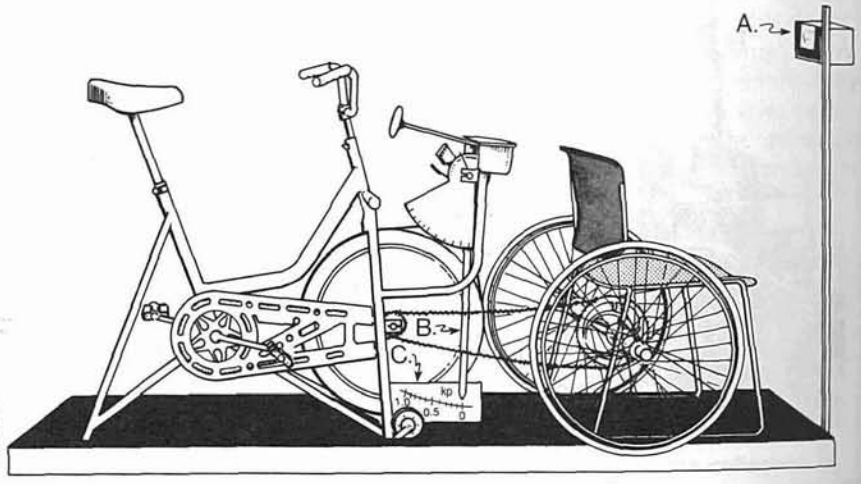

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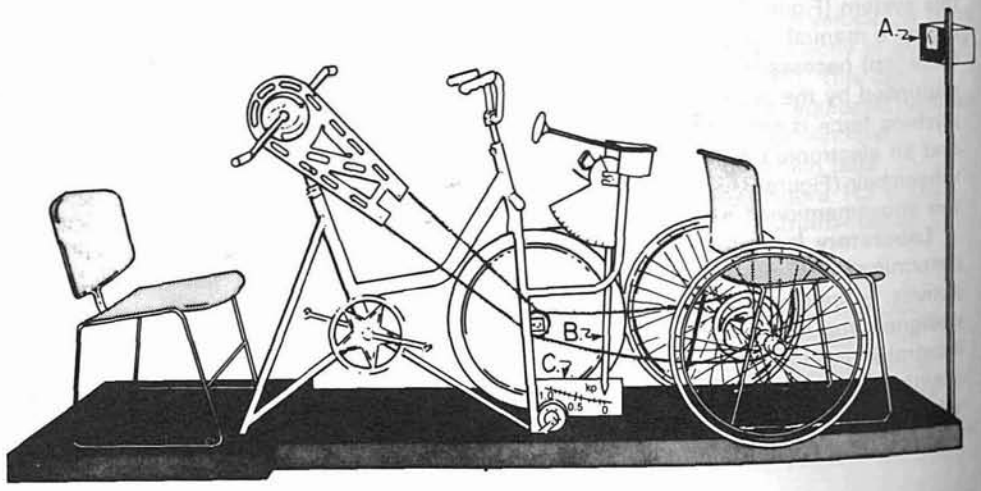
FIGURE 3.
Combination wheelchair-bicycle ergometer. (A) electronic speedometer, (B) lengthened pendular arm, (C) expanded braking force scale.

FIGURE 4.
Combination wheelchair-arm crank ergometer. (A) electronic speedometer, (B) lengthened pendular arm, (C) expanded braking force scale.



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could be established.

Evaluation of Physical Fitness of Wheelchair-Dependent Patients. The objective evaluation of physical fitness of WD patients for wheelchair-type exercise is important for:

1. Predicting capabilities and limitations of patients for wheelchair locomotion over various terrains;
2. Prescribing wheelchairs and instructing patients as to their safe and effective operation;
3. Detecting changes in patient fitness over a period of time; and
4. Evaluating organ system function under stressful conditions (e.g., stress EKG).

Our wheelchair ergometer appears to be quite useful for evaluating physical fitness of WD patients by exercise stress testing. This instrument provides an exercise mode which closely resembles actual wheelchair locomotion (20). It also provides duplicatable power output levels which can be equated to those power outputs required for actual wheelchair locomotion.

We have developed several fitness evaluation protocols for WERG exercise (4,11,14,15,18). These protocols enabled the study of submaximal and maximal power output capability, and corresponding metabolic and cardiopulmonary responses for wheelchair-type exercise. Subject populations studied included:

1. Young women acutely exposed to wheelchair activity (4,14);
2. Young WD patients (11,18);
3. Wheelchair athletes (15);
4. Middle-aged WD VA domiciliary patient-members (5); and
5. Elderly WD VA domiciliary patient-members (5).

In addition to exercise stress testing, we have studied the anthropometry (stature, weight, limb circumference, skinfolds, percent body fat, and grip strength) of elderly WD patients in comparison to ambulatory individuals of similar age (21). Such exercise stress and anthropometric data provide insight into the impact of wheelchair confinement on fitness.

Physical Fitness Improvement of Wheelchair-Dependent Patients. Excessive cardiopulmonary stresses elicited by manual wheelchair activity may in part be due to the users' lack of fitness for upper body exercise. Upper body fatigue may discourage patients from wheelchair locomotion of sufficient intensity and duration to develop and maintain their muscular and cardiopulmonary fitness. A lack of activity may subsequently lead to further losses of physical fitness, and compound rehabilitation problems. Therefore, exercise training programs specifically designed for WD patients may help enhance rehabilitation by improving fitness and reducing the relative stresses of wheelchair locomotion.

To improve one's fitness for wheelchair activity, an exercise mode that specifically resembles wheelchair locomotion is desirable. The wheelchair ergometer appears to be well suited for this purpose. Prior to initiating an exercise training program, and at the conclusion of the program, patient physical fitness could be objectively determined by the protocols described in the previous section. In this way, the effectiveness of the exercise training program could be evaluated by fitness improvement.

To help develop and maintain fitness of WD patients, we have developed interval training programs (intermittent exercise) utilizing WERG exercise (4,15,16). During the course of training, fitness improvements tend to lower heart rate at given power output levels. The continuous monitoring of heart rate during training permits the power output level of the WERG to be increased appropriately to maintain the target exercise heart rate. The effectiveness of these interval training programs for improving fitness have been evaluated by pre- and post-testing the subjects with the WERG fitness evaluation protocols.

Evaluation of the Efficiency of Various Wheelchair Designs. Wheelchair locomotion via the conventional handrim propulsion system has been shown to be inefficient (energy wasteful) (4,6,22) and relatively stressful to the cardiovascular and pulmonary systems (1,2,3,4). Modifications of wheelchair design may improve efficiency and reduce physical stresses encountered by users. In comparing wheelchair propulsion to more efficient modes of locomotion, as walking and bicycling, it is evident that the latter modes employ asynchronous (reciprocal) rather than synchronous (even) limb movements. Since the body may inherently be better suited for asynchronous patterns of movement, wheelchair propulsion systems which permit asynchronous limb movements may be advantageous. In addition, propulsion systems which provide for altering the wheelchair drive ratio (via a gear shift transmission, etc.) would enable mechanical advantage adjustments to facilitate locomotion over various terrains. In this way, the propulsion force-velocity relationship may be altered to permit better matching of the locomotive task to the patient's ability.

To study potential advantages of wheelchair locomotion utilizing asynchronous limb movements over conventional synchronous application of force to the handrims, the wheelchair ergometer was used (7). Because of its stationary nature and its solid axle, the WERG permits both synchronous and asynchronous force application to the handrims. In this way, metabolic and cardiopulmonary responses to both methods of propulsion were compared at identical power output levels. To further study asynchronous propulsion, arm cranking was compared to conventional synchronous handrim propulsion at submaximal (11) and maximal power output levels (18). For this, the combination WERG-ACE was used to equate power output levels. (We have recently completed an in-field study of a wheelchair which utilizes an arm crank propulsion system.)

Potential advantages of altering wheelchair drive ratios were also studied (7). Normal, "high" and "low" drive ratios were simulated on the WERG. For this, power output was held constant while handrim velocity and force were inversely adjusted.

To help facilitate the evaluation of various wheelchair designs, the previously described pushing force instrumentation may be used (13). This system permits the calculation of power output requirements for operating a wheelchair over given terrains. From these data, design alterations may be incorporated to minimize the power output required to propel a wheelchair.

CONCLUSION

Individuals who are unable to walk rely heavily upon wheelchairs for rehabilitation. Our research indicates that manual wheelchair locomotion is inefficient and stressful to the muscular, cardiovascular and pulmonary systems. To improve rehabilitation, these stresses should be reduced. Studies which we have performed thus far suggest that much can and needs to be done to alleviate problems associated with wheelchair confinement ■

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APPENDIX: Definitions relating to SI units of force, work, and power.

FORCE. One kilopond (kp) is a unit of force which acts on a 1 kg mass at the normal acceleration of gravity. One kp equals 9.80665 Newtons (N).

WORK. One kilopond-meter (kpm) is a unit of work which is equivalent to 9.80665 N·m or Joules (J).

POWER. One $kpm \cdot min^{-1}$ is a unit of power which is equivalent to 9.80665 $J \cdot min^{-1}$ or 0.1634 $J \cdot sec^{-1}$ (watt).