Chapter 3

REHABILITATION OF THE UPPER LIMB AMPUTEE

TIMOTHY R. DILLINGHAM, M.D., M.S.*

Formerly, Major, Medical Corps, US Army, Physical Medicine and Rehabilitation Service, Walter Reed Army Medical Center, Washington DC; currently, Associate Professor, Department of Physical Medicine and Rehabilitation, The Johns Hopkins University, Baltimore, Maryland 21239

INTRODUCTION

The devastating trauma suffered during armed conflicts results in substantial numbers of upper and lower extremity amputees. The care of amputees is a major problem facing any army during wartime. In the civilian setting, the primary cause of leg amputations is vascular disease,[1] which accounts for 90% of amputations. Other causes include trauma (7%), malignancy (2.5%), and congenital amputations (0.3%). Trauma is the leading cause of upper extremity (UE) amputations (75%), and typically involves males ages 15 to 45.[2]

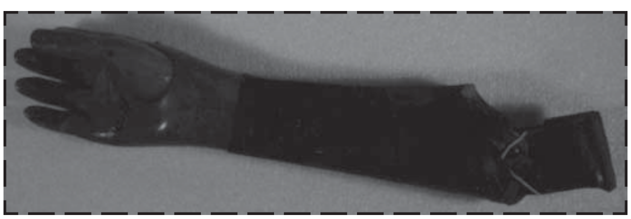
During the Civil War, 3 million troops were mobilized and 20,993 major amputations were documented in the Union Army.[3] Of these amputations, 8,518 were UE amputations and 12,475 were lower extremity amputations. Examples of 19th century post–Civil War era upper limb prostheses are shown in Figures 3-1 and 3-2.

The official statistics for World War II, covering the period between 1 January 1942 and 31 March 1946, indicate that in the Zone of the Interior (the continental United States), 14,912 amputees were treated, including 1,057 soldiers who had two amputations. This number does not reflect partial hand amputations not severe enough to impede continued military service.[3] Lower extremity amputations accounted for 10,620 of those treated, while 3,224 suffered UE amputations.

It is clear from these statistics that UE amputations are frequently seen in wartime and comprise a large percentage of the total number of amputees.

The importance of amputee care became obvious to planners during World War II when they realized that the Veterans Administration (currently, Veterans Affairs) hospital system could not handle the number of war injured amputees. Therefore, in 1943 the army was made responsible for both early care and definitive rehabilitation of amputees, ensuring that all amputees would receive maximum benefits prior to discharge from a military hospital.[4] Because of the enormous numbers of amputees, the U.S. military established five "amputation centers" at ports of debarkation. The major center was established at Walter Reed General Hospital (now known as Walter Reed Army Medical Center) in Washington, DC. The training of medical officers, therapists, and prosthetists was vigorously pursued to ensure that healthcare providers were up-to-date in the care of amputee soldiers.[4]

a



b

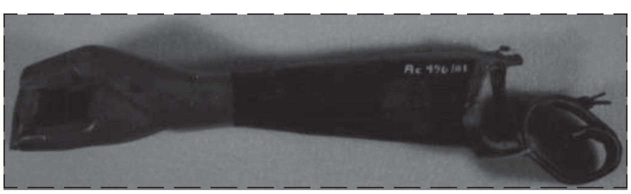
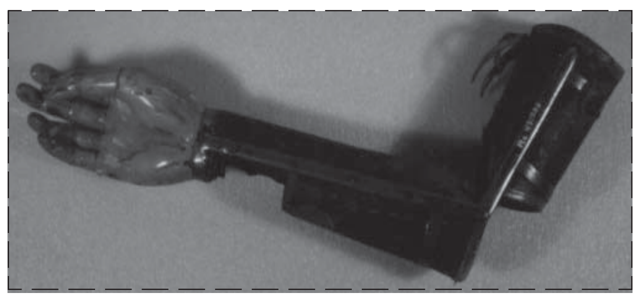


Fig. 3-1 (**a** and **b**). Below elbow prosthesis. Manufactured by Beaufort, in the United Kingdom, between 1875 and 1899. Photograph: Courtesy of Armed Forces Institute of Pathology Museum, Washington, DC.

a



b

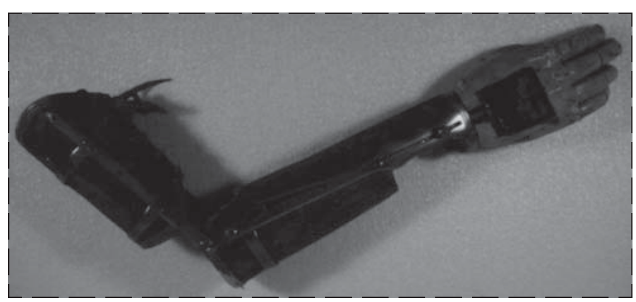


Fig. 3-2 (**a** and **b**). Above elbow prosthesis. Manufactured by Doerflinger Artificial Limb Co., in the United States, between 1875 and 1899. Photograph: Courtesy of Armed Forces Institute of Pathology Museum, Washington, DC.

Even with substantial resources dedicated to amputees, additional development of prosthetic technology was required to best meet the soldiers' needs. To refine and develop prosthesis construction, civilian consultants were used. Because the army was responsible for definitive prosthetic fabrication, contracts were established with companies for the purchase of large quantities of prosthetic devices.[4] For instance, UE prosthetic terminal devices (TDs) were purchased from Dorrance, Hosimer, and Becker companies.

In April 1943, the Office of The Surgeon General directed that all amputees be transferred as soon as possible to designated amputation centers; however, by 1944, it was clear that the original five amputation centers (Bushnell General Hospital in Brigham City, Utah; Lawson General Hospital in Atlanta, Georgia; McCloskey General Hospital; Percy Jones General Hospital in Battle Creek, Michigan; and Walter Reed General Hospital in Washington, DC) were inadequate to meet the needs of amputees sustained in a long and protracted global war. This was particularly true during the intense fighting in Europe during the winter of 1944–1945. Because army hospitals were responsible for the amputee's full rehabilitation, as well as early care, longer military hospital stays were required. For these reasons, two other amputee centers were established: the Thomas M. England General Hospital in Atlantic City, New Jersey; and McGuire General Hospital in Richmond, Virginia. Each hospital had its own prosthetic shop with trained prosthetists. To educate "orthopedic mechanics," three-month training courses were established at the amputee centers. Here technicians were instructed in fabrication of prosthetic devices. Servicemen with amputations were sometimes trained as prosthetists and utilized in limb fabrication shops.[4] The U.S. Surgeon General was

> …insistent that extreme care be exercised to ensure that the fit of each prosthesis was entirely satisfactory and that each amputee be taught to use his prosthesis competently before his discharge.[4]

Hand injuries were tremendously common during World War II. Bunnell, a distinguished hand surgeon who served as civilian consultant for hand surgery to the Secretary of War, described the scope of hand injuries in World War II. Although the statistics for hand injuries during the war (based on Zone of the Interior hospital experience) were inaccurate, an estimated 22,000 major hand injuries occurred in World War II.[5] As Peterson[3] points out, the number of amputations involving the hand was probably much higher than 3,224. Many finger and partial (nondisabling) hand and toe amputations were not seen in the Zone of the Interior hospitals due to the fact that these soldiers were able to continue their military service and remained in the theater of war. Hand injured patients were sent to designated "hand centers," where specially trained surgeons and therapists managed their wounds. Surgeons at these hospitals became quite proficient in hand reconstruction, and occupational and physical therapists played extremely important roles. In fact, these therapists were classified under "physical medicine."[5] The importance of rehabilitation in the functional restoration of the hand following surgery cannot be overemphasized. Bunnell stated that "in all patients in whom it was practicable, it was the general rule to institute early motion and mobilization."[5]

The military has a rich tradition of caring for amputees injured as a result of armed conflict. Indeed, the U.S. Army pioneered the field of amputee rehabilitation out of necessity. Intense wars produce enormous numbers of traumatic amputations in distributions quite different from those seen in civilian medicine. For this reason, amputee care in the military must remain at the forefront of technology, maintaining its readiness to assume the full care of an amputee soldier. Organized multidisciplinary rehabilitation services, initially under the direction of the primary surgeon and then the military physiatrist, must be established at medical centers. The World War II system, where designated amputee centers were established, provides a model for optimal, present day military amputee care. Major military hospitals with modern prosthetic laboratories, where dedicated expert prosthetists, occupational therapists, and physical therapists are organized as a rehabilitation team, are best suited to meet the specific needs of individual amputee soldiers. Early temporary prostheses and definitive state-of-the-art prosthetic devices must be provided to the amputee for full rehabilitation to occur. Early weight bearing using temporary prostheses has been found to be very beneficial to amputees. In fact, in World War I, the Belgian Army Medical Corps demonstrated that early weight bearing improved circulation, hastened stump shrinkage, and prevented muscle atrophy and contractures.[6] The Belgians felt that early ambulation was "far more useful than any form of physical therapy."[6]

In the event of an intense conflict, even of short duration, substantial numbers of soldiers will sustain amputations. The military medical centers must be able to accommodate these casualties. This chapter deals with the rehabilitative care of upper limb amputee soldiers, with continued emphasis on the importance of the amputee as the center of a coordinated interdisciplinary rehabilitation effort leading to fully functional restoration.

HAND AMPUTATIONS

Hand Amputations and Reconstruction

As discussed in the introduction, hand injuries are frequent war wounds. When a partial amputation of the hand is indicated, there are difficult choices regarding whether to reconstruct the hand or proceed directly with a prosthesis. Preserving all possible length is important for all amputations. This is particularly critical in the case of the hand.[5,7,8] There are many techniques for hand reconstruction following a partial amputation, but the scope of this text precludes a complete discussion of these. Interested readers are directed to a work by Bunnell titled *Management of the Nonfunctional Hand—Reconstruction Versus Prosthesis*.[9] This phenomenal work, according to Omer, presents principles which remain valid today.

The general principle regarding hand prostheses is that it is much better to have a painless hand with some grasp function and intact sensation than to have a prosthesis. The most important part of the hand is the opposable thumb. Preservation of sensate skin and all possible length of the thumb should be undertaken.[9] Reconstruction of the hand can provide greatly improved function after injury and should always be considered.

Phalangization of the metacarpals is a useful reconstructive technique in which the web space is deepened between digits, providing for a more mobile digit. This is often performed on the first web space and frequently coupled with rotation osteotomy of the first metacarpal, thus providing useful thumb opposition. An example of this phalangization of the first metacarpal is shown in Figures 3-3, 3-4, and 3-5. For this patient, the deepening of the web space provided improved opposition of the thumb.

Pollicization of a remaining finger can be used to reconstruct the thumb. For this procedure, a remaining finger with intact neurovascular structures and suitable length is moved with its nerve and blood supply to the site of the amputated thumb.[9] This reconstruction provides a sensate opposable digit to act as a thumb, enabling fine and gross grasp. Digit lengthening procedures involve creating a tube pedicle graft from the abdomen along with a bone graft.

The decision to reconstruct an injured hand requires the experience of a skilled hand surgeon who has knowledge of potential functional outcomes with both reconstruction and prosthetic training. In general, prostheses for hand amputations are inferior to the functional outcomes achieved with reconstructed hands.[9]

The optimal reconstructive techniques for thumb and partial hand amputations are delineated in Figure 3-6.[8] Reconstructive techniques for various levels of amputation, as described by Strickland,[8] are presented here. Adequate sensation at the opposing part of the thumb is very im-

Fig. 3-3. Phalangization of the first metacarpal by deepening the first web space (dorsal view).

Fig. 3-4. Phalangization of the first metacarpal (palmar view). Additional skin grafting was required to cover the cleft.

Fig. 3-5. The patient shown in Figures 3-3 and 3-4 demonstrating improved grasp.

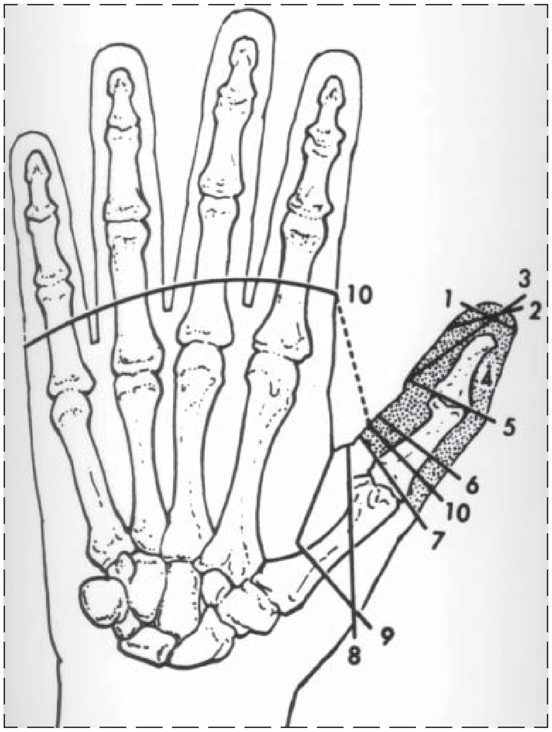


Fig. 3-6. The various thumb amputation levels. The optimal reconstructive procedure for each level is described in the text. Adapted with permission from Strickland JW. Restoration of thumb function after partial or total amputation. In: Hunter JM, Schneider LH, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand*. 2nd ed. St. Louis: CV Mosby; 1984: 755–796.

portant. An amputation occurring at level 1 (see Figure 3-6), requires a full thickness skin graft. For loss of part of the volar pad (level 2), a volar advancement flap is used, whereby the innervated skin from the thumb is transferred distally, with its nerve and blood supply, to cover the defect. At level 3, where the entire volar pad of the thumb is removed, a cross finger flap using sensate skin from the index finger is transferred. Degloving injuries, represented by level 4, are reconstructive challenges and are best approached by using a tubed abdominal pedicle flap to cover the defect, followed by a neurovascular island pedicle flap from another finger to provide sensate skin.[8] Amputation at the interphalangeal (IP) joint results in a functional thumb (level 5). A more proximal amputation through the proximal phalanx of the thumb (level 6) requires deepening the first web space—a phalangization procedure.

Amputation at the metacarpophalangeal (MCP) joint (level 7) can be reconstructed in several different ways. The thumb can be reconstructed by grafting iliac bone to the remaining thumb giving added length, then using skin from the dorsal and lateral aspects of the first metacarpal to cover the bone graft. This procedure, referred to as the "cocked-hat flap," can extend the useful thumb length by 2.5 cm.[8] Another option for this level is pollicization of an adjacent or partially injured digit by transferring the digit with its neurovascular supply to the first metacarpal. Amputation through the distal one-third of the first metacarpal (level 8), can be managed by pollicization of an injured or normal digit, or a lengthening procedure with bone graft, tubed abdominal pedicle flap, and an island pedicle flap placed on the prehensile surface of the extended thumb. Amputation at the proximal two-thirds of the first metacarpal (level 9) requires complete thumb reconstruction by pollicization of the index finger or an injured finger. Toe transfer can also be considered in this case.[8] However, as Beasley and de Bese[10] point out, a toe transfer does not replace sensibility of the working thumb surfaces as would an island pedicle flap from a noninjured sensate part of the hand. Loss of all digits and the thumb (level 10) can be managed by phalangization of the thumb remnant by deepening the first web space, giving the thumb remnant better grasp and opposition.

For single-digit amputations, a distal interphalangeal (DIP) disarticulation is an acceptable procedure.[10] When an index or a middle finger is amputated close to the proximal interphalangeal (PIP) joint, the ability to oppose the thumb is compromised. Ray resection of the injured finger and rebalancing the hand can yield an excellent functional and cosmetic result. For loss of the fourth or fifth finger, or the fourth or fifth metacarpal bones, a ray resection can provide an acceptable cosmetic outcome (Figure 3-7). According to Beasley and de Bese,[10] finger amputations shorter than 18 mm distal to the web space will not accommodate finger prostheses, hence preservation of this minimal length is important.

In the decision to reconstruct a hand, one must weigh the benefits against risks of the procedure. Issues that must be considered are (*a*) whether the procedure will provide sensibility of the grasping surfaces, (*b*) if the treatment will be socially (cosmetically) acceptable, and (*c*) the consequence of the resulting scars.[10]

Hand Rehabilitation

The importance of hand rehabilitation, both concurrent with amputation and subsequent to recon-

Fig. 3-7. A soldier who sustained a gunshot wound that injured the fifth metacarpal bone. Fifth ray resection resulted in a functional and cosmetically acceptable hand.

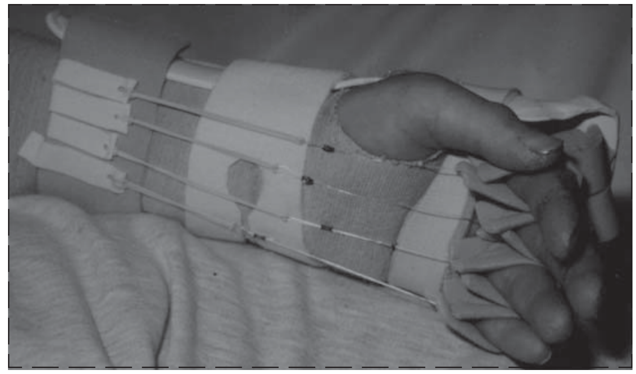


Fig. 3-8. A Persian Gulf War soldier who sustained fragment wounds of the arm, which caused severe nerve injuries, is shown with an orthosis utilizing elastic bands to provide prolonged stretch to contracted tendons and joints.

struction, cannot be overstated. In World War II, when the hand centers were established and Bunnell served as civilian consultant to The U.S. Army Surgeon General, Major General Norman T. Kirk, the rehabilitation of the hand was considered of paramount importance. Procedures for salvaging battle injured hands were taught to surgeons and rehabilitation teams at these centers:

> In all patients in whom it was practicable, it was the general rule to institute early motion and mobilization by activity and steady traction.[5]

Orthotics with traction devices, which applied steady pulling to mobilize joints, were used extensively. Figure 3-8 shows an example of such an orthosis used by a soldier wounded in the 1991 Persian Gulf War. This particular casualty sustained severe nerve injuries (not an amputation), but the same principles hold true for improving the range of motion with prolonged static stretch. Elastic traction is alternated in joint flexion and extension every few hours, providing prolonged range of motion in each direction.

Perhaps the most important means of ensuring optimal function following a reconstructive procedure is through rehabilitation that maintains or improves range of motion, increases strength of residual muscles, and incorporates the reconstructed hand into the casualty's daily activities. Occupational therapy plays a significant role in the rehabilitation process and works closely with surgical and rehabilitation teams. Education of the hand-injured soldier regarding injuries, prosthetic devices, and care of the residual limb, is crucial to maximal restoration. In addition, the amputee must be taught to use his noninjured limb and the prosthetic limb to achieve self-care and acquire vocational and leisure skills. Specially constructed adaptive devices may be required for these tasks[11]; for instance, Patricelli[12] describes a modified cutting board for a patient with a partially amputated hand. Early intervention, with temporary prostheses and rehabilitation training, greatly improves the ultimate acceptance and use of prosthetic devices.[13]

Hand Prosthetic Devices

The proper prosthetic device for a partial hand amputation must be prescribed based on a thorough knowledge of the patient. This includes obtaining detailed information about the soldier's daily activities, vocational interests and needs, avocational (recreational) desires, and expectations about the future with a prosthesis. A thorough physical examination, emphasizing the neurological assessment of strength and sensation, must be performed. Accurate assessment of the residual limb's range of motion and stability in all joints is also necessary. The soldier's cognition must enable the learning of necessary skills for prosthetic use. Vision is very important because a prosthesis provides little sensory feedback. There are many possible prosthetic devices that will effectively improve an amputee soldier's function. However, it is important to realize that function and satisfaction are the ultimate goals, and that frequently an amputee discards prosthetic devices, feeling they are no longer necessary and that they hinder optimal function. In general, partial hand amputations can be divided into several different categories with corresponding prostheses.

Fig. 3-9. A soldier who sustained frostbite injuries and who subsequently had transverse amputations of his second through fifth fingers is shown here using a finger prosthesis to grasp a coin.

Fig. 3-10. The soldier shown in Figure 3-9 with finger prosthesis containing the index and middle fingers (dorsal view) showing the Velcro closure.

Fig. 3-11. Palmar surface of the prosthesis shown in Figure 3-10. This prehensile surface is coated with foam rubber, which increases grasping friction.

Transverse Amputations

Transverse amputations occur at any level and involve one or more digits that can be replaced with cosmetic prostheses or functional finger prostheses. The use of a finger extension prosthesis demonstrating fine pinch is shown in Figure 3-9. It is important to be mindful of prosthetic fabrication principles for all prostheses. Thermoplastic materials contoured to the skin and bony surfaces are very useful.[14] In addition, the prostheses must be lightweight, durable, and washable. Figures 3-10 and 3-11 show how a prosthesis is fitted onto two remaining fingers with sufficient length. Foam rubber, covering active surfaces, increases friction (see Figure 3-11). This concept, demonstrated in Figure 3-12, shows how larger objects can be manipulated and grasped.

Fig. 3-12. Finger prosthesis used to grasp a cup.

Radial Amputations

White and HilFrank[14] categorize amputations based on the amputated side of the hand: radial, ulnar, or central. These combinations of amputations are shown in Figure 3-13. They represent major functional deficits resulting from the amputations, and facilitate conceptualization of appropriate prostheses. Radial amputations involve the thumb and index fingers and compromise fine grasp.[14] Prosthetic devices are fabricated to replace the opposition role of the thumb. Prostheses can be used with or without prior thumb reconstruction, or can complement a reconstructive procedure. Figures 3-3 and 3-4 show a thumb amputation at the MCP joint managed by deepening the first web space. Complementing this reconstructive procedure, a thumb prosthesis was fabricated with orthoplast and a Velcro closure (Figure 3-14). The prosthesis is placed over the thumb (Figure 3-15), effectively lengthening the amputated digit. Grasping is aided by a rubber tip placed on the end of the prosthesis. Functionally, prostheses are often used only for certain activities.

Surgical reconstruction improves the fine grasp of this injured hand (see Figure 3-5). A special thumb prosthesis for the same soldier is shown in Figure 3-16. It fits over the thumb and presents a curved, rubber coated surface that allows fine three-jaw chuck grasp with either the second or third fingers (Figure 3-17). Fine grasping abilities of this amputee, with and without a prosthesis, are contrasted in Figures 3-17 and 3-18.

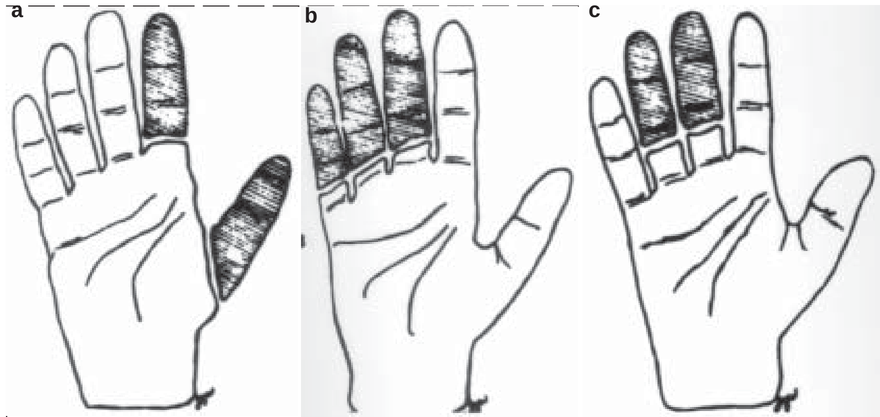


Fig. **3-13.** Classes of hand amputations. (**a**) radial amputations, (**b**) ulnar amputations, (**c**) central amputations. Adapted with permission from White JG, HilFrank BC. Prosthetic and adaptive devices for the partial hand amputee. In: Hunter JM, Schneider LH, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand*. 2nd ed. St. Louis: CV Mosby; 1984: 755–796.

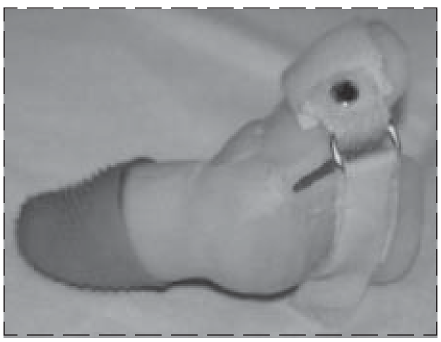


Fig. 3-14. Thumb prosthesis with rubber surface for opposition and a Velcro closure attaching it to the residual thumb.

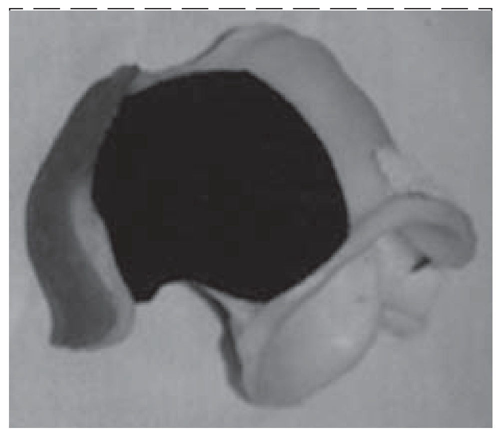


Fig. 3-16. Thumb prosthesis with curved surface for three-jaw chuck fine grasp.

Fig. 3-15. Thumb prosthesis as worn on the residual thumb by the amputee.

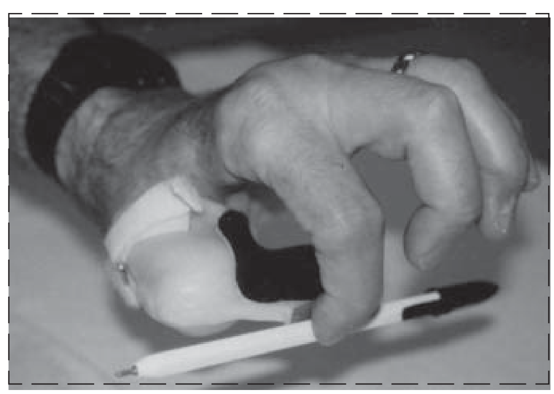


Fig. 3-17. Fine grasp with thumb prosthesis, which allows better opposition of the second and third fingers.

Fig. 3-18. Fine grasp without thumb prosthesis.

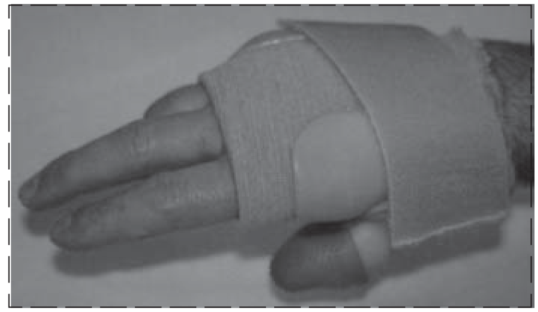


Fig. 3-20. Thumb prosthesis anchored to the residual limb.

Amputation at the proximal metacarpal of the thumb requires a prosthesis or reconstructive surgery. A thumb prosthesis for the right hand of a soldier with an amputation at this level is shown in Figure 3-19. The prosthesis encircles the hand across the metacarpals and is firmly anchored with a Velcro closure (Figure 3-20). A functional, three-jaw chuck grasp is illustrated in Figure 3-21. Figure 3-22 shows fine opposition with a thumb prosthesis opposing the index finger. This active duty soldier, injured in an accidental grenade explosion, was an avid racquetball player. To pursue his avocational goal, the racket handle was encased in a polymer prosthesis (Figure 3-23). The amputee's hand was placed into the prosthesis, and a Velcro closure snugly anchored the prosthesis and the racket to the hand (Figures 3-24 and 3-25). Similar devices can be fabricated to hold cameras, golf clubs, ski poles, and so forth, and the prosthetist or occupational therapist must work closely with the amputee.

Fig. 3-21. Three-jaw chuck grasp using a thumb prosthesis.

Fig. 3-19. Thumb prosthesis for an amputation at the level of the proximal first metacarpal.

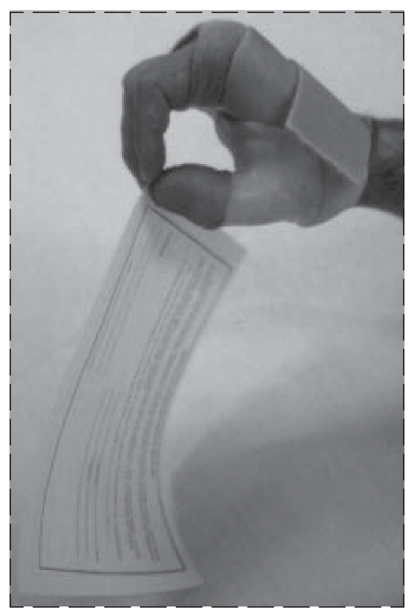


Fig. 3-22. Fine grasp using thumb prosthesis and second finger.

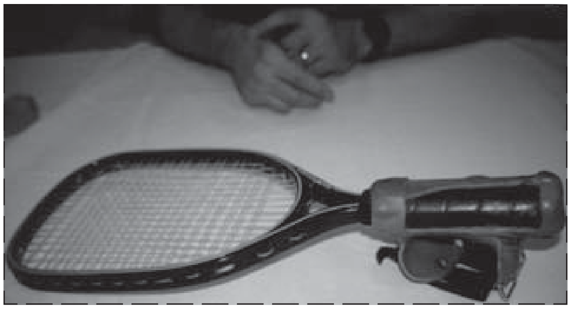


Fig. 3-23. Recreational prosthesis incorporating a racketball racket.

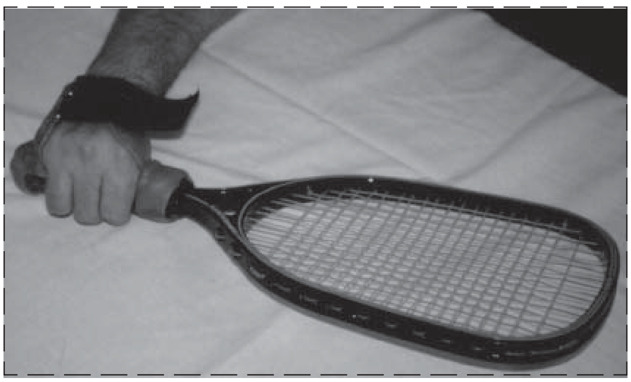


Fig. 3-24. Recreational prosthesis with Velcro closure enclosing the hand.

Fig. 3-25. Recreational prosthesis (palmar view).

Vocationally specific prostheses are also enormously valuable, particularly for soldiers pursuing careers requiring manual skills, such as a carpentry, machine work, auto mechanics, and so forth. Special prostheses enable an amputee to grasp tools and accomplish specific work tasks.

Ulnar Amputations

The fourth and fifth digits, when opposing the thumb or in a hook position, provide powerful grasp. Beasley[7] feels that the fifth finger's importance is greatly underestimated. Beasley and de Bese[10] state that a hand with only a fifth finger and a thumb function better than one with a thumb and an index finger. Full flexion of the fourth and fifth digits at the MCP and IP joints is crucial, and provides a powerful hook and cylindrical grasp.[7,14] Prosthetic substitutions for this function utilize the "scoop" concept.[14]

The scoop concept involves fabrication of a device, proportioned in size to the remaining digits, that will allow a large cylindrical grip and hook grasp. The thumb should be able to oppose this device comfortably. Figure 3-26 shows a soldier with transverse amputations of the middle and ulnar fingers at the MCP joints. A prosthesis for this soldier (Figures 3-27 and 3-28) fits over the distal end of the residual hand and extends proximally over the metacarpals on both palmar and dorsal surfaces, providing a firm attachment to the hand. In addition, a rigid loop passes between the thumb and index finger along with a Velcro strap encircling the wrist, firmly anchoring it to the hand, and enabling this soldier to carry books, briefcases, and other items. Again, a nonslip rubber palmar surface is

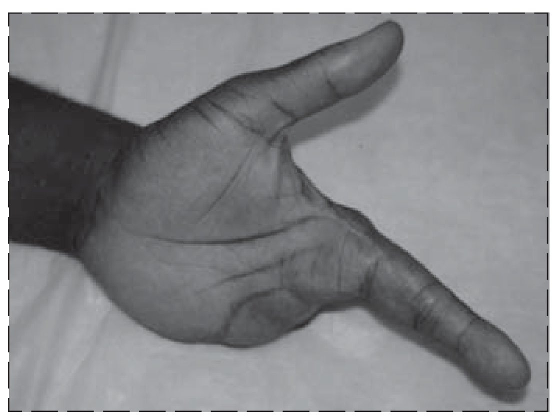


Fig. 3-26. Amputations of the middle, ring, and small fingers at the transmetacarpophalangeal level.

Fig. 3-27. "Scoop" type prosthesis (palmar view).

Fig. 3-28. Firm attachment of prosthesis to the residual hand by means of a Velcro closure (dorsal view).

incorporated into the prosthesis to facilitate grasp.

Central Amputations

Amputations of the middle or ring finger, if not surgically reconstructed, are easily managed with cosmetic prostheses.[7,14] Pillet[15,16] affirms the importance, to the amputee, of having a cosmetic substitute for the amputated part of the hand. For finger prostheses, there must be at least 15 to 18 mm of residual digit for the prostheses to be effectively secured. If the finger lacks this length, deepening the web space can improve suspension.[10,15] Indeed, many prosthetic users desire a functional prosthesis for work related activities and a more cosmetically acceptable prosthesis for social occasions.[10] To be of lasting benefit, cosmetic prostheses must be of high quality and must match the skin tone of the individual. Two shades of skin tone are recommended, one for winter and one for summer, so that skin tone can be matched to skin color changes due to tanning.[16] Also, fingernails and durability are important. Unilateral amputees, who have adjusted to the loss and express reasonable expectations, are optimal candidates for cosmetic prostheses. The bilateral amputee, however, usually places greater importance on the functional aspects of the prosthesis rather than on cosmetic issues.[15]

NOMENCLATURE AND FUNCTIONAL LEVELS

The following discussion addresses the nomenclature for all levels of UE amputations except the hand, which was discussed in preceding sections.

Broad categories of amputations include hand, below-elbow, and above-elbow amputations. Proximal upper limb amputations are called shoulder disarticulations and forequarter amputations (if they involve the pectoral girdle). Levels of amputation are shown in Figure 3-29.

As presented here, the term *residual limb* refers to the stump or remaining part of the amputated limb. To determine lengths of residual limbs, known anatomic points are used. Above elbow(AE) amputations are measured from the tip of the acromion to the bony end of the residual limb.[17] This length is compared to that of the noninjured side, from the acromion to the lateral epicondyle. The percentage of the amputated side relative to the intact side determines the percentages seen in Figure 3-29, which categorize the amputation levels based on functional implications.

Below-elbow(BE) measurements are made from the medial epicondyle to the end of the ulna or radius, whichever is longest in the residual limb. This measurement is divided by the length of the noninjured limb from the medial epicondyle to the ulnar styloid.[17] As in the case of AE amputation levels, functional implications are determined by the level of amputation. For the BE amputee, this primarily involves pronation and supination. BE levels determine forearm pronation and supination with a prosthetic device and affect the type of prosthesis prescribed.

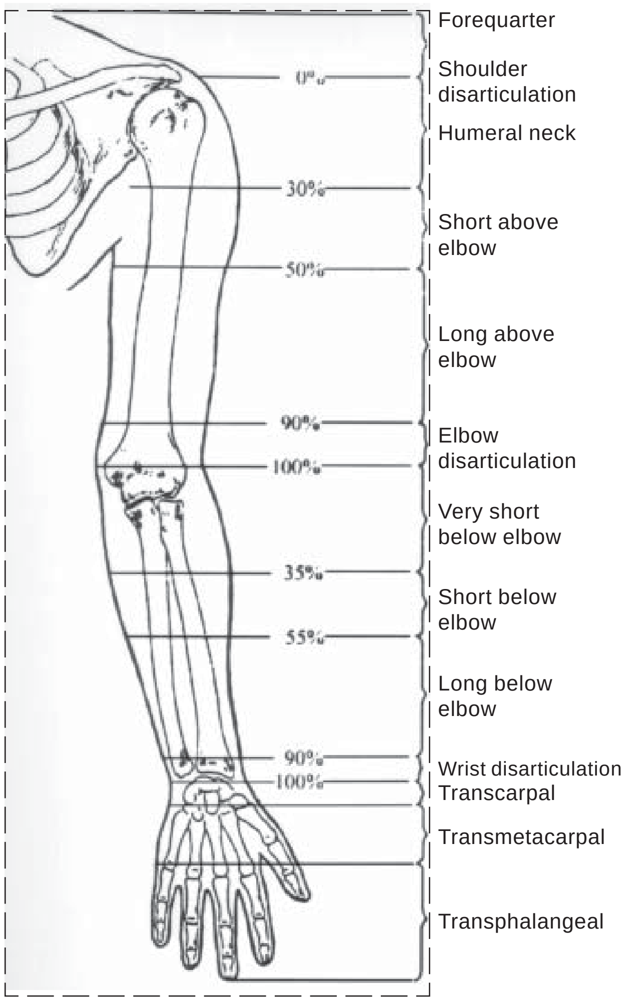


Fig. 3-29. The levels of amputation as defined by the length of the residual limb relative to the noninjured limb. Adapted with permission from Bender, LF. Upper extremity prosthetics. In: Kottke F, Lehmann JF, eds. *Krusen's Handbook of Physical Medicine and Rehabilitation.* 4th ed. Philadelphia: WB Saunders; 1990: 1011.

While wrist disarticulation amputations are rare,[18] Tooms [19]recommends that they are preferable to long BE amputations, because they preserve pronation and supination. Wrist disarticulations allow approximately 120° of pronation and supination compared with 180° in the normal case.[20] However, the actual amount of pronation and supination transmitted to the prosthesis is approximately 50% of that in the residual limb.[18] Modern wrist components easily accommodate this length of residual limb.

A long BE amputation is defined as 55% to 90% of the uninvolved extremity's length. This level preserves between 100° and 120° of pronation and supination.[20] However, pronation and supination decrease as amputation levels become increasingly more proximal. Long BE amputations provide residual limbs that are easily fitted with prosthetic devices. At this level, elbow flexion remains strong and easily transmitted to a prosthesis.

The short BE amputation, 35% to 55% of the corresponding noninjured side (see Figure 3-29), presents problems regarding pronation and supination. Here pronation and supination are absent, for all practical purposes.[20] Pronation and supination of the terminal device (TD) must be incorporated into the prosthesis by means of special wrist units.

Very short BE residual limbs (0%–35%) lack forearm pronation and supination. Additionally, elbow flexion range of motion and elbow flexion power are often reduced.[18] Suspension is often a problem. Elbow flexion range of motion can be increased with the step-up elbow joint, discussed later in this chapter.

The elbow disarticulation level poses some problems with prosthesis fitting, requiring an external elbow joint. Larger mediolateral dimensions of the humeral condyles pose difficulty in fitting a prosthetic socket, and a typical elbow unit would excessively extend the length of the residual limb. Shurr and Cook[18] feel the functional and cosmetic disadvantages of the elbow disarticulation make it suitable only for growing children, where preservation of the epiphysis for growth is important. However, Tooms[19] and McAuliffe[21] disagree and feel that elbow disarticulation is an excellent amputation level because it allows transmission of humeral rotation to the prosthesis. Modern prosthetic fabrication techniques can overcome the cosmetic and socket fit difficulties.[19,22]

The long AE level (50%–90% in Figure 3-29), is quite functional. A prosthesis can be fitted easily, glenohumeral actions are readily transmitted to the prosthesis, and ample muscles remain to control a myoelectric prosthesis (MP). In both the elbow disarticulation and long AE levels, the prosthetic socket terminates below the acromion and allows optimal shoulder movement.[20]

The short AE level (30%–50% shown in Figure 3-29) compromises transmission of glenohumeral motion to the prosthesis.[18] In this case, the prosthetic socket should extend over the acromion.[20]

Functionally, humeral neck and shoulder disarticulation levels can be classed together. These proximal levels lack the strong glenohumeral actions of flexion, extension, and abduction. Prosthetic sockets must extend over the shoulder and enclose part of the scapula and torso. It is important that all humeral lengths be preserved, even in the case of humeral neck amputations, as this residual length aids prosthetic fitting and stabilization.[19] Prosthetic shoulders often include frictional rotation units positioned by the other extremity. Patients generally use these prostheses to stabilize objects, rather than to lift or manipulate them.

Forequarter amputations and shoulder disarticulations usually result from tumor resection. This disabling amputation diminishes biscapular abduction by one half.[18] Myoelectric prostheses (MPs) present a prosthetic alternative for this level; however, difficulty often exists in locating and training myoelectric control sites. The prosthetic arm is attached to a molded frame and fitted around the torso, which stabilizes and suspends the prosthesis.

PRINCIPLES OF AMPUTATION SURGERY

Detailed discussion of surgical procedures encompassing upper limb amputations is beyond the scope of this chapter. The general principles, however, are important to the rehabilitation specialist, and other physicians and healthcare providers who manage war injured amputees. In many ways, war surgery is not analogous to civilian surgery. Special missions of the military, the often austere medical environment, and changing combat situations that require mobility of medical services pose substantial challenges to amputee care. The war environment often limits the sophistication of surgical techniques. For these reasons, principles of military medicine evolved to maximize early care and safe evacuation of an amputee.

The primary indication for amputation is to preserve life and depends on three factors: (1) the extent of the injury, (2) the patient's condition, and (3) the expertise of the surgeon.[23] To enable subsequent reconstruction, all possible length, along with usable skin and soft tissues, should be preserved during an emergent amputation. Preservation of a joint greatly improves a patient's subsequent function, even when there is a short limb below the joint. Basic principles of prompt antibiotic treatment, early vascular repair, and early debridement, and immobilization should be followed.

The extensive contamination of war wounds and the need for evacuation from battlefield hospitals to medical centers has led to the use of the open

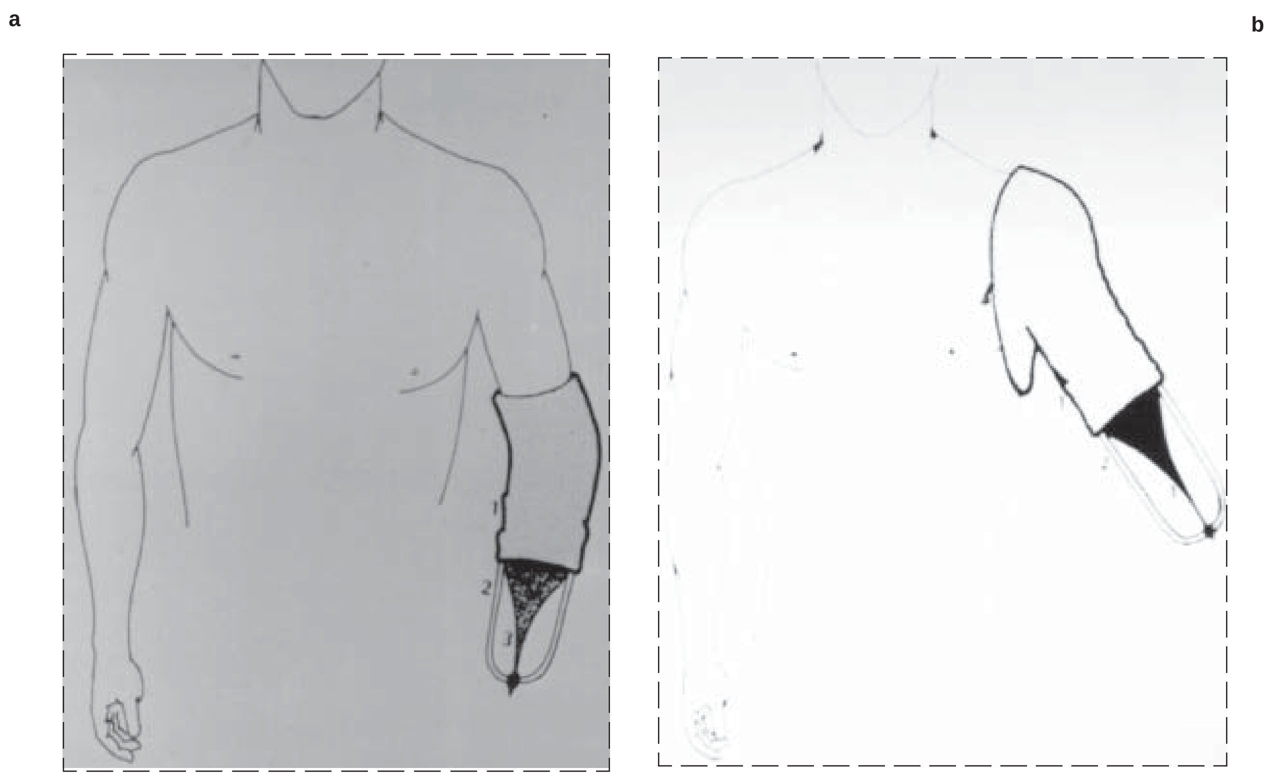


Fig. 3-30. Skin traction systems for (**a**) BE and (**b**) AE amputees. In both Figures, "1" is the cast placed over the residual limb, "2" is an attached frame, and "3" shows a stockinette placed under tension.

circular amputation as the most acceptable procedure in combat situations.[23] Open circular amputation involves severing the limb in layers: skin and subcutaneous tissues, muscle, then bone. Each layer is allowed to retract before incising the next layer, and muscle is retracted proximally before the bone is severed. This yields a stump with enough soft tissue to cover bone. During transport, skin traction is of paramount importance, and must be applied and maintained. The open tissues are dressed prior to transport, then a stockinette is placed over the residual limb and attached to the skin with tape or tincture of benzoin adhesive. Five or six pounds of traction are applied to the skin by means of a traction frame, often attached to a cast (Figure 3-30). All emergent amputations in the forward area are left open.[23] In many cases revision of a traumatic amputation is necessary.

For wrist disarticulations, the optimal surgical procedure utilizes a palmar flap from the hand to cover the distal stump, with resection of ulnar and radial styloids to minimize discomfort in the prosthesis.[19] Palmar and dorsal flaps in a 2:1 ratio provide good coverage.[24] The distal radioulnar joint, which preserves pronation and supination, should be saved.

Below elbow amputations use anterior and posterior flaps to cover the residual bone. Myodesis and myoplasty stabilize muscle ends and are important. For very short BE levels, the biceps tendon can be reattached to the ulna.[24]

Elbow disarticulation yields an optimal level.[21] The medial condyle, however, is sensitive to increased pressure, hence some surgical contouring of this prominence is useful.

For AE amputation levels, equal anterior and posterior flaps are used along with myoplasty of flexor and extensor muscles. If proximal amputations are necessary, it is important to retain the scapula whenever possible.[21] Sufficient skin and soft tissue to cover humeral disarticulations and forequarter amputations is quite important, and McAuliffe[21] recommends suturing remaining muscles to ensure padding and consistent muscle location for electromyographic (EMG) control should an MP be used. McAuliffe also recommends leaving the acromion and the coracoid process to increase leverage for body-powered prostheses. However, Baumgartner[25] suggests that for a shoulder disarticulation, removal of the coracoid process and articular part of the acromion eliminates excessively prominent bony projections, which may hinder prosthetic socket fit.

REHABILITATION

Early Rehabilitation

Rehabilitation of an upper limb amputee should begin as soon as possible following injury. Early intervention by a multidisciplinary team provides the best rehabilitative care, allowing the amputee to achieve the highest possible level of function. Following a traumatic amputation, primary treatment efforts at field hospitals include thorough debridement with preservation of the maximal limb length. Early rehabilitative interventions begun soon after injury can prevent complications of immobility, deconditioning, decubiti, and contractures. Preventing these problems facilitates rapid functional recovery. The concepts delineated in this section pertain to all upper limb amputees.

During armed conflict, there is often a significant time lapse between the time of the injury and the amputee's arrival at a medical center with rehabilitation services. Dillingham and colleagues,[26] demonstrated that most casualties arrived at medical centers in Europe and the United States about 19 days after evacuation from the Persian Gulf War theater. However, there was marked variability, with some casualties incurring much longer transport times.

During transportation, the primary concern with regard to the amputee is that adequate skin traction be constantly applied to prevent skin and subcutaneous tissues from retracting. By their very nature, battle wounds generate large amounts of debris that can contaminate wounds. Although most amputations should be allowed to close by secondary intention, in war situations it may be useful or necessary to perform secondary suture closure on some.[23] When the amputee is managed at a major medical center, surgeons decide when the wound can be closed.

In World War II, the open circular technique with skin traction was U.S. Army policy.[6] The three standard principles were (1) amputation at the lowest level permitting removal of devitalized tissues; (2) nonclosure of the wound; and (3) immediate skin traction, continuing until the residual limb healed. Certainly, during modern wartime these concepts should be followed.

As soon as possible, rehabilitation professionals should begin the rehabilitation process. Initially, this is often a consultative role. After surgery, transfer to a rehabilitation service, with a team of professionals under the direction of a physiatrist, provides the best possible environment for the rehabilitation of an amputee.[27] The rehabilitation team optimally includes a physical therapist, a primary nurse, an occupational therapist, a prosthetist, a psychologist, a social worker or military administrative specialist, and a vocational counselor, in addition to a physiatrist. Although a vocational counselor frequently is unavailable at military medical centers, early consultation by a local Veterans Affairs Medical Center vocational counselor can improve vocational rehabilitation.[27] This large rehabilitation team is clearly possible only at designated military medical centers and not at corps level or evacuation hospitals.

The primary rehabilitation goals are prevention of contractures and decubiti, prevention of excessive muscle atrophy, and maintenance of skin traction on the residual limb. Contracture formation occurs very quickly due to multiple causes: edema, nerve injuries, fractures, and immobilization. During the Persian Gulf War, 10% of the lower limb casualties and 9% of the upper limb casualties who were referred to Army Physical Medicine Services suffered contractures, which complicated rehabilitation efforts.[26] To minimize these problems, all joints must be put through their full range-of-motion exercises whenever possible. Joints that are not moved regularly can form dense collagen in a disorderly fashion within four days, causing gross limitation of movement.[28] When joints are mobilized, loose connective tissue is continually formed.

Contractures are more easily prevented than treated. To prevent them, a joint should be put through its full range-of-motion exercises three times, twice a day.[28] If weakness prevents the patient from doing this, then a healthcare provider must perform this task. War injuries are often severe and life threatening. For these reasons, during acute care and evacuation, routine range-of-motion therapy may seem a secondary priority. It should be emphasized, however, that minimal intervention to prevent contractures will ultimately aid in the soldier's optimal functional restoration. Medics, nurses, therapists, and doctors can all provide joint range-of-motion therapy with very little training. Whenever extremities are taken out of their immobilization devices, if the attending physician gives approval, the joints of that extremity should be gently put through their full range of motion. For UE amputees, particular attention should be paid to preventing shoulder and elbow contractures. Maintenance of scapulothoracic motion, glenohumeral motion, elbow flexion and extension, and pronation and supination are very important.

With immobilization, muscle atrophy and deconditioning occur at an astonishing rate. At prolonged bed rest, a muscle will lose 10% to 15% of strength per week, and 50% in 3 to 5 weeks. Muscle contractions for a few seconds each day at 20% to 30% of maximal contraction will maintain strength.[29] Through early preventive measures, the amputee who maintains strength and mobility is better suited for rehabilitation.

A comprehensive rehabilitation program tailored to the individual soldier begins by obtaining a thorough database of knowledge regarding this person. The information is shared among the rehabilitation team members, and includes a detailed medical history and physical examination along with a comprehensive musculoskeletal evaluation for strength and mobility. Of particular concern to the UE amputee is adequate range of motion in all remaining joints of the residual limb; elbow flexion and extension; forearm pronation and supination; and shoulder flexion, extension, abduction, and adduction. Additionally, scapulothoracic motion and strength play critical roles in powering prostheses; hence, biscapular abduction, elevation, depression, and retraction must be evaluated. In the case of elbow disarticulations, humeral rotation is important. The residual limb must also be assessed for length, scars, and wound healing.

Current functional abilities of the casualty should be evaluated. During the Persian Gulf War, many UE amputees sustained serious wounds of other extremities, which compounded the functional problems brought on by the amputation.[26] Important evaluation elements include: hand dominance, phantom sensations or pain, education, military duties and other vocational interests, social support systems, current living situation, hobbies, ability to perform daily self-care activities, and recreational interests.[30]

Emotional aspects of a traumatic amputation pose considerable challenges for the patient and the care team. Psychological support in the structured, supportive, and educational environment provided by a cohesive rehabilitation team is vital and will help to ensure that emotional issues are adequately addressed.

Rehabilitation includes strengthening the residual limb muscles and the scapulothoracic muscles through active resistive training. Scapular abduction (or protraction) will generate tension in the control cable of a body-powered prosthesis. The muscles that provide this function are the pectoralis major, pectoralis minor, and the serratus anterior. Elbow flexion by the biceps brachii and the brachialis provide lifting capability for the BE amputee. Because significant chest wall scar tissue may impede chest expansion, increased chest expansion should be pursued, particularly if scapulothoracic mobility and strength are compromised because this can improve control cable excursion. For an AE amputee, the elbow locking control cable is powered by combined action of shoulder (scapular) depression, extension, and abduction.[31] The muscles controlling scapular depression are latissimus dorsi, trapezius (lower fibers), and pectoralis major and minor. Major extensors of the glenohumeral joint are latissimus dorsi, teres major, and the posterior deltoid. Muscles abducting the shoulder are the deltoid and supraspinatus. Strengthening these important muscles should be aggressively pursued. Improved range of joint motion, through passive and active prolonged stretching, along with cardiovascular conditioning are important goals to pursue.

Postoperative Prosthetic Fitting

In the case of traumatic upper limb amputees, a temporary prosthesis should be fabricated when the residual limb will tolerate it. This allows the amputee early use of the residual limb with a functional prosthetic device. The term, immediate postoperative prosthesis (IPOP), refers to placement of an immediate rigid plaster or fiberglass dressing in sterile fashion over the wound; this is done in the operating room. IPOP placement minimizes pain, prevents edema formation, facilitates healing, and allows early prosthetic training.[13,17,32] War-injured amputees can be given this type of prosthesis while the open wound is healing by secondary intention, or immediately following definitive closure of the wound. This decision is, of course, made by the primary surgical physicians in concert with input from the rehabilitation team. Residual limbs that require daily monitoring for infection, skin graft success, and so forth, should not be fitted with an IPOP.

Construction of the IPOP is accomplished by covering the wounds with sterile dressings and stockinette followed by application of elastic plaster of Paris.[17] A rigid fiberglass cast material, applied over the plaster, gives added strength. Suspension straps are easily embedded into the layers of cast material. The prosthetist can add the cable housings and harnesses necessary to operate the prosthesis. The IPOP remains in place for a week or so, then is removed and replaced with a new rigid dressing. This process continues until the residual limb has matured and is ready for a more definitive prosthesis.[17] If an IPOP cannot be used due to surgical constraints (skin grafts, etc.), or the need to be able to view a residual limb, a temporary or intermediate prosthesis that can be easily removed, should be fabricated by the prosthetist at the earliest possible time.

Removable temporary prostheses are frequently fabricated from elastic plaster, forming a comfortable inner enclosure for the residual limb. Fiberglass cast material is placed over this to provide strength and a rigid frame onto which prosthetic components can be attached. If a temporary prosthesis cannot be used, then elastic wrapping (Figures 3-31 and 3-32) or elastic stockinettes should be used to mobilize and prevent edema formation in the residual

a

b

Fig. 3-31. (*Continues*)

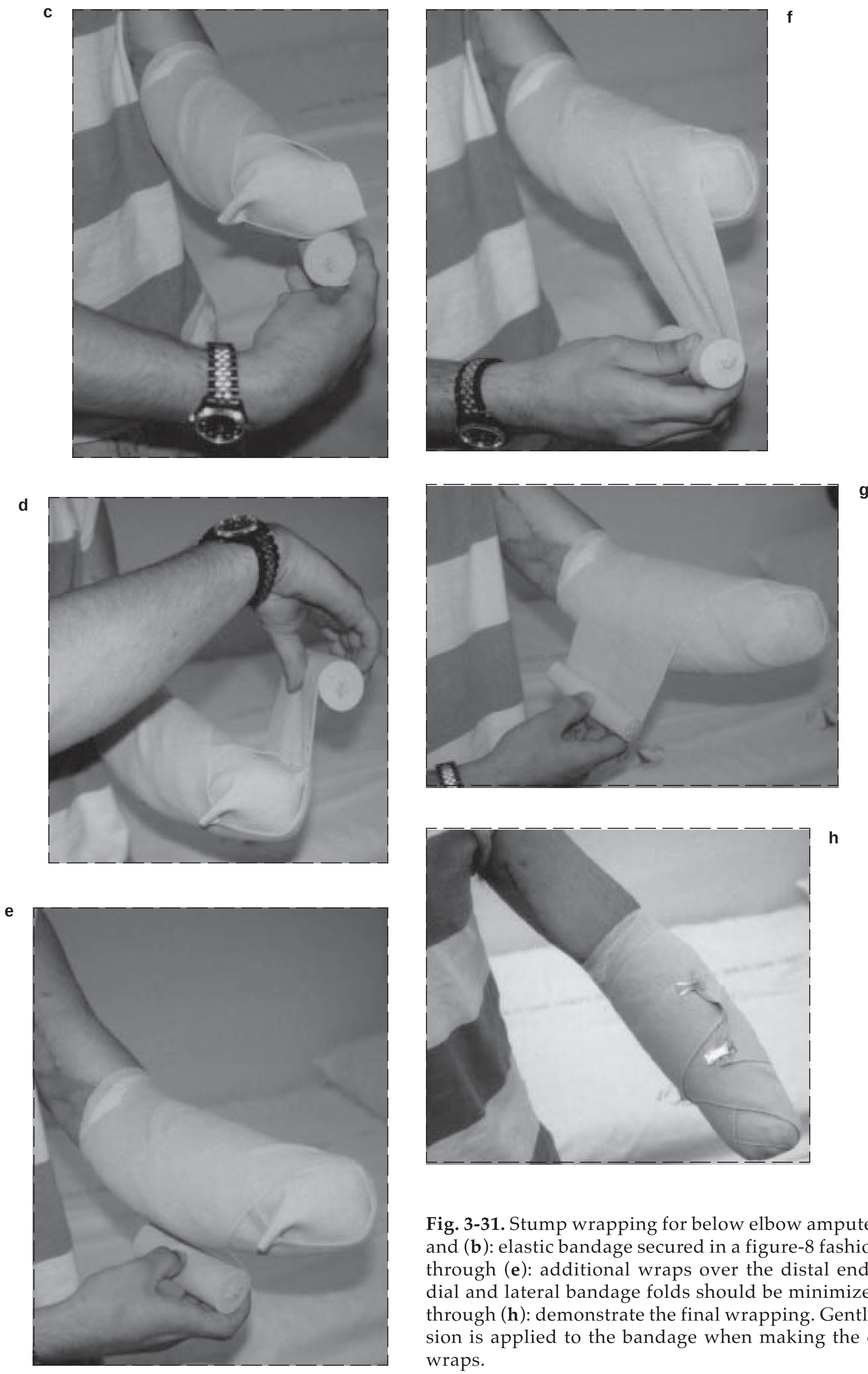


Fig. 3-31. Stump wrapping for below elbow amputee. (**a**) and (**b**): elastic bandage secured in a figure-8 fashion. (**c**) through (**e**): additional wraps over the distal end; medial and lateral bandage folds should be minimized. (**f**) through (**h**): demonstrate the final wrapping. Gentle tension is applied to the bandage when making the distal wraps.

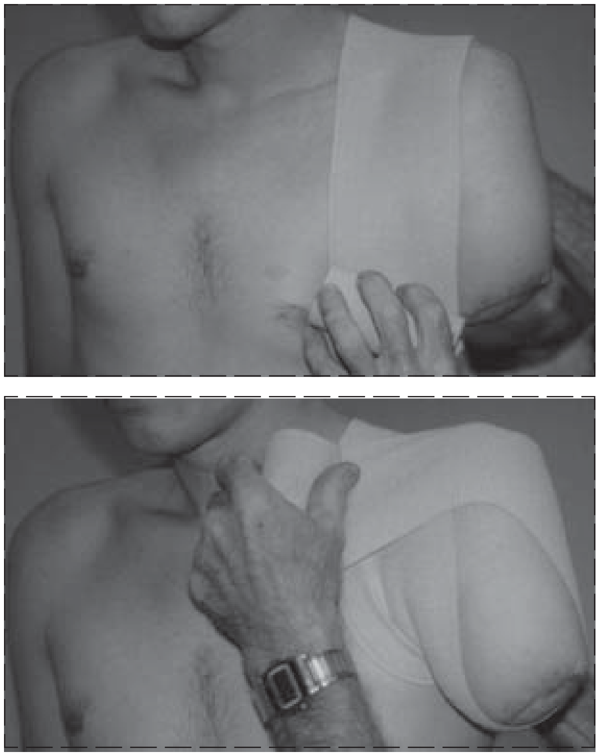


Fig. 3-32. Stump wrapping for above-elbow amputee. (**a**) and (**b**): the initial wrap; slight tension is applied during the residual limb loops. (**c**) through (**e**): cross chest anchoring loops and figure-8 residual limb wrapping.

limb. With elastic wrapping, it is important for the dressing to produce gentle distal compression of the limb. If proximal pressure is too high, the limb will be "choked," thus increasing distal edema.

Military rehabilitation professionals can significantly impact on functional rehabilitation of upper limb amputees through early intervention and prosthetic training. The World War II experience proved this to be true. Malone and associates[13] showed that early prosthetic fitting improves the success of rehabilitation after an arm amputation.

Activities of Daily Living

The occupational therapist is the primary rehabilitation professional involved with prosthetic training in activities of daily living (ADL). When the amputated limb is the dominant limb, the amputee must be trained to use the contralateral upper limb as the new dominant limb.[33] The bilateral amputee poses tremendous rehabilitative challenges and is discussed in a separate section.

Each upper limb amputee must be independent in all basic ADLs before being discharged or sent to a Veterans Affairs Medical Center. A comprehensive list of activities that a unilateral amputee should accomplish with and without a prosthesis is given in Figure 3-33. Activities include eating, personal hygiene, bathing, dressing, and homemaking. Other activities, such as driving, are of great importance to the amputee and must also be addressed.

Name	Age	Sex	Occupation
Type of amputation	Type of terminal device		
Therapist	Date(s) of test		

RATING GUIDE

0. Impossible
1. Accomplished with much strain or many awkward motions
2. Somewhat labored or few awkward motions
3. Smooth, minimal amount of delays and awkward motions

PERSONAL NEEDS:	0	1	2	3
Put on shirt				
Fasten buttons: cuff and front				
Put on belt				
Put on glove				
Put on coat				
Lace and tie shoes				
Tie a tie				
File finger nails				
Polish finger nails				
Set hair				
Clean glasses				
Squeeze toothpaste				
Put on a bra and fasten				
Use a zipper				
Hook garters				
Take bill from wallet				
Light a match				
Open pack of cigarettes				
EATING PROCEDURES:				
Carry a tray				
Butter bread				
Cut meat				
DESK PROCEDURES:				
Use dial telephone				
Use phone and take notes				
Use pay phone				
Sharpen pencil				
Use ruler				
Use scissors				
Remove and replace ink cap				
Fill fountain pen				
Fold and seal letter				
Use card file				
Use paper clip				
Use stapler				
Wrap a package				
Type				
Write				
COMMENTS:				

GENERAL PROCEDURES:	0	1	2	3
Use key in lock				
Open and close window				
Play cards and shuffle				
Wind a clock				
Assemble wall plug				
HOUSEKEEPING PROCEDURES:				
Wash dishes				
Dry dishes				
Polish silverware				
Peel vegetable				
Cut vegetable				
Open a can				
Manipulate hot pots				
Sweeping				
Use dust pan				
Use vacuum cleaner				
Use wet mop				
Use dry mop				
Set up ironing board				
Iron				
Wash and wring out laundry				
Hang up and take down laundry				
Thread needle				
Sew on button				
USE OF TOOLS:				
Layout				
Saw				
Plane				
Sand				
Drive screws				
Hammer				
File				
Drill				
Power tools				
Gravel pit				
CAR PROCEDURES:				
Drive				
Change tire				
Use Jack				

Fig. 3-33. The rating guide for "Single Upper Extremity Amputation—Activities of Daily Living," which provides a comprehensive list of activities of daily living that a unilateral amputee should be able to accomplish. This list does not include any special recreational or vocational goals that the amputee may deem important. Adapted with permission from Atkins DJ. Adult upper limb prosthetic training. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee.* New York: Springer-Verlag; 1989: 49.

Training in prosthetic use starts with education regarding basic prosthesis function. The amputee is first trained in opening and closing of the TD and, in the case of an AE amputee, in locking and unlocking the elbow. Residual limb care with proper hygiene and cleaning of the prosthetic socket is taught. Putting on and removing the prosthesis can be difficult and is practiced with the assistance of a therapist. All activities learned in therapy must be reinforced by nurses working with the patient. Prosthesis wear is advanced slowly, with initial periods of only 15 to 30 minutes, followed by careful skin evaluation for possible excessive pressure.[31] Basic activities, such as grasping and lifting, are taught. Realistically, the unilateral amputee will use his intact limb for most activities, with the prosthetic limb assuming a stabilizing and positioning role.[31] Functional modifications of clothing, with loops and assistive devices, are often used to help the amputee develop independence.[34] Knowledge of the amputee's vocational and avocational interests is important because training in these areas, along with fabrication of special adaptive devices, can dramatically improve an amputee's outlook for the future. The realization that previous recreational activities can still be pursued and that the ability to work is attainable will have a positive impact on the amputee's attitude.

Canty[35] reported on amputee care in World War II at Mare Island Naval Hospital in Vallejo, California. The rehabilitation program there included early stump conditioning by means of wrapping and exercises. Physical therapists initiated exercises early in the course of treatment, often while the casualty was still at bed rest. Occupational therapists provided the soldiers with a variety of art materials and hobby activities to use while recuperating. This gave them pursuits to fill nontreatment time and provided relaxation to further improve psychological adjustments to the new disability. Round table discussions provided valuable group support for the amputee. As the soldier improved, aggressive physical training was instituted. Prevocational activities, tool work, and driving were taught along with dancing and sports.

Brown[36] has described the rehabilitation at Fitzsimons Army Hospital in Aurora, Colorado, of amputees from the Vietnam War. This program stressed a holistic approach to rehabilitating the individual. In addition to functional activities, a vigorous avocational program was pursued. Using appropriate adaptive equipment, amputees were taught snow skiing, swimming, scuba diving, and water skiing. Other important skills such as driving were taught. These activities served to place the new amputee successfully in settings outside the hospital, furthering the optimal rehabilitation and psychological adaptation.

In the military, most amputees do not remain on active duty but are discharged to Veterans Affairs Medical Centers in their local area for continued care. It is important that consistent follow-up visits be established so that education and support continue. The rehabilitation process goes on for many years, and upper limb amputees require routine prosthetic repair and maintenance throughout their lives.

BELOW ELBOW PROSTHESES

The soldier with a BE amputation is best managed by a rehabilitation team utilizing the previously mentioned rehabilitation principles. Early prosthetic training, widely recognized as the optimal way to rehabilitate amputees,[13,17,32,37] along with comprehensive rehabilitation, promotes functional independence. BE amputees require prostheses with particular components and adaptations to meet their special needs. Components that comprise a permanent prosthesis for BE amputees can be broken down into a series of devices: a socket, prosthetic suspension, prosthetic control, a wrist unit, and a TD. The physician and care team, in concert with the patient, define an optimal prosthesis.

Prosthetic Sockets

The prosthetic socket is actually composed of two sockets. An inner socket conforms exactly to the residual limb, providing a firm purchase. The outer socket fits over the inner socket and matches the contour of the opposite arm. The extent to which the prosthetic socket extends proximally depends on the length of the BE amputation. For a wrist disarticulation or a long BE amputation where some pronation and supination remain, the prosthetic socket should only extend proximally to about 1.5 cm below the epicondyles of the humerus.[17] The socket should have adequate relief for the radius and ulna when the elbow is flexed.[18] Check sockets provide a means of ensuring adequate fit. These are made from a clear, low temperature thermoplastic, which is fit to the residual limb. An example is shown in Figure 3-34. The check socket is modified to accommodate any tender bony areas and to ensure adequate fit. Once fit has been optimized

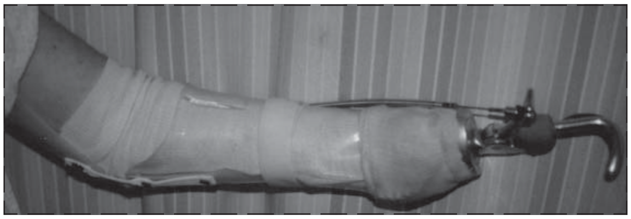


Fig. 3-34. A below-elbow amputee with clear thermoplastic check socket. The check socket can be modified, thus, optimizing fit and comfort. Note the attachment of a terminal device with fiberglass casting material.

with this socket, a positive mold, using plaster of Paris, is made from the socket. The final prosthesis is then fabricated using the positive mold as a template.[18]

For short and very short BE levels, the socket must extend more proximally. The special Muenster socket is a self-suspending socket that depends on pressure at the posterior olecranon over the triceps tendon and snug pressure around the biceps tendon to provide purchase on the limb. Suspension is not generated by attachment over the humeral epicondyles.[18] This socket is for light duty use and is well suited to myoelectric BE prostheses. If it is anticipated that the amputee must bring the prosthesis to the mouth or face, any socket can be put into some flexion.

For very short BE residual limbs, a split socket with step-up or variable-gear hinged elbow can be used. This consists of a small, mobile inner socket attached to variable-geared elbow hinges that move more than the forearm part of the prosthesis. With a 2:1 gear ratio, a very short residual limb can move less distance in flexion, while moving the external socket with the TD through twice as much excursion.[17,18] This is particularly helpful where the residual limb has limited range of motion in flexion, as in the case of contracture or heterotopic bone formation. It should be noted that the power (force) of lifting is decreased by a factor of 2, but this is the compromise required with a split socket and step-up hinges.

Terminal Devices and Wrist Units

A variety of TDs is available, which can provide specific and general functions desired by the user. Terminal devices are often easily interchanged. In most cases, they are used for prehension, but can also be specialized for hammering or other manual work. Considerable research has been invested on the improvement of both body-powered and myoelectric TDs.[11,38–44]

Common categories of TDs are the hook and the hand. Hooks are generally used in performing manual labor. Hands are thought to provide better cosmesis, particularly with myoelectric TDs (see the Myoelectric Prosthesis section in this chapter). Power to operate the TD is derived from other body muscles through a cable system (body powered) or by electric motors from a battery powered system (externally powered). Body-powered TDs typically produce voluntary opening, with rubber bands providing the closing force.[17,18,45]

In the United States, all hooks and hands have the same ½-in., 20-thread stud for attachment to wrist units. This allows ease of TD interchangeability.[17] Often amputees will have two TDs, one for functional activities and one for cosmesis.

Typical hook TDs are made from steel, for durability, or aluminum, for decreased weight.[18] Dorrance hooks are a common type of prescribed hook. These are made of either aluminum or steel and are numbered by size, with the largest number being the smallest size.[17,18] Hooks can be plastic coated, or neoprene-lined for better grip. The "thumb" of the hook is where the control cable attaches. A Dorrance hook is shown in Figure 3-35.

Recreational TDs provide the user with the ability to participate in a particular activity that would not otherwise have been possible. In a Canadian survey,[46] encompassing 2,176 amputees, the respondents reported that lack of information regarding

Fig. 3-35. A Dorrance Hook.

newer prosthetic components and lack of adaptive equipment for recreational activities were major concerns. Indeed, the ability to pursue avocational interests is valuable in terms of exercise and also in promoting psychological and social benefits.[11] Many TDs are made for special activities. A TD with a guitar pick attached can allow UE amputees to play the guitar. Another TD with a flexible cable attached between the prosthesis and a golf club, meets the U.S. Golf Association's regulations and enables the amputee to perform controlled powerful strokes.[11] This device can be changed from one golf club to another. Similarly, special attachments can be purchased or fabricated that allow amputees to grasp cross country and downhill ski poles.[11] The most common required characteristics of recreational prosthetic devices are durability, low weight, and strong suspension.

Vocationally specific TDs make life easier for the amputee performing special manual tasks. Driving often requires a cup or ring (Figure 3-36) attached to the steering wheel of a car, or a "Y" shaped TD with a nonslip rubber coating.[40]

A wrist unit is an important part of a prosthetic prescription. It connects the TD to the prosthesis and substitutes for the lost ability to pronate and supinate the forearm. This unit requires a detailed knowledge of the amputee's function and areas of vocational and avocational interest. Wrist units allow quick interchangeable use of various TDs. Some wrist units have a friction ring that limits TD rotation, and the TD is placed in the desired position by pushing it against an object or with the other hand.[17,45] The variable-friction wrist unit allows friction adjustability from low to high.[45] A thin friction wrist unit is available for amputees with wrist disarticulations.

Fig. 3-36. A steering wheel driving attachment for an amputee.

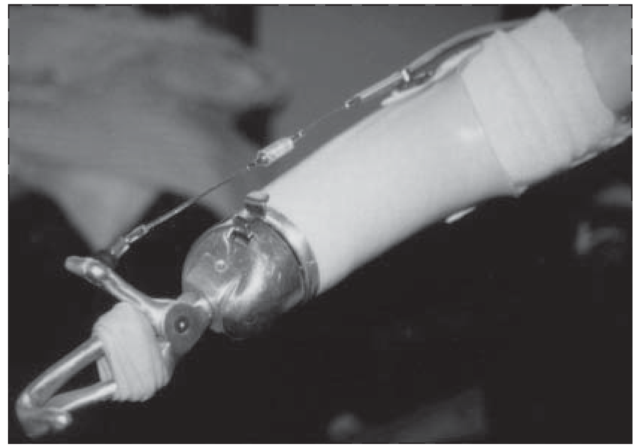


Fig. 3-37. A below-elbow prosthesis with a wrist flexion unit. The wrist unit is set without flexion.

Another type of wrist unit is the quick change unit, which has a mechanism that allows the amputee to set the TD in the desired position and then lock it.[17,45] This unit is preferred in cases where the person needs to perform heavy lifting or manipulate heavy objects.

Wrist-flexion units are special devices that allow the user to set the TD in some degree of flexion. This unit is useful for bilateral amputees who require the prosthetic extremity to perform dressing and personal hygiene activities with the TD close to the body (Figures 3-37 and 3-38).[17]

Suspension and Control

Suspension of the BE prosthesis and control of the TD are closely related and will be discussed simultaneously.

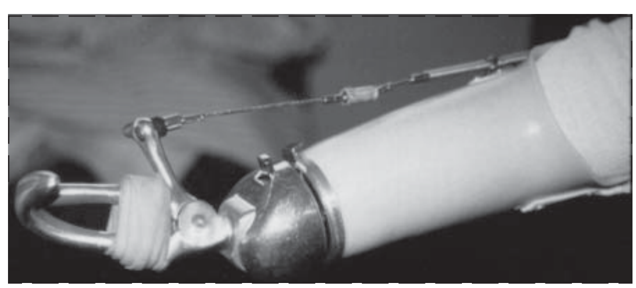


Fig. 3-38. A below-elbow prosthesis with a wrist flexion unit. The wrist flexion unit is set in a flexed position.

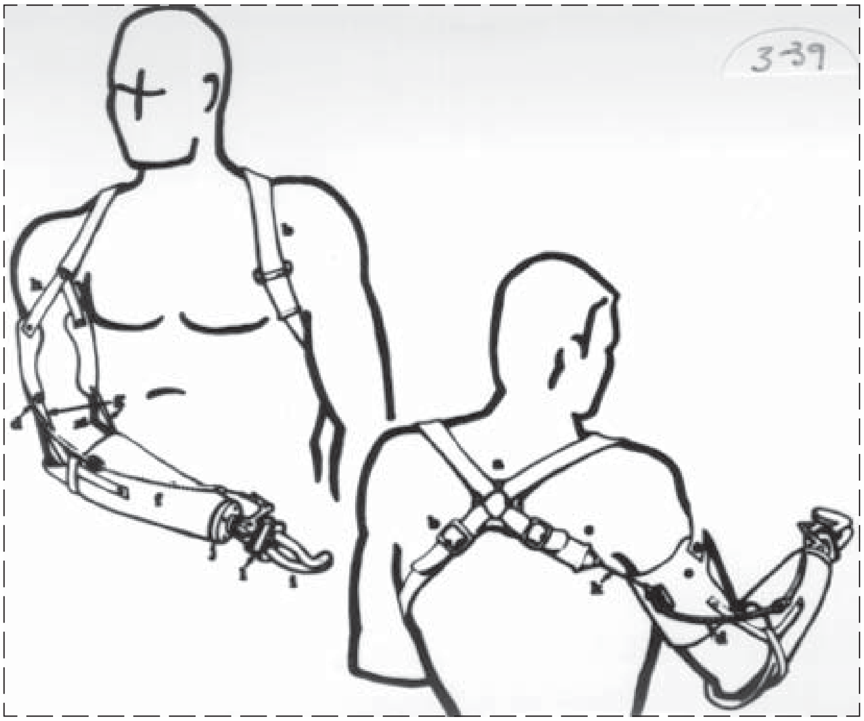


Fig. 3-39. The standard components of a BE prosthesis. The components are a: "O" ring of the figure-8 harness; b: axillary loop strap with adjustable buckle; c: Bowden cable control strap (adjustable); d: single-control Bowden cable outer cable housing; e: triceps pad; f: dual-walled socket; g: flexible elbow "hinges"; h: "Y" strap attaching figure-8 harness to the triceps pad; i: terminal device; j: wrist unit; k: inner braided steel cable that moves inside the cable housing; and l: elastic bands providing closure of the hook.

The BE amputee requires elbow joints (hinges), a triceps pad, and a figure-8 harness to suspend the prosthetic socket (Figures 3-39 and 3-40). The elbow hinges can be flexible straps (in the case of long BE amputees), or can be rigid metal hinges. The rigid hinges provide heavy-duty suspension for the aggressive user and for amputees with short and very short BE amputation levels. Rigid hinges do not allow pronation and supination, however.[17,18,45] Rigid hinges can have a single pivot, a polycentric pivot, or a step-up hinge used with a split socket.[17]

Figure 3-39 shows a figure-8 harness for a typical BE prosthesis. Posteriorly, an "O" ring is located below the C-7 spinous process and slightly to the sound side.[18] The anterior suspension strap is situated along the deltopectoral groove, and the control strap is attached posteriorly and inferiorly to the "O" ring. Shoulder abduction and scapular protraction through scapulothoracic motion provide force for the control cable.[18] The cable can also be combined with glenohumeral flexion.[31] The anterior suspension strap attaches to a "Y" strap and the triceps pad. The triceps pad redirects the suspensory force between the socket and the torso.[45] The cable operating the TD is called a Bowden control cable, and consists of a braided steel inner cable that moves inside a steel housing. The BE amputee control system is termed a single-control system, as the cable controls only one action: the opening of the TD. The cable housing is attached to the socket so that humeral flexion and scapular abduction produce tension in the inner cable, thus opening the TD. Elastic bands of varying tensions close it.

Fig. 3-40. Below elbow amputee with prosthesis.

ABOVE-ELBOW PROSTHESES

For the body-powered AE prosthesis, the same information applies regarding TDs and wrist units as in BE prostheses. Differences between AE compared to BE prostheses mainly involve the additional elbow mechanism, the humeral rotation device, and the suspension and control systems. Sockets are of dual-walled design. Suction sockets can be fitted to the AE amputee, providing better suspension, and allowing a figure-8 harness to be used alone for control.[22,47]

For the AE amputee with preserved humeral motion, a Utah Dynamic Socket (UDS) is available (Figure 3-41).[22] A conventional socket for a long AE amputation extends to the deltoid, but with abduction, it can "gap" at the proximal and lateral ends over the deltoid. It also rotates inwardly, with rotational stresses induced by lifting. The UDS has a lowered wall over the lateral deltoid and thus minimizes gapping. It contains added projections that extend over the chest anteriorly and posteriorly, providing rotational stability and minimizing suspensory needs.[22]

Elbow units for AE amputees can be flexed into the desired position and then locked with a locking control cable derived from the harness. Myoelectric elbows can also be used. Indeed, hybrid myoelectric and body-powered prostheses are quite functional. Passive control of humeral rotation is accomplished by means of positioning an elbow turntable (humeral rotation device) to the desired position.[45] Marquardt and Neff[48] describe a surgical procedure in which the residual humerus in long AE amputees is angulated to a 70° bend by means of an osteotomy. This angulated distal humerus more effectively transmits humeral rotation to the socket.

Although there are many different harness designs, their functions are identical: to suspend the prosthesis and operate active prosthetic components.[45] An example of a typical body-powered AE prosthetic system is shown in Figure 3-42. The TD and wrist units are similar to those of the BE prosthesis. The AE prosthesis requires the installation of an elbow joint and, generally, a turntable in the socket to allow placement of the prosthesis in the

a

b

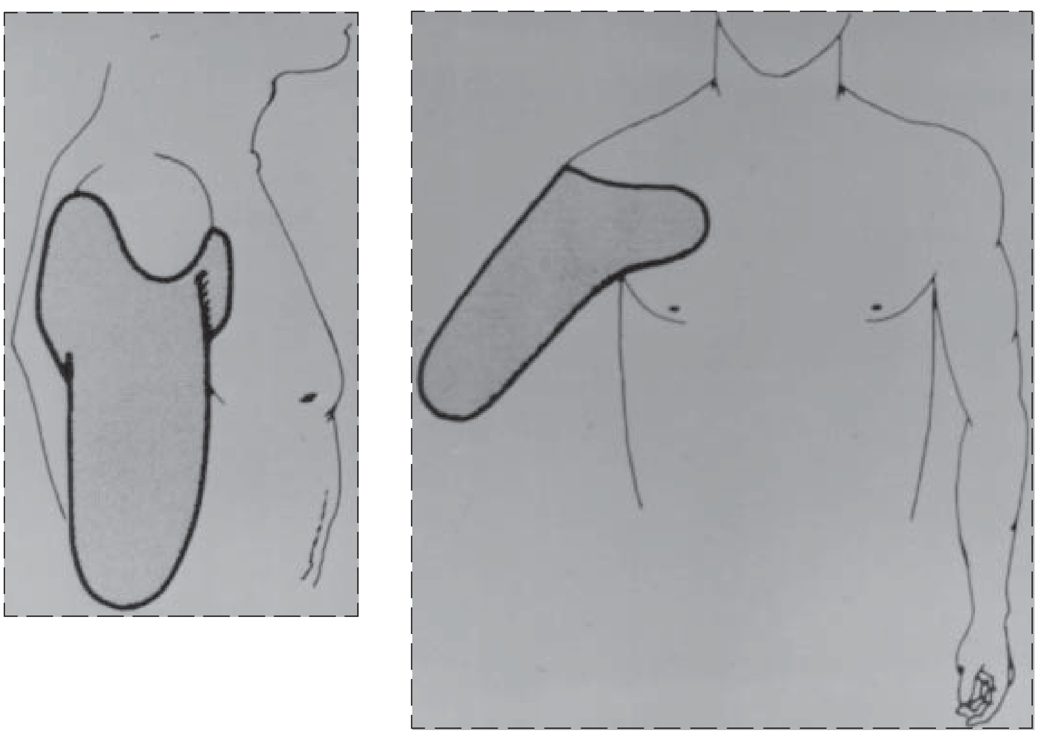


Fig. 3-41. The Utah Dynamic Socket, (**a**) lateral view and (**b**) frontal view, showing extension over pectoralis muscle. Reprinted with permission from Bowker JH, ed. *Atlas of Limb Prosthetics: Surgical and Prosthetic Principles*. St. Louis, MO: Mosby-Yearbook, Inc. 1992: 262.

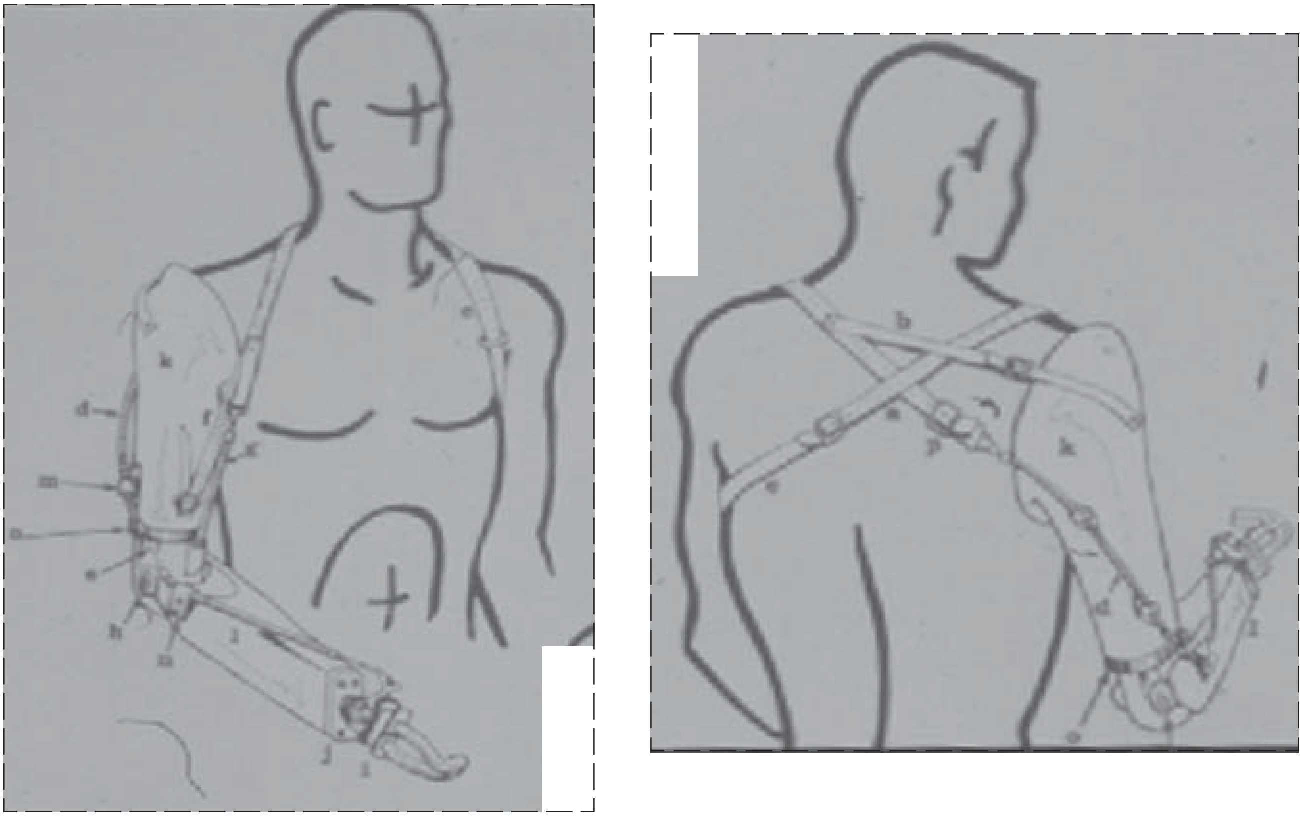
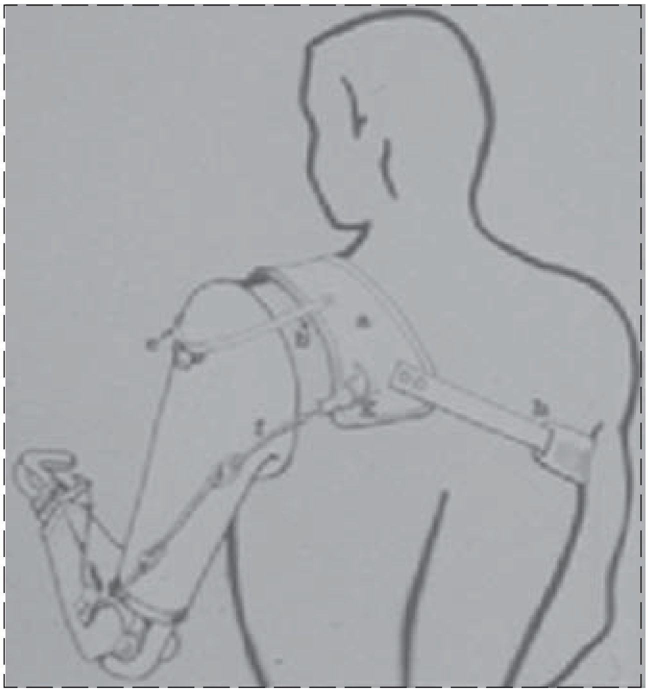


Fig. 3-42. The standard above elbow prosthesis. The components are a: modified figure-8 harness; b: lateral suspension strap for the harness (adjustable); c: axillary strap; d: dual control Bowden cable; e: bare area of Bowden cable; f: anterior elastic suspension strap; g: elbow locking control cable and adjustable strap; h: hinged elbow; i: terminal device; j: wrist unit; k: dual walled AE socket; l: forearm part of prosthesis; m: cable attachment to socket; n: cable attachment to forearm; o: friction joint for passive humeral rotation; and p: adjustable dual control cable strap.

desired position of humeral rotation. The control cable is called a dual-control cable because it operates both elbow flexion and TD opening. An elbow-locking cable (see Figure 3-42) locks the elbow when the desired position is achieved. The figure-8 adjustable harness forms the basis of the suspension system, but requires additional straps. The anterior adjustable suspension strap attaches to the prosthesis and has an elastic component. An adjustable lateral strap provides the primary suspensory force. The control cable is operated by means of an axillary loop of the harness around the contralateral limb, just as with the BE system. The adjustable elbow-locking cable originates near the anterior suspension strap. Elasticity of the anterior suspension strap allows sufficient excursion to operate the elbow lock.

Another type of suspension uses a saddle harness (Figure 3-43) and provides added suspension for someone who routinely performs heavy lifting. This padded saddle fits over the shoulder and provides a firm anchor for prosthesis suspension straps and control cables. Sometimes a cable housing, with a steel cable running through it and attaching anteriorly and posteriorly to the socket, suspends the prosthesis.[17] Figure 3-43 shows the saddle with two "V" straps that suspend the prosthesis and minimize internal and external socket rotation. An elastic suspensory strap and an elbow-locking cable passes anteriorly, in the deltopectoral groove. The elbow-locking cable is activated by shoulder extension, abduction, and depression.[31] Posteriorly, the dual-control cable is attached to the harness by another adjustable strap. Scapular abduction, shoulder abduction, and humeral flexion operate this cable. A strap passes around the chest and under the contralateral axilla, securing the saddle and prosthesis to the torso.



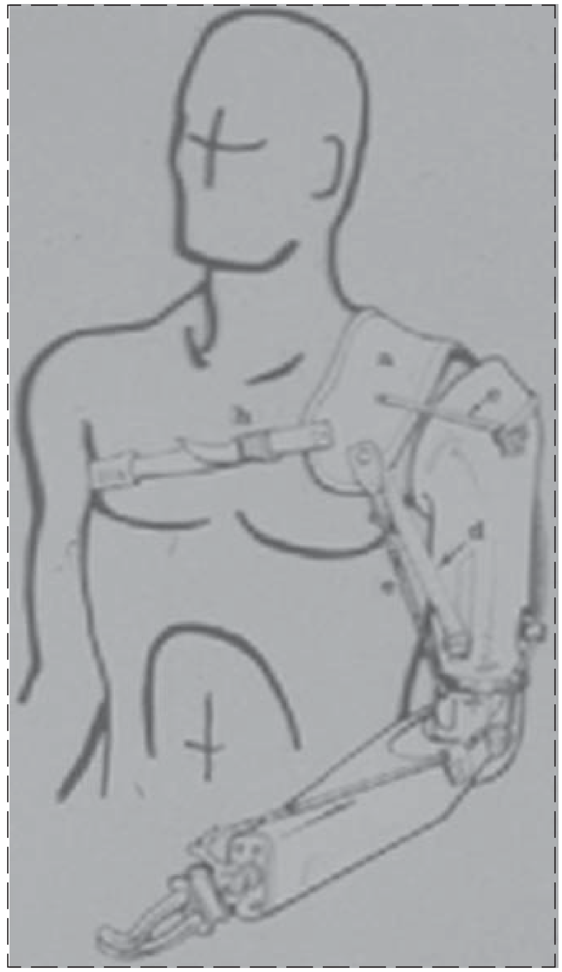


Fig. 3-43. A saddle harness suspension system. The components are a: saddle suspension; b: posterior "V" strap; c: anterior "V" strap; d: anterior elastic suspensory strap; e: elbow locking cable and adjustable strap; f: dual control Bowden cable; g: dual control cable strap (adjustable); and h: chest strap (adjustable).

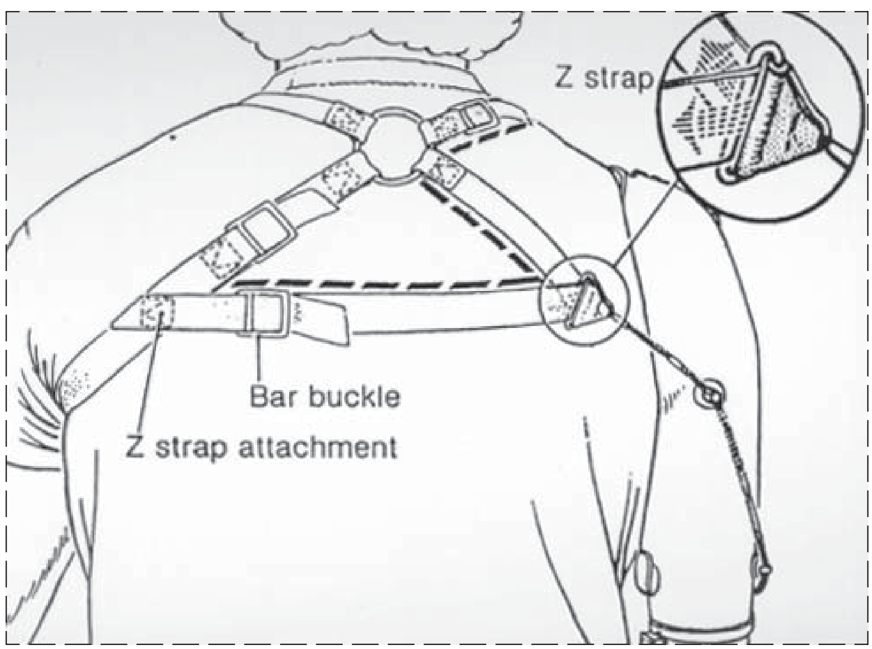


Fig. 3-44. A "Z" strap attachment allowing the control cable to glide back and forth as the prosthesis is used with the humerus in an abducted position. Reprinted with permission from Reyburn TV. The "Z" straps: Harnessing modifications for patients with upper-extremity amputations. *Arch Phys Med Rehabil*. 1991;72:250–252.

Many variations of the control and harness system exist. A modified figure-8 harness, with an anterior strap to operate the cable, can also be used.[45] A "Z" strap for the dual-control cable has been described.[49] This strap allows the TD to be used with the arm above raised 90°, and limits the problem of the "O" ring riding up the neck (Figure 3-44). In order to operate a dual-control cable, which flexes the elbow and also opens the TD, considerable cable excursion is required. Two inches of cable excursion are required to flex the elbow,[20] and approximately 2 in. of excursion can open the TD with the elbow in neutral.[18] Scapular abduction, along with humeral flexion and abduction, provide the force and excursion generated in the dual-control cable for elbow flexion and TD opening.

The humeral-neck amputee has difficulty both flexing the prosthetic elbow joint and opening the TD because all of the motion must come from biscapular abduction. The force and excursion generated by humeral flexion are approximately 63 lb and 2.1 in., respectively.[20] Biscapular abduction produces about 2 in. of excursion[18] with good force generation. According to Taylor,[20] arm (humeral) extension can generate 2.3 in. of displacement and 56 lb of force. This is much more than the ⅝- to ¾-in. excursion and minimal force needed to operate the elbow lock. Chest expansion can also be used to operate an elbow lock.[18] Of course, the exact excursions and forces that each individual can generate are quite variable, depending on individual build, coexisting injuries, and the exact placement of control cables. However, the figures quoted above illustrate some of the difficulties in prosthetic control.

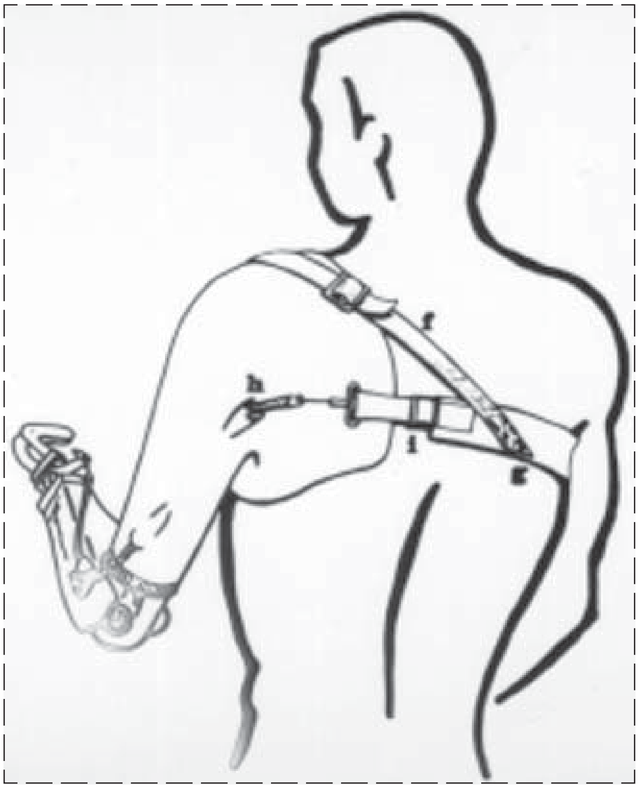
HUMERAL NECK, SHOULDER DISARTICULATION, AND FOREQUARTER PROSTHESES

At these amputation levels, the loss of humeral flexion (in the case of a shoulder disarticulation or humeral neck amputation) and unilateral loss of scapular motion (with a forequarter amputation) severely limits the amount of body-powered control. The prosthetic socket for a shoulder disarticulation and humeral neck amputation must extend over the shoulder to stabilize the prosthesis. A humeral neck amputation is shown in Figure 3-45. The prosthesis for this individual is illustrated in Figure 3-46. Forequarter amputations require an extensive prosthetic socket to stabilize the prosthesis; the socket is often attached to a frame that encompasses the torso. A prosthesis for an individual with a forequarter limb loss (a child with congenital limb loss) is shown in Figure 3-47. Here the prosthesis is firmly mounted to a body jacket, stabilizing it on the trunk. Loss of humeral extension to control the elbow-locking cable can be overcome by using chest expansion to operate the lock (see Figure 3-46). Another way to operate the elbow lock is a nudge control with a button attached to the prosthetic shell and depressed by the chin.[31] There are shoulder joints available that allow flexion, extension, abduction, and adduction.[45] However, the joint must be passively placed in the desired position by the other hand.

Fig. 3-45. Humeral neck amputation.

An important principle to remember is to save any residual humeral length. This allows better prosthetic fit, improves stability of the socket, and minimizes its movement. If myoelectric controls are required, the socket must consistently provide an intimate fit with respect to those control muscles.

Hybrid prostheses, with some body-powered actions and some myoelectric actions, can be used.[45] An example of this is an AE amputee could operate elbow flexion with a body-powered cable, and control the hand myoelectrically. The hybrid prosthesis can be particularly useful in the situation where body power cannot provide sufficient force and excursion in the dual-control cable to operate both actions.



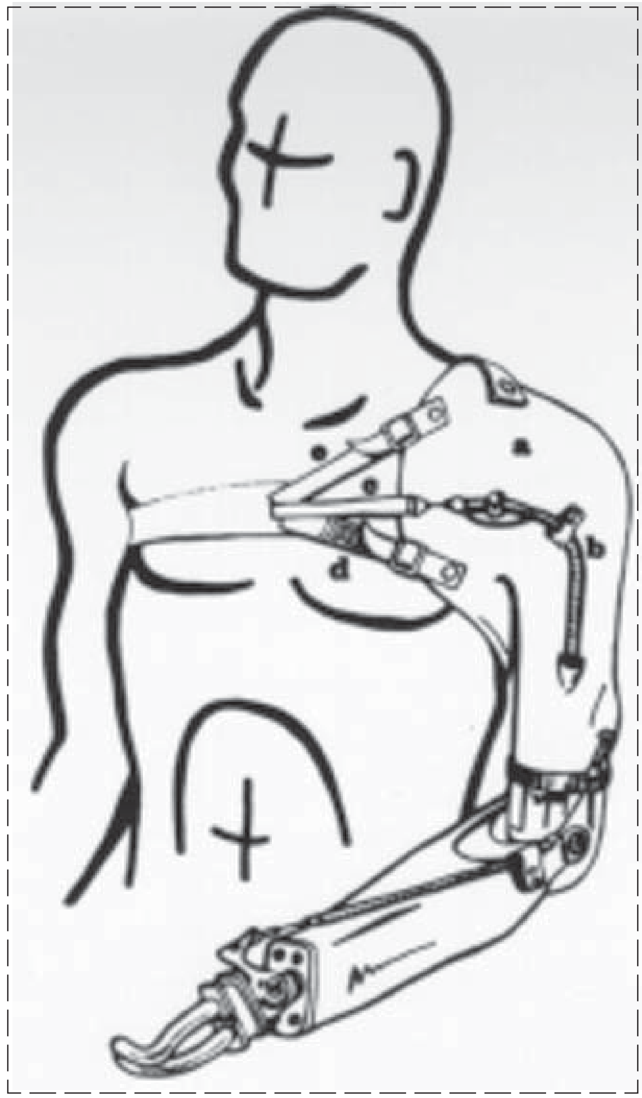


Fig. 3-46. Illustration of humeral neck amputation prosthesis using chest expansion to operate the elbow lock. Note the socket extending over the shoulder. The components are a: dual walled socket; b: elbow locking cable and housing; c: chest expansion elbow locking control strap (adjustable); d: elastic suspensory strap (adjustable); e: anterior suspensory strap (adjustable); f: posterior suspensory strap (adjustable); g: chest strap (adjustable); h: dual control cable and housing; and i: dual control cable strap (adjustable).

Fig. 3-47. Prosthesis for a forequarter amputee.

RESIDUAL LIMB PROBLEMS

Skin and residual limb problems in the upper limb amputee are similar to those of the lower limb amputee; however, because residual upper limbs are not load bearing like lower limbs, less abnormal forces are applied. Abnormal stresses are caused by lifting, in which case the socket presses on the distal residual limb. While lifting, the proximal socket in an AE amputee can exert high forces on the shoulder. If pain in the BE or AE amputee at the distal anterior end increases with resisted elbow or humeral flexion, the cause is probably excessive pressure or boney osteophytes.[50] Treatment is to relieve the pressure of the inner prosthetic socket over the painful area by placing a distal foam pad in this area. Other effective relief measures include increasing the surface area of the socket to distribute forces over a larger stump area. Wrist disarticulations may have styloid pain, which also can be treated with distal padding or surgical styloid reduction.[50]

Residual limb choking can occur if the proximal socket is too small and lacks total distal contact. The residual limb end may become bulbous and edematous. Distal end contact with the socket should be evaluated. This evaluation can be accomplished by inserting a clay ball into the socket and determining if it is deformed when the prosthesis is worn, or by making a lipstick mark over the residual limb and seeing if the lipstick rubs onto the inner socket. If total contact is lacking, the socket can be refabricated or a distal foam pad can be inserted inside the socket. If sensitive skin due to skin grafts or surgical scars is present, the socket can be lined with a soft inner liner to protect the limb from shear and compressive forces.

Phantom sensations after the amputation involve a common feeling that the limb is still present. Phantom pain is the abnormal increase in these sensations with painful, disturbing qualities.[50] Reasons for the pain are not clear and no single treatment strategy is optimal.[50,51] Schnell and Bunch[50] recommend a systematic approach to the painful limb, including a thorough history and examination to differentiate limb infection, postsurgical pain, or other referred pain. For the upper limb amputee it is important to remember that ischemic cardiac pain and chest wall lesions can be referred to the arm or shoulder; liver or gallbladder problems may cause diaphragm irritation. Cervical radiculopathy can cause a painful residual limb. If phantom pain is present, the frequently recommended treatment is early prosthetic fitting and use. Desensitization therapy may be of benefit. Transcutaneous electrical nerve stimulation (TENS) is often helpful, as are a variety of medications, including tricyclic antidepressants, anticonvulsants, or beta blockers.[51]

Neuromas are naturally occurring phenomena resulting from sectioned nerve ends that attempt to regenerate. If a tender area on the residual limb causes a sharp shooting pain with light tapping or palpation, then a neuroma may be present. This can be managed with local steroid and anesthetic injections. Surgical resection may be necessary if there is no resolution and the pain is functionally limiting.[50,51]

Tendinitis and bursitis may develop due to overuse of, or abnormal chronic stress caused by, the socket. These conditions can be treated with nonsteroidal antiinflammatory medications, modification of activities to include relative rest and stretching, socket modification to decrease abnormal stresses, local steroid injection, or a combination of these measures.

Skin problems, such as fungal infections, can be reduced by daily washing of the residual limb and socket with soap and water followed by thorough drying.[50] Occasionally, contact dermatitis occurs due to a local allergic reaction to a particular material, such as foam, tape, leather, and so forth. Treatment involves identification of the agent and its removal from the prosthesis.

BILATERAL UPPER LIMB AMPUTEES

The loss of both upper limbs is a tremendous psychological trauma for the wounded soldier. In addition to the immense difficulty in accepting the loss of normal arm function, the amputee must overcome special functional difficulties that are not faced by the unilateral arm amputee, who can use the remaining limb for most activities.

The bilateral proximal upper limb amputee is totally dependent for all self-care activities until optimal rehabilitation occurs. Wounded soldiers with additional injuries such as blindness, deafness, or brain injury, pose substantial rehabilitation challenges.

The amputee may become independent with prostheses, but proper prescription and training in the use of assistive devices is often more important for independence.[52] The bilateral BE amputee has more chance of regaining independence than the bilateral AE amputee. If the bilateral AE amputee cannot oppose the residual limbs, this person may never gain independence. For some bilateral AE amputees, one residual limb is longer and more functional than the other, hence this limb takes over most of the prosthetic activities. Baumgartner[52] and Hermansson[34] each recommend that the bilateral UE amputee use an MP on one side and a body-powered prosthesis on the other. Bilateral upper limb amputees show preference, however, for body-powered prostheses, citing proprioceptive feedback, fewer repairs, and increased fine motor dexterity as reasons for the preference.[31] Bilateral amputees may be totally dependent on their prostheses for achieving function in their daily activities.

Figure 3-48 is a comprehensive list of activities the rehabilitation team can use as a guide to ensure that the amputee can meet all functional needs. The list includes many activities that may

Fig. 3-48. (*Continues*)

Fig. 3-48. The rating guide for "Bilateral Upper Extremity Amputation—Activities of Daily Living," which provides a comprehensive list of bilateral upper extremity amputee activities. Adapted with permission from Atkins DJ. Adult upper limb prosthetic training. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee.* New York: Springer-Verlag; 1989: 52, 53.

not necessarily be the goals of the patient; however, this list serves as a guide to comprehensive rehabilitation training, environmental modifications, and adaptive equipment needs. Other activities, vocational and avocational, may also be pursued if they are goals of the individual amputee.

Dressing poses major difficulties for the bilateral upper limb amputee. Congenital amputees, who grow up as bilateral amputees, learn to use their feet with astonishing dexterity and are able to become quite independent in this manner.[52] Of critical importance to success in this area is modification of clothing. These modifications include loose shirts, elastic waistbands, well placed loops, and Velcro fasteners that replace buttons and belts. A dressing hook or "tree" can position items of clothing such that the amputee can maneuver into them. The mouth and teeth are important and are frequently used to assist the amputee with grasping cuffs and collars.

Devices to position washcloths, soap, and facial care articles are very helpful.[31,52] Other helpful devices are foot-operated sinks, push button telephones that can be dialed using the nose, and automobile adaptations that enable independent driving.[52]

Toileting, understandably, is an area of self-care that is of major concern for the bilateral amputee, and there are many strategies for overcoming the inherent problems. Toilets with a water jet and air blower can be used.[52] However, this limits the amputee to using only that particular modified toilet. A fixed, wall-mounted device that consists of a stick projecting from the wall near the toilet can be used.[53] This device is approximately the height of the toilet seat and can swivel to a position over the toilet. Toilet paper is wrapped around the stick by the foot, and the patient wipes by squatting on the stick. The used toilet paper is then eased off of the stick into the toilet. Some amputees can use their prosthetic devices to wipe themselves. Wrist flexion units are particularly important to incorporate into these prostheses. Friedman[54] describes a number of devices used by the bilateral upper limb amputee to perform toileting. These include long sticks with end pieces to hold toilet paper, and variations on the wall-mounted toilet paper holder. Some of these devices can be easily transported, making the individual independent when using other toilets. Clothing adaptations; Velcro zippers; and loose, easily removed pants are helpful. There are even toilet seat–mounted devices to aid females in placement of vaginal tampons. Feminine hygiene can be managed by sanitary napkin attachment to undergarments. Particular techniques for independent perineal wiping involve placing the toilet paper on the toilet seat with feet, then rocking the buttocks over the toilet seat. Alternatively, the amputee can place toilet paper on the heel of one foot and squat over the heel.

One particular surgical procedure described and used extensively in India and Third World countries, is the Krukenberg procedure.[55,56] This procedure is used for BE residual limbs. It effectively divides the radius and ulna with their respective groups of forearm flexor and extensor muscles and creates a "claw-like forearm." The ulnar and radial halves of the "claw" can be opened and closed voluntarily, to effectively grasp objects (Figure 3-49). The major advantage to the procedure is that the opposing surfaces, which grasp objects, retain tactile sensation. The procedure is especially helpful for amputees who also have impaired vision.[55,56] These patients cannot adequately use conventional prostheses (CPs) due to lack of visual input. The disadvantage of the Krukenberg procedure is what some consider the unsightly appearance of Krukenberg limbs.[56] For Third World countries with limited availability of trained prosthetists, the Krukenberg procedure is an alternative to conventional prostheses.[55]

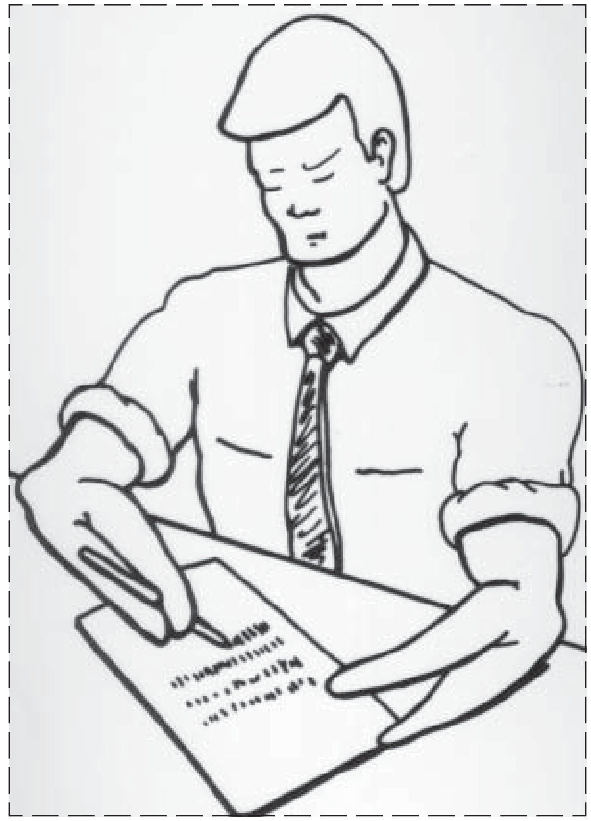


Fig. 3-49. Illustration of a bilateral below elbow amputee with Krukenburg limbs. Adapted with permission from Mathur BP, Narang IC, PipLani CL, Majid MA. Rehabilitation of the bilateral below-elbow amputee by the Krukenberg procedure. *Prosthet Orthop Int*.1981:5:135-140.

MYOELECTRIC PROSTHESES

Myoelectric prostheses represent significant technological developments offering alternatives for selected upper limb amputees beyond conventional prostheses. The first practical MP was demonstrated in Hanover, Germany in 1948, by Reinhold Reiter of Munich.[57] It was not until 1960 that another practical device was presented; this was in Moscow, USSR, at the First Conference of the International Federation of Automatic Control. Development of improved MPs continued throughout the 1970s in the United States, Canada, England, Denmark, Sweden, and Japan. Commercial systems became available during this time. For the BE amputee, the prescription and provision of these devices is now common in some European countries, even more so than the CPs. By 1985, between 10,000 and 20,000 MPs had been fitted to upper limb amputees worldwide.[58] Significant developments and refinements have occurred in the microprocessor control of these prostheses. Additionally, the continued advancement of power source (battery) and drive motor technology enhances the functional usefulness of the MP.

As with any prosthetic device, the advantages and disadvantages of prosthetic fitting must be carefully balanced in order to optimize the ultimate functioning of an individual. Myoelectric prostheses are only a part of comprehensive amputee rehabilitation management. The patient must continue to remain the center of informed decision making with regards to the fitting of the appropriate prosthetic device. The rehabilitation team must comprehensively evaluate the amputee. The amputee should be educated in all aspects of self-care and prosthetic needs, including being made fully aware of the special requirements of an MP, and being helped to develop a realistic perception of MP capabilities. Many patients may choose to abandon their prostheses (MP and CP) altogether in favor of unencumbered independence with the remaining upper extremity. The experience reflected in the literature suggests that for the BE amputee the MP presents a satisfactory and often appealing alternative to the CP, particularly when cosmesis is an issue.[57–63] For progressively higher levels of amputation, the functional improvements and performances are less satisfactory.[57] Myoelectric prostheses can improve the function of selected UE amputees and should be available for soldiers.

Bioengineering and Myoelectric Control

Control of myoelectric prostheses involves deriving myoelectric signals from voluntary control muscles. The signal results from the contraction of a chosen muscle on the residual limb and is recorded by surface electrodes implanted in the prosthetic socket. Electrodes must maintain contact with those particular muscles from which the control signals are derived, and the signal varies with the force of contraction. (The biophysics of myoelectric control and many of the technical considerations regarding signal extraction are available from other authors.[64–66]

The recorded myoelectric signal is first amplified, then processed into a control signal governing the electric motors that operate the prosthesis. The magnitude of the processed signal is roughly proportional to the isometric force exerted by the muscle,[67] and the microprocessor makes decisions based on the strength of the myoelectric signal.

The myoelectric signal can control a prosthetic movement or force through either digital or proportional control.[68] In proportional control, the magnitude of the myoelectric signal determines the speed or force of the prosthetic action. For example, if a particular muscle controls grip force, then the larger the myoelectric signal, the greater the grip force would be. Digital control systems determine the force or speed of prosthetic action by the duration of muscle contraction up to a preset limit. Hence, a prolonged myoelectric signal in a control muscle would cause grip force to increase. Sears and Shaperman[68] compared these two control types in a survey of MP users. They found that digital control users who subsequently switched to proportional control reported improved responsiveness with proportional control. Proportional control, however, resulted in shortened battery life. Amputees who had used digital control prior to the proportional control, preferred the latter. It was also noted that patient education is of great importance in the level of effectiveness achieved with these devices.

Two-state control involves the use of one muscle to control one action. When the amplitude of the electrical signal reaches a preset level, a particular action occurs. This is shown in Figure 3-50. As myoelectric activity increases to a certain point, an action occurs—in this case, closing the TD. For ex-

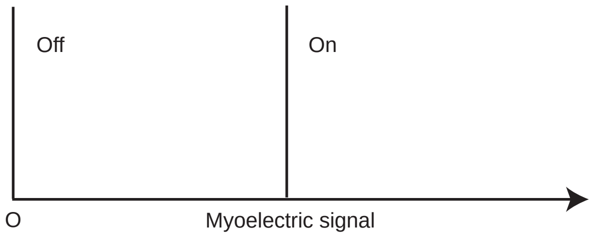


Fig. 3-50. A two-state control system. Adapted with permission from Scott RN. Biomedical engineering in upper extremity prosthetics. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

ample, this control system would utilize the biceps to open a TD, and the triceps to close the device. Proportional control can be combined with this system, varying the rate or force of opening or closing in response to the amount of myoelectrical signal.

An obvious disadvantage to the two-state control system is that the need for multiple muscles to control prosthetic movement makes the complex control of the TD and other actions, such as wrist flexion and extension, difficult to incorporate into an MP system. Three-state control overcomes some of these limitations. This is diagrammatically illustrated in Figure 3-51, and involves using three levels of muscle contraction (three states), each state controlling one action. In Figure 3-51, A through D represent preset cutoff points that define the states of control. Point A represents maximum background noise level. This level should be less than level B, where a particular action begins. From zero to B is state I and the device driver remains off. With B greater than A, the background noise will not accidentally operate the prosthesis. At point B, a defined action occurs and, in this case, the device closes. As the myoelectric activity increases, level C is reached, at which time the device opens. The action continues until maximum voluntary contraction occurs, level D. Level C must be substantially less than D to allow prolonged control of the prosthesis without muscle fatigue.

More sophisticated MP control methods utilizing myoelectric signals have been reported. Scott[57,65] determined that using individual motor units to control an action is possible, but requires intense concentration and, consequently, is not widely used. The technical details of myoelectric signal extraction for multidegree freedom prostheses is discussed by other authors.[66,69]

Herberts and colleagues[70] described a pattern recognition system in which a phantom limb was "moved" by the amputee, and EMG patterns were analyzed. The amputee visualized the phantom limb as if it were moving. During wrist flexion, wrist extension, pronation, supination, and finger flexion and extension, myoelectric patterns, from six electrodes attached to the residual limb, were analyzed. Four subjects were evaluated and clear patterns were identified, yet these subjects did not have the opportunity to use this complicated prosthesis at home.[70]

In another study, Almstrom and colleagues[44] reported on five subjects who used Swedish multifunctional prosthetic hands. Maintenance of this complicated device was a major problem. Fatigue in residual limb muscles from controlling the hand was also noted as a drawback. The amputees reported that compensatory shoulder and arm movements were decreased due to the many motions the hands provided. The authors concluded that compactness and reliability are necessary for prosthetic acceptance. It was pointed out that this type of system could also eventually incorporate proportional control. Myoelectric pattern recognition as a method of controlling myoelectric prostheses requires considerable technological progress before it can be widely used. Bergman and coworkers[43] demonstrated that amputees may choose conventional myoelectric hands over the more complex ones.

A new system for MP control is the Servo Pro system (marketed by Motion Control, Inc., a division of IOMED, Salt Lake City, Utah). For difficult-to-fit amputees who lack appropriate muscle sites for myoelectric control, this system uses a force sensor, which is placed in the harness, to control the MP from graded tension produced by the ampu-

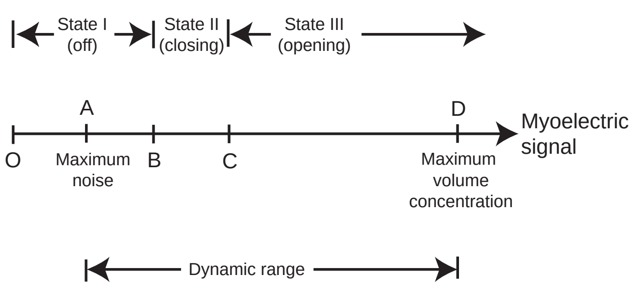


Fig. 3-51. A three-state control system. Adapted with permission from Scott RN. Biomedical engineering in upper extremity prosthetics. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

Fig. 3-52. Myoelectric electrodes embedded in a prosthetic socket.

tee. Proportional control is maintained. This system presents a myoelectric alternative for patients without adequate muscle control, such as those with brachial plexus injuries, shoulder disarticulations, or forequarter amputations.

Sensory feedback with an MP occurs from vibration of the prosthesis and from the noise of the motor. Various attempts have been made to improve the sensory feedback.[71] Pressure sensors in the fingertips of the prosthesis can register pinch force and process the information. Chappell and Kyberd[41] describe such a prosthetic hand, which governs grip through sensors incorporated into the fingertips. The residual limb was then stimulated by electrical impulses of increasing frequency, which corresponded to the increasing levels of force being exerted. Even though electrical stimulation of the residual limb can interfere with the myoelectric control signals,[64] this interference can be minimized by stimulating the remaining nerves of the residual limb.[71] Korner[71] showed that this form of sensory feedback is feasible and could provide the amputee with information about the MP. Implantable electrodes can be used; however, they frequently fail.[72]

Prosthetic Components

The myoelectric device incorporates special systems into a properly fitted prosthesis. The prosthetic socket contains embedded electrodes that contact control muscles on the residual limb (Figure 3-52). The myoelectric signal is amplified and then processed by a microprocessor responsible for interpreting the EMG signal. Rechargeable nickel cadmium batteries provide energy for drive motors that operate elbow, wrist, and TDs.[73] A commercially available MP is shown in Figures 3-53 and 3-54.

Fig. 3-53. The Utah myoelectric prosthesis. Photograph: Courtesy of Motion Control, Inc., a division of IOMED, Salt Lake City, Utah.

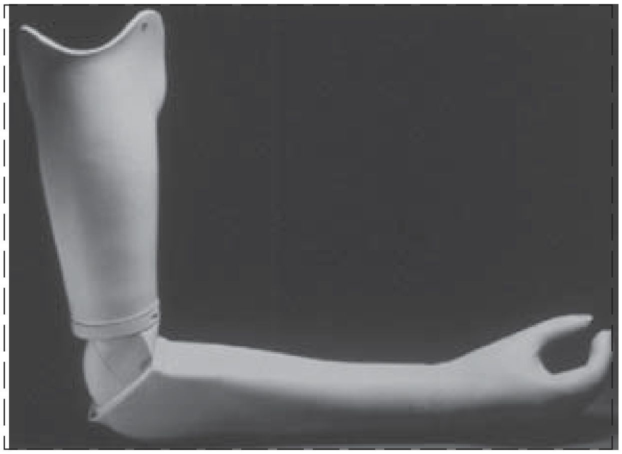


Fig. 3-54. The Utah myoelectric prosthesis with cosmetic cover. Photograph: Courtesy of Motion Control, Inc., a division of IOMED, Salt Lake City, Utah.

Two examples illustrate MP prescriptions.

Example 1

A 20-year-old female soldier sustaining a long traumatic BE amputation and desiring comfort and cosmesis in her prosthesis, decides she wants an MP. A prosthetic prescription could include some of the following variations in components:

1. BE myoelectric prosthesis with total contact, double walled, hard socket (Muenster socket) for suspension. The Muenster socket is similar to that used with a CP, and provides suspension.
2. Wrist flexor and wrist extensor controls for the myoelectric hand. The supinator muscle can also perform this activity in the case of a short BE amputation.[73]
3. Proportional two-state control. This is generally determined by the type of MP available from manufacturers.
4. A powered wrist rotator. This device demands an additional muscle control site. One in four Utah arm users have a powered wrist unit.[73] Another option is a friction wrist unit placed into the desired position with the opposite hand.

Example 2

A 34-year-old male soldier with an AE amputation decides on an MP. A prescription might include these variations:

1. AE myoelectric prosthesis.
2. A total contact, dual walled, hard socket with the inner wall containing myoelectric electrodes.
3. Figure-8 suspension.
4. Biceps and triceps control of the myoelectric elbow and hand. The Utah arm locks the elbow when the elbow position is maintained for a brief, preset period of time. Unlocking occurs with a brief cocontraction of both control muscles. Control transfers to the TD after the elbow is locked.[73] Proportional control can be used.
5. Conventional body-powered elbow flexion and myoelectrically controlled TD. This hybrid prosthesis combines the advantages of an MP and a CP.

Evaluation of Myoelectric Prosthetic Candidates

The comprehensive evaluation of an amputee who chooses an MP is similar to that of an upper limb amputee who uses a CP. There are, however, additional training issues specific to MP users.

Each amputee should be evaluated by the rehabilitation team as early as possible. Comprehensive assessments of the amputee's thoughts regarding the amputation should be discussed. A detailed history concerning the patient's vocational and avocational interests along with a complete medical evaluation should be obtained. The amputee's wishes, in terms of ultimate function and appearance of a prosthesis, should be thoroughly addressed.

A physical examination, as with any amputee, includes a complete evaluation of all organ systems, with close attention paid to the musculoskeletal and neurological systems. A candidate for an MP must have available muscle sites on the residual limb that can be trained to provide independent voluntary contractions. These muscles will control the prosthesis. An intact motor control system to the residual limb includes: (*a*) upper motor neuron input from the brain to the spinal cord; (*b*) lower motor neuron continuity to the control muscles; and (*c*) intact, nonatrophied muscles capable of generating and sustaining a useful myoelectric signal.

The decision to use an MP instead of, or in addition to, a CP is complex. Selection of the optimal prosthesis incorporates patient wishes, status of the other organ systems, adequate residual control muscles to control a prosthetic limb, functional goals of the patient (vocational and avocational) and issues of cosmesis. The patient and the rehabilitation team together make these decisions, remembering that independence and maximal function of the individual patient is the ultimate goal.[74] Substantial experience with BE amputees supports routine use of myoelectric BE prostheses for appropriate candidates.

Rehabilitation of the Myoelectric Prosthesis User

If the decision is made to provide and train an amputee in the use of an MP, additional education must be employed beyond the comprehensive rehabilitation described for all amputees. This involves the selection of specific myoelectric control muscle sites to control the prosthesis. The type of prosthesis to be used, its control system (two-state or three-state), and any other special requirements such as cocontraction of muscle groups, should be known in advance. A myoelectric testing device identifies suitable muscle sites; it measures the surface EMG signals. Typically, BE amputees use wrist flexors and wrist extensors to operate the TD. Above-elbow amputees typically use biceps and triceps to control the prosthesis.[73] Proximal muscles of the scapula can be used. A biofeedback system is useful for training control muscles.[74] As the amputee contracts a muscle, feedback is provided to the patient regarding the contraction. According to Spiegel,[74] fine control of myoelectric activity by the amputee, is the most important part of the rehabilitation process. If a patient can consistently control muscle signals, successful MP training often occurs. The minimum myoelectric signal amplitude required is approximately 15 μV.[73]

As in the case of a body-powered prosthesis, early fitting optimizes rehabilitation. When the residual limb tissues will accommodate a temporary socket, surface electrodes embedded into it can be used to train the amputee and also to determine if the MP will be accepted and incorporated into the patient’s activities.

Training initially involves learning to perform the simple activities of opening and closing the TD or flexing and extending the elbow. As progress is made, other ADLs are addressed. To practice fine control, the amputee can learn to pick up styrofoam without crushing it.[74] The unilateral amputee should also be independent without a prosthetic device, and every MP user should be trained in body-powered prosthesis use for special activities and in case of MP malfunction.[27,59]

All aspects of prosthetic maintenance must be learned by the amputee, and the MP user must treat the device with care. General precautions are to avoid carrying loads greater than 50 lb, lifting more than 2 lb, and not using the arm for hammering or with vibrating machinery.[73] In addition, the MP should be kept clean and dry.

Trends in Myoelectric Prosthetic Use

MPs have been extensively prescribed in Europe whereas there has been limited use in North America.[58] The literature provides insight into issues centering around acceptance and function of amputees using MPs.

Stein and Walley[63] studied the functionality of 20 MP users who had previously used CPs, and compared them to 16 current CP users. They found that MP users completed tasks much more slowly than CP users. However, the MP users preferred myoelectric to CPs in 60% of the cases.

Weaver and colleagues[62] measured arm function and subjective assessments in unilateral congenital amputees before and after being fitted with an MP. Pinch force was increased. A 65.6% increase in the Bimanual Functional Assessment was documented. Eight of 10 adolescents fitted with an MP preferred it to the CP, citing better cosmesis as a major advantage. Of note was the fact that cosmetic gloves covering the Otto Bock hands required frequent replacement.

Northmore-Ball and associates,[61] in a retrospective study of injured workers in Ontario, Canada, found a low rejection rate for MPs. People with desk jobs used their MPs at work more frequently than those amputees performing manual labor. The most common reason for not using the MP was fear of damaging it.

Although not applicable to wounded soldiers, Sorbye[60] documented that children with BE amputations could be successfully trained with an MP even when fitted as young as age 2.5 years. Increased maintenance requirements were again noted to be a drawback.

It appears that MPs can provide better cosmetic outcome and increased hand function. The technical drawbacks of frequent glove tears and the need for increased maintenance when compared with CPs, can possibly be eliminated as technology progresses. In certain war-injured amputees, an MP could provide optimal function. As with all amputees, the rehabilitation principles must be followed. The multidisciplinary team must be involved in the functional restoration of war injured amputees from the earliest time after injury to the time when the casualty has achieved optimal independence.

PROSTHESIS CHOICE

Prosthesis choice for AE and BE amputees is a complex decision made by the patient with advice and guidance from the rehabilitation team. The first decision involves which type of prosthesis to provide. The general categories are body powered or CPs and MPs. Sears[75] provides a useful framework for deciding which type of prosthesis to choose.

Categories of basic needs (see Table 3-1) are prioritized by each prosthetic candidate. The importance of each need depends on individual career goals, functional goals, cultural background, and daily activities. These categories are further subdivided providing additional information as to what a patient may prefer. In each category, the optimal control choice and TD (shape) choice is shown with an X.[75] For example, the Greifer Otto Bock hook is a myoelectric hook that is durable and used for rigorous work.

An excellent conceptualization for determining the optimal prosthetic prescription is shown in Figure 3-55. This figure presents two axes, the vertical being a control axis and the horizontal the TD axis. This vector approach helps define the most functional prosthesis and TD. The primary areas in relative importance are comfort, cosmesis, function, reliability, and cost.[75] The vector sum of these needs indicates the quadrant that represents the optimal prescription for that particular individual. For example, a young female soldier with a traumatic BE amputation may prefer comfort and cosmesis with less concern for function or cost (Case 1). The net vector would place her desires in the quadrant representing an MP with a hand as the TD.

Active duty amputees rarely return to active military duty following injury, so consideration as to the optimal prescription would likely include future vocational plans along with current considerations as to functional activities. Suppose an amputee enjoys carpentry work, and wants a simple, reliable, and durable prosthesis as he spends free time camping and pursuing other outdoor activi-

TABLE 3-1

EXPANDED BASIC NEEDS TABLE USED FOR EVALUATING PROSTHETIC ISSUES

	Control Choice		Shape Choice	
Basic Needs	**Body Power**	**Myoelectric**	**Hook**	**Hand**
Function				
Fine tip prehension	—	—	x	—
Cylindrical Grip (large diameter)	—	—	—	x
Cylindrical Grip (small diameter)	—	—	x	—
Flat prehension	—	—	x	—
Hook and pull	—	—	x	—
Pushing/holding down	—	—	—	x
Handling long-handled tools (handle must slide)	—	—	x	—
Ruggedness	x	—	x	—
High grip force	—	x	—	—
Delicate grip force	—	x	—	—
Visibility	—	—	x	—
Cosmesis	—	—	—	x
Comfort				
Low weight	x	—	x	—
Harness comfort	—	x	—	—
Low effort	—	x	—	—
Reliability and convenience	x	—	x	—
Low cost	x	—	—	—

Adapted with permission from Sears HH. Approaches to prescription of body-powered and myoelectric prostheses. *Phys Med Rehabil Clin North Am.* 1991;2(2):364.

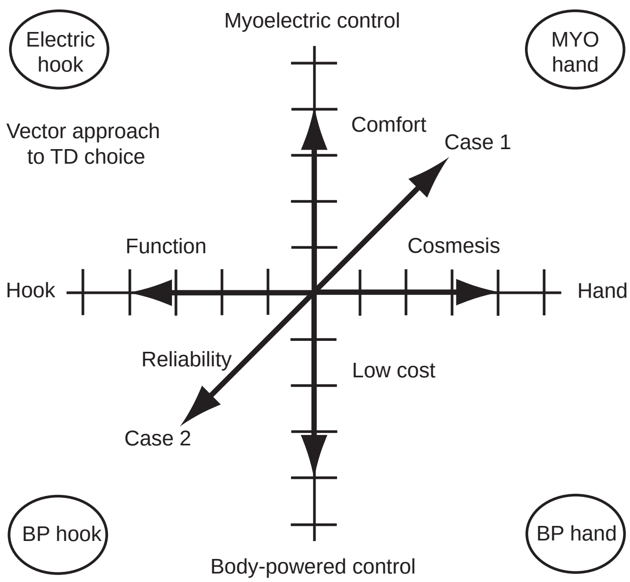


Fig. 3-55. The vector approach to terminal device prescription. Adapted with permission from Sears HH. Approaches to prescription of body-powered and myoelectric prostheses. *Phys Med Rehabil Clin North Am.* 1991;2(2):365.

ties. Cosmesis and cost are not issues to him. He knows other amputees who use hook devices so he is familiar with their appearance. In this case, reliability and function produce a net vector indicating a body-powered hook (Case 2).

This view of prescription provides an estimation of what is optimal. Sears[75] recognizes that there are many other factors that impact on the prosthetic decision, such as motivation, body image, and expectations. Early fitting and training with a temporary prosthesis allows a trial period in which the amputee can judge whether an MP or CP is suitable. All myoelectric users should be proficient with a CP because a CP will likely be used while the MP is being serviced, and because certain activities require a more rugged and durable prosthesis.

When deciding between an MP and a body-powered device, the strengths and weaknesses of each device must be considered. Spiegel[74] lists the relative advantages and disadvantages of MPs. It is important to remember that as technological improvements in myoelectric components, fitting, and production occur, many of the disadvantages may no longer apply.

Cosmesis is a major advantage of the myoelectrics. Weaver and colleagues[62] fitted 10 adolescents with myoelectric BE prostheses with Otto Bock hands and skin tone cosmetic gloves. Eight of the 10 preferred the MP, citing better cosmesis as one of the reasons.

The ability to use an MP in all planes of arm motion and overhead has been cited as one advantage.[74] Other advantages are higher pinch strength with an MP, and a graded grip strength or speed due to proportional control. Stump socks are not used with MPs, because they interfere with electrode contact. In BE prostheses, often no auxiliary suspension is necessary.

The disadvantages of MPs include high cost, frequent breakdown with high maintenance costs, technical complexity, and greater weight when compared to CPs. Reduced durability is also a major issue. Northmore-Ball and coworkers[61] in a retrospective survey of injured workers with MPs, found the major reason for not wearing MPs all the time was fear of damaging them. Sorbye[60] also noted that maintenance of MPs in children was a problem. According to Sears and associates,[73] only one week of training is necessary to train prosthetists in fitting and prescribing myoelectric devices. However, it is only the larger medical centers, which have trained, experienced rehabilitation teams, that routinely prescribe MPs and rehabilitate the receiving amputees.

VOCATIONAL OUTCOMES OF AMPUTEES

The complete rehabilitation of an amputee requires the achievement of all functional goals and the assumption by the amputee of an expected societal role involving productive work. This is particularly important for the war-injured soldier who will have many productive years remaining after injury.

Statistics regarding amputees who return to active military duty are not readily available, but a review of data from a U.S. Army Physical Evaluation Board over a 1-year period (1988–1989), revealed that only 2.3% of amputees return to active duty. Historically, during times of prolonged major conflict, amputees were utilized to perform many noncombat tasks. In World War II, amputees were sometimes trained in prosthesis fabrication and utilized in military hospitals.[4] The British Royal Air Force retained amputees on active duty, finding it more costly and time consuming to train new aircraft mechanics than to retain the amputees.[76,77] During the Civil War, amputees and other disabled soldiers frequently guarded bridges, maintained prisoner of war camps, and performed other necessary duties. These soldiers belonged to the "Corps of Invalids," later renamed the Veterans Reserve Corps because of the negative connotation of the former name.[78]

In a follow-up study of amputees from the Vietnam War, Curley and colleagues[79] found that when comparing the social and vocational outcomes of amputees to those of noninjured Vietnam veterans, the amputees fared less well. The amputees showed twice the unemployment rate, earned less money, held more blue collar jobs, and obtained fewer college degrees than their noninjured counterparts. These results underscore the need for emphasis on vocational rehabilitation. Steinbach described the Israeli experience in rehabilitation of war-injured amputees and pointed out the importance of vocational counseling "as soon as possible after the injury."[80] Steinbach reported that 96% of Israeli amputees at discharge had vocational plans with 28% returning to their previous jobs. Unfortunately, the percentage who returned to active military duty was not stated. Ryan and coworkers[81] conducted a follow-up study of World War II amputees treated by U.S. Navy physicians. These authors followed 200 amputees and found that 78% were working or pursuing higher education. They again pointed to the need for addressing vocational issues while the injured soldier convalesced at a military hospital, stressing the inclusion of driving.

The war injured amputee poses many vocational challenges to the rehabilitation team, but the field of vocational rehabilitation has dramatically expanded in the last few decades.[82] Vocational rehabilitation includes an accurate evaluation of functional limitations of the disabled individual, particularly in work simulation tasks, and reintegration into a vocation in which the person can succeed.

The civilian experience relates similar findings and also highlights interventional strategies for improving vocational outcome. The literature[83,84] suggests that amputees do have higher unemployment than their able bodied counterparts. Only a small percentage of amputees return to their previous jobs.[83] Shepherd and Caine[85] noted in their series on traumatic UE amputees, that at follow-up only 36% had returned to their previous work, with 32% requiring retraining before doing other work, and 32% not working at all. The reasons for reduced vocational outcomes were addressed by Sheikh[86] in a study of limb injuries and amputations. Surprisingly, this author found that the exact type of limb injury (fracture, amputation, or soft tissue injury) had little if any effect on vocational outcome. However, variables such as motivation, low level of disability, short duration of unemployment, a vocational retraining program, and low unemployment in the general population strongly influenced return to work. Some of these variables are potentially modifiable through appropriate rehabilitation. Millstein and associates[87] in their review of 1,010 Canadian amputees, found that 89% of upper- and lower-limb amputees returned to work, but most (75%) changed jobs. For upper-limb amputees the return to work rate was 93%. The authors found that younger ages, comfortable and routine prosthetic use, and provision of vocational services were associated with return to work. Phantom pain and residual limb pain, along with multiple amputations, negatively impacted on return to gainful employment. Most of these Canadian amputees were injured as a result of work-related accidents.

Helm and associates[88] in their series on lower extremity amputees, found that prosthetic fit and pain were important variables affecting amputee function. Other authors[89,90] strongly support early vocational intervention. Brown[90] notes that simulated work tasks coordinated with occupational therapy and other rehabilitation professionals, can develop skills used in pursuing alternate careers. Returning to work on a part-time basis can also be advantageous.[90]

CONCLUSION

From the preceding discussion it is clear that many amputees require a change in career after their amputations, but that the majority can successfully find and maintain gainful employment. Intervention by rehabilitation professionals is very important. A comfortable and functional prosthesis, achieved through trained physiatrists and prosthetists working to optimize construction, alignment, and fit, is enormously important. Vocational counseling early in the amputee's postoperative period, with subsequent retraining, improves vocational outcomes. Earlier return to work favors a better vocational outcome and should be pursued whenever possible. Phantom limb pain and other painful residual limb problems should be aggressively addressed.

Return to active military duty following amputation is a complex issue involving the soldier's motivation; command support; special, highly developed skills that the soldier may possess; and the policy and needs of the armed forces at that particular time. The vocational restoration of injured soldiers is an important goal. Indeed, if the nation becomes engaged in a prolonged conflict, the rehabilitated soldier could potentially be a vital asset to the war effort, particularly in the small, and more technically complex army that is envisioned for the future.

There are amputees who remain on active duty, some in combat units; however, they are the exceptions. These individuals find that they require durable prosthesis that can accommodate active vocations and that they also require routine prosthetic replacements.

Upper limb amputees pose special rehabilitative challenges to the military. Designated amputation centers where skilled surgeons and rehabilitation professionals work in a coordinated fashion can best meet the needs of amputee soldiers.

ACKNOWLEDGMENTS

The author thanks Bill Discher, Armed Forces Institute of Pathology, Walter Reed Army Medical Center, Washington, DC, for his superb illustrations of prosthetic devices; and Harold H. Sears, PhD, Vice President and General Manager, Motion Control, Inc., a division of IOMED, 1290 West 2320 South, Suite A, Salt Lake City, Utah 84119, for the myoelectric slides and technical advice regarding myoelectric prostheses.

REFERENCES

1. Stern PH. The epidemiology of amputations. *Phys Med Rehabil Clin North Am*. 1991;2(2):253–261.

2. Leonard DA, Meier RH. Prosthetics in rehabilitation medicine. In: DeLisa JA, ed. *Rehabilitation Medicine Principles and Practice*. Philadelphia: JB Lippincott; 1988.

3. Peterson LT. Amputations: Historical note. In: Mullins WS, Cleveland M, Shands AR, McFetridge EM, eds. *Surgery in World War II*: *Orthopedic Surgery in the Zone of the Interior*. Washington, DC: Office of The Surgeon General, US Department of the Army; 1970.

4. Peterson LT. Administrative considerations in the amputation program. In: Mullins WS, Cleveland M, Shands AR, McFetridge EM, eds. *Surgery in World War II: Orthopedic Surgery in the Zone of the Interior*. Washington, DC: Office of The Surgeon General, US Department of the Army; 1970.

5. Bunnell S. Conclusions on the care of injured hands in World War II. Derived from the experiences of the civilian consultant for hand surgery to the Secretary of War. In: Bunnell S, ed. *Surgery in World War II: Hand Surgery*. Washington, DC: Office of The Surgeon General, US Department of the Army; 1955.

6. Peterson LT. General clinical considerations of amputation. In: Mullins WS, Cleveland M, Shands AR, McFetridge EM, eds. *Surgery in World War II: Orthopedic Surgery in the Zone of Interior*. Washington, DC: Office of The Surgeon General, US Department of the Army; 1970.

7. Beasley RW. Surgery of hand and finger amputations. *Orthop Clin North Am*. 1981;12(4):763–803.

8. Strickland JW. Restoration of thumb function after partial or total amputation. In: Hunter JM, Schneider LH, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand*. 2nd ed. St. Louis: CV Mosby; 1984.

9. Bunnell S. Management of the nonfunctional hand—Reconstruction vs. prosthesis. In: Hunter JM, Schneider LH, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand*. 2nd ed. St. Louis: CV Mosby; 1984.

10. Beasley RW, de Bese GM. Upper limb amputations and prostheses. *Orthop Clin North Am.* 1986:17(3):395–405.

11. Michael JW, Gailey RS, Bowker JH. New developments in recreational prostheses and adaptive devices for the amputee. *Clin Orthop.* 1990:256:64–75.

12. Patricelli J. Adapted knife for partial hand amputated patients. *Am J Occup Ther.* 1982;36(3):193–194.

13. Malone JH, Childers SJ, Underwood J, Leal JH. Immediate post-surgical management of upper extremity amputation: Conventional, electric and myoelectric prosthesis. *Orthot Prosthet*. 1981:35(2):1–9.

14. White JG, HilFrank BC. Prosthetic and adaptive devices for the partial hand amputee. In: Hunter JM, Schneider LH, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand*. 2nd ed. St. Louis: CV Mosby; 1984.

15. Pillet J. The aesthetic hand prosthesis. *Orthop Clin North Am.* 1981;12(4):961–969.

16. Pillet J. Aesthetic hand prostheses: Its psychological and functional potential. In: Hunter JM, Schneider LH, Mackin EJ, Callahan AD, eds. *Rehabilitation of the Hand*. 2nd ed. St. Louis: CV Mosby; 1984.

17. Bender, LF. Upper-extremity prosthetics. In: Kottke F, Lehmann JF, eds. *Krusen's Handbook of Physical Medicine and Rehabilitation*. 4th ed. Philadelphia: WB Saunders; 1990.

18. Shurr DG, Cook TM. Upper-extremity prosthetics. In: Shurr DG, Cook TM, eds. *Prosthetics and Orthotics*. Norwalk, Conn: Appleton and Lange; 1990.

19. Tooms RE. Amputation surgery in the upper extremity. *Orthop Clin North Am.* 1972;3(2):383–395.

20. Taylor CL. The biomechanics of control in upper-extremity prostheses. *Orthot Prosthet*. 1981;35(1):7–28.

21. McAuliffe JA. Elbow disarticulation and transhumeral amputation/shoulder disarticulation and forequarter amputations. In: Bowker JH, Michael JW, eds. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles*. 2nd ed. St. Louis: Mosby-Year Book; 1992: 22.

22. Andrew JT. Prosthetic Principles. In: Bowker JH, Michael JW, eds. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles*. 2nd ed. St. Louis: Mosby-Year Book; 1992.

23. Bowen TE, Bellamy RF. *Emergency War Surgery*. 2nd ed. Washington, DC: US Government Printing Office; 1988.

24. Ouellette EA. Wrist disarticulation and transradial amputation. In: Bowker JH, Michael JW, eds. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles*. 2nd ed. St. Louis: Mosby-Year Book; 1992.

25. Baumgartner RF. The surgery of arm and forearm amputations. *Orthop Clin North Am.* 1981;12(4):805–817.

26. Dillingham TR, Spellman NT, Braverman SE, et al. *Analysis of Casualties Referred to Army Physical Medicine Services During Wartime. Am J Phys Med Rehabil.* 1993;72(4):214–218.

27. Van Lunteren A, Van Lunteren-Gerritsen GH, Stassen HG, Zuithoff MJ. A field evaluation of arm prostheses for unilateral amputees. *Prosthet Orthot Int*. 1983;7:141–151.

28. Kottke FJ. Therapeutic exercise to maintain mobility. In: Kottke FJ, Lehmann JF, eds. *Krusen's Handbook of Physical Medicine and Rehabilitation*. 4th ed. Philadelphia: WB Saunders; 1990.

29. Halar EM, Bell KR. Rehabilitation's relationship to inactivity. In: Kottke FJ, Lehmann JF, eds. *Krusen's Handbook of Physical Medicine and Rehabilitation*. 4th ed. Philadelphia: WB Saunders; 1990.

30. Meier RH. Evaluation of and planning for acquired upper-limb amputee rehabilitation. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

31. Atkins DJ. Adult upper limb prosthetic training. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

32. Dalsey R, Gomez W, Seitz WH, Dick HM, Hutnick G, Akdeniz R. Myoelectric prosthetic replacement in the upper-extremity amputee. *Orthop Rev*. 1989;18(6):697–702.

33. Atkins DJ. Postoperative and pre-prosthetic therapy programs. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

34. Hermansson LM. Structured training of children fitted with myoelectric prostheses. *Prosthet Orthot Int*. 1991;15:88–92.

35. Canty TJ. Amputee rehabilitation. *Arch Phys Med Rehabil*. April 1951;32:219–221.

36. Brown PW. Rehabilitation of bilateral lower extremity amputees. *J Bone Joint Surg Am.* 1970;52(4):687–700.

37. Bailey RB. An upper extremity prosthetic training arm. *Am J Occup Ther*. 1970;24(5):357–359.

38. Meeks D, LeBlanc M. Preliminary assessment of three new designs of prosthetic prehensors for upper limb amputees. *Prosthet Orthot Int*. 1988;12:41–45.

39. Kruit J, Cool JC. Body-powered hand prosthesis with low operating power for children. *J Med Eng Technol*. 1989;13(1/2):129–133.

40. Sensky TE. A simple and versatile driving appliance for upper-limb amputees. *Prosthet Orthot Int*. 1980;4:47–49.

41. Chappell PH, Kyberd PJ. Prehensile control of a hand prosthesis by a micro-controller. *J Bioeng*. 1991;13:363–369.

42. Lewis EA, Shevedos CR, Sowell TT, Houston VL. Clinical application study of externally powered upper-limb prosthetics systems: The UA elbow, the UA hand, and the UA/NU myoelectric hand systems. *Bull Prosthet Res*. 1975;10-24:51–136.

43. Bergman K, Ornholmer L, Zackvisson K, Thyberg M. Functional benefit of an adaptive myoelectric prosthetic hand compared to a conventional myoelectric hand. *Prosthet Orthot Int.* 1992;16:32–37.

44. Almstrom C, Herberts P, Korner L. Experience with Swedish multifunctional prosthetic hands controlled by pattern recognition of multiple myoelectric signals. *Int Orthop*. 1981;5:15–21.

45. Muilenburg AL, LeBlanc MA. Body-powered upper limb components. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

46. Chadderton HC. Consumer concerns in prosthetics. *Prosthet Orthot Int*. 1983;7:15–16.

47. Levack H. Suction socket prosthesis for A.E. amputees. *Can J Occup Ther*. 1971;38(3):121–124.

48. Marquandt E, Neff G. The angulation osteotomy of above-elbow stumps. *Clin Orthop*. 1974;104:232–238.

49. Reyburn TV. The “Z” straps: Harnessing modifications for patients with upper-extremity amputations. *Arch Phys Med Rehabil*. 1991;72:250–252.

50. Schnell MD, Bunch WH. Management of pain in the amputee. In: Bowker JH, Michael JW, eds. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles.* 2nd ed. St. Louis: Mosby-Year Book; 1992.

51. Vaida G, Friedmann LW. Postamputation phantoms: A review. *Phys Med Rehabil Clin North Am.* 1991;2(2):325–353.

52. Baumgartner RF. Management of bilateral upper limb amputees. *Orthop Clin North Am*. 1981;12(4):971–977.

53. Weiss-Lambrou R, de Sart M, Moreau R, Duquette J. Brief on new toilet independence for the severe bilateral upper-limb amputee. *Am J Occup Ther.* 1985;39(6):397–399.

54. Friedman L. Toileting self-care methods for bilateral high level upper limb amputees. *Prosthet Orthot Int.* 1980;4:29–36.

55. Visuthikosol V, Wonglousarakum S, Navykarn T, Druavit A. The Krukenberg procedure in the bilateral amputee after electrical burn. *Ann Plast Surg*. 1991;27(1):56–60.

56. Mathur BP, Narang IC, PipLani CL, Majid MA. Rehabilitation of the bilateral below-elbow amputee by the Krukenberg procedure. *Prosthet Orthot Int*. 1981;5:135–140.

57. Scott RN. Biomedical engineering in upper extremity prosthetics. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

58. Kritter AE. Current concepts review myoelectric prostheses. *J Bone Joint Surg Am.* 1985;67(4):654–657.

59. Datta D, Kingston J, Ronah DJ. Myoelectric prostheses for below-elbow amputees: The Trent experience. *Int Disabil Stud.* 1989;11(4):167–170.

60. Sorbye R. Myoelectric prosthetic fitting in young children. *Clin Orthop*. 1980;148:34–40.

61. Northmore-Ball MD, Heger H, Hunter GA. The below-elbow myoelectric prosthesis: A comparison of the Otto Bock myoelectric prosthesis with the hook and functional hand. *J Bone Joint Surg Br.* 1980;62(3):363–367.

62. Weaver SA, Lange LR, Vogts VM. Comparison of myoelectric and conventional prostheses for adolescent amputees. *Am J Occup Ther*. 1988;42(2):87–91.

63. Stein RB, Walley M. Functional comparison of upper extremity amputees using myoelectric and conventional prostheses. *Arch Phys Med Rehabil*. 1983;64:243–248.

64. Scott RN. Feedback in myoelectric prostheses. *Clin Orthop*. 1990;256:58–63.

65. Scott RN. Myoelectric control systems research at the Bio-engineering Institute, University of New Brunswick. *Med Prog Technol*. 1990;16(1–2):5–10.

66. Kelly MF, Parker PA, Scott RN. The application of neural networks to myoelectric signal analysis: A preliminary study. *IEEE Trans Biomed Eng.* 1990;37(3):221–230.

67. Winter DA. *Biomechanics of Human Movement*. New York: Wiley and Sons; 1979.

68. Sears HH, Shaperman J. Proportional myoelectric hand control: An evaluation. *Am J Phys Med Rehabil.* 1991;70(1):20–27.

69. Herberts P, Kaiser E, Magnusson R, Peterson I. Power spectra of myoelectric signals in muscles of arm amputees and healthy normal controls. *Acta Orthop Scand*1973;44(2):161–193.

70. Herberts P, Almstrom C, Caine K. Clinical application study of multi-functional prosthetic hands. *J Bone Joint Surg Br.* 1978;60(4):552–560.

71. Korner L. Afferent electrical nerve stimulation for sensory feedback in hand prostheses. *Acta Orthop Scand*. 1979;Suppl:178.

72. McNeal DR, Waters R, Reswick J. Experience with implanted electrodes. *Neurosurgery*. 1977;1(2):228–229.

73. Sears HH, Andrew JT, Jacobsen SC. Experience with the Utah arm, hand, and terminal device. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

74. Spiegel SR. Adult myoelectric upper-limb prosthetic training. In: Atkins DJ, Meier RH, eds. *Comprehensive Management of the Upper-Limb Amputee*. New York: Springer-Verlag; 1989.

75. Sears HH. Approaches to prescription of body-powered and myoelectric prostheses. *Phys Med Rehabil Clin North Am*. 1991;2(2):361–371.

76. Wynn Parry CB. The management of injuries to the brachial plexus. *Proc R Soc Med*. 1974;67:488–490.

77. Eldar R, Ohry A. Preparation of a hospital rehabilitation system for war and other disasters. *Med War*. 1990;6(7):105–111.

78. Adams GW. *Doctors in Blue: The Medical History of the Union Army in the Civil War*. Dayton, Ohio: Morning Side House; 1985.

79. Curley MD, Walsh MJ, Triplett RG. Some adjustment indices of oral-maxillofacial war casualties, limb amputees, and non-injured veterans. *Mil Med*. 1982;147:572–574.

80. Steinbach T. Total rehabilitation for amputees in special conditions. *Prosthet Orthot Int*. 1977;1(2):125–126.

81. Ryan TC, Jones DT, White WL, Orr TE, Walters W. Management and rehabilitation of naval battle casualty amputees. *Ann Surg.* 1946;124(6):1047–1056.

82. Davis DJ, Paasuke L. Vocational evaluation and rehabilitation. In: Delisa JA, ed. *Rehabilitation Medicine Principals and Practice*. Philadelphia: JB Lippincott; 1988.

83. Khoury SA. Evaluation of amputees. *Int J Rehabil Res.* 1983;6(4):449–454.

84. Kejlaa GH. The social and economic outcome after upper limb amputation. *Prosthet Orthot Int*. 1992;16:25–31.

85. Shepherd WG, Caine D. Vocational end results following rehabilitation of upper-extremity amputees. *Med J Aust*. 1968;2(4):167–169.

86. Sheikh K. Return to Work following limb injuries. *J Soc Occup Med.* 1985;35:114–117.

87. Millstein S, Bain D, Huster GA. A review of employment patterns of industrial amputees: Factors influencing rehabilitation. *Prosthet Orthot Int*. 1985;9:69–78.

88. Helm P, Engel T, Holm A, Kristiansen VB, Rosendahl S. Function after lower limb amputation. *Acta Orthop Scand*. 1986;57:154–157.

89. Schafter R. Occupational therapy for lower extremity problems. *Am J Occup Ther.* 1973;27(3):132–137.

90. Brown LKW. Traumatic amputation: Mechanism of injury, treatment and rehabilitation. *AAOHN J*. 1990;38(10):483–486.