Prosthetics Research and the Amputation Surgeon

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EXCEPT in abnormal circumstances, man is born into his world with four mobile members which extend from his trunk like branches from a tree. These so-called "limbs" he uses in manifold complex patterns, first to serve his immediate personal needs and second to shape his own environment as best he can. Although in early life man reveals the history of the race by crawling about on all fours, he shortly assigns to two of the limbs chiefly, but not exclusively, the functions of supporting the body and of moving it from place to place. The "legs" thus become the principal weight-bearing members and the generally accepted means of locomotion.[3] To the more versatile "arms" man assigns most of the more complex functions of daily living and of creative activity. No doubt to this "division of labor" can largely be attributed the rather remarkable development of art and science and literature and industry and most of the other creative manifestations of human life.

Because, however, the limbs extend from the body proper, they are particularly susceptible to damage, either from lack of nutrition and disease or by external forces of one kind or another. Since the limbs are not "vital" organs in the same sense as, say, the heart or the liver, it is possible under favorable conditions to remove one or more without loss of the whole living organism, especially since the advent of modern surgery, anesthesia, and the newer drugs and blood substitutes. That is to say, a man has a chance of living on, though a natural member be discarded. We thus have as a result of war, accident, and disease a sizable number of individuals lacking part or all of one or more limbs, and to these must be added those persons born with malformed or missing limbs. All these people, now known generally as "amputees," are obviously handicapped, to greater or lesser degree, in the performance of all those functions ordinarily carried out by the arms and legs, and in extreme cases there may be no residual function at all. To restore lost functions in as great a measure as possible has long presented a challenge to certain people, mostly, as might have been expected, to amputees themselves.

THE BACKGROUND

Early amputations undoubtedly were more often than not traumatic events leading to a prompt death. Occasionally, however, history records amputees who survived their bloody and painful experiences. One famous example was Hegesistratus, who, captured and chained by the Spartans, amputated his own foot in order to escape *(73)*. With the slow development, over the centuries, of surgery in general, amputations came to be performed more frequently. Typically they were desperate efforts to save life. Such works as those of Pare *(69)*, of the sixteenth century, described the techniques. In some cases, a tight tourniquet was applied and left intact until the distal portion was lost by spontaneous amputation. In others, the amputation was conducted with

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[3] **It should be recalled that with a little practice man can walk on his hands, but it is not a very comfortable behavior or one that can long be continued.**

knife and saw, and bleeding was controlled by cauterization.

From the beginning it seemed obvious that the amputation should be as distal as feasible in order to conserve the maximum bony lever. Many surgeons, however, preferred a disarticulation at a joint whenever that was possible. For they had found that infection was relatively unlikely to enter the bone through the normal surfaces which could be retained with disarticulation, whereas, in the days before aseptic surgery, osteomyelitis was all too common when the marrow cavity was opened by amputation through the shaft of a bone.

Roughly a century ago the introduction of anesthetics made prolonged surgery possible, and not long after that the germ theory and antiseptic and aseptic surgery greatly increased the chances of surviving either accidental wounds or surgery. These factors made possible the comparatively long and complicated amputations now taken for granted, the revision of otherwise unsuitable stumps, and the elective amputations in cases of serious disease or deformity.

At about the same time, wars involving European powers, and especially the American Civil War, led to large numbers of surviving amputees. Also, and again more or less simultaneously, the rapid development of heavy industry and of railroading resulted in many traumatic amputations in civilian life, especially in the United States. All these factors increased interest in amputation surgery and in limbmaking for the large numbers of surviving amputees.

AMPUTATION SURGERY AND THE ART OF PROSTHETICS

Artificial limbs of one kind or another date from antiquity. Particularly during the fifteenth, sixteenth, and seventeenth centuries, crudely functional artificial arms came to be made, chiefly by armorers, who were already experienced in a related field. Of many known examples, the arm and hand made about 1509 for Goetz von Berlichingen *(74)* is by far the best known (Fig. 1, page 47), numerous copies having been constructed for museums. In this and others of the period, joints were flexed by the other hand and locked by ratchets. Springs returned the joints when the ratchets were released by pressure on a projecting knob. In all such armorlike arms and hands, iron was used, sometimes with holes punched to reduce weight. Leather doublets or sockets, often with laces, commonly were used for several centuries.

Near the end of the eighteenth century, Klingert *(19,52)* introduced an above-elbow arm with most of the natural motions controlled by ten catgut cords fastened to a vestlike garment and moved individually by the sound hand. Since in most cases the sound hand might better have performed the intended action, this impractical prosthesis was a classic pioneer in exceeding what some nowadays call the "hardware tolerance" of the amputee. In 1818, Peter Ballif *(18,51)* of Berlin developed the first voluntary control by use of trunk and shoulder muscles. His hand was of the voluntary-opening type *(38,98)* with springs to close the fingers and thumb. To the Dutch sculptor, Van Peeterssen, is attributed the first above-elbow prosthesis with harness control permitting voluntary flexion of the artificial elbow joint *(52)*.

As the art of armormaking declined, limbmaking on the Continent came to be carried on usually in conjunction with the making of braces, and consequently the artificial legs produced there typically evidenced steel sidebars and molded leather corsets similar to those used in braces. At the time of the Napoleonic Wars, the wooden leg, used from earliest times, was provided, for example, by Potts of London for the Marquis of Anglesey and others *(40,86)*. Wood reinforced by rawhide was used customarily in the United States, although a variety of other structural materials has been suggested in the journal literature and in patents.

Comte de Beaufort *(53)* invented a number of artificial arms as well as legs, some of which were approved for French veterans of the Crimean and Italian campaigns. In 1858, he presented to the French Academy of Medicine a hand with an alternator mechanism and a double-spring hook *(54)*. Dorrance *(33)* introduced in America the well-known voluntary-opening split hook with rubber bands to close a movable finger against a rigid one. He and others rapidly produced a variety of hook shapes intended for specific trades.

WORLD WAR I

World War I led to a revival of interest in amputations and in artificial limbs, notably in Germany, Belgium, and England. All these countries had rather extensive programs involving the cooperation of surgeons, limbfitters, and engineers. Publications based on World War I experience *(17,50,58,59,80)* indicated considerable progress in understanding of amputation techniques, of the need for prompt rehabilitation of amputees, and of the importance of fit and alignment of the prosthesis. The development of many new devices and components for artificial limbs for both upper and lower extremity was described perhaps most impressively in *Ersatzglieder und Arbeilshilfen (17).* Martin's second book *(59),* prepared for the International Labour Office, and Little's text *(50)* were particularly useful because they offered critical analyses following impartial descriptions of prostheses and mechanisms.

The wooden leg came to be used widely throughout the Continent as well as in England and in the United States. Aluminum, introduced by Desoutter *(32,49,86)* in England in 1912, was used particularly in England and to a lesser extent elsewhere. The fiber leg was used by a substantial number of limbmakers, particularly in the United States. Despite the large number of knee locks and ankle joints permitting lateral motion, described in patents and in medical and technical literature, most above-knee amputees used a simple uniaxial hinge for the knee joint and a single-axis ankle joint. Rubber bumpers were used widely in place of the tendons popular in the nineteenth century. It is interesting to note that in 1922 Little remarked *(57)* that most leg amputees had to use at least one stick.

For the upper extremity, a great many artificial arms, hands, and working tools were developed during World War I, as can be seen from the major books on prostheses of the period *(17,50,58,59,80).* American designers generally used the split mechanical hook closed by rubber bands and separated from the forearm by a rubber washer which provided stability by friction but which at the same time permitted pronation-supination by means of the other hand. Europeans generally preferred passively operated clamps and special tools so designed as to be interchangeable by a disconnect at the wrist. Either a clamp, as on a machine tool, or a locking bolt engaging any one of a series of holes in a disc was used to fasten the tool in the selected position of pronation or supination. For working purposes, the attachment for the tool was often placed at the end of the socket, far above the normal hand level, so as to decrease the leverage of the load on the stump. For dress wear, a cosmetic forearm and terminal device could be attached in place of the tool.

Various wooden hands, usually with spring-loaded or voluntarily controlled thumbs, were shown in the literature of many countries. Generally, it was assumed that such hands were for dress and for light office use only, either bare or covered with a leather or fabric glove. Often the fingers were curved permanently to carry a briefcase. The Carnes arms and hands *(25,26,27),* patented in 1912, 1922, and subsequently, were widely sold in the United States for many years. During World War I they were widely admired abroad and were described in detail by Schlesinger *(20)* and to a lesser extent by Martin *(60)* and by Little *(56).*

Similar devices, under the general name "Germania," were built in Germany after entrance of the United States into hostilities. Most authors admired the dexterity achieved by the Carnes devices—particularly because of their ingenious construction, the passively adjustable wrist flexion, and the possibility of coordinating supination with elbow flexion to assist in eating—but criticism was leveled at complexity, relatively heavy weight, lost motion, and the restriction against interchange of a hook for the hand.

WORLD WAR II

Surgical authorities during World War II advocated *(44,45)* typical "sites of election" (Figs. 1 and 2) based upon the extensive practical experience of the surgeons as well as on the advice of many of the more active limbfitters, who were notably successful in fitting good stumps at these "sites of election" but

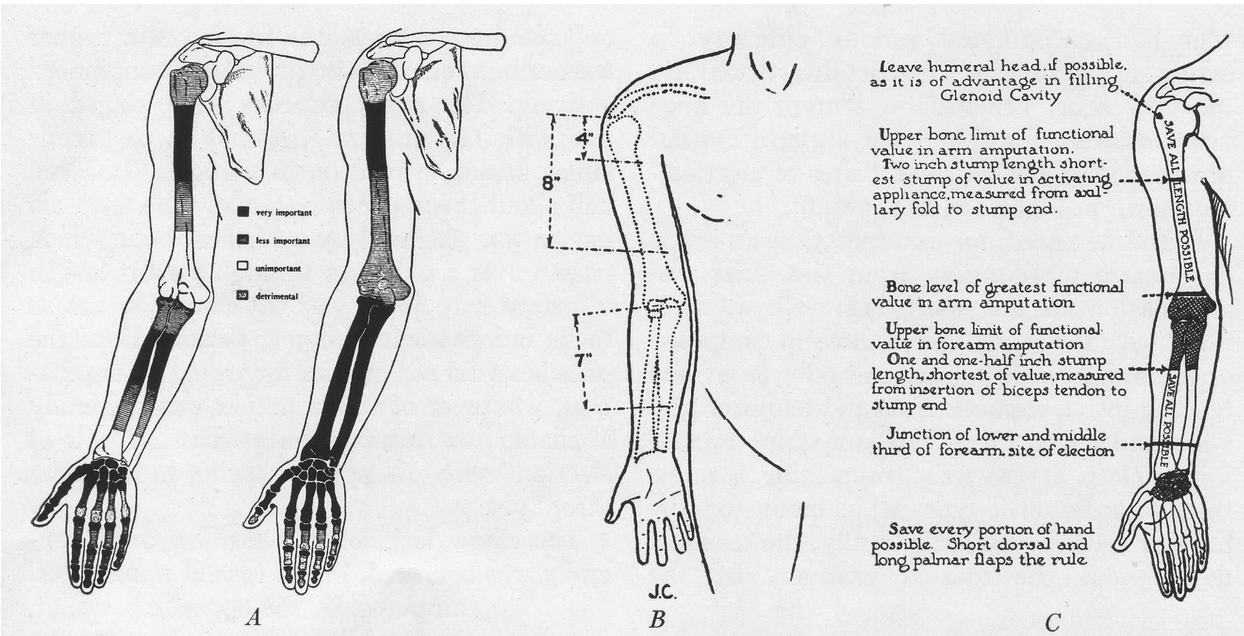


Fig. 1. Typical "sites of election" for amputation in the upper extremity, from well-known texts, by permission of the respective publishers. In general the sites became progressively less restricted. ***A,*** **Recommendations of zur Verth** ***(100),*** **as reproduced by Vasconcelos** ***(94)*** **reporting to the 3rd Brazilian and American Surgical Congress, Rio de Janeiro, November 1943. Original caption labels left drawing as representing functional values for an "intellectual," right drawing as for a "workman." Note that zur Verth favors more lever for a "working man."** ***B,*** **Recommendations of Langdale-Kelham and Perkins** ***(45).*** **They state, ". . . but limb-makers are unable to fit a limb that allows the patient to pronate and supinate, for the circumference of the forearm changes its shape during rotation and the socket is either too tight to permit the change of shape or too loose to secure a firm hold on the stump. . . ."** ***C,*** **Recommendations of Kirk** ***(44).*** **Note increasing emphasis on saving all length possible. Kirk's text suggests that wrist disarticulation is rather unsatisfactory and that few if any prostheses make use of pronation. The elbow disarticulation is tolerated but criticized.**

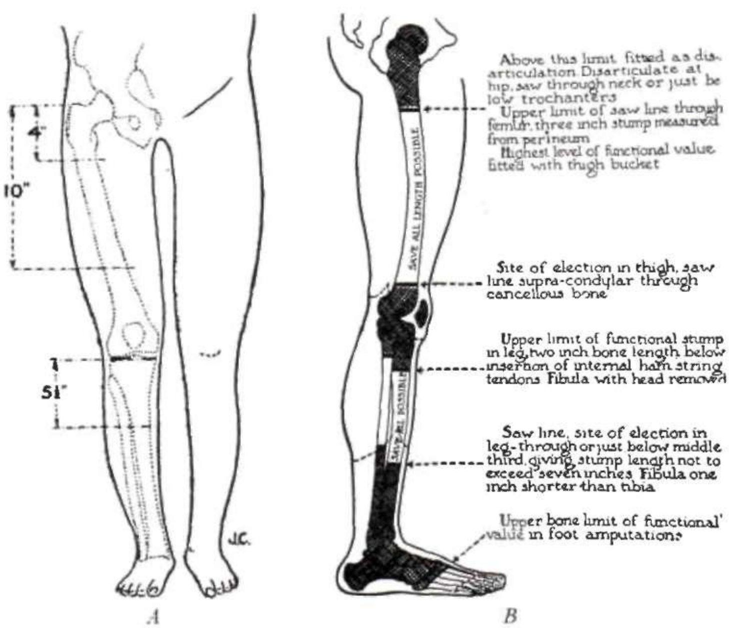


Fig. 2. Typical "sites of election" for amputation in the lower extremity, from well-known texts, by permission of the respective publishers. ***A,*** **Recommendations of Langdale-Kelham and Perkins** ***(45).*** **These authors condemn the Syme.** ***B,*** **Recommendations of Kirk** ***(44).*** **Although Kirk does not show a Syme, he agrees with the Canadians that a properly fitted Syme's amputation is ideal for the "laboring man."**

who had encountered serious difficulty in fitting such stumps as the wrist disarticulation, the very short below-elbow stump, the knee disarticulation, or the Syme stump. Typical prostheses for the so-called "sites of election" are shown in Figures 3, 4, 5, and 6.

It will be noted, for example, that all levels of forearm amputation, from the wrist disarticulation to the short below-elbow, were fitted with the same type of forearm composed of a molded leather socket, usually laced, extending into a cosmetic shell and reinforced by volar and dorsal metal sidebars which formed a crosspiece at the wrist supporting a screw thread or bayonet-type attachment for the hook or artificial hand. Typically, the terminal device could be rotated passively by the opposite hand against the friction of a rubber washer but could not be pronated or supinated actively. The metal sidebars were hinged in line with the humeral epicondyles to permit elbow flexion in relation to a buckled or laced cuff about the upper arm. Usually the terminal device was operated by a leather thong which passed over a pulley or through a short length of helical wire housing at the elbow joint so as to be independent of elbow flexion. Since the prosthesis did not provide for pronation-supination, whatever of this function was originally available in a stump amputated at the "site of election" soon disappeared owing to muscular atrophy.

The elbow lock for above-elbow arms generally was operated, in the case of a unilateral amputee, by the opposite hand, or, in the bilateral arm amputee, by pressure against the body or against a table. It usually consisted of a sliding bolt engaging one of three or four holes in a metal strap surrounding the carved wooden elbow portion below the molded leather or fiber humeral socket. Cotton webbing and rather heavy leather shoulder saddles were commonly used in the arm harness, and leather thongs transmitted forces to flex the elbow and to operate the terminal device.

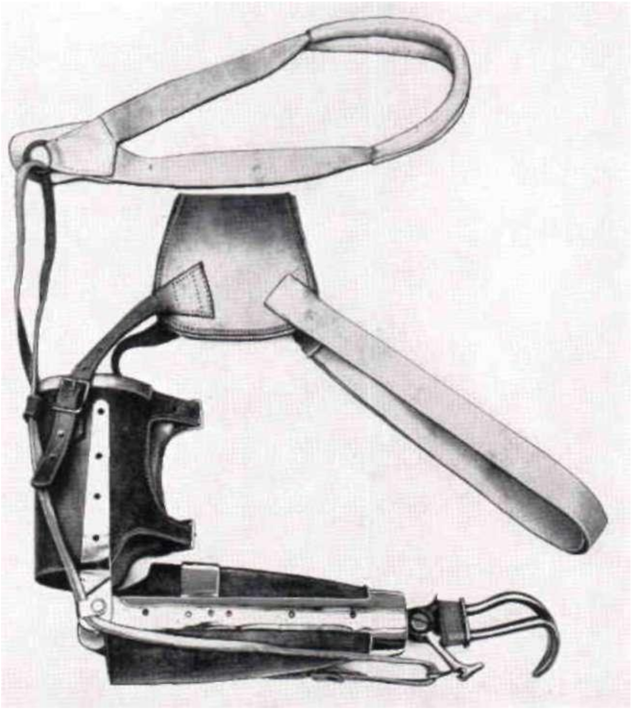


Fig. 3. Typical prosthesis for amputation below the elbow, made about 1945-47. Note modled leather socket, steel sidebars and single-axis joints permitting elbow flexion only, full upper-arm cuff with two straps, heavy leather shoulder saddle and webbing cheststrap, and double leather thong passing over pulleys at the elbow joint to open the voluntary-opening hook. Rubber bands closed the hook and determined the gripping force. Changing the number of rubber bands to vary the gripping force was possible but inconvenient. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans A administration.*

During the period of World War II, the typical unilateral leg amputee in the United States, including many hip-disarticulation cases, walked without the aid of a cane, although the above-knee amputee usually walked with the relatively fixed cadence for which the fixed friction about the knee bolt was adjusted. Any attempt to walk faster or slower led to excessive heel rise or to a tendency to drag the toe. The below-knee artificial leg was often carved from a wooden block by trial-and-error fitting. Alternatively, a leather socket, molded over a modified plaster replica of the stump, was inserted into a fiber, metal, or occasionally •

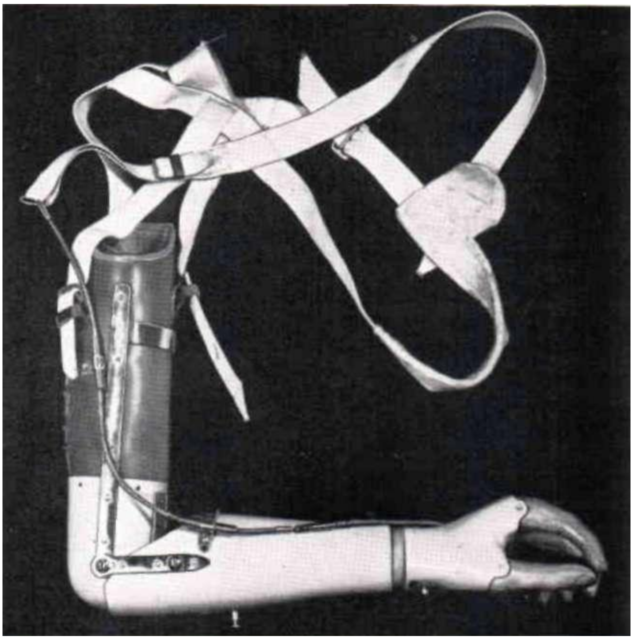


Fig. 4. Conventional prosthesis for amputation above the elbow, made about 1945-47. Note the molded leather socket (with the unusual rear opening and laces), wooden elbow shell and forearm, and push button projecting from lower surface of forearm to control elbow locking by pressure on table top through the sleeve or by use of the opposite hand. Such elbows provided a maximum of five locking positions. A relatively complex harness of cotton webbing supported the prosthesis on the stump and controlled a helically wound rawhide thong sliding through short lengths of stiff housing rigidly mounted above and below the elbow. Tension in the thong flexed the elbow when it was unlocked. When the elbow was locked, tension was transmitted to close the hand, which could be locked by means of the button projecting from the volar portion near the wrist. A desirable disconnect in the thong and a screw thread at the wrist permitted substitution of a hook for the hand. The harnessing pattern for a given level of amputation varied markedly among different limbmakers. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

a wooden shank. Sometimes, in an effort to increase conformity to the stump, a certain degree of softness or of ability to flow plastically was imparted by a thin lining of felt, wax, or relatively pliable leather.

The above-knee leg was occasionally held to the body by suspenders, but by 1945 a large percentage of above-knee amputees used a pelvic band and metal hip joint. Usually the hip joint permitted the leg to swing in one plane only, although in some designs an additional axis permitted abduction and adduction. In England, and rarely in the United States, a third axis, substantially vertical, also permitted a limited amount of rotation, although about an axis outside the body several inches from the ball and socket of the natural hip joint.

ERA OF ANTIBACTERIAL TECHNIQUES

During World War II, blood, plasma, and antibiotics came to be used widely to increase the chances of survival at the time of injury as well as to permit more extensive surgery. The Surgeon General of the U.S. Army ordered open amputation exclusively, to be followed by skin traction until a revision operation could be performed. This flat order unquestionably reduced the incidence of infection and gangrene *(87)* from combat injuries to U.S. Servicemen in World War II, as compared to experience in previous wars or to the experience of certain other military forces. It undoubtedly led also to the conservation of many stumps which, under other circumstances, would have been reamputated at the "site of election" above the next joint in order to avoid rapid spread of infection and gangrene. According to Veterans Administration records, for example, the U.S. forces had over two thirds of their lower-extremity amputations below the knee, whereas during the American Civil War and among the Filipino Scouts and guerrillas *(88)* and the Yugoslavian guerrillas *(71)* in World War II, it was estimated that at least half of all lower-extremity amputations were above the knee. Little (55), in a sample of 1030 amputations among the English forces in World War I, found only 219 "leg" (below-knee) and 441 "thigh" (above-knee) stumps in a total of 723 lower-extremity amputations.

On the other hand, there is no question that the order for open amputation, followed by traction and a second, or revision, operation, led to prolonged hospitalization for some cases

Fig. 5. Conventional wooden prosthesis tor amputation below the knee, made about 1947. Note the usual leather thigh corset, leather thong or lace, leather back-check to prevent hyperextension of the knee, single-axis mechanical knee and ankle joints, and wooden toe fastened to wooden foot by a belting hinge. Usually a webbing waist belt was connected by an elastic strap to an inverted Y-strap straddling the patella and attaching near the front brim of the shank to help suspend the prosthesis and to extend the knee. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

which safely could have been performed primarily as closed amputations, particularly as antibiotics became available late in World War II. Furthermore, many of these "military" amputations, performed as they were far behind the lines, were really essentially civilian in nature. It seems very questionable that there would be a need for performing as many open amputations in civilian practice where risk of infection and gas gangrene is relatively low. The surgeon has a responsibility to use open amputation and traction when there is a clear risk, yet to consider prudently the much shorter care which will be needed with a primary closed amputation when it is feasible medically.

NEW CONCEPTS IN REHABILITATION

The large military amputation centers in World War II provided an excellent opportunity to study the entire problem of amputee rehabilitation *(4)*. Although civilian surgeons generally had been in the habit of dismissing the patient when the amputation scar had healed, leaving him to search for limbfitting services with only the guidance of the classified telephone directory and the perplexing visits of amputee salesmen and demonstrators, the military Services reawakened the responsibility of the surgeon for more complete rehabilitation through the stages of prosthetic fitting, training, and subsequent follow-up. Similarly, the Services assumed responsibility for the necessary vocational guidance and counseling.

WARTIME PROBLEMS

Because of the dramatic concentration of hundreds of amputees in a single hospital, however, the large military amputation centers drew considerable public attention—both favorable and unfavorable and generally overdramatic. In operating their limbshops, they encountered difficulties because of the scarcity of experienced personnel (P). This problem was partially corrected, though never completely solved, by diligent effort to locale limbfitters who had been drafted and to see that they were reassigned to limbshops at amputation centers. In every case, however, the bulk of the limbshop staff was necessarily made up of men who perhaps had mechanical aptitude but who were without previous training or experience in the limb industry.

At the same lime the commercial artificial-limb industry was kept very busy with its private cases from civilian life and with the veterans from previous wars, while some of its younger men were drafted into the Services. Besides this, the generally good business conditions during and immediately following World War II, together with the manpower shortage, led to the employment or advancement of a great many amputees who, during the previous depression, had had great difficulty in finding and holding jobs. Many of these people wished to procure new limbs, thus further overloading the commercial limb industry.

To add to the difficulties, the industry was then neither certified nor licensed, and it consisted, as it does today, of several hundred relatively small workshops. While some of its members had had formal education in other fields, there had never existed in this country any means for formal training in the arts and sciences basic to limbmaking and limbfitting. The sudden release, within a limited number of months, of some 21,000 veterans from military amputation centers imposed upon the industry an exceptional burden. These men had been fitted in the military centers with a serviceable, adequate, but admittedly "temporary" prosthesis, with the understanding that soon after their release the Veterans Administration, through civilian contractors, would provide a permanent prosthesis. Indeed, an additional or spare permanent prosthesis also was provided as a matter of policy.

The confused state of affairs about the end of World War II, and during the year or so immediately thereafter, was further complicated by a series of sensational stories in some of the newspapers concerning difficulties with

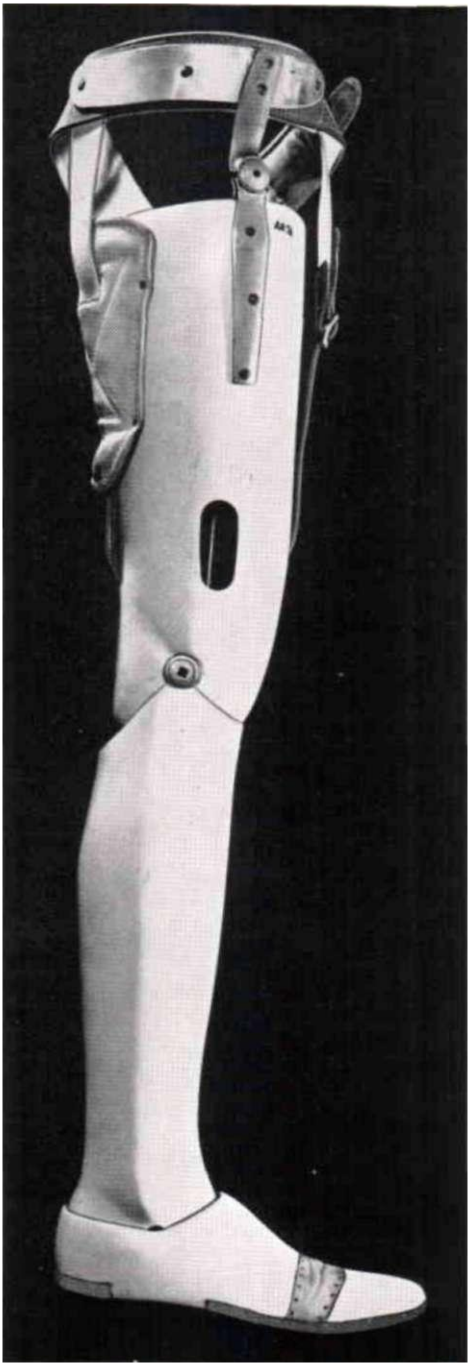


Fig. 6. Conventional wooden prosthesis for amputation above the knee, made about 1947. Note reinforced pelvic band and single-axis hip, knee, and ankle joints. Elastic straps from front and rear of pelvic band are joined by a leather strap passing under a roller ahead of the knee bolt so as to extend the knee from a flexed position. In other prostheses of the same type, refinements of workmanship included inlaying the hip joint into the wood and reinforcing it with rawhide, covering the metal pelvic-band reinforcement with leather, and providing a continuous leather-covered sponge-rubber layer on the sole of the foot. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

the limbs provided by the military centers and covering a series of indictments and trials of certain members of the commercial limb industry for alleged violation of the Antitrust Acts. The rather emotional atmosphere then prevailing in regard to amputees led to dramatic stories but in many cases to neglect of the basic difficulties.

CASUALTIES FROM KOREA

Substantially all factors concerned have since been greatly improved, so much so in fact that there were no difficulties of this type over the treatment of amputees returning from the Korean conflict. The relatively calm and orderly handling of these casualties, with the close cooperation of all concerned, was a tribute to the progress which had been made since 1945 in both technical and administrative aspects. Much of this change has been due to the fine cooperation of the commercial limb industry, now emerging into a prosthetics profession. It also has been influenced by the greater interest of surgeons in amputations and amputee rehabilitation, by the development of the team concept in this area as in so many other areas of medicine (and indeed in science generally), by the contributions of many sound administrators, and by the results of much hard work in the research and development laboratories.

Some of the major changes which have influenced the amputation surgeon have been proven clinically by experience with casualties from Korea. Concepts of level of amputation and certain of the techniques of surgery have been affected. Perhaps most important, there is now a greater interest in postoperative care and in the rehabilitation responsibilities of the medical profession.

LEVEL OF AMPUTATION AND MODERN PROSTHETIC REPLACEMENT

The surgeon's first decision in amputating is the selection of the site. Perhaps the influence of the Artificial Limb Program, sponsored by the Government and coordinated by the Committee on Artificial Limbs of the

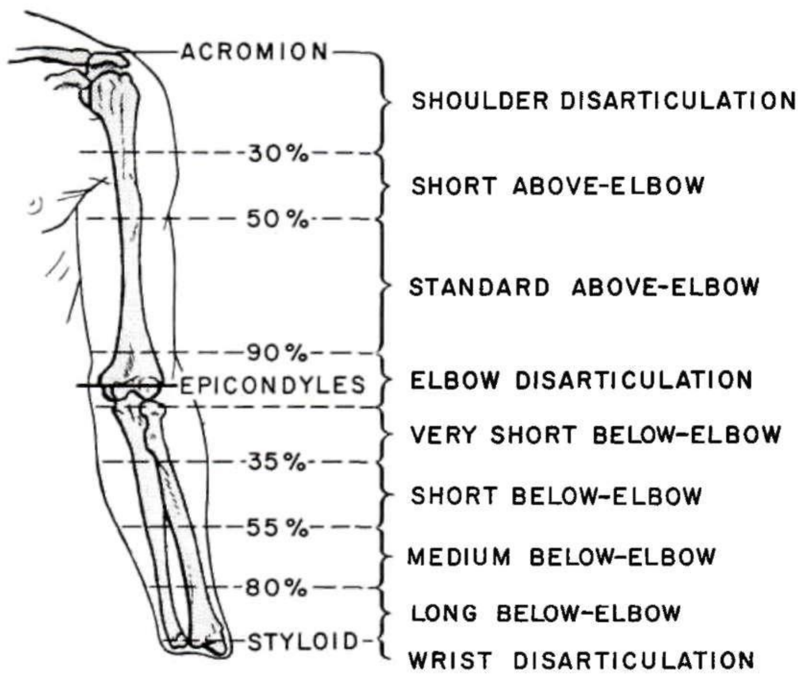


Fig. 7. Definitions of upper-extremity amputee types. Lengths above elbow are measured as percentages of distance from acromion to epicondyles; lengths below elbow are measured as percentages of distance from epicondyles to styloid. From *Manual of Upper Extremity Prosthetics {91).*

National Research Council, can be shown most dramatically by a review of the changes in recommended level. From a few definite "sites of election," the development of new principles and devices has made possible reaffirmation of the policy *(6,8)* of "save all possible length." Every level, with the possible exception of the below-knee amputation, has benefited, particularly in the upper extremity, where it is now possible to define at least nine amputee types (Fig. 7), all of which can be fitted successfully. In many cases the new devices not only permit satisfactory fitting of longer stumps but often replace additional functions beyond the important increase in bony lever.

THE UPPER EXTREMITY

The Below-Elbow Cases

The Wrist-Disarticulation Case. The wrist-disarticulation prosthesis is a good example of the development of a simpler appliance which yet permits better appearance and additional function than did the conventional prosthesis of 1945. At the end of World War II, the wrist disarticulation, if retained at all and not later reamputated at a higher level, was fitted with a laced, molded leather socket supported by steel sidebars jointed at the elbow, quite similar to that shown in Figure 3, with rather bulky harness and a leather thong for power transmission. Elbow flexion and terminal-device operation were the only functions provided, pronation-supination being prohibited by the single plane in which the elbow hinge operated. The entire appliance was bulky, the uncoated leather soon absorbed perspiration and became objectionable, and the almost complete encasing of the forearm made the prosthesis uncomfortable in warm weather. Because of the screw thread attaching it to the wrist, the terminal device, whether hook or mechanical hand, projected appreciably beyond the opposite natural hand, resulting both in limited function and in undesirable appearance. No cosmetic covering faired the gap between the mechanical hand and the wrist.

In contrast, there has been developed under the program of the Advisory Committee on Artificial Limbs a light and sanitary plastic-laminate prosthesis (Fig. 8) which covers only the distal portion of the stump and extends only a short distance up the radial side to support tipping loads while still permitting pronation and supination *(99).* Extending farther up the ulnar aspect, the socket provides adequate leverage and bearing area to permit comfortable resistance to large loads on the terminal device which tend to tip the socket about the stump when the forearm is in the horizontal position. The snug, "screw-driver" fit of the bony prominences at the wrist into the terminal portion ensures rotation of the socket and terminal device as the radius glides around the ulna. Since this rotation decreases progressively up the forearm until, at the elbow, there is no relative displacement, it is necessary to cut away as much as possible of the radial aspect from the socket. But removal of socket material decreases both the weight of the prosthesis and discomfort in warm

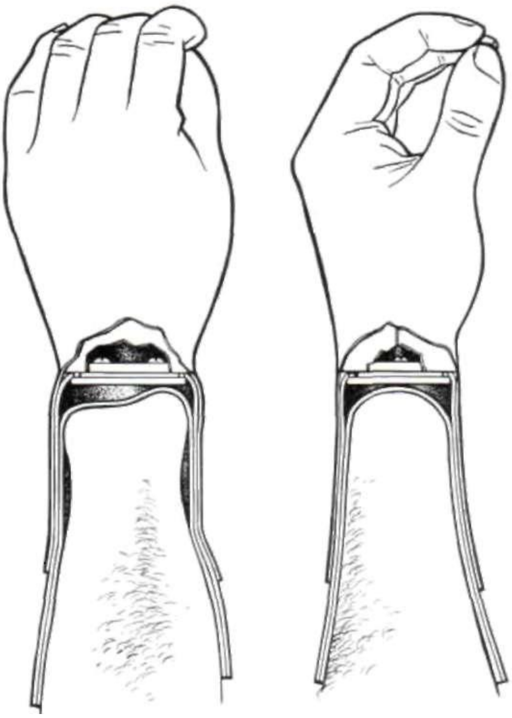


Fig. 8. Cutaway views of light and simple plastic prosthesis for wrist disarticulation, with APRL hand attached to plate embedded in end of forearm to conserve length. The plastic cosmetic glove drapes neatly over the junction. A separate socket similarly attached to a hook (as in Figure 9) is easily substituted to avoid disconnecting the terminal device, as is customary in the usual foiearm.

weather. The plastic-laminate socket and nylon coating of any leather *(47)* used in this or any other prosthetic or orthopedic appliance will prevent absorption of perspiration and the consequent development of odors.

Very simple harness is adequate. For the rare amputee requiring only an extremely light-duty prosthesis, the socket can be held on the bulbous stump by a strap like that for a wrist watch to close a keyhole slot so as to clamp the socket firmly just above the bulging styloids. In this case, the only harness necessary is the cable and loop about the opposite shoulder. Practically all amputees, however, require a somewhat more secure, yet still minimum harness, as shown in Figure 9, with a light triceps pad held by an inverted Y-strap whose fork is higher than the fully tensed biceps. A very simple figure-eight harness is used, and the steel Bowden cable transmits energy quite efficiently without stretching and without catching the shirt sleeve.

To shorten the prosthesis markedly in order to match the length of the opposite arm, the proximal wall of the APRL No. 4C hand *(38,39,98)* may be fastened to a plate built into the distal wall of the plastic-laminate socket, as shown in Figure 8. Thus the plastic cosmetic glove can readily bridge the gap between the hand and the prosthesis and extend up under the shirt or coat sleeve of the wearer. A similar plan can be followed with the APRL hook *(38,39,98)* by removal of the stainless-steel stud and plate by which the hook case is normally fastened to the wrist disconnect. On other types of hooks, the stainless-steel stud can be removed or shortened and a suitable fastening plate added by welding or brazing. For wrist friction, thin rubber 0-rings may sometimes be used instead of thicker rubber washers, thus further decreasing length.

In many cases, it has been found entirely feasible, both technically and economically, to

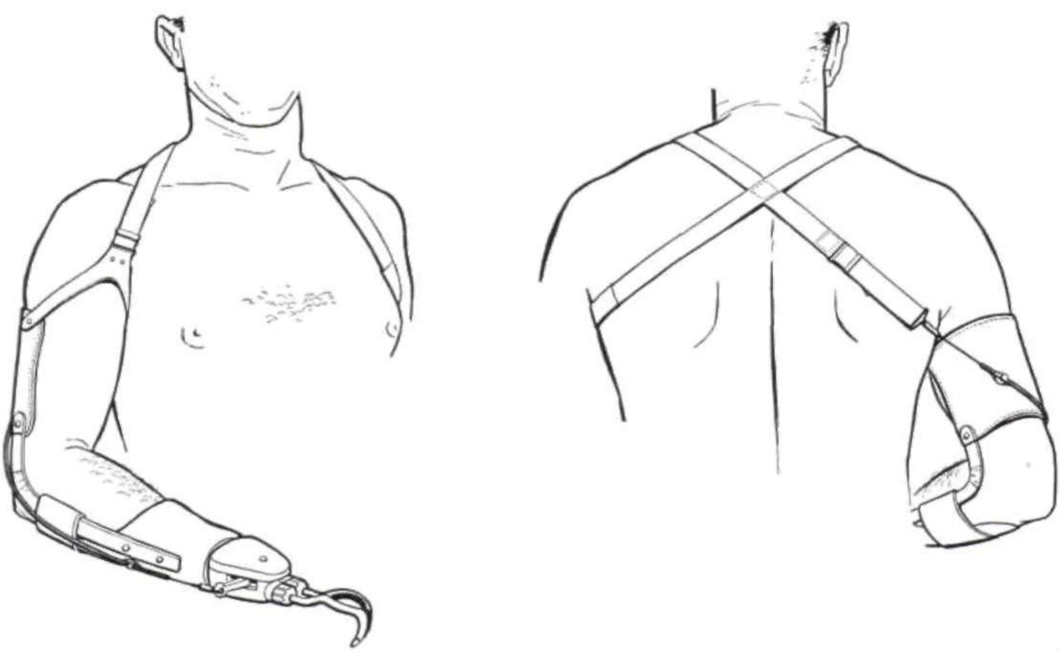


Fig. 9. Prosthesis and harness for wrist disarticulation or long below-elbow stump. Note simple figure-eight webbing entirely across back, with no cheststraps. A steel Bowden cable transmits energy to the hook with improved efficiency. An open upper-arm harness, consisting of triceps pad and inverted Y-strap, leaves biceps free from pressure. Flexible leather straps as elbow hinges, suggested years ago but seldom used, permit pronation and supination as well as elbow flexion. The APRL hook case may be laminated into the forearm to conserve length

supply two sockets, one laminated to a hand and the other to a hook, to be worn interchangeably. The added length due to a conventional wrist disconnect and stud is thus avoided. Snap fasteners between the flexible leather elbow hinges and the forearm socket, plus the disconnect feature of the control-cable attachment post, permit interchange of prosthesis without changing the harness. Thus the amputee can make the interchange from hand to hook simply by rolling up his sleeve, it being unnecessary for him to remove his shirt.

The Long Below-Elbow Case. In many shorter below-elbow stumps, a similar type of prosthesis, but without the bulges for the styloids, can be applied to permit the amputee to use his remaining pronation and supination. The key factors are flexible elbow hinges and the "screw-driver" fit of the end portion of the stump in the socket with increasingly loose fit proximally. The fact that pronation and supination may be retained encourages the surgeon to make every effort to avoid fusion of the radius and ulna owing to bone spurs or similar causes and to instruct the amputee to participate in physical therapy designed to redevelop muscular control.

The Medium Below-Elbow Case. In the medium below-elbow stump, the limited amount of pronation and supination is worth retaining, yet it is inadequate to permit direct control of the prosthesis. Accordingly, the step-up type of rotation device (Fig. 10) has been developed. Early attempts at an automatic lock were frequently disappointing, particularly if the amputee tended to snap the prosthesis when used with a wrist-flexion unit, because the high inertia forces jammed the locking surfaces and caused permanent dents which thereafter caused chattering or even failure to lock. Instead, a simple lock has been supplied on an experimental basis, some mechanical problems remaining to be solved. A simple bolt in the stabilized outer socket engages one of a series of holes in the rotating portion of the wrist whenever the elbow is flexed more than a few degrees but is withdrawn at maximum elbow extension (Fig. 10, detail). This device is particularly desirable even with a short, almost conical below-elbow stump which, with elbow extended, participates in humeral rotation from the shoulder. The entire extremity rotates within the triceps pad and outer socket, which are stabilized by the harness. With the socket and terminal device rotated to the desired position, the amputee returns his stump to its normal position with the elbow axis parallel to the mechanical elbow hinges, flexes the stump, and thus locks the wrist in the desired position.

In such applications, step-up gears are normally provided to increase the rotation of the terminal device in relation to that of the socket. A lock is desirable partially to transmit torsional loads on the terminal device through the elbow hinges to the open humeral cuff, but

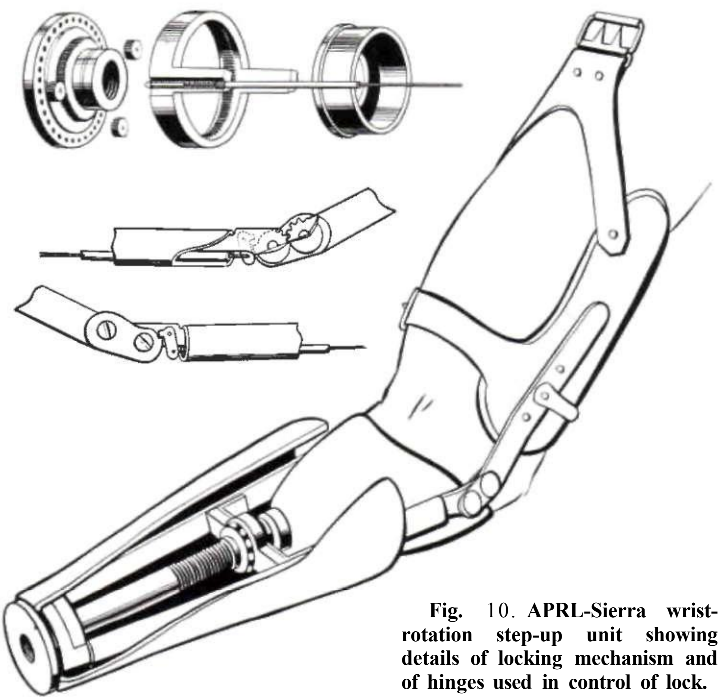


Fig. 10. APRL-Sierra wrist-rotation step-up unit showing details of locking mechanism and of hinges used in control of lock.

it is particularly desirable with outside Bowden-cable control of the terminal device to permit the torsional component of tension in the cable, when it spirals about the forearm, to be transmitted to the upper arm without stress upon the stump. The mechanical advantage of torque at the terminal device or control cable over the stump is due, of course, to the step-up gearing used to increase rotation of the terminal device.

The Short Below-Elbow Case. For rather short below-elbow amputations, a geared polycentric hinge (Fig. 11) has been developed. In some cases, it permits easier fitting of the socket and may hold the socket more firmly on the stump. For still shorter stumps, the socket may be attached to the link connecting the two axes of rotation, while the forearm is attached to the lower geared segment (Fig. 12), thus providing a *fixed* ratio of 2:1 between degree of flexion of the artificial forearm and degree of flexion of the below-elbow stump and socket. It has been found, however, that this fixed ratio has only limited application.

Fig. 11. Hosmer PC-100 polycentric hinge, particularly suited for medium to short below-elbow stumps. By virtue of the mechanical linkage, it sometimes aids in permitting extreme flexion in cases where the stump retains a full range of motion so that step-up hinges are unnecessary.

The short below-elbow stump is another example of the new principle of saving all possible length. Formerly, most surgeons and limbmakers would have agreed that such short below-elbow stumps could not be fitted satisfactorily. Such a stump tends to slip out of the conventional socket and also may exhibit no useful control of the elbow joint. Frequently, it was advised that such cases be reamputated at the "site of election" in the humerus. Late in World War II, however, both in Canada and in at least one U.S. Army amputation center, hinges were developed, similar to those shown in Figure 13, which permitted a step-up of forearm movement as compared to stump movement, a *variable* ratio compensating roughly for the resistance encountered and the strength of the stump at various positions.

As seen in Figure 14, the short but well-

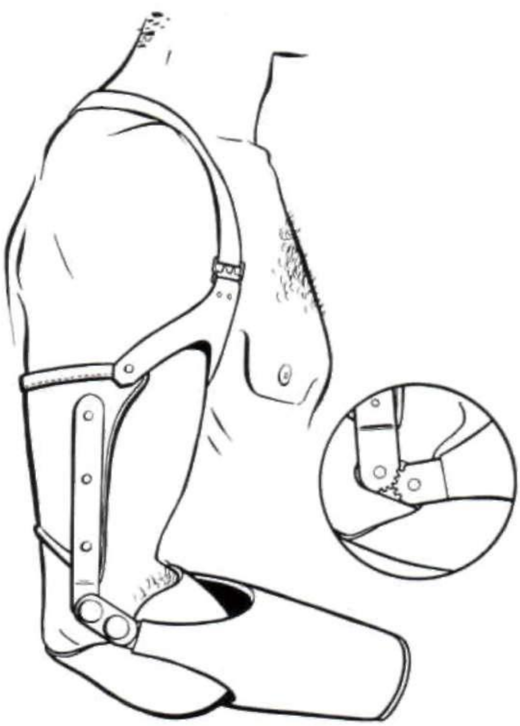


Fig. 12. Geared step-up hinge (Hosmer MA-100) for very short below-elbow stumps of limited range of motion. The stump socket is fastened to the center link connecting the two geared links, which in turn are fastened to the upper-arm cuff and the forearm shell. The ratio of flexion of the forearm shell to that of the short stump is thus 2:1.

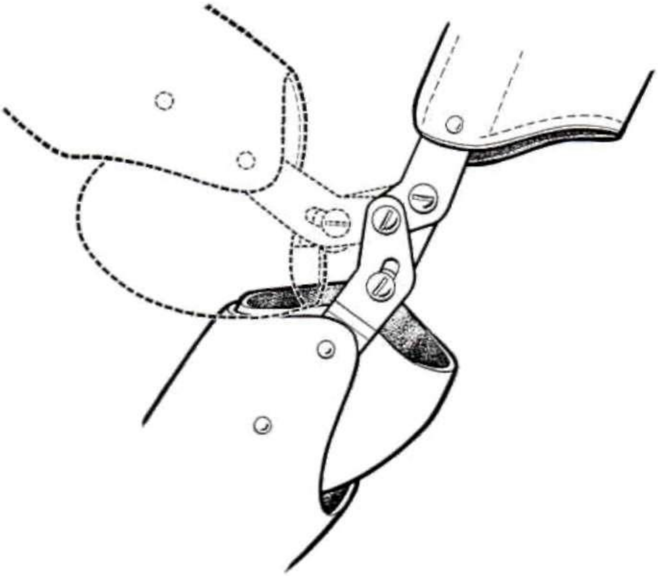


Fig. 13. Hosmer variable-ratio step-up hinge for very short below-elbow stumps. Here, unlike the case with the geared hinge of fixed ratio (Fig. 12), the sliding lever system provides a changing ratio of stump action to forearm action as flexion increases, the change in any given design depending upon the relative location of the three pivots and upon the shape of the slots for the sliding pivot. In the design shown, the ratio is 1:1.8 in the fully extended position; at 90 deg. of forearm flexion it is 1:1.3; and at 135 deg. of forearm flexion it returns again to 1:1.8. Thus the changing moments of cable tension and of gravity acting on the forearm and object held can be compensated for so that the force necessary for lifting is substantially the same in all positions.

fitting socket comes as high into the antecubital space as possible so as to restrain the flesh without being pushed off. Sometimes rolling of this anterior brim of the socket and notching of the socket to fit around the biceps tendon, yet curving higher on each side of the

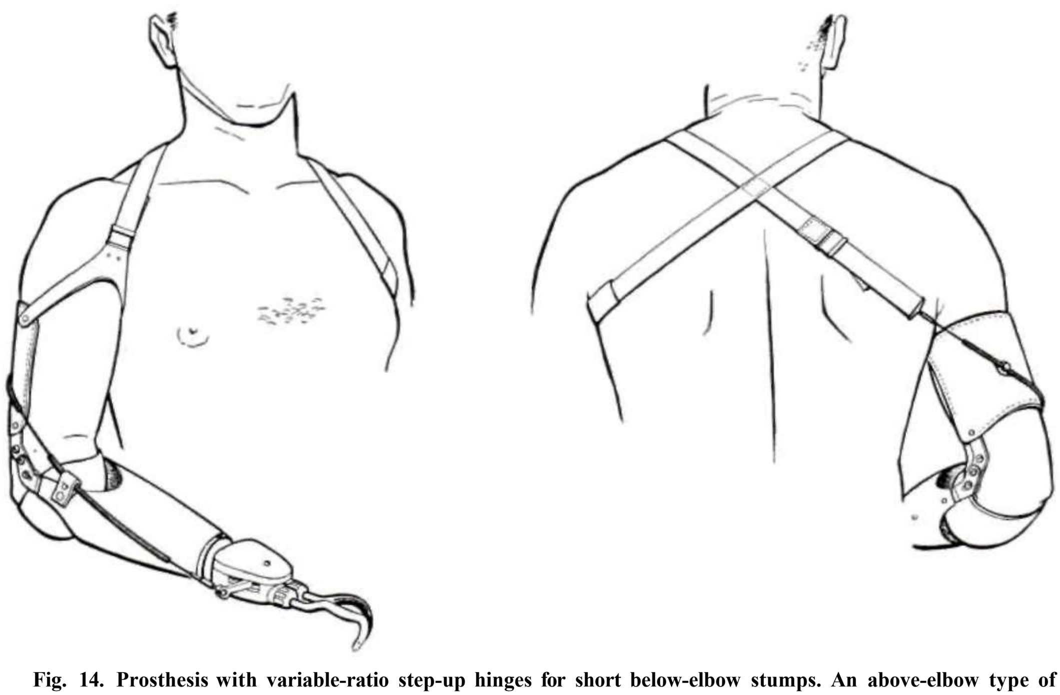


Fig. 14. Prosthesis with variable-ratio step-up hinges for short below-elbow stumps. An above-elbow type of cable control assists in flexing the forearm shell.

biceps, are feasible.[4] Since there is no appreciable pronation-supination at this level, the biceps tendon remains in a fixed position rather than tending to migrate from medial toward lateral as it does when a longer stump moves from pronation to supination. The posterior rim of the socket is carried as high as possible, substantially to the olecranon. In some cases it is possible to hook the socket brim over the olecranon to help pull the stump into the socket during flexion.

The middle pivot of the step-up hinges is substantially opposite the humeral epicondyles, which define the anatomical elbow axis. The lower hinge moves in its slot during elbow flexion, as indicated in Figure 13. The lower proximal end of the forearm shell must be cut out in order to clear the short stump at extreme elbow flexion. But since this type is used on short below-elbow stumps, there is no serious protrusion of the stump beyond the general line of the forearm socket and, therefore, no appreciable bulge in the coat sleeve.

Customarily, an auxiliary lift for the forearm is provided by an above-elbow type of harness, with two separate pieces of cable housing attached to the forearm and to the triceps cuff but bare cable running from a space between the two separated pieces of housing, as shown in Figure 14. By voluntarily controlling the position of the stump, the amputee can effectively "lock" the forearm as if by a mechanical elbow lock and can thus operate the terminal device by increased tension on the control cable without causing further flexion of the forearm. By means of stump action, he also can press downward firmly enough on the forearm to perform functions such as holding papers on a table or holding a fork to stabilize a piece of meat while it is cut by a knife held in the opposite hand.

[4] **In only** *apparent* **contradiction, Shallenberger** *(93),* **from experience in 1946-47 with two short-below-elbow amputees** *on whom the cineplastic operation had been performed, with consequent severing of the biceps tendon,* **recommended a high and almost horizontal front brim with adequate corners on the medial and lateral sides. He found that the flesh was thus restrained at the top and front of the stump and was instead forced out at the sides, where it could not interfere with elbow flexion. He thus found the bearing area to be much greater, with consequent relief of pressure on the stump. In general the same situation would not prevail in the ordinary below-elbow amputee whose biceps tendon is intact.**

The Elbow-Disarticulation Case

The elbow disarticulation was for many years frowned upon because of the difficulties of fitting it with a conventional prosthesis with laced molded-leather socket and elbow lock and joint requiring a bolt extending the full width of the elbow. In such a design, of course, the mechanical lock was necessarily fitted below the end of the stump, thus making an overly long humeral section and a correspondingly short forearm section, usually preventing the amputee from reaching his mouth with the terminal device, as well as creating an awkward appearance and difficulty in using the amputated elbow as a support on the desk top, and the like. Capable of end-weight-bearing, the elbow-disarticulation stump, however, is useful as a support without the prosthesis, as in rolling over in bed. Its bulbous and irregular shape serves as a key to stabilize the prosthesis against rotation about the long axis of the humerus.

To conserve these functions, therefore, the external lock shown in Figures 15 and 16 was developed to fit on the *outside* of the socket in line with the humeral epicondyles and the anatomical axis. The artificial forearm can thus be of a conventional length, and the terminal device can be brought to the mouth readily. The locking circle is, however, necessarily of a smaller diameter than would be available in a conventional above-elbow type of prosthesis, so that in the present model the number of locking positions is reduced to five (Fig. 16). Although numbering more than in the earlier conventional above-elbow or brace locks, the five positions are less than the 11 or even infinite number of positions provided by above-elbow locks which have been developed in the ACAL research program.

The APRL-Sierra outside-locking elbow hinge has another special application in the very short below-elbow stump where range of motion is insufficient to operate a forearm through a step-up elbow hinge but where a small residual motion is adequate to operate the locking mechanism diagrammed in Figure

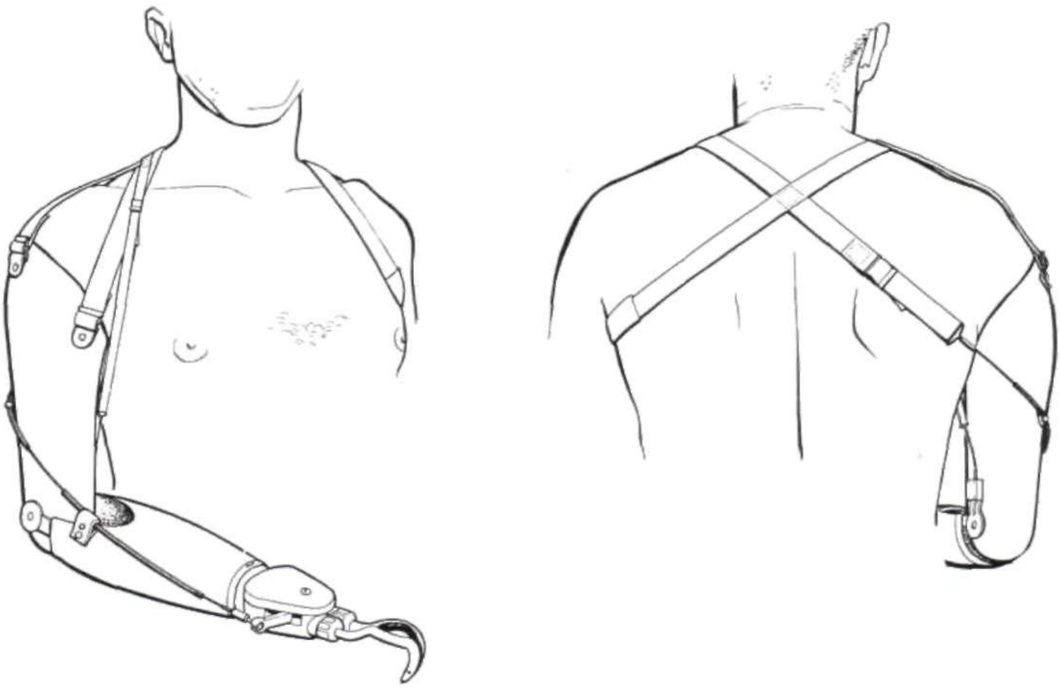


Fig. 15. Prosthesis for elbow disarticulation, with APRL-Sierra external elbow lock (Fig. 16) and same dual control as used on above-elbow prostheses. To accommodate bulbous humeral condyles, a channel may be left in the socket, a lacer may be used, or a slotted, flexible, plastic-laminate socket and clamping strap may be loosened and expanded enough to permit entry and withdrawal and yet provide adequate control during use.

16. In the arrangement shown in Figure 17, elbow locking is effected by stump motion rather than by motion of the shoulder, thus giving a more natural appearance and more freedom than could be obtained with an elbow disarticulation or an above-elbow stump.

The external elbow lock has already been used occasionally for applying artificial-arm principles to arm braces. The situation in that entire field should improve rapidly in the near future. Occasionally, patients have requested, or surgeons have recommended, amputation of an arm when disease or injury have left a flail elbow. It has seemed that improved artificial arms would actually provide the patient with more function. It must be remembered, however, that the damaged arm provides at least some support and perhaps sensation, and consequently every effort should be made to replace the lost functions of stability, control, and voluntary movement by suitable bracing. Polio cases, retaining sensation and an erratic distribution of muscle activity, offer a special challenge.

The outside-locking hinge of Figure 16 is normally fitted as shown in Figures 15 and 17 for control from the proximal joint. Presumably, though, it could be inverted and controlled from the distal end of the arm if some portion capable of even a little voluntarily controlled movement with very nominal forces were available in the hand or wrist. A ring on a finger or extreme hyperextension of the wrist could, for example, be used to trigger the elbow lock, thus simplifying the harnessing, particularly if the shoulder were also weakened.

It may be noted parenthetically that some work has been done *(92)* both by rehabilitation centers and by prosthetists and orthotists to drive paralyzed fingers with mechanisms adapted from the artificial-hand field or to hyperextend a paralyzed hand on a "cock-up" wrist splint and substitute a hook on a rotary or even on a ball-and-socket mounting on the volar aspect of the wrist. Even with a quadriplegic there has been enough control of shoulder movement to provide the necessary voluntary control for the hook, supplementing at least a weak biceps action for forearm flexion and supination. The relatively heavy hook extending from the volar aspect of the wrist will provide by gravity forearm extension and a tendency toward pronation. Since the degree of paralysis and of loss of sensation may be so variable, in the entire field of arm bracing the role of the doctor is even more important than it is in rehabilitation after amputation. Correspondingly, there is an even

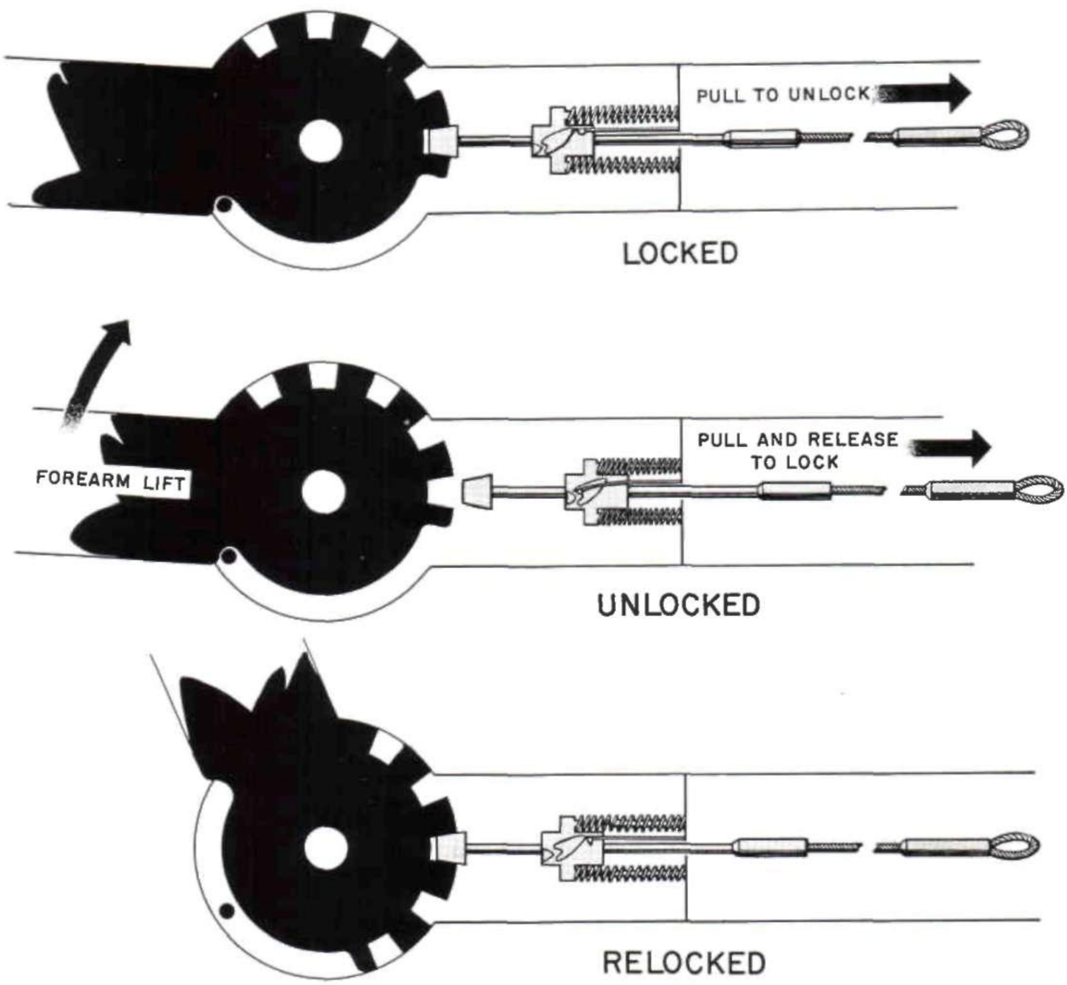


Fig. 16. Schematic diagram of APRL-Sierra external elbow lock, intended for elbow disarticulation but also useful with very short below-elbow stumps or with paralyzed arms. Top, locked position. Next pull on lock-operating cable in upper right withdraws locking plunger from the wedge-shaped notch in forearm piece and raises the alternator crosshead, thereby compressing the two helical springs. Pin on the thin leaf spring follows right side of inverted heart-shaped cam until it slips into notch at bottom of cam. Relaxing cable drops the alternator crosshead slightly until the pin and leaf spring hold the cam and locking plunger in the unlocked position (middle). Subsequent tension on the cable raises the alternator crosshead enough so that the leaf spring can straighten until its pin follows the left side of the heart-shaped cam back to original position. Meanwhile the helical springs force the crosshead down and push the locking plunger into a tooth in the lower portion attached to the forearm (bottom).

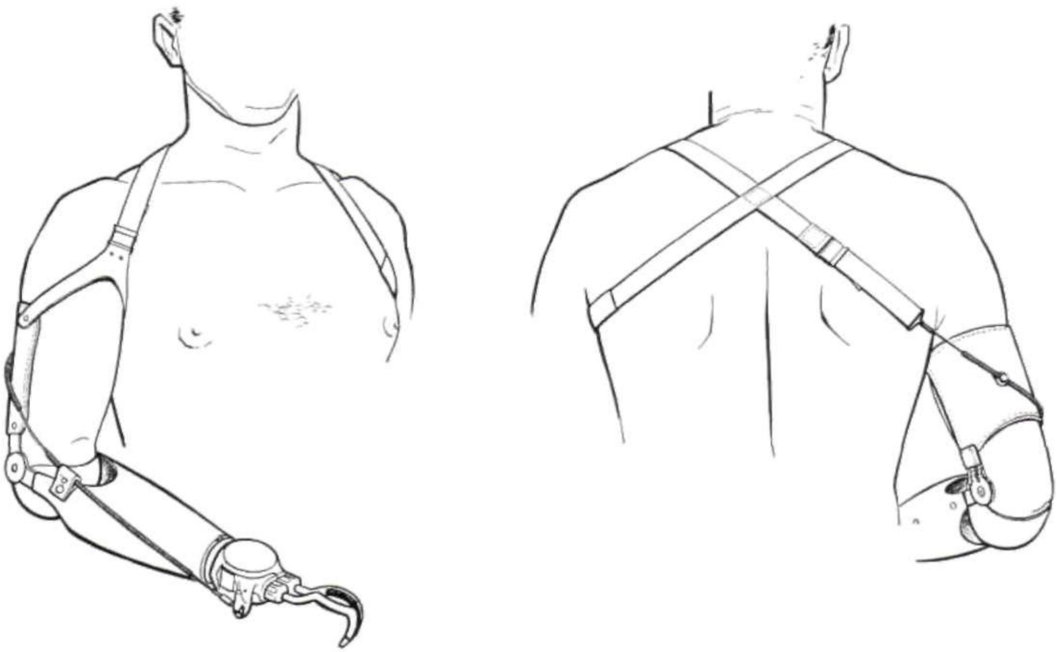


Fig. 17. Prosthesis for very short below-elbow stumps of such limited motion that step-up hinges are inadequate. The external elbow lock is controlled by a convenient cam, lever, or cable system triggered by the limited stump motion, and the forearm shell is flexed by an above-elbow type of harness. By this system the elbow lock is more easily operated than in a conventional above-elbow type of control. The Northrop-Sierra voluntary-opening two-load hook *{38,39)* shown here is usually considered to be a left hook, that is, as used on a right arm the operating lever is in the little-finger position rather than in the thumb position. This arrangement results in a more nearly straight control cable of higher efficiency than is possible when the operating lever is on the medial side, in which case the cable must spiral over the forearm. More often, particularly in the case of bilateral arm amputees, voluntary-opening hooks are fitted with the operating lever, and also the control button for changing the load, located on the medial side.

greater challenge to the ingenuity of the prosthetist, the engineer specializing in prosthetics, and the manufacturer in adapting or developing special appliances for the individual case and to the patience of the therapist in redeveloping even faint voluntary movements which might control triggers for locking mechanisms.

The Above-Elbow Cases

In the above-elbow stump, as much as possible should be saved consistent with the nature of the injury or disease. Even a very short above-elbow stump may be useful as an anchor point, and in experimental work on electric arms *(2,3)* such a stump has been used to control the necessary switches and clutches (Fig. 18). A stump of nothing more than the head of the humerus helps to round out the shoulder and to provide a much more secure stabilization of the "shoulder-disarticulation" socket.

Nevertheless there remains a challenge to the engineer and prosthetist in providing improved shoulder-disarticulation and very high-above-elbow arms with passive or voluntarily controlled humeral flexion and abduction. A number of designs were shown in the literature *(17)* after World War I, but none appears to have been practical. The sectional plates *(91)* used in the ACAL research program have facilitated independent construction of the socket and remainder of the prosthesis and their subsequent alignment. Sometimes they have been provided with rotation to facilitate donning of clothing with

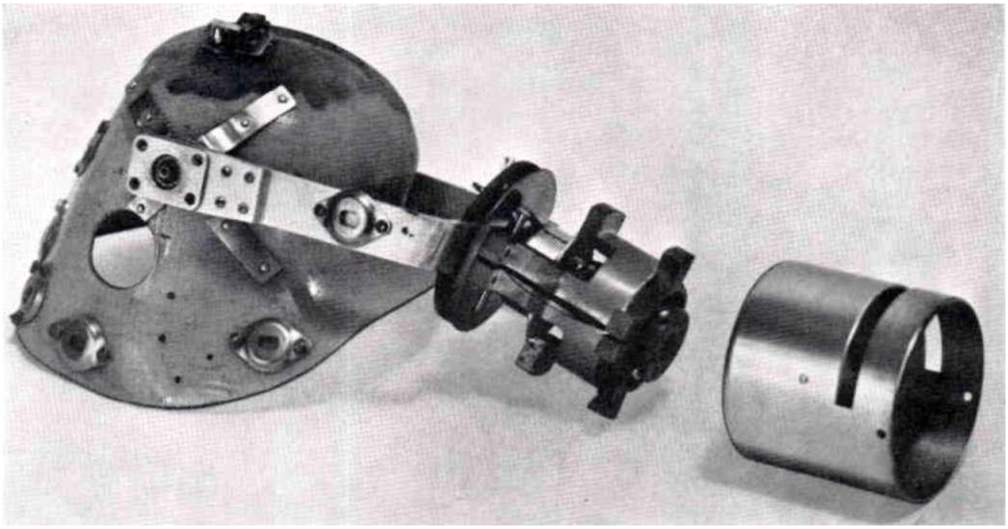


Fig. 18. Shoulder cap for electric control by shoulder motion or by short humeral stump or both. From Alderson *(2)*.

the humeral section flexed, followed by return of the humerus to a vertical position. Such joints of the humeral section to the shoulder cap have not permitted abduction, however, and have not normally permitted voluntary or passive forward flexion of the humeral section about the shoulder joint to bring the elbow-forward and permit the terminal device to reach the mouth.

The conventional sectional plates have been solid and thus have been suited only for a true shoulder disarticulation, but it should be feasible to leave an opening through which a very short stump, such as the head of the humerus and its surrounding socket, could protrude into the hollow humeral section. Provision of a sector of a complete circular track, rather than the elongated D-shape which has been used, would also result in better cosmetic appearance when the artificial humeral section is flexed forward. Possibly a simple lock to stabilize such humeral flexion could be controlled by a very short above-elbow stump, even if passive adjustment with the other hand, or by gravity in connection with torso movement, were necessary because of the weakness of the stump.

Attempts to provide voluntary control of humeral abduction and rotation have been reported in the literature. Alderson *(2,3)* developed an experimental arm of the shoulder-disarticulation type in which shoulder lift against the anchorage of a groin strap generated either elbow flexion followed by humeral abduction or humeral abduction alone, depending on whether the elbow were free or locked. At least one commercial limb manufacturer recently has experimented with a "universal shoulder joint" permitting a combination of actively and passively controlled motions including upper-arm rotation by means of a turntable located in the humeral section.

THE LOWER EXTREMITY

In the lower extremity, although there have been definite changes in techniques and devices, the influence of the Artificial Limb Program has not as yet markedly changed the levels of amputation. Work is, however, going forward rapidly, particularly at the Lower-Extremity Clinical Study operated at the University of California using facilities of the U.S. Naval Hospital at Oakland. It is to be expected that in the next few years more definite changes can be recommended *(95)*. Meanwhile, the principal effects of wartime experience and of the ACAL research program have been increased emphasis on the Syme and knee disarticulation and a better understanding of muscle functions, particularly in relation to the suction socket for above-knee amputees.

The Below-Knee Cases

The Syme Amputation. While the Syme amputation is more than a century old, it has until recently been considered controversial, with firm advocates and bitter opponents. In some cases, criticism has rightly been directed toward very long below-knee stumps which, however, were not true Syme amputations with the normal heel flap and capable of full end-weight-bearing. Experience at military amputation centers during World War II seems to have confirmed the successful results which have been reported by the Canadians ever since World War I (5). A recent Canadian report *(31)* on the Syme amputation describes surgical precautions, conventional and experimental Syme prostheses, and clinical experience.

Although the Syme amputation requires meticulous surgery, in the absence of sepsis, and careful attention to all details, a successful result provides much greater freedom of action for the amputee and enables him to remain on his feet for long periods. The broad surface of tissues anatomically adapted to weight-bearing offers the Syme amputee a great advantage over the below-knee amputee with limited areas offering a wedgelike support for the stump and pressing upon tissue which has not been accustomed to weight-bearing.

The prosthesis for the Syme has been improved, on an experimental basis, by the Canadians (Fig. 19) and, more recently, by the Prosthetic Testing and Development Laboratory of the Veterans Administration (Fig. 20). Both types use a plastic laminate in place of molded leather for greater sanitation as well as for greater strength with decreased weight and bulk. Both use Fiberglas extensively for high strength.

Considerable success has attended efforts to reduce the bulk at the ankle by eliminating the steel sidebars which, in earlier prostheses, projected beyond the malleoli on the medial and lateral aspects, thus adding thickness to a zone already the broadest portion of the ankle. The steel sidebars had, in any case, been mechanically rather ineffective in sustaining bending loads, as when the weight of the amputee is supported on the ball of the foot, because the material was close to the neutral axis or central portion of the bars *(15).* In the newer designs, this portion over the malleoli is relatively thin, but bending moment is resisted more effectively by the most anterior portion, ahead of the tibial crest, and by the posterior portion at a greater lever arm than was available in the older, narrow, metal bars. To avoid fatigue failures, special care must be taken to achieve a smooth posterior cut in the shell-like prosthesis. The bulbous malleoli are introduced into the prosthesis by opening a posterior portion, which may then be closed either in trap-door fashion by a hinged portion of the shell or by a fabric- or nylon-coated leather portion held by a slide fastener, laces, or adjustable straps.

The shell-like combination socket and shank section, with the end-bearing pad, is molded over a plaster model of the stump to attain uniform fit. A slightly soft lining may be used throughout the socket. Relief is provided along the sharpest portion of the tibial crest so as to maintain comfort when weight is carried on the ball of the artificial foot and there is a tendency for the socket to press sharply on the upper portion of the tibia. Under such conditions, firm counterpressure, distributed comfortably, is also required just above the malleoli on the posterior portion of the tibia and fibula. Ankle action may be provided by a laminated sponge-rubber heel which is compressed at heel contact, giving the equivalent of plantar flexion, or by a rubber-block ankle joint with a shallow V-shaped section removed to accommodate the long stump.

The Short Below-Knee Case. Short, badly scarred, below-knee stumps have heretofore sometimes been reamputated above the knee or have been used in a permanently flexed position in the so-called "bent-knee" or "kneeling-knee" prosthesis reminiscent of pirate tales. In either case, the advantages of voluntary control of knee-joint movement are lost.

The U.S. Navy below-knee "soft" socket *(24),* an outcome of recent research, consists of

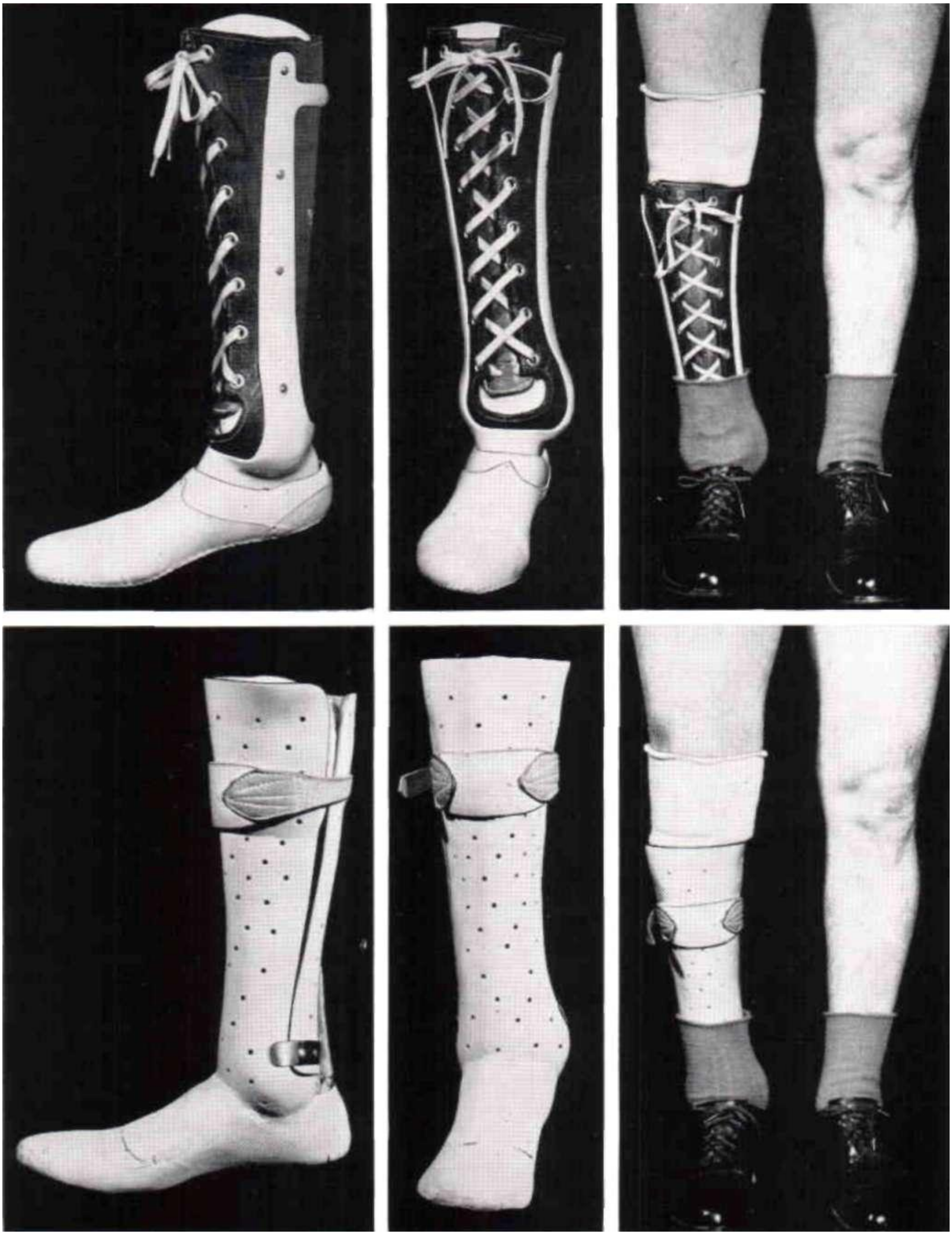


Fig 1,9 Piosthescs for S\ me's amputation. Above, conventional S\ me prosthesis with typical bulk> and unattractive design at ankle and with bothersome shank lacer. Below, Syme prosthesis developed b\ the Canadians ',?/). Same slum]) in the two cases. Note improved (osmetic appearance and simplified method of donning The Canadian model consists oi a perforated plastic-laminate shell with thin, cellular-rubber lining, the whole considerably lighter than the conventional design above. Rear portion ean he opened to admit bulbous stump. \el material is effectively distributed to withstand large bending loads. \o ankle joint is used, but the loot is formed ol cemented layers of cellular rubber around a reinforcing tongue projecting from the socket to the ball of the foot. Pressure on heel compresses the rubbei to give the equivalent of plantar flexion. *Photo* couiiesy Canadian Deparhnc-nt ol Ve.tera.ns Alluirs.*

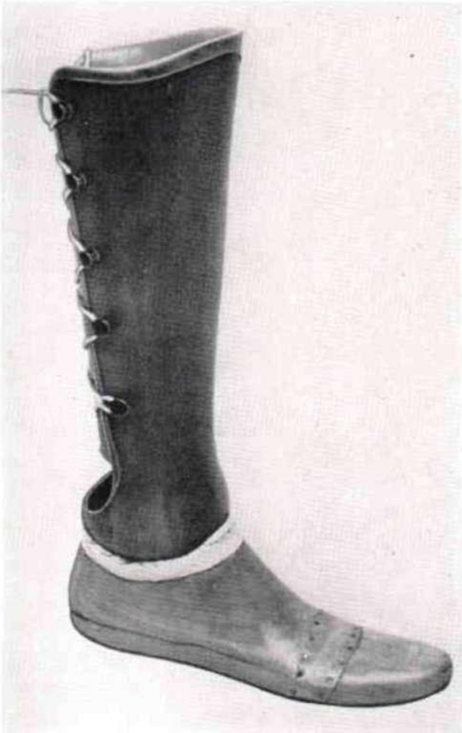
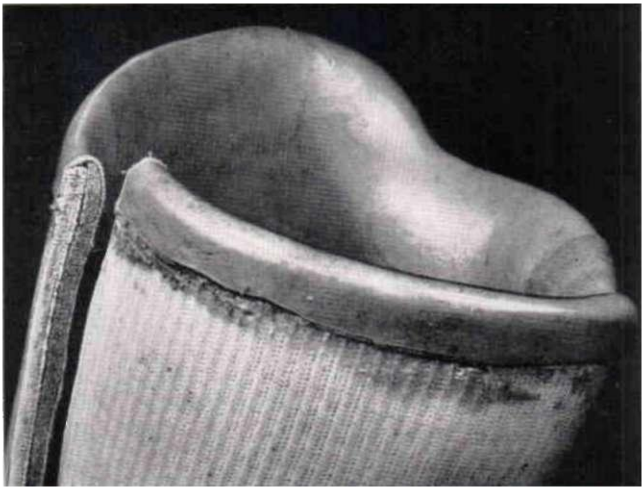


Fig. 20. Experimental Syme prosthesis designed and tested at the VA's Prosthetic Testing and Development Laboratory on request of the Orthopedic and Prosthetic Appliance Clinic Team, New York. It combines a molded plastic-laminate shell with rear opening, thin sponge-rubber lining, and an adaptation of the U.S. Navy functional ankle (95) using two-durometer rubber block.

a plastic lining backed by a thin layer of sponge rubber and a rigid or, recently, a rather flexible shell (Fig. 21). An improvement on earlier commercial sockets with felt or wax lining, it may be fitted to any below-knee stump, but particularly it has permitted conservation of short, sensitive, badly scarred stumps. The weight-bearing impression of the stump dipped in plaster yields a much more accurate replica than do most wrapped plaster-bandage impressions. In general, it seems reasonable to believe that any technique for making a socket from a cast is likely to produce a more accurate fit more rapidly and with less discomfort than is a trial-and-error carving process *{65)*. The thin sponge-rubber lining giving the "soft" socket its name seems to be only one of several factors contributing to its usefulness.

Careful location of the mechanical knee joints is always important. The work of the University of Denver *(30)* indicated the possibilities, for below-knee amputees in general, of improved fitting of conventional legs with single-axis knee joints by more careful location of the knee joints. Particularly recommended were fixtures and tools to ensure that the mechanical joints on opposite sides of the prosthesis are on a common axis. Polycentric joints did not seem necessary. The report considered, however, the possibility of a mechanical joint of the single-axis type at the knee, but mounted high up on the thigh

Fig. 21. U.S. Navy "soft" socket for below-knee amputation, cut to show plastic sheet lining rolled over brim, thin ('^-inch) sponge-rubber lining, and flexible plastic-laminate outer shell, all formed over male plaster model of the stump. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration*



corset by a pivoting joint of limited angular range, in place of rigidly riveting the upper joint bar to virtually the full length of the corset. This idea has been proposed in the German literature *(62)*. In such a case, probably a reinforcing band should be mounted in the thigh corset to ensure that the upper joints are kept on a common axis.

The very short below-knee stump, with the tibia amputated in the broad condylar area and with trabecular bone structure, is often suited to take a high fraction of weight-bearing on the distal end, in contrast to the usual below-knee stump of much smaller diameter, limited bearing area, and with thick, hard cortex surrounding a medullary canal. If the thickness of pads at the end of the stump is gradually increased, particularly if the pad in contact with the stump end is carefully molded to the irregularities of the stump, an increasing fraction of end-weight-bearing may often be tolerated.

These circumstances deserve careful investigation before any thought is given to re-amputation above the knee, which in the past has often been suggested for such stumps. End-weight-bearing is both more nearly normal with respect to mechanical characteristics, promoting calcification, and is desirable in avoiding any tendency toward lordosis. The very short below-knee stump often can be fitted successfully by very careful forming of the socket. Special care is needed in shaping the posterior brim to accommodate the hamstring tendons, yet to rise into the popliteal space as much as possible without cutting off circulation. The "slip" socket, elastically supported to stay in contact with the stump during the swing phase, is an old idea often indicated for short stumps.

Even if a very short below-knee stump cannot take appreciable weight-bearing on its end and on the flaring tibial condyles, it may be fitted with a long, ischial-supporting thigh corset and the sturdy external mechanical joints which would be used in a knee-disarticulation prosthesis. In this case the below-knee amputee, like the above-knee amputee, must rely upon mechanical stability of the prosthesis during the stance phase with the knee in full extension, but at a minimum he has proprioceptive sense of knee position and usually some limited ability to control slight knee flexion to return the knee to full extension, thus saving himself from some falls. Partial control of heel rise at the beginning of the swing phase and of knee extension at the end of the swing phase permit a more graceful gait and a better range of cadence than generally can be attained with above-knee prostheses.

The Knee-Disarticulation Case

The knee disarticulation, an old type of amputation, typically has been fitted with a molded leather socket provided with a lacer to permit the entry of the bulbous end of the stump. This type of prosthesis has mechanical joints and sturdy metal sidebars similar to those in the below-knee prosthesis. Normally, no mechanical friction has been used, and consequently gait tends to be limited to a single cadence. Any attempt to walk more rapidly leads to excessive heel rise and to "slamming" of the artificial shank into full extension just before heel contact *(28,96)*. Normally, extension is limited by thongs similar to the back-check in a below-knee artificial leg. Since the knee cannot be extended or stabilized voluntarily, the joints are arranged to give mechanical stability at full extension, as in an above-knee leg *(75,96)*.

Many prosthetists have objected to the knee disarticulation as a level of amputation because of discomfort of the long, molded, leather socket, tendency toward breakage of the side-bars, and the lack of mechanical friction. Amputation at a higher level has frequently been advocated. The knee disarticulation, however, provides definite advantages over the above-knee amputation. If the end of the stump is properly fitted, a broad weight-bearing area is available. Normal transmission of weight through the shaft of the femur minimizes the tendency toward the lordosis often developed in above-knee amputees as the result of weight-bearing on an ischial support located back of the normal hip joint *(35)*. Clearly, disarticulation offers the maximum bony lever of any amputation at or above the knee.

A recent informal survey of some of the knee-disarticulation cases performed under supervision of one of the authors (R.H.A.) at Thomas England General Hospital during World War II has indicated satisfaction of the patient with this type of amputation and prosthesis. In spite of the gait deficiencies noted, these knee-disarticulation amputees feel that they walk well, continue to prefer this level of amputation, and refuse any consideration of reamputation above the condyles to become more conventional above-knee amputees. Although some knee-disarticulation prostheses providing knee friction are reported in the literature *(78),* much more needs to be done in this respect.

The Above-Knee Cases

In the above-knee amputation, at all locations as much length as possible should be conserved. Gritti-Stokes and similar end-bearing stumps have in many cases been fitted successfully with the suction socket *(35,41),* although attachment of the muscles is then particularly important to avoid development of excessive negative pressure owing to displacement of muscle bulk in the necessarily limited clearance volumes available with long stumps and end-bearing pads. Some have found difficulties in fitting such cases with the suction socket and have preferred to rely on a conventional pelvic-band suspension, perhaps with a second hinge permitting abduction. In either case, the longer the above-knee stump the better.

As regards the above-knee case, the principal development thus far of the Artificial Limb Program has been the reintroduction of the suction socket, with many far-reaching effects on stump shape, muscle conservation, socket fit, and alignment, accompanied by increased need for the cooperation of many disciplines and the launching of a program of education and certification. As for the first of these, the suction-socket program shifted emphasis from the excessively flabby, conical stump (Fig. 22) desired for the so-called "plug" fit to a more nearly cylindrical stump with firm muscles stoutly attached to the bone. In the suction socket, the muscles are needed both to control the newly found freedom about the hip joint and to provide a gripping action by bulging against the walls of the socket, thereby decreasing the negative pressure required to carry the weight of the prosthesis. Similarly, introduction of the suction socket led to replacement of the typical conical socket of triangular or circular cross section (Fig. 23) by a more nearly rectangular socket (Fig. 24). The latter, developed in Germany within the last generation, has a better basis in physiological and anatomical fact, appears to be a necessity with the suction socket, and has, of course, also been used successfully with an increasing number of pelvic-band conventional limbs without use of suction.

Fig. 22. An above-knee socket with nearly circular cross section and steeply conical form intended to support a conical, atrophied stump by side-bearing. Typically, a substantial roll of flesh developed over the rim around most of the circumference. The straps were used with suspenders. Adjustment for atrophy and shrinkage of the stump was easily made by additional stump socks, since the stump was regarded as a jellylike mass whose shape was easily distorted, with little definite relation between socket shape and stump shape. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

As for alignment, introduction of the suction socket has forced the prosthetist to pay more attention to details, since, unlike the case of the conventional above-knee leg, errors in alignment cannot here be concealed by trial-and-error bending of the pelvic band and metal, single-axis hip joint which forced

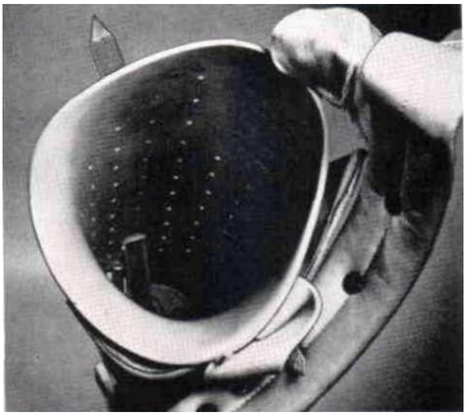


Fig. 23. Conventional socket for "plug" fit of above-knee stumps, showing rounded, triangular top portion of prosthesis for right thigh (looking forward and laterally). Note shelving flare below gluteal crease and ischium and broad, horizontal flare through perineum and adductor region. A considerable roll of flesh develops over this flare also, as in Figure 22. Socket shown here is made of metal and perforated, but the style often was used in wooden sockets as well. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

conventional legs to swing in a single plane regardless of their inertia and the gait of the amputee. With the suction socket in correct alignment, the amputee balances his weight completely on the leg, since he has no pelvic band and hip joint to lean against for support. Conversely, however, attention to better alignment has led to decreased stress in the hip joints and pelvic bands of those legs which, for one reason or another, are still fitted with pelvic bands. If one thinks of the suction socket as being fitted with an imaginary hip joint carrying zero stress, it is apparent that a comparable alignment will result in minimum stress in a real hip joint and pelvic band of a conventional leg and, therefore, to greatly reduced risk of breakage.

In a very short above-knee leg, the suction socket *plus* auxiliary suspension, either the Silesian bandage (Fig. 25) or the conventional hip joint and pelvic band (Fig. 6), has permitted conservation of greater *effective* stump length than would be possible with the same stump in a conventional leg with hip joint and pelvic band but with a "plug" fit. In donning the suction socket, the flesh is pulled into the socket with stockinet, in contrast to the tendency of the conventional stump sock and "plug" fit to push the soft tissues upward and out of the socket. The auxiliary suspension provides greater control and stability than would be available in a pure suction socket. The more logical anatomical fit of the quadrilateral shape, including some ischial support, avoids the roll of flesh in the adductor region and the skin irritations and furuncles so commonly seen with the "plug" fit. Thus, some very short above-knee stumps fitted with this combination of suction socket and auxiliary suspension can function as if with a conventional above-knee leg without the necessity of flexing the stump permanently in a tilting-table type of socket such as would be used for a hip disarticulation.

Extremely short above-knee stumps, with little more than the neck of the femur, can be fitted in some cases with the "saucer" type of socket *(29)* in place of the tilting-table type

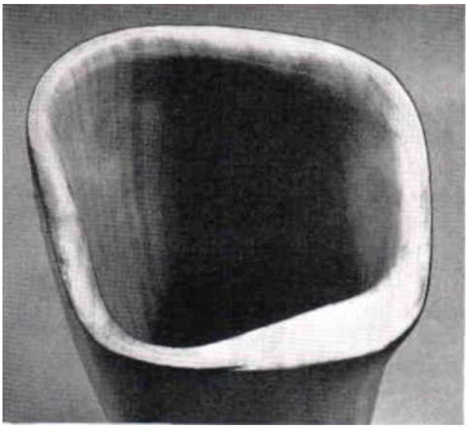


Fig. 24. Substantially rectangular or quadrilateral plan of top of socket for left above-knee prosthesis (seen from the rear), typically used for the suction socket but also applicable with soft belt or mechanical hip joint and pelvic band. Note the definite but narrow ischial support, slightly sloping forward and down and well rounded on its forward edge. The medial wall is thinner than the flare in a "plug" fit, since it should *not* provide a shelf or support against vertical load but should, in order to provide horizontal support during the stance phase, reach into the perineum as high as feasible wdthout striking the pelvis. A nearly square anteromedial corner provides relief for the prominent adductor tendons. A high forward wall keeps the ischium on its support. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

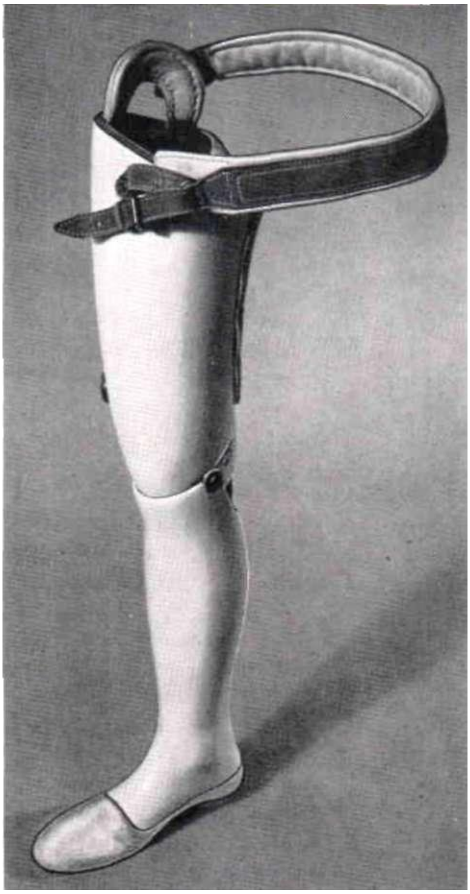


Fig. 25. Model of German suction-socket prosthesis with Silesian bandage, or trochanteric belt, with padded horseshoe encircling the trochanter, soft leather belt posteriorly around the pelvis, and V-shaped strap from anterior of socket through ring of the belt. The pelvic belt aims to assure vertical support during the swing phase, while the V-strap provides support against unwanted abduction and external rotation. *Courtesy Prosthetic Testing and Development Laboratory, U.S. Veterans Administration.*

generally used throughout the world with a true hip disarticulation *(17,42,50,50,63,68,80).* Often the knee joint is locked during standing and walking, so that the amputee walks stiff-legged. In this case the prosthesis is often built shorter than the sound leg. Sometimes, however, adequate alignment stability can be obtained to permit a free knee joint. The thigh section is sometimes locked to the tilting-table socket so that the back muscles can function to stabilize a free knee as do the hip extensors in the above-knee amputee.

Hiyeda *(42),* in 1942, and independently the Canadian Department of Veterans Affairs *(61)* have used free joints at both hip and knee, with the hip joint farther forward and the knee farther to the rear than usual (Fig. 26). A posterior elastic strap helps to extend the hip joint. Either the saucer socket or the lilling-table type may be built of plastic **laminate** instead of from the older, molded leather, but if for some reason leather is used, the nylon coating developed at the Army Prosthetics Research Laboratory *(47)* will make it much more sanitary.

PARTIAL AMPUTATIONS

Wherever possible, of course, partial hand or foot amputations should be performed in preference to major amputations.[5] Much work was done during and immediately following World War II on the surgery of the hand *(23),* and interest has been lively since the formation of the American Society for Surgery of the Hand. In the recent Korean conflict, a great many partial hand and partial foot amputations were performed safely, whereas in previous times many of these cases would have required major amputations, probably as below-elbow or below-knee amputations at the former "sites of election."

In recent years, satisfactory cosmetic gloves have been developed by the commercial prosthetics industry *(85),* at the Army Prosthetics Research Laboratory *(48),* in the Navy *(66),* and in the Veterans Administration's Plastic Artificial Eye and Restorations Clinics. These have made possible adequate cosmetic fitting of many partial hand amputations while retaining some function. Moreover, various operable terminal devices for partial hand amputations have been developed both commercially and on an experimental basis in the ACAL program. Sometimes a small hook is mounted on a molded socket and controlled by a conventional cable or by wrist movement. On an experimental basis, the mechanism and

[5] In general, partial amputations should be considered only when normal sensation and good blood supply can be retained.

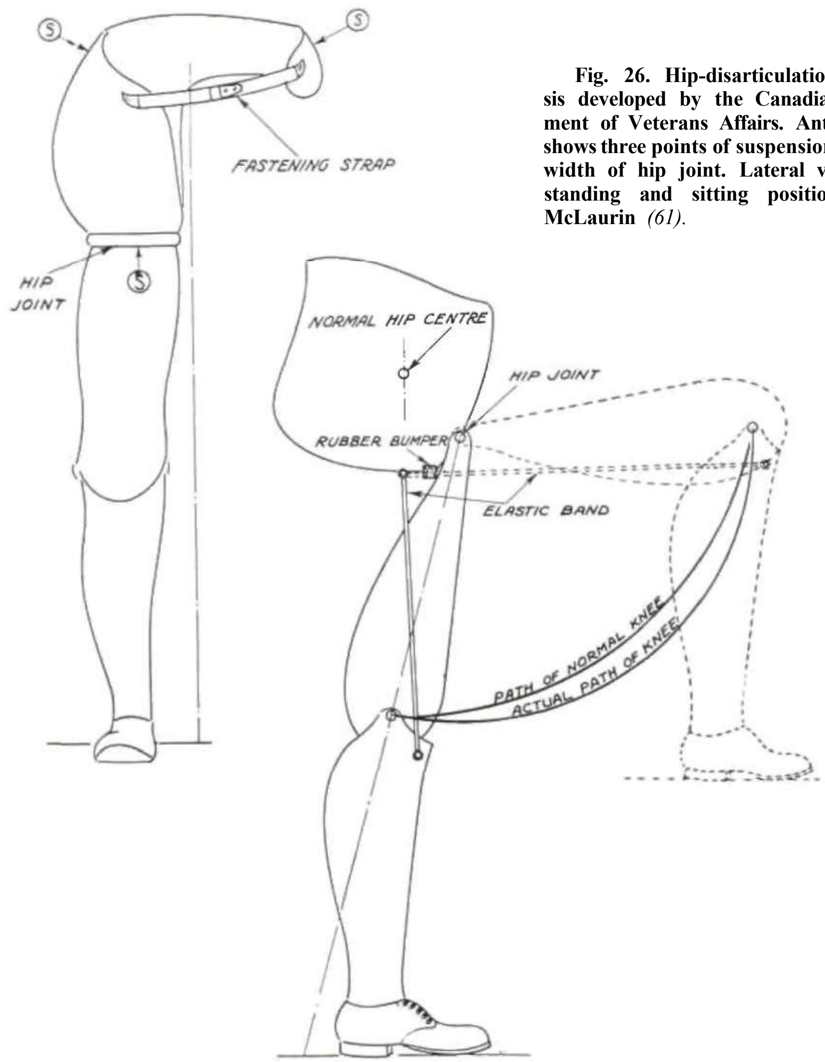


Fig. 26. Hip-disarticulation prosthesis developed by the Canadian Department of Veterans Affairs. Anterior view-shows three points of suspension© and full width of hip joint. Lateral view shows standing and sitting positions. From McLaurin *(61).*

wrist plate of an APRL hand have been removed, the transmetacarpal stump allowed to fit within the hand shell, and the side frames of the mechanical hand hinged opposite the anatomical wrist joint to a light forearm cuff. Thus wrist flexion and forearm rotation are preserved. Such cases clearly present individual challenges to the prosthetics clinic team *(14)* and to the designer and manufacturer.

RECAPITULATION

Decision as to the level of amputation, then, can be recapitulated in terms of saving all length possible.[6] This policy is justified not only by new devices, developed predominantly in the Artificial Limb Program, but also by the spectacular advances in recent years in many fields of medicine and related sciences. Blood, plasma, and antibiotics have helped to control shock and infection and have made possible

[6] An exception may be the below-knee amputation. At the present time, and until further information is available, the below-knee stump should not extend more than 6 in. below the tibial plateau.

prolonged and precise operations. Medical schools and residency training programs are only beginning to give more attention to education in the broad field of prosthetics to make the new findings available to the practitioner. The various medical societies are now devoting to this broad field more and more time on their programs and more space in their exhibits. Special courses, such as those on the suction socket held at various locations throughout the country, and the Institutes on Upper-Extremity Prosthetics at UCLA *(12, 13,84),* are bringing specialized knowledge to the doctor, the prosthetist, and the therapist. More attention is given to individual prescription rather than to "sites of election," with increasing cooperation and expert consultation from the prosthetist as to devices available but without dictation of sites merely because they might be more convenient. Best of all, there is now greater interest in over-all rehabilitation and continued follow-up on the part of the medical profession to see that every amputee, regardless of level of amputation, achieves the greatest possible restoration to normal life.

NEW TECHNIQUES IN AMPUTATION SURGERY

There is no need here to describe in detail the techniques of amputation surgery, since they are all so well presented in numerous other sources, for example, by Slocum *(81).* Certain points reflecting the experience of the Artificial Limb Program *(11)* may, however, be worthwhile. These may first be illustrated in terms of a typical amputation with primary closure, chiefly that producing an above-knee stump for which suction socket is intended, followed by notes on some of the special conditions at other levels of amputation.

THE GENERAL CASE

Skin Flaps and Subcutaneous Tissue

In general, the skin flaps are approximately equal on the anterior and posterior sides and are so curved as to meet neatly without undue skin tension but without leaving "dog ears." The usual amputation has a central scar, although in some of the special cases of weight-bearing stumps there is usually a longer flap on one aspect so as to move the scar out of the end-weight-bearing zone. Even for the below-knee amputation without end-weight-bearing, a longer posterior flap has sometimes been advocated to take advantage of the presumably richer blood supply and more liberal muscle and fascia, but the advisability of this technique has not yet been sufficiently evaluated for it to be recommended here. Since when divided the skin and other soft tissues retract, the skin flaps are initially outlined distal to the intended level for sawing the bone, thus compensating for the successive retraction of the various layers and permitting the bone eventually to be sawed through at the edge of spontaneously but temporarily retracted tissues.

The subcutaneous tissue may be regarded as a gliding mechanism, enabling the skin to move freely over the deeper fascia and achieving the goal of freely movable skin without an adherent scar. The subcutaneous tissue is cut perpendicularly to the skin, without beveling, and both are allowed to retract as they are cut, without undermining.

Fascia

A complete fascial envelope is very desirable, primarily to secure the severed muscles to each other and to the bony lever. Besides this, as Lawrence *(46)* has suggested, piston action of the bone within the soft tissues of the stump may help to pump fluid from the stump. Presumably this action is more effective if the fascial envelope is completely closed in order to force fluid displacement upward through the veins and lymphatic channels. In contrast, an opening in the fascial envelope may permit a compensating pulsation of the soft tissues through the defect, thus failing to generate effective pumping action. Although as yet there is little direct evidence to support such views, the reasoning seems logical.

A further advantage of the fascial envelope is to avoid bulging of muscle through a defect in the deep fascia. Accordingly, it is also desirable, when feasible, to repair traumatic defects in the fascia and to refrain from removal of fascia during any plastic operations intended to remove bad scars.

The tough fascia lata plays a special role while the above-knee amputee is on the artificial leg during the stance phase. Acting as a guy wire at the most favorable leverage to balance body weight falling medial to the ischial support, it helps to support the pelvis in a substantially horizontal position with minimal expenditure of muscular energy. Hence every reasonable effort should be made to secure firm attachment of the severed end of the fascia lata to the bony lever and to the fascia on the medial side of the stump in order to replace its former anchorage below the knee, as in the intact leg.

The incision through the fascia is parallel to the initial skin incision but at the level of the retracted superficial tissues. Like all aspects of amputation surgery, it should be clean and precise.

Muscles

The importance of muscles has been emphasized by the Artificial Limb Program in connection with the suction socket *(35,41),* as a vital part of the cineplasty studies *(10,43, 77,83),* and in analysis of the forces, motions, and hence the energy costs of both normal and pathological gait *(34,79,89).* Only from reattachment of the severed ends of the muscles is it possible to attain control of the stump, particularly when greater freedom of action is made possible by improved devices, as, for example, by the suction socket. Moreover, the muscles must be held at substantially their original "rest length" in order to attain the greatest force during contraction *(43,77).* Appreciation of this fact was brought out especially in connection with the cineplasty program, but of course the principle applies to all other muscles. A brief review of muscle physiology, mostly of features known for over 50 years but re-emphasized by recent research, is in order.

The Nature of Muscle Forces. The muscle studies at the University of California in connection with cineplasty *(43,77)* have re-emphasized the importance of the early studies by Blix *(16)* of force-length characteristics. Briefly, as shown in Figure 27, the force developed by a muscle is related to the length of the muscle at the time the force is exerted. Any attempt to stretch a relaxed muscle beyond its rest length results in an increasing resisting force, as shown by the

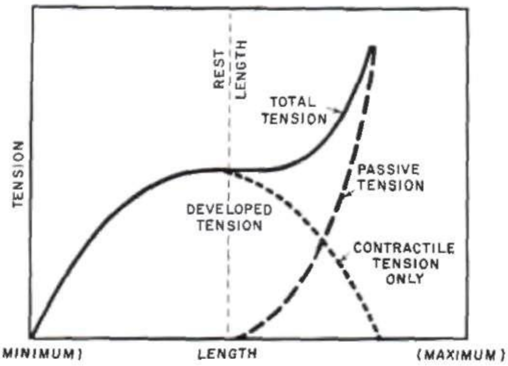


Fig. 27. Idealized length-tension curves for a typical muscle. Note that the passive-tension curve rises sharply when the relaxed muscle is stretched beyond rest length and that maximum voluntary force with isometric contraction is available at or near rest length. Clearly, use of a muscle in a contracted position yields both lower force and less available energy. From Inman and Ralston *(43).*

"passive-tension" curve. If the muscle is restrained at its rest length and then stimulated as vigorously as possible, a certain maximum force can be generated. Full excitation of all the fibers, as by electrical stimulation, yields this maximum force for isometric contraction, although in practical voluntary use only part of the muscle fibers are activated at a given instant, so that a much lower value is attained when the subject "tries as hard as possible."

If now the muscle is allowed to shorten, that is, to move toward the left of the rest length in Figure 27, stimulation results in some maximum isometric muscle force less than the value attained at rest length. Continued shortening results in decreasing forces measured isometrically until, at some value of contraction varying somewhat in different muscles but roughly 60 percent of the original length of the muscle, no force can be exerted.

Beyond rest length, an increased total tension may be developed upon isometric contraction. The exact shape of the curve varies with the nature of the muscle, its past history of stretching or contraction over prolonged periods (especially noticeable in muscles in which the cineplastic operation has been performed), and with the individual case. When the passive-stretch force is subtracted from the total tension attained by isometric contraction, the resulting *net* force available voluntarily tends in general to decrease again as the muscle is elongated beyond the rest length. Thus the curve of the *net* force is roughly an inverted parabola with its maximum at or slightly beyond rest length. Since this curve varies with individuals and with training and exercise (which affect both the cross-sectional area of a muscle and the shape of the passive-stretch curve), examples can be found which depart markedly from this schematic pattern. Nevertheless, the general principle leads to a number of interesting conclusions relating to the surgery of both upper and lower extremities.

Applications of Muscle Mechanics. It is immediately apparent from Figure 27 that, if a muscle is allowed to retract, temporarily or permanently, it cannot attain a voluntary force as great as would be possible at or near the original rest length. Prosthetic devices should be utilized, as far as practicable, with the appropriate muscles near, perhaps slightly beyond, the rest length. A cineplastic tunnel, for example, should be so harnessed that most objects will be picked up with the tunnel near the rest length *(83).* As is well known, the hamstrings, if reattached to the end of the femur in an above-knee amputee, can serve as hip extensors. On the basis of known muscle mechanics, they will be most effective when the hip is somewhat flexed but will be considerably less effective when the hip is fully extended or when it is hyperextended just at the end of push-off. The amputee may then attempt to supplement hip extension by using his back muscles, thus producing lumbar lordosis. Alignment of the socket bore and condition of the back-check controlling extension of the thigh socket relative to the shank will both affect the length of the hamstrings and hence the ability of the amputee to stand securely and to push off forcefully *(41).* Permanent contracture of a muscle will result in a movement of the passive-tension curve toward the left in Figure 27 and, in general, in a steeper shape of the curve, thus resulting in greater passive tension with only little stretching of the muscle. Thus the maximum force which can be attained voluntarily will be reduced substantially, and the effect may be more serious than the simple reduction in range of motion. Avoidance of contractures is thus mandatory.

Workers at the University of California have studied the moment (or force X leverage) available about the hip joint in relation to the angle of adduction or abduction of the stump. Since the gluteus medius and tensor fasciae latae are at their rest length when the stump is in its normal position, under slight passive stretch with an adducted stump, but allowed to contract when the stump is abducted, it is not surprising to find that the available moment about the hip joint decreases markedly from the adducted into the abducted region. Forcible abduction of the stump against the socket wall is essential to keep the pelvis level during the stance phase *(41,75),* and consequently maximum available abduction moment about the hip is desirable to avoid an apparent gluteus medius limp. Therefore, workers at the University of California have reasoned, it is highly desirable to maintain as much adduction as feasible of the socket bore in space and in relation to the remainder of the prosthesis. Experiments with controlled fitting and alignment on the University of California adjustable leg *(76)* have indeed shown this reasoning to be valid. In contrast, fitting of the socket to an abducted stump and "straight" alignment of the shank to the socket result in an appreciable limp.

Stump Muscles in Prosthetic Control. Muscles may have within a socket several actions particularly favorable in the above-knee suction-socket leg. General bulging of the muscle belly during contraction increases the diameter of the stump in the zone of the maximum muscle belly, thus helping to grip the walls of the socket and producing frictional forces which help to support the prosthesis. Muscle bulging and even the contour of the relaxed muscles help to key the correspondingly irregular socket against rotation about its longitudinal axis and thus aid in voluntary control of rotation of the prosthesis.

Conversely, the muscles of the thigh sometimes become detached from the cut end of the bone and the overlying fascia but by some mischance become attached to the superficial tissues, as through the scar. Contraction of such muscles causes a pistonlike retraction of the end of the stump, a condition that may cause discomfort in any case, especially if simultaneous contraction of opposing muscles tends to stretch the scar, and one that is particularly undesirable in a suction socket. Pistonlike retraction of the stump end, analogous to withdrawal of the plunger from a hypodermic syringe, develops additional negative pressure in the space between the end of the stump and the floor of the socket. Such excessive negative pressure, far beyond that necessarily created by the weight of the prosthesis, may tend to cause edema.

If stump retraction seems apt to occur, the physician should consider all factors carefully before prescribing a suction socket and, if he decides to proceed with one, should caution the limbmaker to leave adequate clearance volume between the end of the stump and the sealing floor. In that case, the change of volume owing to movement of the soft tissue will be only a small percentage of the original volume, so that the resulting negative pressure will be only a correspondingly small fraction of the barometric pressure. But with long above-knee stumps, because of the problem of locating the mechanical knee joint, it may not be feasible to allow adequate clearance volume, in which case the suction socket may be contraindicated.

Movements of muscle bellies also may create a wedging action within a relatively conical socket, thus tending to force the socket off the stump and to increase negative pressure in a suction socket, but this effect is not likely to prove serious in the relatively cylindrical, well-muscled stump recommended *(41)*. Wedging action may, however, be desirable in the thigh muscles of a below-knee amputee so as to provide additional support on the somewhat conical thigh corset, thus relieving the below-knee stump of some of the pressure to which it would otherwise be subjected.

Muscles or tendons passing over the brim of the socket may also tend to force the prosthesis from the stump when the muscles are tensed, again tending to increase negative pressure in a suction socket. This effect can be minimized by careful fitting of the socket.

Muscle tissue acts as a pump to promote return circulation of blood and lymph, as is well known. Obviously, this effect is particularly important in the suction socket to reduce tendency toward edema, and hence vigorous muscle activity is doubly desirable.

Securing Muscles at Rest Length. For all these reasons, it is highly desirable that the muscles be secured to the end of the stump at their rest lengths. Accordingly, the muscles are cut at the levels of the spontaneously retracted superficial tissue and fascia. If necessary, the cut muscles may be sutured to their overlying fascia. Later, when the fascia is closed and sutured over the end of the stump, the muscles will be carried back from their spontaneously retracted position substantially to their rest lengths. It is desirable to have not a mass of loose muscle tissue over the end of the stump but rather a neatly tailored muscle and fascial closure with the muscles restored to their rest length, that is, simply pulled back against the natural tone.

To suture muscles to each other at the end of the stump, as has sometimes been recommended in the past, is unnecessary. In fact, the sutures would probably pull out of muscle alone. Suturing of the tough fascia is much more effective, so that it is unnecessary, as well as undesirable, to suture muscles to holes drilled in the bone.

In a few special cases, the tendons of the muscles may be sutured together. For example, in the case of knee disarticulation, the tendons of the hamstrings and quadriceps may be sutured in the patellar notch. Generally, the intention is to secure, by healing and scarring processes, the cut ends of the opposing muscles to each other, to their overlying fascia, and to the bone.

Bone

With the possible exception of the below-knee amputation (see footnote, page 30), the surgeon will plan to save the maximum practicable length of bony lever. The saw line is made at the level of the naturally retracted soft tissues. Before the bone is sawed, the periosteum is cut cleanly around with a sharp scalpel, taking special care to avoid loose flaps of periosteum, which may later form bone spurs. The bone is then sawed off squarely. There is no need to remove a periosteal cuff, and there should be no attempt to elevate the periosteum.

In general, it is not necessary to bevel the bone cortex.[7] Preliminary anatomical studies of bone ends at the U.S. Naval Hospital at Oakland, California, and at the University of California Prosthetic Devices Project have shown that the bone end, when treated as already described, may round over spontaneously within a few months so that the medullary cavity tends to become sealed *(70)*. This simply confirms clinical observations already made from amputation of long duration.

Nerves

The aim of the surgeon is to sever the nerves in such a manner that the inevitable neuroma will be embedded in soft tissue at a point where it will not be stimulated. Thus, it should not be permitted to reattach to scar or bone in such a manner that the fibrils of the neuroma become stretched at every step owing to piston action of the bone within the tissues or to movement of the scar as a result of muscular action. The neuroma should also be far enough up the stump so that it is not subjected to unusual pressure from use of the prosthesis.

The most desirable technique, it has been realized for some years, is to dissect the nerve carefully from the neurovascular bundle, pull it gently from its sheath, and cut it cleanly with a sharp instrument. The severed nerve is then allowed to retract up its nerve sheath into soft tissue. The major cutaneous sensory nerves, which are less obvious, deserve the same careful attention given to the major nerve trunks.

Contrary to the advice in some earlier texts, experience of the past decade has shown clearly that no injections of alcohol or other chemicals should be given. Rather, the nerve should be left entirely alone after it has retracted into the tissue. Much clinical experience, and recently the studies of the Pain Project at the University of California *(36,37,90)*, have indicated that formation of a neuroma must be expected at every cut nerve. Resection of a neuroma once formed will therefore merely lead to development of another neuroma at a higher level. Difficulties are encountered from a neuroma only if it is stretched or compressed. Although phantom pain is sometimes triggered by the stimulation of a neuroma, there are so many other possible causes that repeated surgery to remove a neuroma each time one forms generally is not justified.

THE SPECIAL CASES

The Upper Extremity

The Wrisl-Disarticulation Case. In the wrist disarticulation, the distal joint between the radius and ulna must carefully be preserved to permit free motion of the radius over the ulna during pronation and supination. Occasionally it may be wise to round off any exceptionally sharp surfaces on the styloids, but in general the styloids can be accommodated by careful fitting of the molded plastic-laminate socket (Figs. 8 and 9).

The Long Below-Elbow Case. Similarly, in the long below-elbow stump, every effort should be made to preserve free motion of the radius over the ulna to retain pronation and supination. Cutting of the bones permits the radius to approach the ulna, resulting in shortening, and hence weakening, of the pronator teres. Although with training the weakness can be overcome, the proximity of the radius to the ulna makes bone spurs or actual bony bridging between the two bones much more of a hazard to adequate pronation-supination. Thus careful, clean cutting of the periosteum is of particular importance.

The Short Below-Elbow Case. Where there is the possibility of a very short below-elbow amputation, the short stump always should be preserved if at all medically feasible, in preference to amputation at or above the elbow. In some cases, for example where rolling and notching of the socket brim (Fig. 14) might be inadequate to prevent an intact biceps from pushing the socket from the stump during elbow flexion, the surgeon may

[7] **The single exception is the anterior tibial crest in the below-knee amputation, where beveling is desirable but without extending the beveled surface to the medullary cavity. In special cases, such as the Syme, there will be modifications of the general surgical technique. See page 36.**

consider cutting the biceps tendon to permit fitting the socket brim higher than usual. If biceps cineplasty is performed for such cases, the biceps tendon will, of course, be resected and the cut end carefully covered over or imbricated to prevent reattachment. In this case severing the biceps tendon may in some instances permit higher fitting of the socket while simultaneously preserving a useful function for the biceps muscle.

The Elbow-Disarticulation Case. The elbow-disarticulation prosthesis with the new external lock (Fig. 15) has encouraged the preservation of the elbow-disarticulation stump whenever feasible medically. As with any end-bearing stump, it is probably desirable to place the scar line away from the weight-bearing area. The irregular shape of the humeral condyles may be retained to assist in anchoring the socket against rotation. Careful attention to the nerves is desirable to prevent formation of sensitive neuromata in the areas which will be subject to load during end-weight-bearing or as a result of bending loads upon the prosthesis when the elbow is locked.

The Short Above-Elbow Case. The very short above-elbow stump should be preserved so far as medically feasible in preference to a true shoulder disarticulation or, worse, forequarter amputation. Even the short stump will serve to key the socket and provide greater stability. In some cases the short stump can be used for control of a lock. In experimental work on an electric arm, a very short above-elbow stump has been used to operate a keyboard of switches and clutches (Fig. 18) for control of the electrically driven motions as well as to control an electric elbow lock while a turntable lock above the elbow joint was controlled by a button pressed by the pectoral muscle *(3).*

Cineplasty Cases. In general, upper-extremity candidates for later cineplasty operations *(7,10,82)* can undergo the original amputation in the same manner as do those amputees who will use conventional prostheses. Thus far ACAL has accepted cineplasty in the intact biceps of a below-elbow amputee only (Fig. 28; see also Fig. 12, page 61), and in the case of a veteran prior approval from the VA Central Office is required. For many years cineplasty has been performed in a variety of locations and by many different techniques. In the Artificial Limb Program, it has been performed experimentally in a number of locations in various individuals, including the biceps in above-elbow amputees and the pectoralis major for short above-elbow and shoulder-disarticulation cases *(82).* But before such procedures can be recommended, problems remain to be solved.

The general principle is to preserve muscle length and attachment at the time of the original amputation so as to prevent permanent contraction. The distal end of the muscle is released only at the time of the cineplasty operation so as to permit prompt exercise and stretching of the muscle soon after the tunnel has healed. Special attention should, of course, be given to repair of any injuries proximal to the intended saw line in order to assure full innervation and blood supply and to avoid serious scarring of the remaining stump.

The Lower Extremity

The Syme Amputation. In the Syme amputation, in contrast to amputation at many other levels, preservation of the normal heel flap permits weight-bearing on tissue normally accustomed to full body weight and impact. The incision has a special shape across the instep so as to permit the shelling out of the calcaneus from the heel flap and the later formation of a suture line across the anterior aspect of the stump *(5,31,81).* To provide good bearing, the bones are sawed just above the articular cartilage and in such a plane that the cut surfaces will be parallel to the floor when the amputee stands (not necessarily perpendicular to the long axes, as, for example, in the case of a bowlegged or knock-kneed patient).

To ensure preservation of circulation in the heel flap, little if any tailoring is performed. Dog ears left at each side of the heel flap will disappear with proper postoperative wrapping. Contrary to the usual rule, the tendons are simply cut and permitted to retract without attempting to suture the tendons in place or to attain fascial closure. If a good Syme stump cannot be obtained, the surgeon should perform a conventional below-knee amputation, since a very long below-knee stump

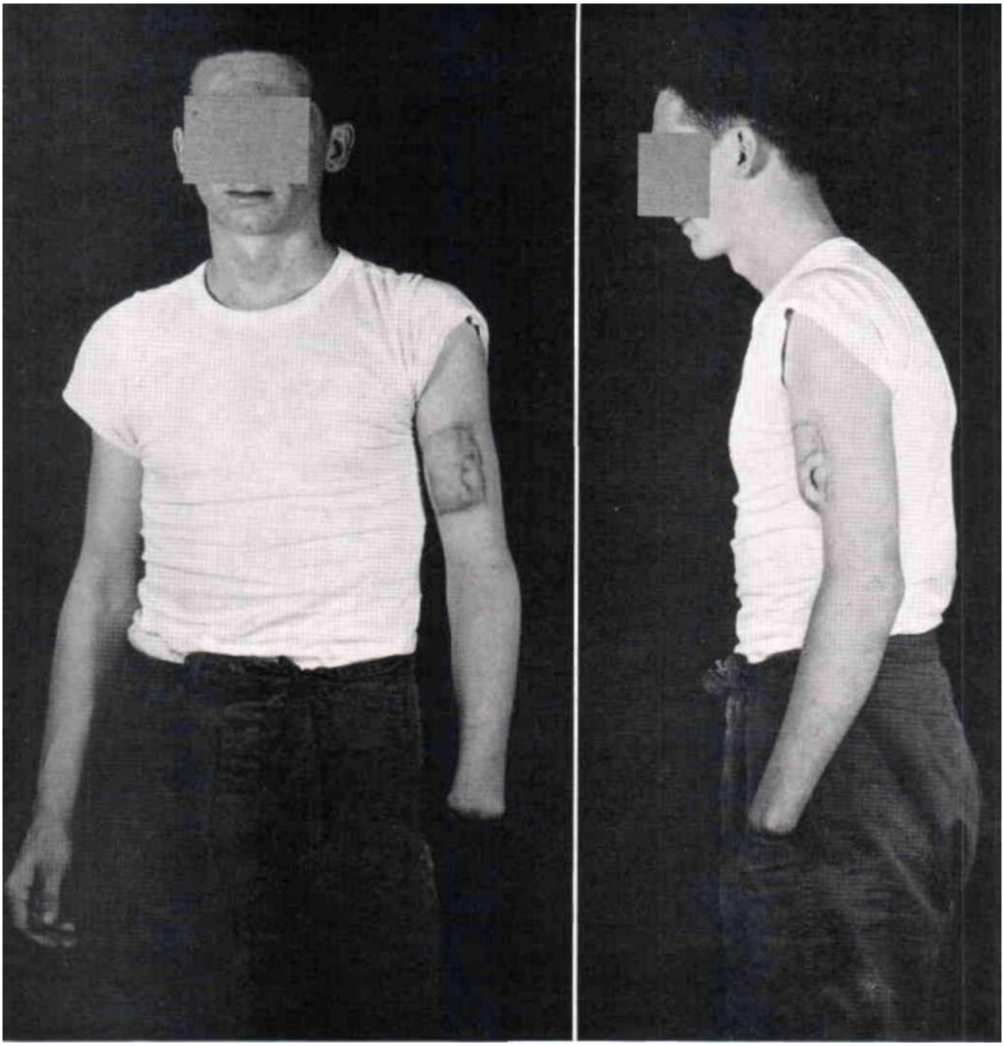


Fig. 28. **Typical biceps muscle tunnel in below-elbow case, six months postoperative.** *Courtesy Army Prosthetics Research Laboratory.*

extending to the lower third of the shank frequently breaks down from poor circulation.

The Knee-Disarticulation Case. In the knee disarticulation, an exceptionally long anterior flap is necessary for closure of the stump and so that the suture line may be posterior and out of the end-weight-bearing zone. In general, the cartilage is simply left in place. The patella, although routinely left in place, may be removed to give extra length to the anterior flap when needed for adequate closure. The patellar tendon is sutured to the hamstring tendons in the patellar notch between the femoral condyles, but no attempt is made to prevent the tendons from gliding.

SUMMARY

Techniques advocated, partly as a result of World War II and subsequent experience and partly as a result of the ACAL program, may be summarized as follows:

1. With the possible exception of the below-knee amputation, save all length of stump considered surgically feasible.

2. Preserve the muscles at their rest length.

3. Attempt to secure attachment of opposing muscles to each other and to the bony lever during the healing process through suturing of the opposing fasciae, without attempting to suture the muscles to each other or to the bone,

4. Avoid attachment of the muscles to the scar.

5. Secure a complete fascial envelope.

6. Secure a smooth and freely movable scar, usually central but displaced in the case of end-weight-bearing stumps (or possibly where skin on one side of the stump has a much better blood supply and gliding fascia than that on the other).

7. Sever a nerve cleanly and allow it to retract into soft tissue, without injection and with as gentle treatment as possible.

POSTOPERATIVE CARE

The doctor should in every case maintain continuing supervision and responsibility for the postoperative care of the amputee. Just what are the relative responsibilities of the surgeon and of the doctor of physical medicine, where the latter is available, is subject to discussion and, in the present state of knowledge, will necessarily vary from place to place depending upon their respective interests, training, and available time for both professional and administrative duties. But it is important for the patient's welfare that there always be available some single physician who is familiar with the case and who can take responsibility for seeing that the patient receives maximum cooperative service from the nurses, therapists, prosthetist, vocational counselors, and others concerned.

BANDAGING

Although the extremely shrunken, conical stump of former days is no longer desired, it is obvious that some muscles (such as the vastus group of the thigh in an above-knee amputation or the soleus in a below-knee case) will no longer have as important functions as before and can be expected to atrophy. It is desired that these muscles atrophy slowly without deposition of an equivalent amount of fat. Careful application of an adequately wide elastic bandage, in accordance with well-known techniques *(22,97),* will hasten the desired shrinkage.

Immediately after the amputation, therefore, the wound is dressed and the stump wrapped with broad elastic bandage. But the bandage will become loose in a few hours and should be replaced by a fresh one, usually every four hours during the day. The used bandage is washed and dried, the usual precautions being taken to restore its elasticity. After a suitable interval, usually 10 to 14 days, sutures are removed, the wound re-dressed, and elastic bandage again applied. Meanwhile, the patient should be taught to cooperate in the application of the elastic bandage so that, when dressings are no longer needed, he may himself learn to reapply fresh elastic bandage several times a day as needed to prevent edema and to encourage shrinkage of tissues no longer functional.

The bandage is made snug at the distal end, with no constriction at a higher point on the stump, and it must be carried above the next intact joint, for example up to the thigh in the case of a below-knee amputation or above the hip and around the waist as a hip spica in the case of the above-knee amputation. To avoid rolls of flesh, all parts of the stump must be bandaged, notably the adductor region high into the crotch in the case of the above-knee amputation. The patient must be cautioned against developing above the stump a local constriction which would lead to poor circulation. Likewise, bandaging should avoid a bulbous mass of soft tissue at the end of the stump, which would interfere with later fitting.

BED POSTURE

Every effort should be made to restore full range of motion of the stump as early as possible without risk of tearing the muscles from their newly organizing attachments to the bone. The patient should be discouraged from remaining in a fixed position, such as sitting in a wheelchair with the hip and knee flexed, or lying in bed with the stump propped up on a pillow *(21).* It should be carefully explained to him that some temporary discomfort and inconvenience will be necessary to ensure subsequent full range of motion and effective use of a prosthesis. The leg amputee should lie in bed with his legs parallel, without abduction and external rotation of a thigh stump or flexion of a below-knee stump.

TRACTION

In the event of a preliminary open amputation, the line of skin traction should be toward the center of the bed, and the patient should be checked frequently to be certain that he is lying with his pelvis parallel to the bottom of the bed. In no case should he be permitted to slant the pelvis and thus, in effect, to abduct the stump. In the more common closed amputation in civilian life, traction is seldom necessary unless, in an attempt to conserve greater bone length, exceptionally short skin flaps have been used and it is desired temporarily to remove tension from the suture line.

EXERCISES

Restoration of strength and of full range of stump motion can begin when the muscles have become adequately attached to the bone, with gentle voluntary exercises at first to prevent detachment. Restoration of strength will depend both upon developing maximum size of the cross section of the muscle and upon stretching of the muscle stump so that it operates near the amputation rest length, as already discussed. The role of a low passive-tension curve is particularly important, and of course exercises should be prescribed with due regard to the patient's general condition.

Home exercises, conducted by the amputee first merely by setting the muscles and later by using simple and readily available apparatus, are particularly important. Much can be done with a flatiron, a pail filled with increasing amounts of water or sand, or other convenient weights attached by a piece of sash cord over a pulley or doorknob to a towel about the stump. Elaborate gymnasium equipment or exercise tables obviously are not essential, convenient as they may be for the well-equipped rehabilitation center. The amputee and his family should be convinced of the importance of sensible home exercises, not only immediately postoperatively but whenever indicated throughout the rest of the amputee's life to maintain good stump condition and to avoid the flabby, weak, and contracted stump so often seen in an amputee of long duration. The amputee should be convinced of the need for maintaining adequate range of motion and strength in order that he may use his prosthesis effectively, gracefully, and with minimum effort. But of course he should be discouraged from intermittent extremes leading only to exhaustion.

GENERAL HEALTH

Finally, general body tone is important both for good health and good spirits as well as for effective use of a prosthesis. The leg amputee, for example, must have good triceps to use crutches when necessary and good abdominal muscles to minimize the risk of lordosis. The arm amputee will use muscles of the trunk and opposite shoulder in supporting, positioning, and operating his prosthesis. All young, healthy amputees should be encouraged to take part in swimming, skating, bowling, table tennis, or other sports as appropriate.

Every amputee should be cautioned against obesity, which in the lower extremity increases the load on the stump and in any case increases the difficulties facing the prosthetist. Because of the difficulties encountered from alternate tightness and looseness of the socket, all wearers of prostheses, and especially those using the suction socket, should be cautioned against violent fluctuations of body weight. Where indicated, all possible conditions causing obesity should be corrected, and patients should be supervised by a physician to stabilize body weight at normal for the individual.

REHABILITATION RESPONSIBILITIES

An important result of World War II military experience, of subsequent work under the ACAL program, and of the increasing numbers of amputation clinics both in the Veterans Administration and in private institutions has been the increased interest by the medical profession in its responsibilities for lifetime rehabilitation for amputees. These include not only the obvious medical responsibilities but also psychological aspects; pain and phantom sensations; teamwork with others concerned in the prescription, fitting, training, and checkout of the prosthesis; and referral for any necessary vocational counseling and retraining.

Psychological aspects of amputation are particularly important *(J)*. In many cases the doctor can provide appropriate psychological services, but in other cases referral to a clinical psychologist or to a psychiatrist may be desirable. Sometimes preoperative discussion and psychological preparation may be possible, especially if the amputation is elective or if the need for amputation can be foreseen. The prospective amputee himself should, when possible, decide realistically that amputation is preferable to other alternatives and that it is not "the end of the road."

In many cases the patient can be helped preoperatively or postoperatively to accept amputation and to begin a realistic estimate of the possibilities of worthwhile rehabilitation through discussion with other amputees of the same level who have been rehabilitated successfully. Clubs of amputees *(64,72)* are beginning more and more to provide, on request of doctors and hospitals, levelheaded, rehabilitated amputees for just this purpose. Such amputees are not to be confused with the overenthusiastic salesman type or with the psychologically disturbed exhibitionist, who so often has demonstrated his remarkable prowess without making the patient aware of the nature of his stump, the differences between his condition and that of the patient, and the fact that so much depends upon the general physical condition and the will power of the patient. Just as there are professional golfers, there are also professional amputees. These persons can often perform remarkable feats not ordinarily desirable in or to be expected of the average amputee and one, as is usually the case, unwilling to make a career of stunts with a prosthetic device. Realistic discussions of the responsibilities of the patient, yet of the many important and fascinating things which remain possible, will be most effective.

A matter of great importance is attention to the attitudes of those associated with the patient. Members of the family will wish to help in every way, yet their efforts must be guided intelligently toward help in the real difficulties while avoiding overprotectiveness generated by pity, which all too soon might turn into rejection. The employer can be helped to realize that the amputee may again return to useful work, whether at his former job or at some other and perhaps better and more skilled job after suitable vocational guidance and retraining.

Sometimes the handicapped person, perhaps for the first time receiving professional guidance and being forced to think carefully about his future, will aim at more education and a much higher economic level than before the amputation. After all, much of the heavy labor of industrial countries is being taken over by machines. Unaffected by the amputation, the patient's brain power and ability to make decisions and to control the machines will command a higher value.

Friends and acquaintances too must learn to accept the amputee for the many qualities he has left and to admire his demonstrated fortitude and cheerfulness rather than to pity him or even to shrink from him because of past memories of an amputee beggar. Finally, society as a whole must learn to accept not only amputees but all handicapped and disabled persons on the basis of their inherent dignity, ability, and worth as human beings, not on the superficial basis of individual differences in physical condition due to crippling disease, congenital defects, or mutilating injuries. In the past, amputees, like members of other minority groups, have encountered unreasoning psychological prejudices unworthy of the brotherhood of man.

PAIN AND PHANTOM SENSATION

The amputee will need counseling, both in the acute stage and perhaps occasionally throughout his life, about the nature of pain in the stump, phantom sensation, and phantom pain. Postoperatively, pain is handled as in the case of any other operation. But the amputee may be puzzled that he still has a sensation of the missing member, perhaps in some bizarre position. He can be assured that at least 85 percent of other amputees, and perhaps practically all amputees other than congenital, retain such feelings. Phantom sensations have long interested neurologists and psychologists and recently have come in for study in considerably more detail at the University of California *(90)*. It appears that such sensations are related to the continued activity of the cortex on which the missing limb was originally projected but which no longer receives the normal bombardment of constant new sensations of position, temperature, pressure, and so on.

Phantom *pain* is rare. It occurs only in a small fraction of amputees. Sometimes it appears to be related to specific physical difficulties in the stump or in the remainder of the body, such as pressure on a neuroma or traction upon a neuroma which has, unfortunately, become caught in scar tissue and is stimulated by muscular movement or piston action of the stump in the socket. In other cases, it may be related to some cause further up the body which might have been sought immediately in a normal individual but which might be neglected in the amputee. For example, a ruptured disc in the spine immediately would be sought from certain classic patterns of pain radiating down the leg, but the same might be overlooked in an amputee who complains that pain radiates into his missing phantom limb.

Studies at the University of California involved injecting salt solution, as a stimulant, into the various vertebral segments of both normal volunteers and amputees in order to produce radiation of pain which could be mapped systematically *(36,37).* In some cases, radiation of the pain into the phantom limb of an amputee resulted in disappearance of the phantom sensation itself after a short period, concurrently with disappearance of pain in the rest of the body (Fig. 29). In other cases, distribution of phantom pain was altered, and in a few cases the phantom pain became worse. In general, however, workers at the University of California believed that phantom pain could be alleviated by one or more of a series of systematic attacks. No single remedy was found that applied to all cases.

PROSTHETICS CLINIC TEAMWORK

The duties of the physician on the prosthetics clinic team have been well outlined by Bechtol *(14).* The increasing success of prosthetics clinic teams in overcoming the problems of the amputee, as well as those of the wearers of braces and orthopedic shoes, has brought a rapid expansion of amputee clinics in both government and private circles. Indeed, the teamwork concept has been utilized increasingly at many levels of rehabilitation for many kinds of disabilities and throughout scientific research generally. Each member of the team needs humble realization of his own limitations,[8] appreciation of the contributions to be made by each of the other members, and, of course, an understanding of the participation of the patient himself as a member of the team created in his behalf. Thus only can there be created a realistic basis for self-confidence in the total effectiveness of the team as an integrated unit. In the Veterans Administration's Orthopedic and Prosthetic Appliance Clinic Teams, the Chief of the Prosthetic and Sensory Aids Unit is the administrative "key" to the success of the individual clinic.

LIFETIME RESPONSIBILITY

The surgical responsibilities immediately after operation have, of course, long been obvious. But no more can the doctor dismiss the patient when the scar is healed—with advice to "look in the classified telephone book for a limbmaker." Rather, the doctor should serve as captain of the prescription team in its efforts to see that the amputee is provided with the best current prosthesis suited to the individual and with adequate training in its use, and he should assume continuing responsibility throughout the lifetime of the amputee.

The doctor should, for example, have the clinic administrator arrange for periodic checkup examinations at proper intervals, perhaps once a year. Thus the amputee can be checked for adequate fitting and can be informed of new improvements as they become available, both from the commercial industry's own developments and from the Artificial Limb Program as it makes tested devices available to the industry. The gait of lower-extremity amputees can be observed, facility in the use of upper-extremity prostheses can be noted, and, if necessary, further periods of training may be prescribed. Other problems, such as

[8] Webster's definition of "teamwork" reads in part as follows: "Work done by a number of associates, usually each doing a clearly defined portion, but all subordinating personal prominence to the efficiency of the whole"!

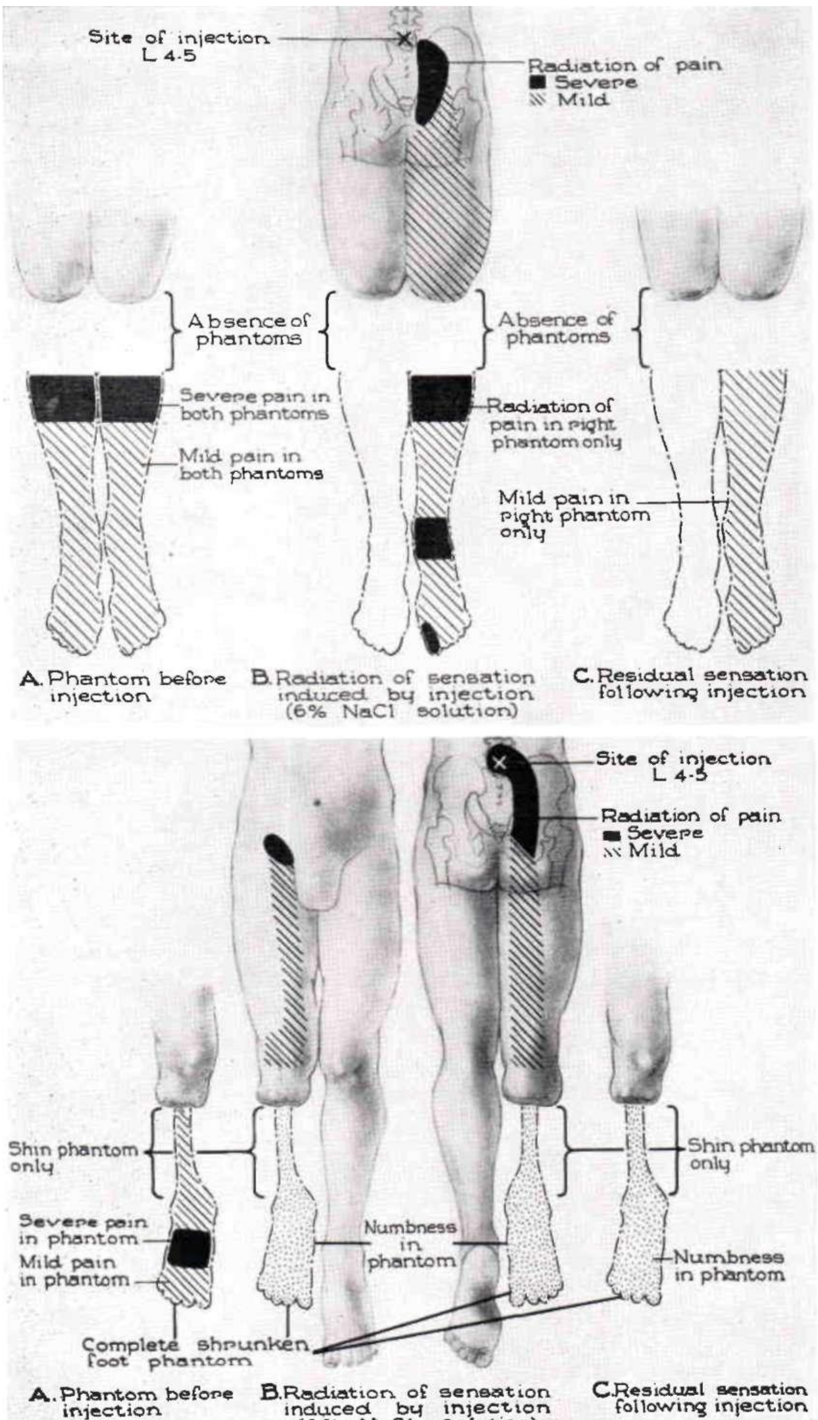


Fig. 29 Typical patterns of pain radiation in the phantom limbs of two subjects. *Courtesy University of California Medical School*

obesity, spinal curvatures, skin difficulties, and so on can be detected and corrected before they become serious. Frequently, all the amputee needs is a reminder for encouragement to brush up on his old skills. Reassurance and renewed encouragement are of important psychological value to the amputee patient.

Finally, the experienced patient, returning for his routine checkup, serves as an example lo improve the morale of the more recent patients sitting in the waiting room. The successfully placed and well-rehabilitated patient, grateful for his own return to active life, will be glad to assist by visiting more recent patients in the hospital. He may be called upon whenever his unique physical condition, type of work, or hobby makes him especially suitable to help a person of similar circumstances.

THE NEW KNOWLEDGE AND THE MEDICAL PROFESSION

The challenge to the medical profession will thus be clear. There has been a rapid increase in knowledge of prosthetic devices themselves, in methods of performing amputations, and in the philosophy of amputee management. Medical education must somehow fit into the medical curricula and into the crowded training programs for interns and residents the new knowledge and changing viewpoint in amputee rehabilitation *(9)*. Exhibits at medical meetings and papers in the medical journals offer some of this new knowledge. The new 800-page collaboration, *Human Limbs and Their Substitutes* (see *Digest,* this issue, page 77) presents a much more extensive range of knowledge and broader point of view than is possible in a single article. The busy practitioner, especially the general surgeon to whom amputation is only a rather incidental part of practice, must somehow find time to keep abreast of new knowledge and philosophy while conserving the best principles he has learned in the past.

Finally, there is a growing need for geographically spaced centers for performing amputations and to serve as bases for orthopedic and prosthetics clinic teams serving civilians as well as veterans. Perhaps only thus can those with specialized knowledge best serve the patients, especially those with unusual problems. Indeed, such centers could serve as agencies of the Artificial Limb Program, pointing out needs and priorities based on clinical experience and providing facilities for field tests and educational activities.

CONCLUSION

Thus, it can be seen that marked changes have taken place from the days of the few sharply delimited "sites of election" and the few types of prosthetic appliances available for them. The changes thus far have perhaps been most marked in the upper extremity, where a whole new armamentarium of appliances has been developed and rigorously tested both in the laboratory and in clinical studies. The findings have been made available to physicians, therapists, and prosthetists through a series of Institutes on Upper-Extremity Prosthetics at the University of California at Los Angeles. Even so, the present *Manual {91)* shows interim devices which should be greatly improved in years to come. Improved function and appearance are certain, and perhaps there will be some limited sensibility of position, contact, and gripping force.

In the meantime, however, a great deal of work also has been done on the lower extremity. Although relatively few new devices, such as the U.S. Navy above-knee artificial leg *{67,95)* and the suction socket have been accepted, a great many new devices and many changes in practice are being tested at the laboratory and clinical levels. It is to be expected that, in the next few years *{95),* an equivalent to the upper-extremity armamentarium will be released in an array of new devices for the lower extremity, such as stable knees, means for preventing stumbling, and perhaps forcible ankle push-off. Current inventors' designs and test models eventually will be tested through a systematic transition procedure and released for routine use.

To those close to the heart of the ACAL program for nearly a decade, the changes noted herein have occurred so slowly and so imperceptibly in the pressure of daily emergencies that they have not been realized fully.

Until brought out by a systematic review or by a chance conversation with someone untouched by the genuine progress which has been made, the alterations lie buried in the seeming monotony of obvious "good practice." Yet all these little modified details in technique, new or revived appliances, and perhaps more profound changes in points of view and philosophy add up strikingly to benefit the individual amputee.

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