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Artificial Limbs

A Review of Current Developments

ADVISORY COMMITTEE on ARTIFICIAL LIMBS

National Academy of Sciences
National Research Council

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Artificial Limbs

BRYSON FLEER, *Editor*

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ADVISORY COMMITTEE on ARTIFICIAL LIMBS

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

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Bioengineering—Blueprint for Progress

AUGUSTUS THORNDIKE, M.D.[1]

THE limbs of man move in space and time, in response to systems of internal and external forces, and in accordance with the laws of mechanics. To restore to any satisfactory extent the functions lost through amputation of an extremity therefore requires intimate knowledge not only of the structure, form, and behavior of the normal limb but also of the techniques available for producing complex motions in substitute devices activated by residual sources of body power. Since adequate replacement of a natural limb with an artificial one requires successful integration of the human mechanism with a toollike device, the biomechanical features of the stump and the physical characteristics of the prosthesis must be wedded as nearly as possible into a single, functional entity.

Two-sided as this problem would now obviously appear, it is only in comparatively recent years that the medical sciences of surgery, anatomy, and physiology and the physical one of engineering have been brought together in a unified attack upon the whole problem of amputee rehabilitation. Until recently, surgeons, with few exceptions, had little or no understanding of engineering problems. And heretofore the design and construction of artificial limbs has been conducted mostly by artisans who, however ingenious they may have proved to be, were mostly without formal education in engineering or anatomy. Besides this, except in isolated instances the two worked separately and alone. All of which no doubt accounts for the fact that, as late as World War II, the available artificial limbs fell far short of the standards of accomplishment attained in other fields of research and invention.

In the research program coordinated by the Advisory Committee on Artificial Limbs, National Research Council, there have been brought together in harmonious working relationship the individual skills of surgeon and engineer in a sort of mutual bioengineering to produce truly functional artificial limbs. As a result, there has been in the field of prosthetics perhaps more progress during the past decade than in all the preceding 2000 years of limbmaking.

Because the lower limb is more essential to human activity than is the arm,

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and also doubtless because the basic functions of the leg are easier to replace than are those of the arm, progress in artificial arms and hands has from the earliest times always lagged far behind developments in artificial legs. This circumstance was reflected in the fact that, when the Artificial Limb Program was established in 1945, much more had already been accomplished in replacements for the lower extremity than in those for the upper. And consequently developments in the ACAL program to date have been most noticeable in upper-extremity prosthetics, despite extensive engineering studies of normal and amputee locomotion and refinements in the techniques of lower-extremity fit and alignment.

In any case, the development of prosthetics had necessarily to follow the pattern of developments in surgery, and conversely the surgeon's philosophy with regard to "sites of election" and other matters was necessarily dictated by the character and availability of such prostheses as there were. Since the science of amputation surgery and the art of limbmaking proceed as one, the standards and practices in one field dictate standards and practices in the other, and vice versa. That each of these has now been brought to understand more fully the problems of the other may be looked upon as a major achievement in the art of prosthetics.

In the following pages of this issue of ARTIFICIAL LIMBS is to be found substantial evidence that the engineering profession, working with the amputation surgeon, has provided new thoughts, new ideas, and new approaches to the problem of providing adequate functional replacements for the limbless. In the whole Artificial Limb Program there exists no better example of cooperation toward progress than is demonstrated here. In the first of two articles, a surgeon and an engineer collaborate in describing the latest devices and techniques arising from systematic research and the influence which these developments ought rightly to exert upon the philosophy of modern amputation surgery. In the second, an engineer outlines the methodology required in investigation of the normal limbs and in the design of useful replacements. Only through such teamwork in biomechanics can truly great advances in the field of prosthetics be expected. The development of the thirty Veterans Administration and other civilian orthopedic and prosthetic appliance clinic teams has resulted in the better distribution of new knowledge toward improved fitting and alignment of artificial legs and in the design and construction of improved artificial arms.

The program of research coordinated by the Advisory Committee on Artificial Limbs involves the participation of government, university, and industrial laboratories. The Veterans Administration, the Army, and the Navy provide the necessary funds for the operation of their own establishments, while the VA provides the contractual authority with the funds necessary for work in the universities and in industrial laboratories. Out of this cooperative effort there have come within recent years improved functional prostheses for almost every level of amputation, particularly for those special amputee cases heretofore considered unsuited for an artificial limb. With the mutual cooperation of surgeon and engineer, there has resulted a cross-fertilization of ideas and a new set of modalities in the rehabilitation of amputees.

Nevertheless, the presently available devices, though anthropomorphoid in form, are far from anthropomorphoid in function. Unfortunately, no artificial limb, however elaborate, can ever serve as an ideal substitute for a natural member unless it incorporates some of the features of sensory and muscular control characteristic of the limb it replaces. Therein lies the challenge of the future—to devise mechanisms which not only simulate the motions and the functions of normal limbs but which also provide appropriate feedback of information such as occurs in natural arms and legs. In our present state of knowledge, the ultimate goal of the limb designer is still a long way off. Further progress depends largely upon the continued cooperation of surgeon and engineer, of prosthetist and therapist, and of the amputee himself.

Prosthetics Research and the Amputation Surgeon

RUFUS H. ALLDREDGE, M.D.,[1] AND
EUGENE F. MURPHY, Ph.D.[2]

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 vest-like 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, limb-fitters, 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 limb-fitters, who were notably successful in fitting good stumps at these "sites of election" but

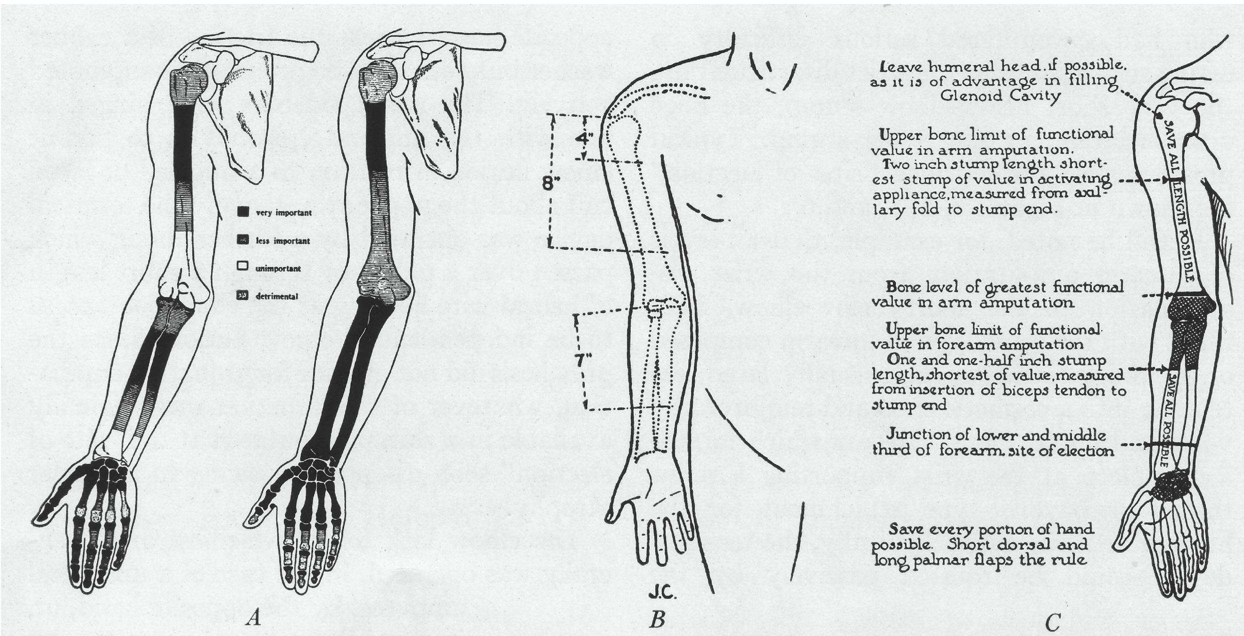

Fig. 1. Typical "sites of election" for amputation in the upper extremity, from well-known texts, by permission of the respective publishers. In general the sites became progressively less restricted. *A,* **Recommendations of zur Verth** *(100),* **as reproduced by Vasconcelos** *(94)* **reporting to 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.**

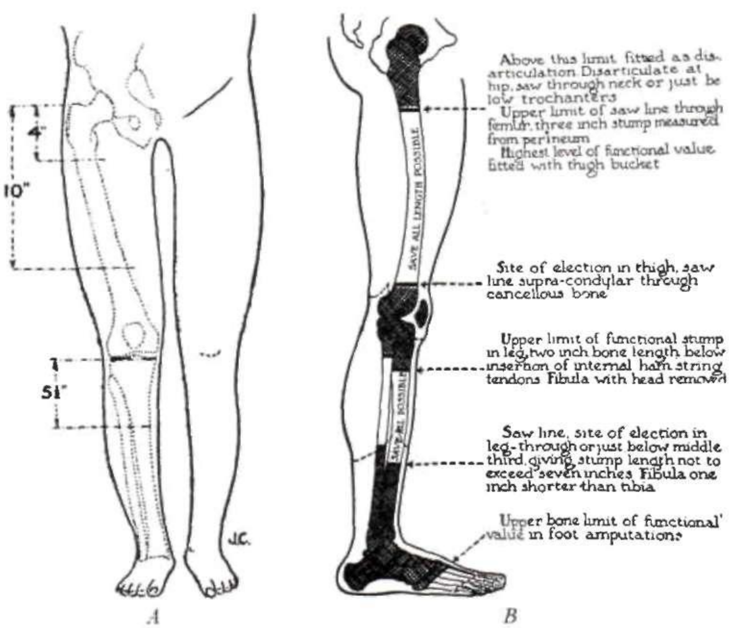

Fig. 2. Typical "sites of election" for amputation in the lower extremity, from well-known texts, by permission of the respective publishers. *A,* **Recommendations of Langdale-Kelham and Perkins** *(45).* **These authors condemn the Syme.** *B,* **Recommendations of Kirk** *(44).* **Although Kirk does 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.

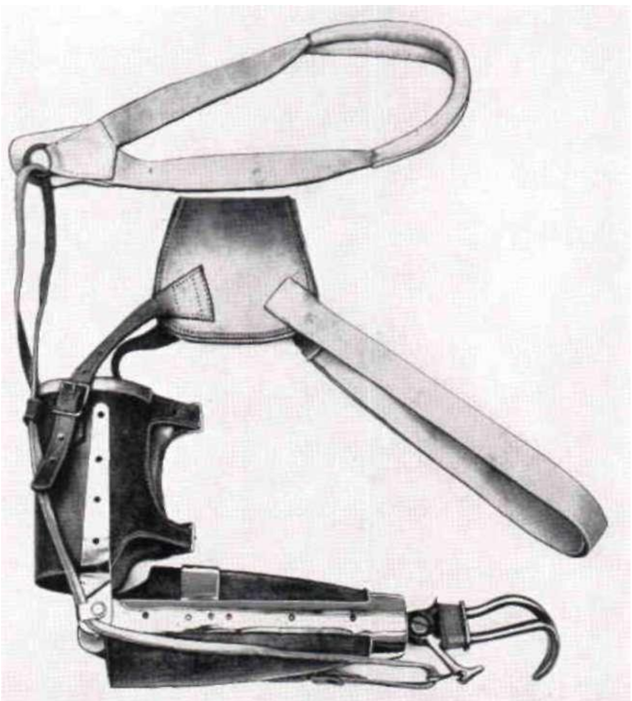

Fig. 3. Typical prosthesis for amputation below the elbow, made about 1945-47. Note modled leather socket, steel sidebars and single-axis joints permitting elbow flexion only, full upper-arm cuff with two straps, heavy leather shoulder saddle and webbing cheststrap, and double leather thong passing over 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

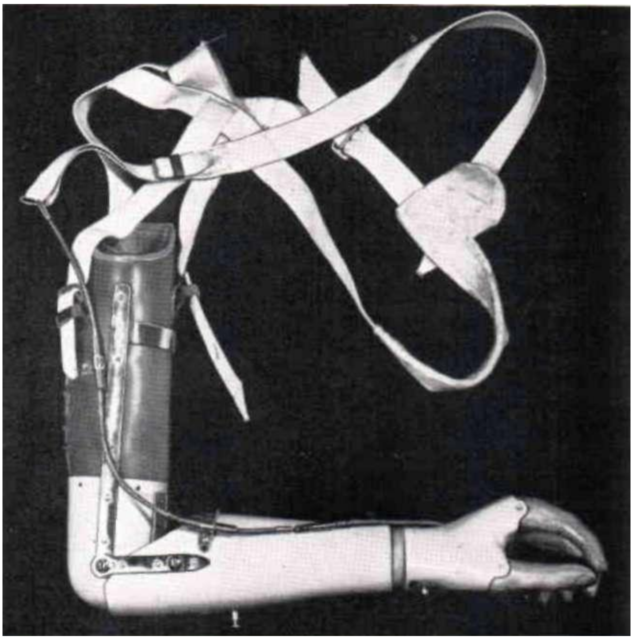

Fig. 4. Conventional prosthesis for amputation above the elbow, made about 1945-47. Note the molded leather socket (with the unusual rear opening and laces), wooden elbow shell and forearm, and push button projecting from lower surface of forearm to control elbow locking by pressure on table top through 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

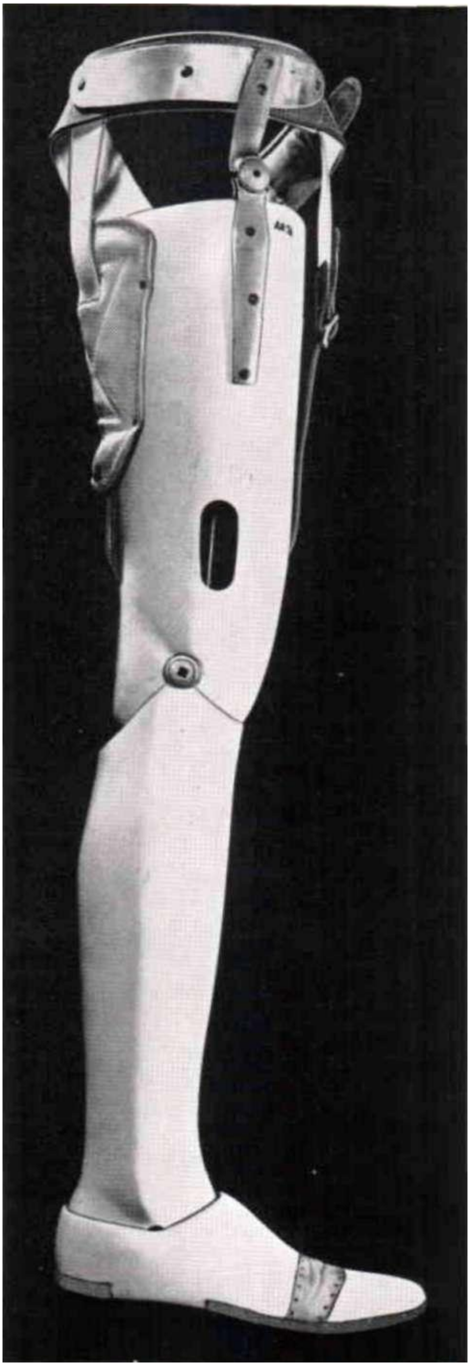

Fig. 6. Conventional wooden prosthesis for amputation above the knee, made about 1947. Note reinforced pelvic band and single-axis hip, knee, and ankle joints. Elastic straps from front and rear of pelvic band are joined by a leather strap passing under a roller ahead of the knee bolt so as to extend 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

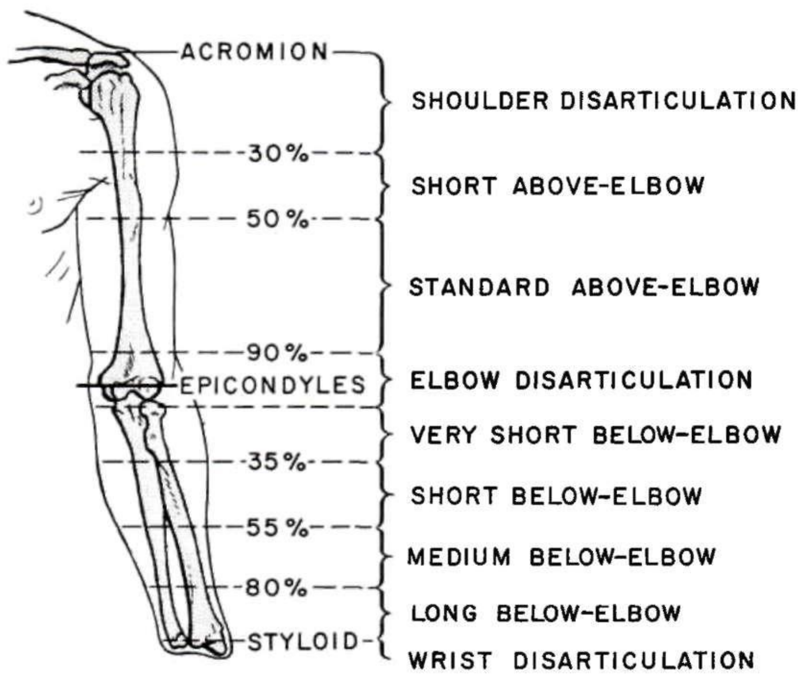

Fig. 7. Definitions of upper-extremity amputee types. Lengths above elbow are measured as percentages of distance from acromion to epicondyles; lengths below elbow are measured as percentages of distance from epicondyles to styloid. From *Manual of Upper Extremity Prosthetics {91).*

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

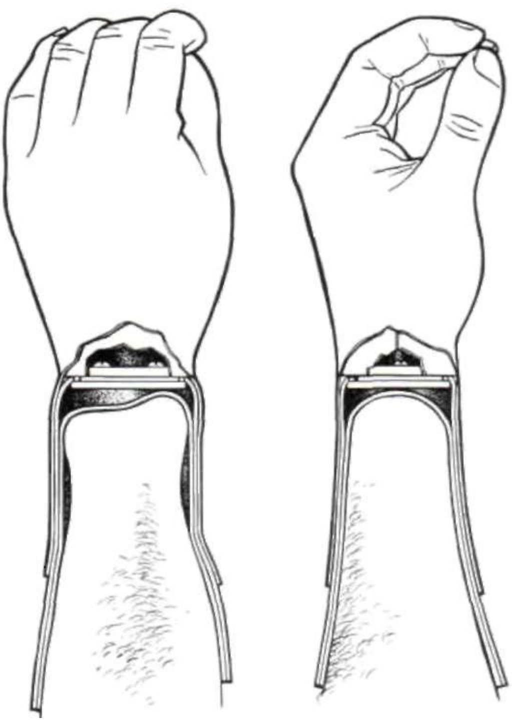

Fig. 8. Cutaway views of light and simple plastic prosthesis for wrist disarticulation, with APRL hand attached to plate embedded in end of forearm to conserve length. The plastic cosmetic glove drapes neatly over the junction. A separate socket similarly attached to a hook (as in Figure 9) is easily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

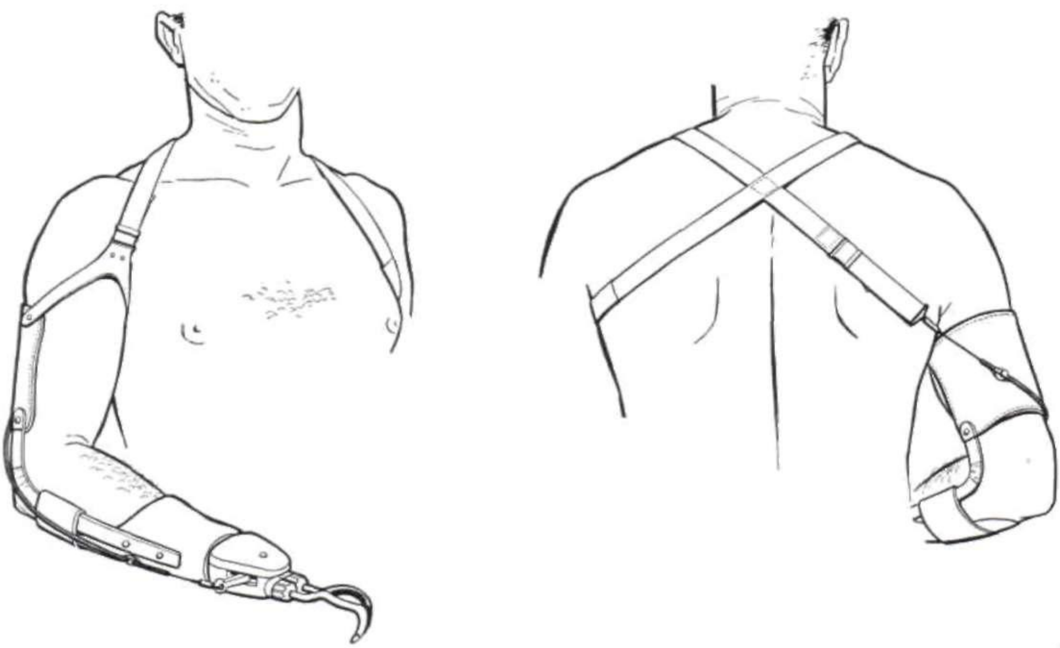

Fig. 9. Prosthesis and harness for wrist disarticulation or long below-elbow stump. Note simple figure-eight webbing entirely across back, with no cheststraps. A steel Bowden cable transmits energy to the hook with improved efficiency. An open upper-arm harness, consisting of triceps pad and inverted 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

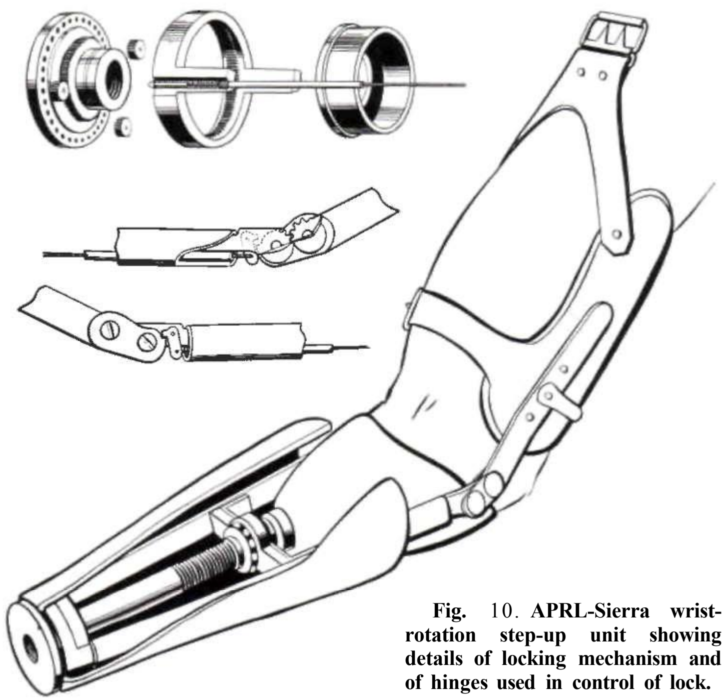

Fig. 10. APRL-Sierra wrist-rotation step-up unit showing details of locking mechanism and of hinges used in control of lock.

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

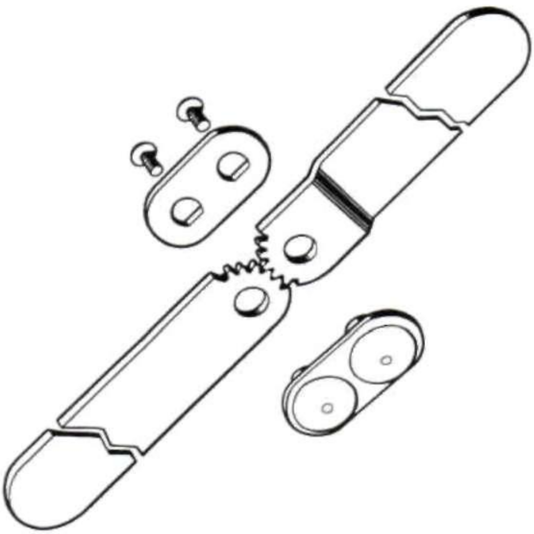

Fig. 11. Hosmer PC-100 polycentric hinge, particularly suited for medium to short below-elbow stumps. By virtue of the mechanical linkage, it sometimes aids in permitting extreme flexion in cases where the stump retains a full range of motion so that step-up hinges are unnecessary.

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.

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-

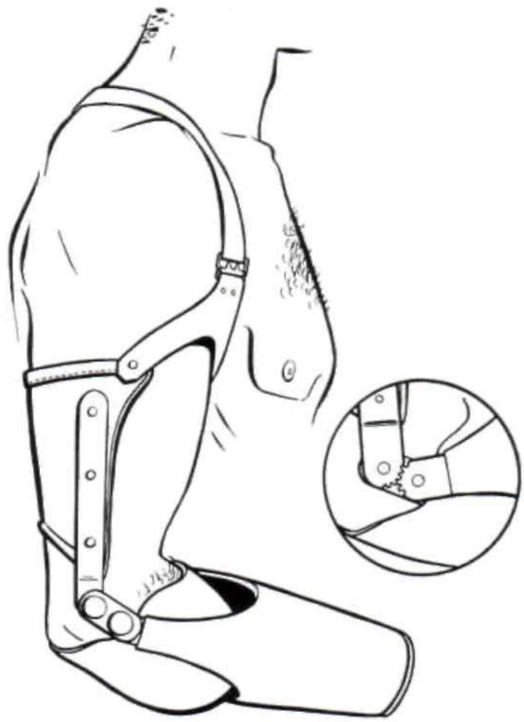

Fig. 12. Geared step-up hinge (Hosmer MA-100) for very short below-elbow stumps of limited range of motion. The stump socket is fastened to the center link connecting the two geared links, which in turn are fastened to the upper-arm cuff and the forearm shell. The ratio of flexion of the forearm shell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

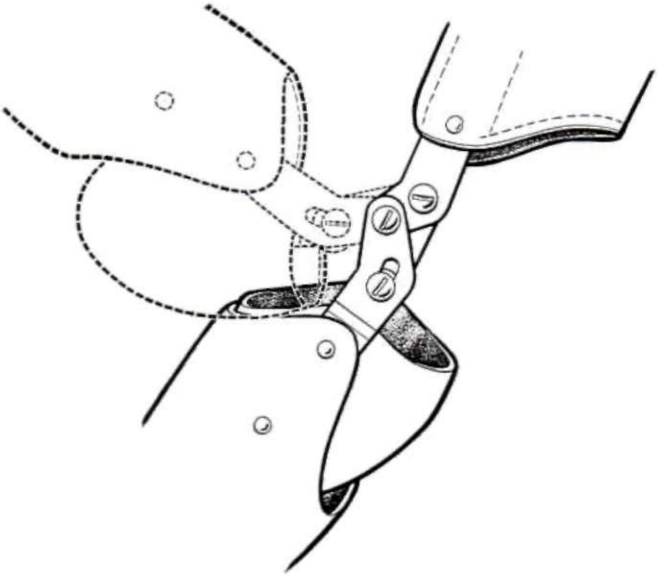

Fig. 13. Hosmer variable-ratio step-up hinge for very short below-elbow stumps. Here, unlike the case with the geared hinge of fixed ratio (Fig. 12), the sliding lever system provides a changing ratio of stump action to forearm action as flexion increases, the change in any given design depending upon 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

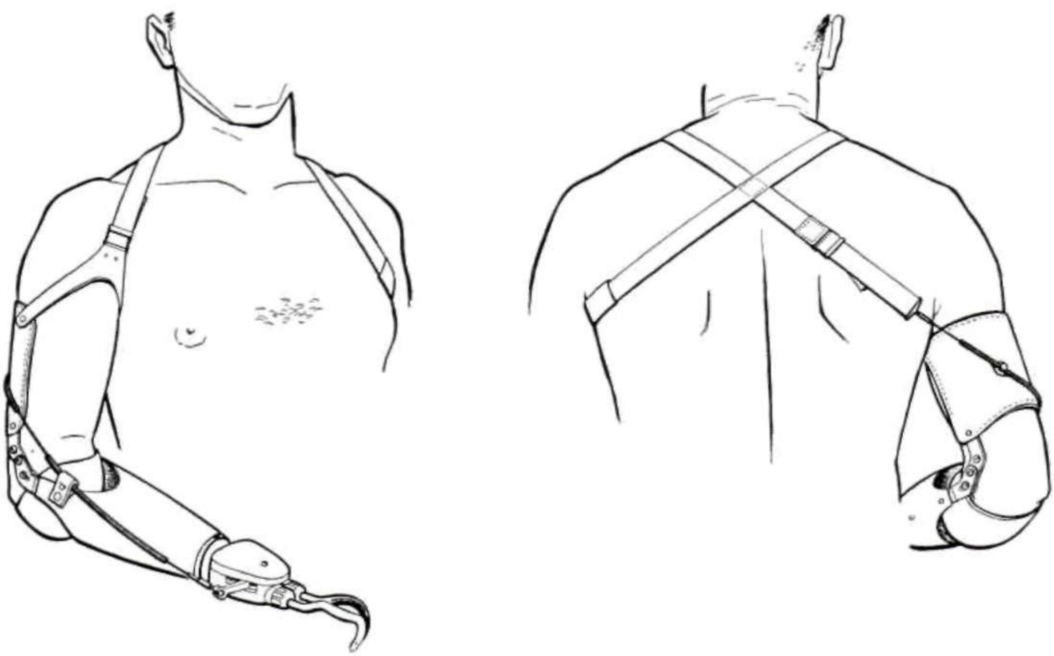

Fig. 14. Prosthesis with variable-ratio step-up hinges for short below-elbow stumps. An above-elbow type of cable control assists in flexing the forearm shell.

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.

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

[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.**

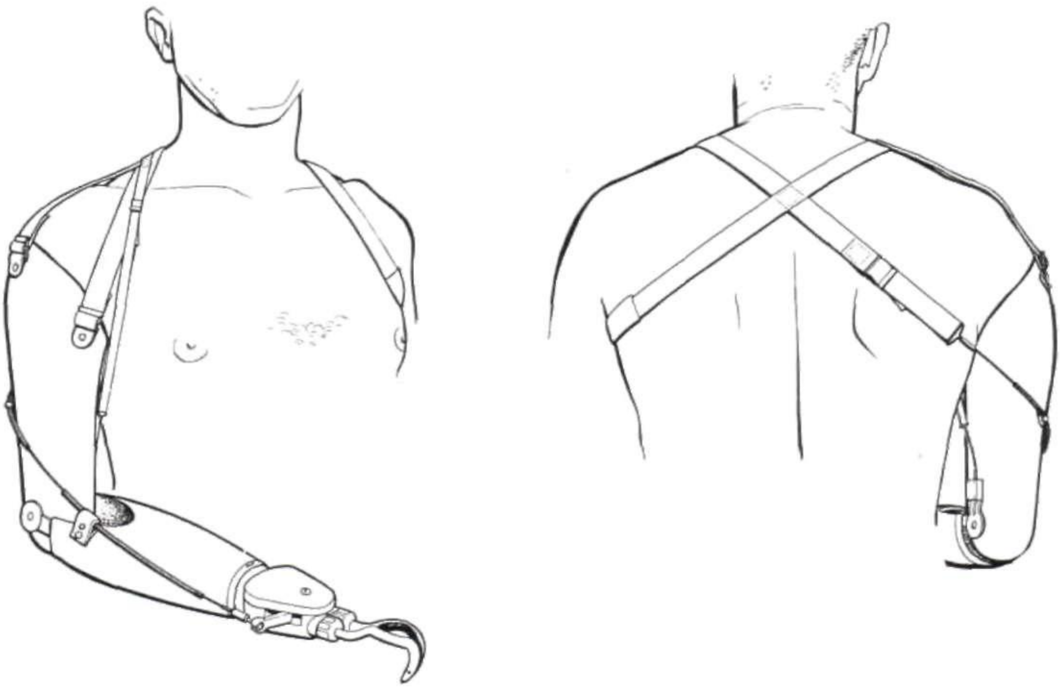

Fig. 15. Prosthesis for elbow disarticulation, with APRL-Sierra external elbow lock (Fig. 16) and same dual control as used on above-elbow prostheses. To accommodate bulbous humeral condyles, a channel may be left in the socket, a lacer may be used, or a slotted, flexible, plastic-laminate socket and 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

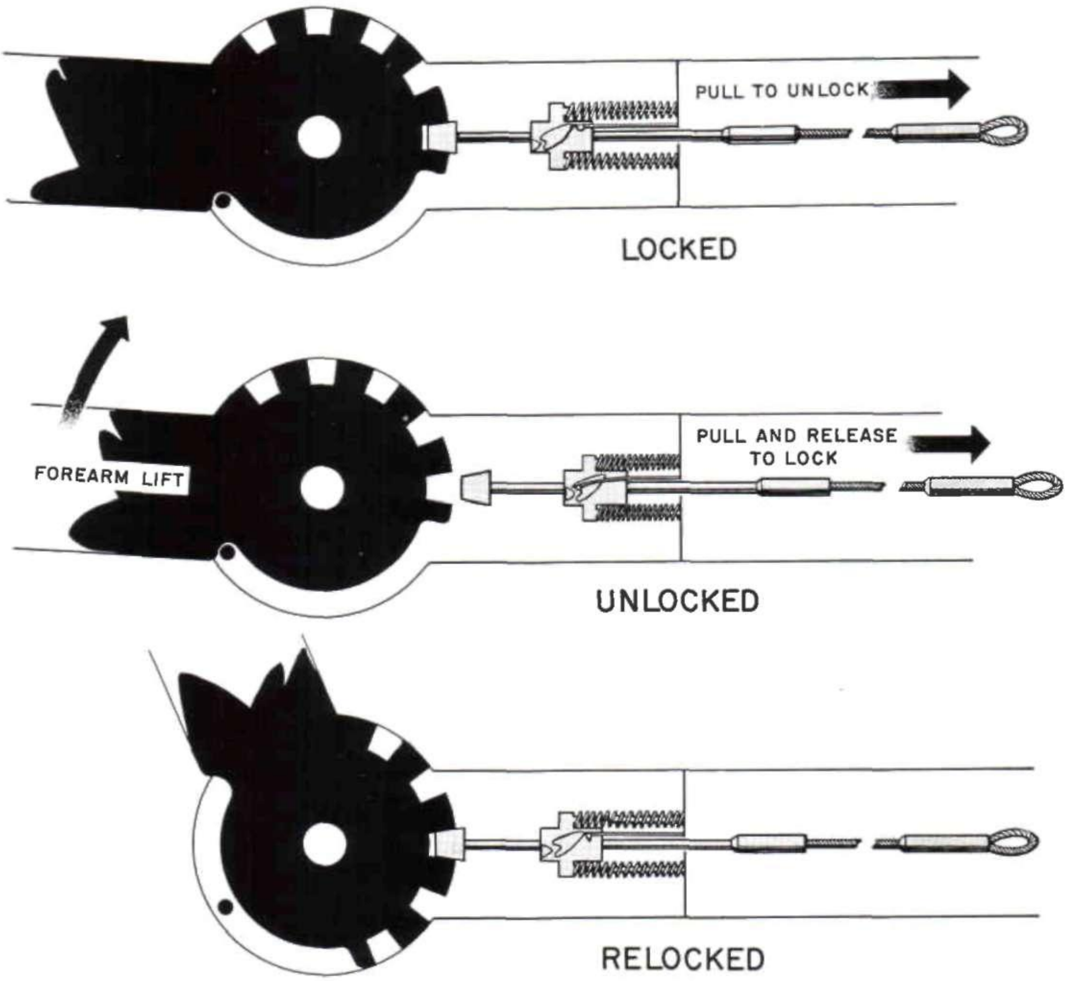

Fig. 16. Schematic diagram of APRL-Sierra external elbow lock, intended for elbow disarticulation but also useful with very short below-elbow stumps or with paralyzed arms. Top, locked position. Next pull on lock-operating cable in upper right withdraws locking plunger from the wedge-shaped notch in 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).

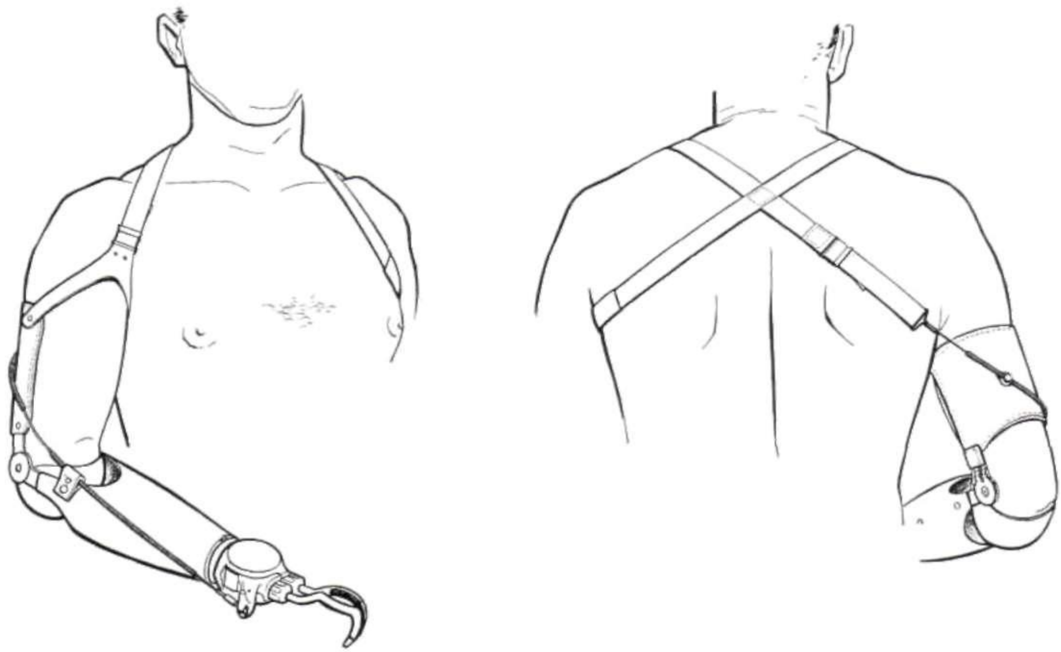

Fig. 17. Prosthesis for very short below-elbow stumps of such limited motion that step-up hinges are inadequate. The external elbow lock is controlled by a convenient cam, lever, or cable system triggered by the limited stump motion, and the forearm shell is flexed by an above-elbow type of harness. 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

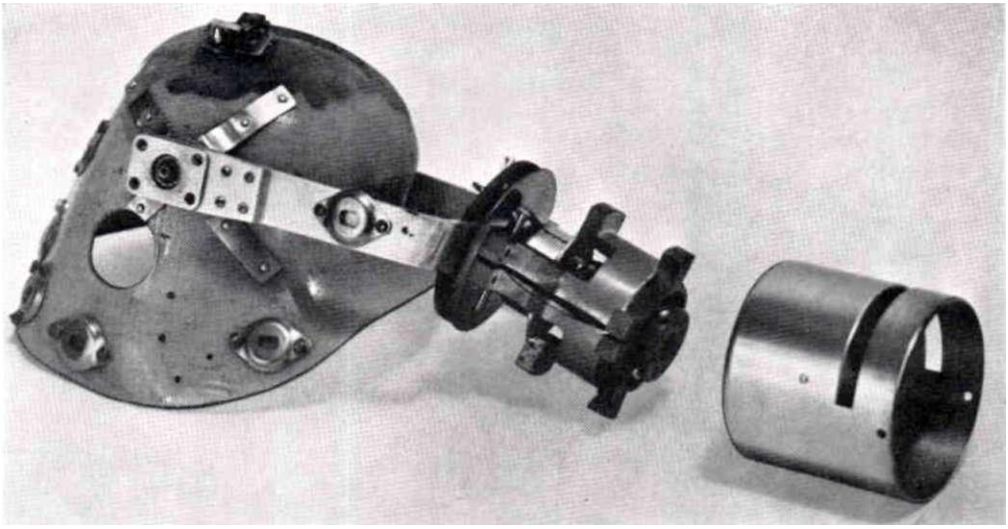

Fig. 18. Shoulder cap for electric control by shoulder motion or by short humeral stump or both. From Alderson *(2)*.

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

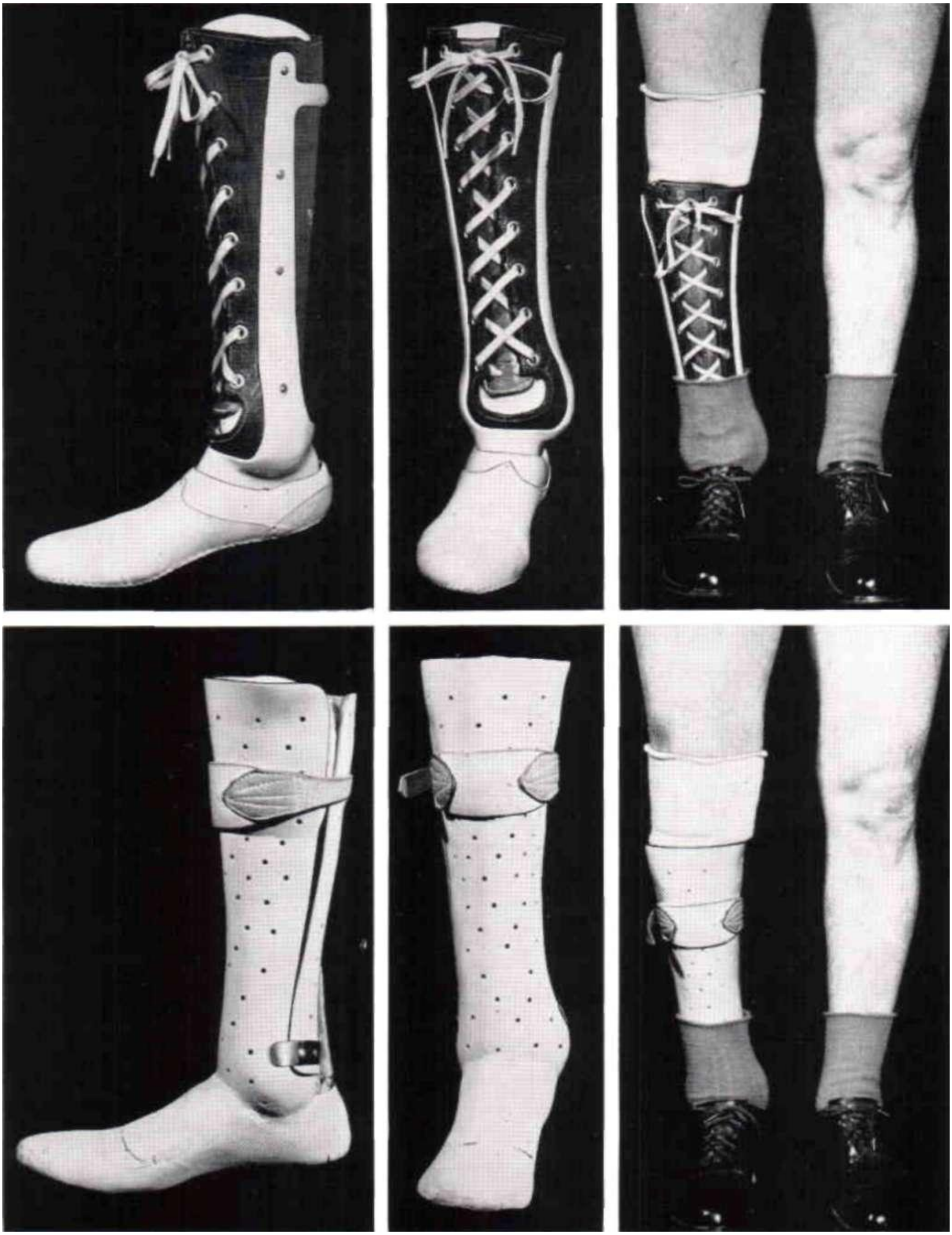

Fig 1,9 Piosthescs for S\ me's amputation. Above, conventional S\ me prosthesis with typical bulk> and unattractive design at ankle and with bothersome shank lacer. Below, Syme prosthesis developed b\ the Canadians ',?/). Same slum]) in the two cases. Note improved (osmetic appearance and simplified 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.*

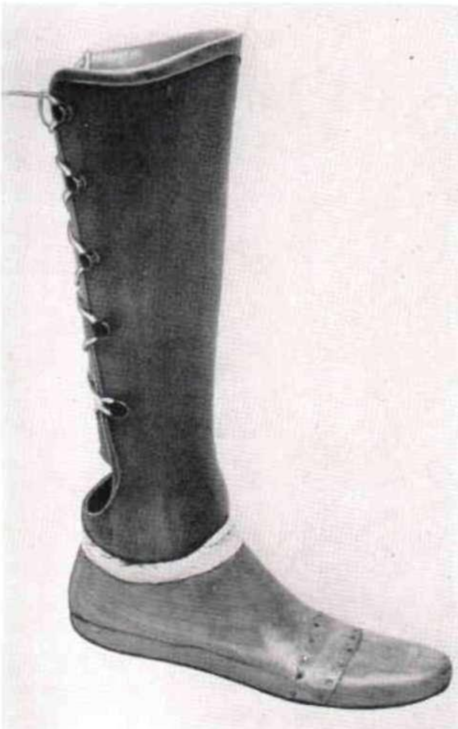

Fig. 20. Experimental Syme prosthesis designed and tested at the VA's Prosthetic Testing and Development Laboratory on request of the Orthopedic and Prosthetic Appliance Clinic Team, New York. It combines a molded plastic-laminate shell with rear opening, thin sponge-rubber lining, and an adaptation 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

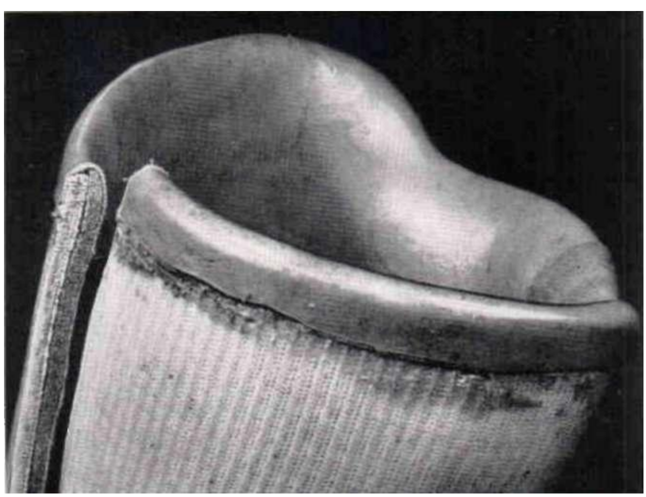

Fig. 21. U.S. Navy "soft" socket for below-knee amputation, cut to show plastic sheet lining rolled over brim, thin ('^-inch) sponge-rubber lining, and flexible plastic-laminate outer shell, all formed over male plaster model of the stump. *Courtesy Prosthetic Testing and Development Laboratory, U.S.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

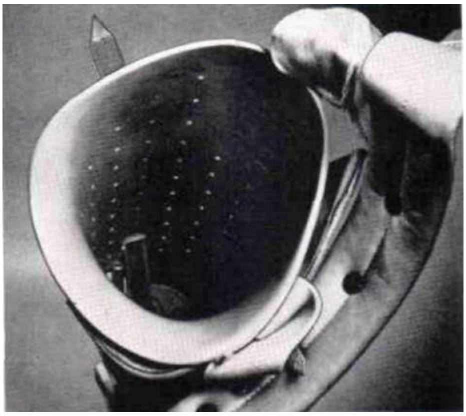

Fig. 23. Conventional socket for "plug" fit of above-knee stumps, showing rounded, triangular top portion of prosthesis for right thigh (looking forward and laterally). Note shelving flare below gluteal crease and ischium and broad, horizontal flare through perineum and adductor region. A considerable 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

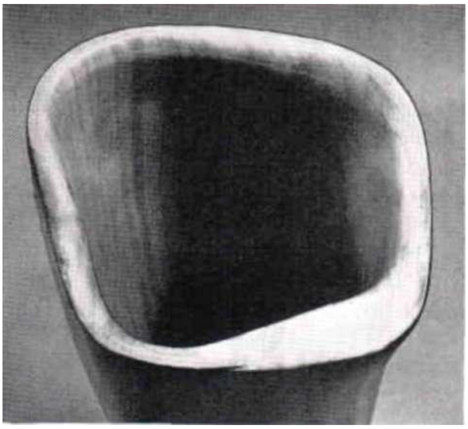

Fig. 24. Substantially rectangular or quadrilateral plan of top of socket for left above-knee prosthesis (seen from the rear), typically used for the suction socket but also applicable with soft belt or mechanical hip joint and pelvic band. Note the definite but narrow ischial support, slightly sloping 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.*

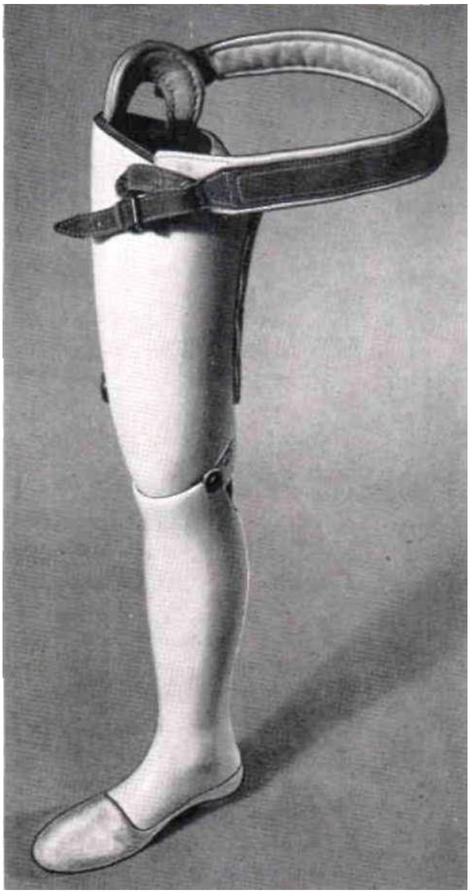

Fig. 25. Model of German suction-socket prosthesis with Silesian bandage, or trochanteric belt, with padded horseshoe encircling the trochanter, soft leather belt posteriorly around the pelvis, and V-shaped strap from anterior of socket through ring of the belt. The pelvic belt aims to assure vertical 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.

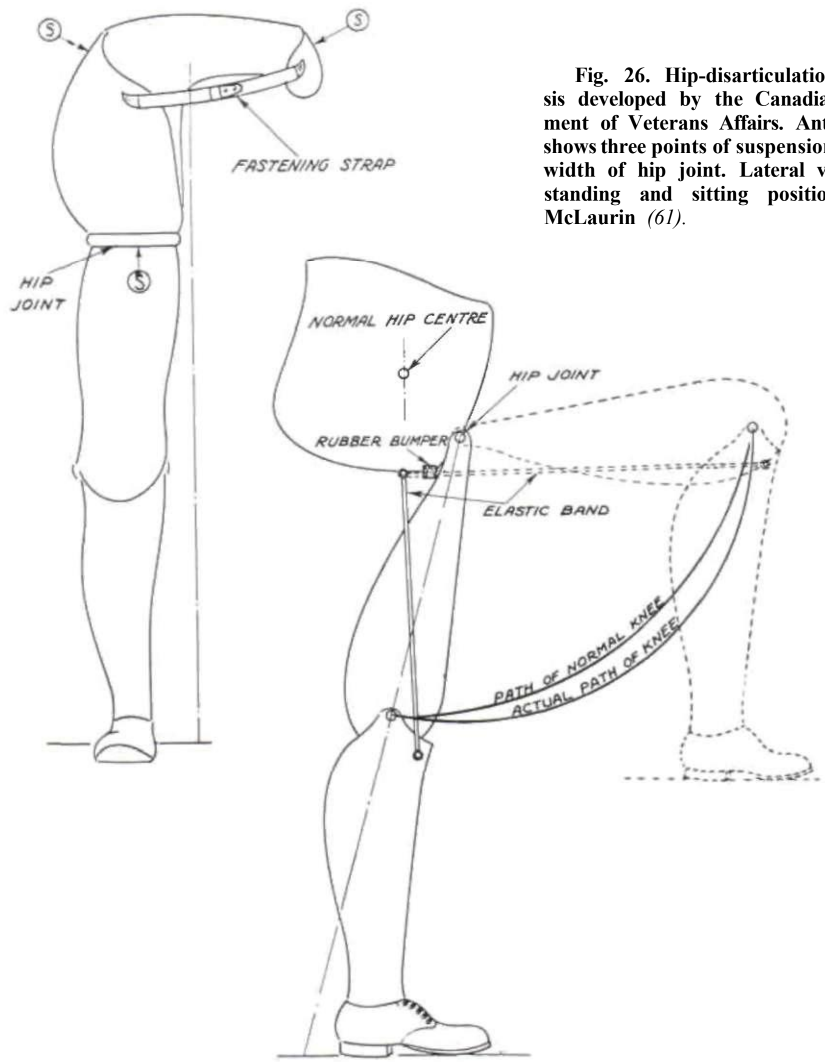

Fig. 26. Hip-disarticulation prosthesis developed by the Canadian Department of Veterans Affairs. Anterior view-shows three points of suspension© and full width of hip joint. Lateral view shows standing and sitting positions. From McLaurin *(61).*

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

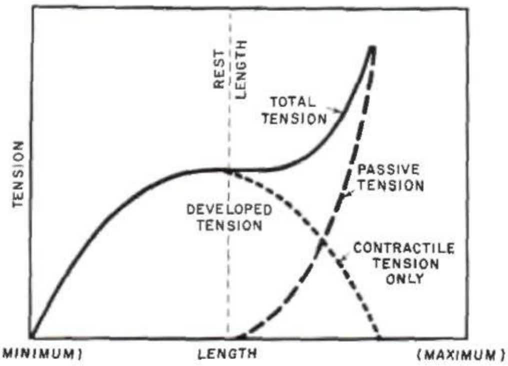

Fig. 27. Idealized length-tension curves for a typical muscle. Note that the passive-tension curve rises sharply when the relaxed muscle is stretched beyond rest length and that maximum voluntary force with isometric contraction is available at or near rest length. Clearly, use of a muscle in a contracted 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

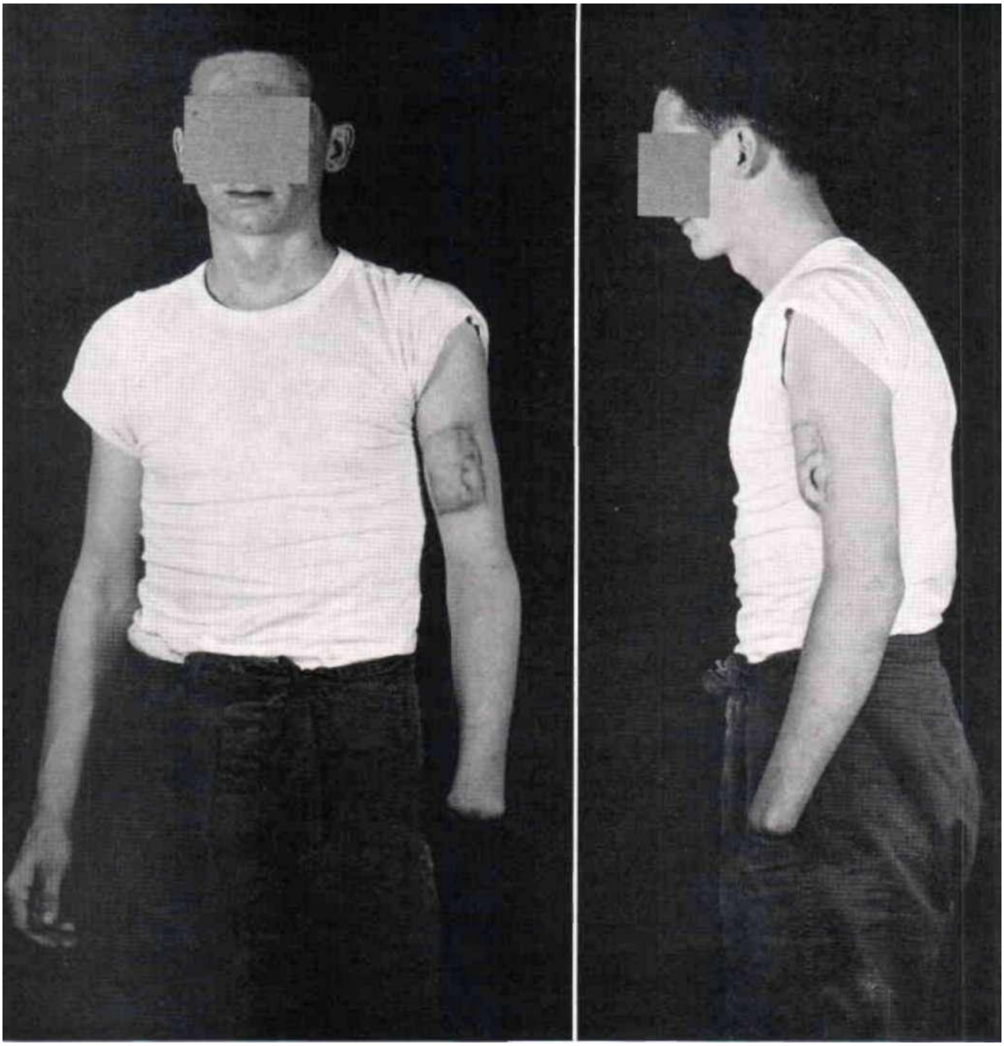

Fig. 28. **Typical biceps muscle tunnel in below-elbow case, six months postoperative.** *Courtesy Army Prosthetics Research Laboratory.*

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"!

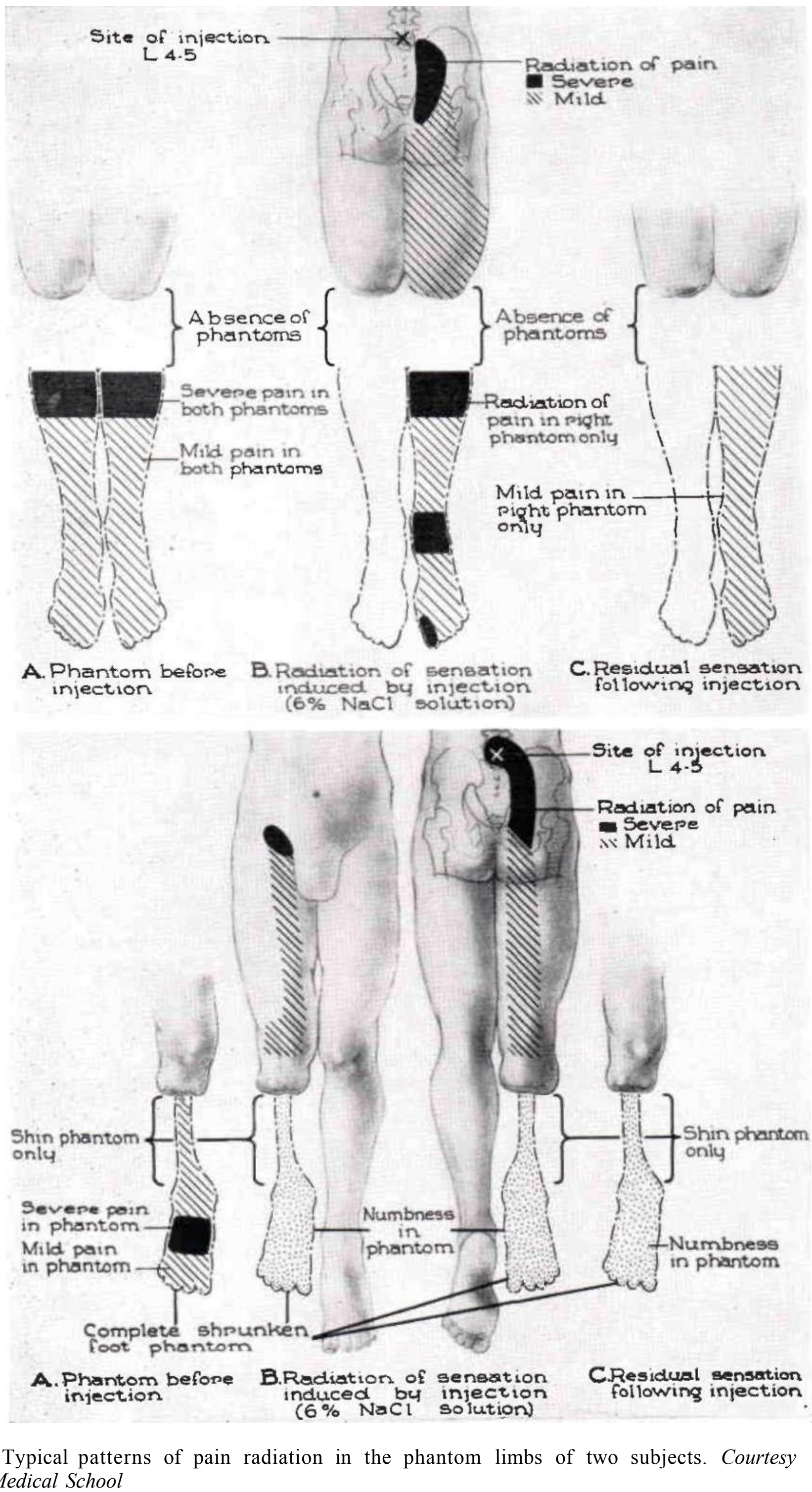

Fig. 29 Typical patterns of pain radiation in the phantom limbs of two subjects. *Courtesy University of California Medical School*

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.

ACKNOWLEDGMENTS

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Prosthetics Research and the Engineering Profession

RENATO CONTINI, B.S.M.E.[1]

IN the establishment of any program in prosthetics,[2] whether it be a program devoted to research on and development of new and improved devices, or whether it be a program for the dissemination of knowledge in the application of these devices, guidance must come primarily from the medical sciences. In any such program, one can appreciate the role of the physician, either the surgeon involved in the amputation or the physiatrist concerned with the physical rehabilitation of the patient. To a lesser extent perhaps, the role of the physical and occupational therapist, in implementation of the prescription established by the physician for medical rehabilitation or re-education, also is generally appreciated.

Since there can be no prostheses without a limbmaker, the role of the prosthetist cannot be underestimated. Certain attempts at the fabrication of artificial limbs may be traced back to the time of the Roman Empire. Several ingenious devices made during the sixteenth century (Figs. 1 and 2) still are in existence. The major impetus, however, was received as a result of the Napoleonic Wars, of the War between the States, and of the Franco-Prussian War. Improvements in medical practice had by then made it possible to save a much larger number of men who had lost limbs than had been possible earlier. There thus developed a well-defined craft which reached its peak during World Wars I and II and which established with the medical profession a working relationship directed toward the fabrication of acceptable prosthetic devices.

To the efforts of these three professional groups—medicine, therapy, and limbmaking—there have been added in more recent rehabilitation programs the efforts of the social worker, of the psychologist, of the psychiatrist, and of the counselor in vocational guidance, the over-all purpose being to return the amputee to a more successful and better-adjusted position in society. The organization and functions of a modern prosthetics clinic team, as most usually accepted, have been fully and ably described by Bechtol *(6).*

Important as is the role of each of these disciplines, the progress that has been made

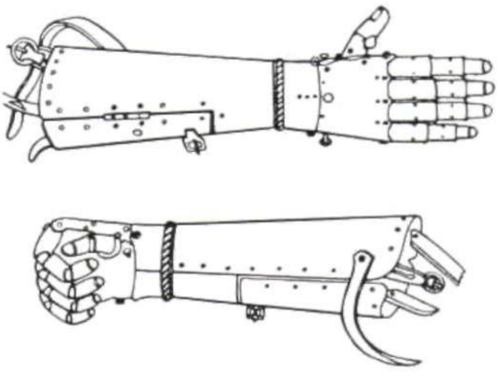

Fig. 1. Iron hand of Goetz von Berlichingen, A.D. 1509. From Faries *(23),* by permission. See also Thomas and Haddan (55).

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[2] **A prosthetic device may be defined as one which attempts to restore, in function or appearance or both, any portion of the external human anatomical structure that has been impaired or removed owing to injury or to some degenerative process. In the broadest sense, therefore, artificial eyes and false teeth, as well as braces and artificial limbs, are prostheses. In the more commonly accepted sense, however, prosthetic devices usually refer to artificial arms and legs. The present discussion is concerned with the role engineering must take in the development, fabrication, and application of artificial limbs.**

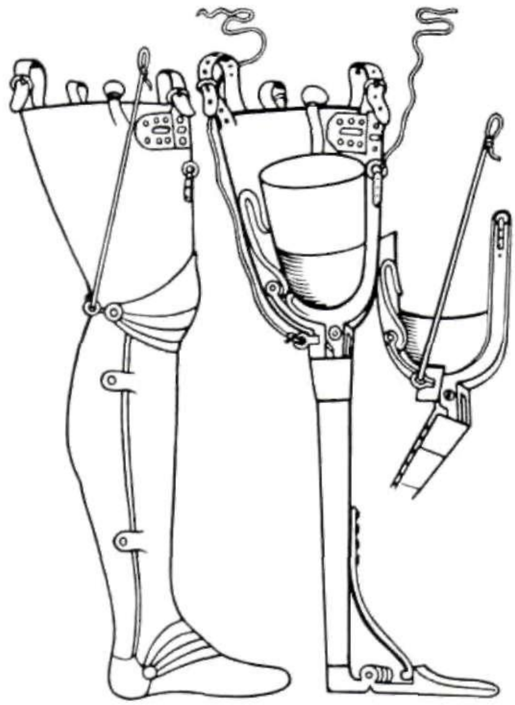

Fig. 2. Leg of Ambroise Pare, A.D. 1561. From Faries *(23),* **by permission.**

in prosthetics in recent years may be attributed, in large measure, to the interest the problem has aroused in a substantial number of engineers. The role of engineering in a prosthetics program is not as yet well understood or fully appreciated by the general public. We speak of the role of engineering, rather than of the role of the engineer, because we are concerned more with the application of certain basic physical principles than with the particular individual who applies them. When these principles are well understood and applied by the physician, therapist, or prosthetist, each will function better in his own role. Unfortunately, in our present system of education no provision is made for imparting the basic principles of engineering in courses of instruction for any of these other disciplines. As a consequence, until recently such advances as were made in prosthetic devices came about primarily as a result of much trial and error rather than as the outcome of a planned approach.

Any program directed to the development of new prosthetic devices may be divided into three major stages. The first is concerned with basic research. Second is the translation of knowledge gained in the basic research stage into a specific design for a particular device. And third is the application of the device to the amputee and the evaluation of functional gain. But of course a program does not necessarily proceed in such an orderly fashion. Before a device is finally accepted for general application, it may be necessary, and in fact it often is, to retrace the sequence not once but many times in order to gain additional information and understanding. We shall consider later the role of engineering in each of these stages.

THE BACKGROUND

Man performs activities in a variety of ways controlled by physical law. The manner in which he does so has thus interested scientists since the time of Leonardo da Vinci (1452-1519), who made the first systematic study of human movements and described them in his *Note on the Human Body (37).* In 1679-1680, Borelli *(10),* a pupil of Galileo, published *De Motu Animalium,* the first treatise which applied the sciences of physics and mathematics to human and animal activity. The mathematicians and physicists of the eighteenth century—Bernoulli, Euler, and Coulomb—tried to develop rational mathematical formulae for determination of the capacity of human work.

The number of investigators increased greatly in the nineteenth and early twentieth centuries, and the two World Wars gave still greater impetus to research in the general field of human locomotion and activity. In Germany, France, England, Russia, and the United States, with different objectives perhaps but directed toward the same general problems, Fischer *(25),* Fick *(24),* Gilbreth *(30),* Amar *(4,5),* Martin *(40),* Schlesinger *(50),* Schede *(49),* Bernshtein (<?), Steindler *(51),* Elftman *(20,21,22),* Henschke and Mauch *(32),* and the groups at the University of California *(56)* and at New York University *(42)* have studied human performance. Each, individually or as groups, contributed to the increasing

knowledge both in the general areas of human activity and in the specific application of this knowledge to prosthetics.

From the time of Leonardo, almost every investigator in this field either was primarily a physical scientist, or, if not, had a very intimate knowledge of physics and mathematics. In the later period particularly, the major contributors to the increasing knowledge of human performance have been engineers, physical scientists, or anatomists and physiologists with training in the physical sciences. A more comprehensive review of the investigators in this field is that of Contini and Drillis *(14).*

BASIC RESEARCH IN HUMAN MOTIONS

In the design of any structure or mechanism, for whatever purpose, the engineer usually proceeds from a set of established specifications. These specifications may describe the function of the device, the space it may occupy, the activity it must perform, the forces which may be applied to it and which it must withstand, the chemical and physical damage to which it may be subjected, the working life expected of it, how often it should be overhauled or maintained, and what it may cost. To design a prosthetic device properly, similar specifications should be prepared. Some of the requirements for a satisfactory prosthesis may be developed from known data, that is, from information obtained empirically over extended periods of time and from the experience of countless amputees. Other information, however, and perhaps the more important in the design of prostheses, can come only after systematic experimentation. To supply this information, then, is the purpose of the program in basic research.

Every human movement takes place in time and space and is controlled by external and internal forces and by the mass of the parts involved. The internal forces are generated in the muscles and transmitted through the limbs to tools, controls, instruments, or other objects. The external forces are those of gravity, inertia, ground reaction, and air resistance. When the body is at rest, the external and internal forces are in equilibrium; when it is in motion, the resultant of these forces has some value other than zero.

Of course human movements may be observed and the pattern of movement described subjectively. But unless these movements can be recorded and measured precisely, no true understanding of the movement can be had, nor can repeated movements be compared objectively in the same individual or between different individuals. As technology has moved ahead, engineering knowledge has made it possible to develop instruments and techniques for recording and measuring movements and the forces which affect these movements. Although it would be interesting, as an historical aside, to review the methods used by earlier investigators, it is more profitable to describe some of the recent developments.

METHODS OF MEASUREMENT

The invention of photography in the middle of the nineteenth century, and the subsequent improvements in photographic techniques, have made it possible to record motions and displacements exactly (Fig. 3). The development of motion-picture photography, of interrupted-light photographic techniques, and of a combination of the two as obtained in the gliding cyclogram has made it possible to measure not only displacement but also the rate and change in rate at which movements occur. By these techniques, then, we can obtain displacement, velocity, and acceleration. Once these quantities are known, and when the mass of the total moving body or of its segments can be obtained by other measures, the forces acting on the body, the energy costs, and the power requirements can all be computed.

Motion-Picture Photography

Of the photographic techniques mentioned, motion-picture photography is used perhaps most universally. By mechanical or electromechanical means, a light-sensitive film is transported at a known, fixed rate past a lens and shutter. The film-transport mechanism is synchronized with the shutter so that a picture is taken each time the film is advanced one frame. The speed at which pictures are taken may be varied between sequences to suit the particular need, and the shutter speed may be varied to stop the action down to the smallest

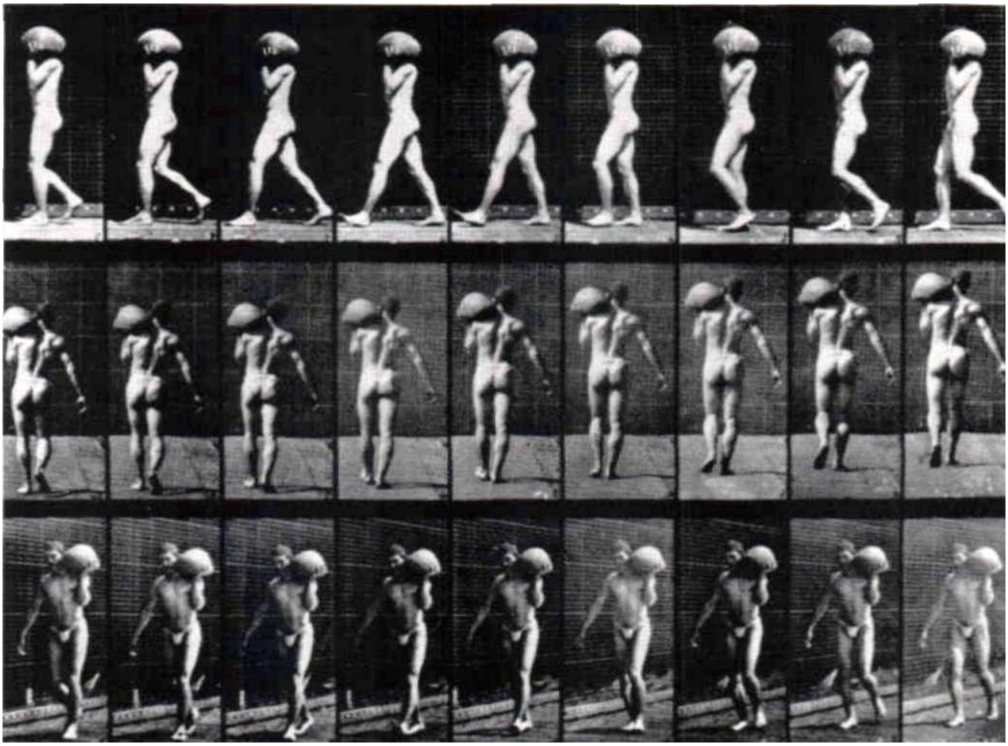

Fig. 3. Walking with 75-lb. load. Subject photographed synchronously from three points of view. Time intervals: 0.075 sec. From Muybridge *(41)*

fraction of time consistent with the particular apparatus and with the object being photographed.

With conventional motion-picture equipment, frequencies of up to 128 frames per second have been photographed, action being stopped down to the order of one five-hundredth of a second. Within these limits most human activities may be photographed adequately. A timing device—in effect a large clock, driven by a synchronous motor, and with the dial subdivided into hundredths of a second—permits measurement of the variability in time between frames and in exposure time (Fig. 4). Sometimes x-ray and motion-picture photography have been combined. By this means it is possible not only to record the motion of a limb but also to observe any relative motion between the activating skeletal structure and the external surfaces.

Although this method of motion recording has been used extensively, and even though it may be quite adequate for some measurements, it has certain disadvantages which detract from its general usefulness. In the reduction of data, for example, each frame must be registered in two of the three major coordinate axes, some point being maintained as a control. The location of each moving segment must be determined from a constant frame of reference, a matter which introduces possible sources for error. And it has been found that the transport mechanism does not always respond at the same rate, so that the interval of time between frames, on which the computations depend, may not always be constant.

Interrupted-Light Photography

When the activity to be recorded is not a repetitive one, as in jumping, or is repetitive but progresses along a linear axis, as is the case with the walking pattern of a leg amputee, interrupted-light photography can be used. In this system the film is stationary in the camera. The lens shutter is kept open, while a slotted disc, driven at the desired speed by a synchronous motor through a gear or pulley system, rotates before the shutter in such a way as to admit and exclude light alternately. The speed at which the disc rotates and the number of slits in the disc together determine the time increment between exposures. The width of the slit (that is, the size of the angle included in the slit) and the rotation speed of the disc determine the time of exposure. In the studies conducted at New York University in conjunction with the Veterans Administration's Prosthetic Testing and Development Laboratory, the disc rotates 20 revolutions per second and the slit is 14 degrees wide, so that the exposure time is of the order of one five-hundredth of a second and each revolution results in one exposure (Fig. 5). These conditions are optimum for the particular application, but they can be modified for other applications. In the system developed by the Prosthetic Devices Study, Research Division, New York University, working with the VA's PTDL, the light is supplied by a single photoflood bulb and is returned by reflective tape, such as *Scotch-lite,* which marks the points to be photographed. Similar results might be achieved with an open lens and a strobe-flash source of light.

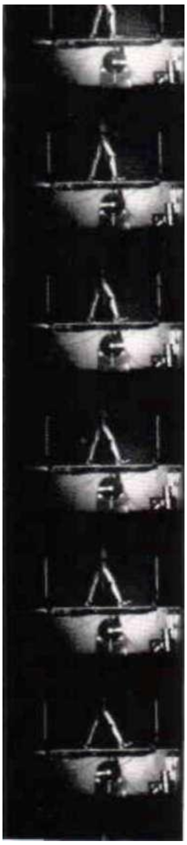

Fig. 4. Typical motion picture of walking. *Courtesy Prosthetic Devices Study, New York University.*

The obvious advantage of this system is that it provides a complete pattern of a total movement, such as the forward progression of an amputee for two or three strides, all of which may be recorded on one film. Reduction of data is greatly simplified, since the measures of vertical and horizontal displacement are taken directly from a single set of axes. The error then is only that which the operator may make in measuring. The time increment is as constant as permitted by the variation in speed of a synchronous motor.

The Gliding Cyclogram

When the motion to be recorded is repetitive in limited space, the interrupted-light method cannot readily be employed, for the pattern of points cannot then be distinguished as to occurrence in time. To overcome this difficulty, Bernshtein *(7)* in Russia and Drillis *(15)* in Latvia developed the gliding cyclogram. This method is similar to that previously described except that here the film is transported across the field at a constant rate but at one that may be varied to suit the particular activity being recorded. Under these circumstances, the position of any point can be identified both in space and time. Even if, in a repetitive motion, a point on a moving segment is returned to an original position, the image in the initial and succeeding instances will be displaced on the film by the distance the film has been transported in the elapsed time increment. If, for example, a point were moving in a circular path, its locus would appear on the film as a cycloid. Although this method increases the amount of work to be done in data reduction,[3] suitable graphic shortcuts reduce this work differential to a minimum. As will be apparent (Fig. 6), the gliding cyclogram has special advantages in recording the motion of arm activities, many of which are repetitive and overlapping.

The Tachograph

Although each of these methods permits the measurement of displacement, velocity, and acceleration, other methods of instrumentation

[3] **Since a constant value—the distance the film is transported in an increment of time—must always be subtracted from the measured horizontal displacement of a point.**

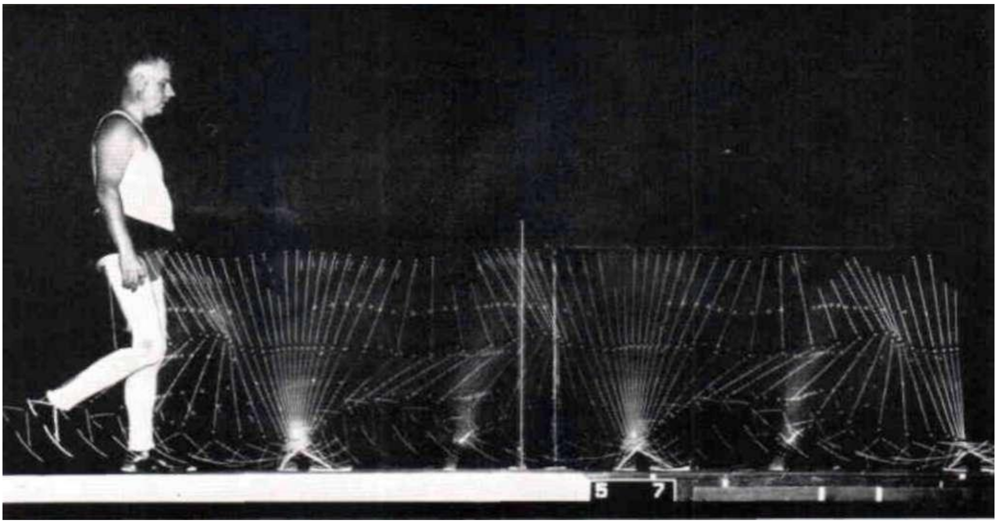

Fig. S. Typical stick diagram of walking. *Courtesy Prosthetic Devices Study, New York University.*

give direct measurement of velocity and acceleration in certain situations. Velocities along one axis may be measured with a tachograph, a device consisting of a fine cable connected to a moving body, continuing in a closed loop, and driving the rotor of a generator (Fig. 7). Since the voltage is proportional to the angular velocity of the rotor, which in turn is proportional to the velocity of the body, the voltage generated is a direct measure of the linear velocity.

The Accelerometer

Another electrodynamic device, the accelerometer, measures accelerations directly. Essentially, this instrument consists of a small, compact mass supported by a spring device. When the mass is suddenly accelerated, its inertia deflects the spring by an amount dependent upon the acceleration and the spring constant. By suitable means, such as by differential transformers, the deflection is converted into a change in voltage proportional to the displacement and thus proportional to the acceleration imparted to the accelerometer. More recently, accelerometers have been devised employing strain gauges (see below).

Direct-Recording Force-Measuring Devices

Displacement and velocity permit us to describe a motion; acceleration and mass permit us to compute the forces which affect the motions. Sometimes it is possible and desirable to measure forces directly. A number of such force-recording devices have been made possible by technological advancement in the past 20 years.

The Strain Gauge. The strain gauge, which has been used in innumerable applications, is such a device. Essentially, it consists of a

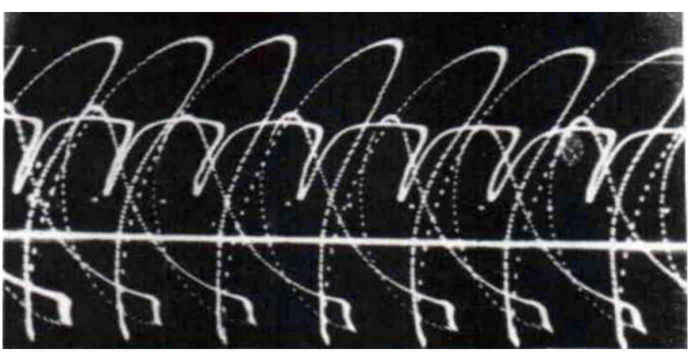

Fig. 6. Gliding cyclogram of the axe stroke in woodcutting. From Drillis *(16).*

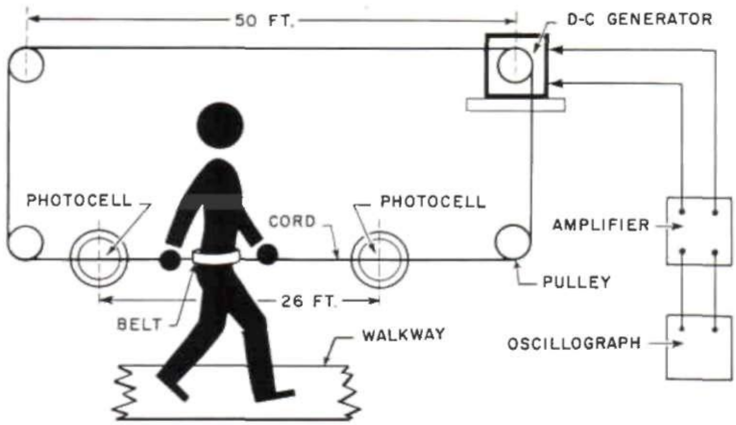

Fig. 7. The tachograph—a system for recording linear velocity. From an NYU report *(43).*

fine wire of known cross-sectional diameter and electrical resistance, arranged in a packet (not unlike a *Band-Aid)* so that it may be attached directly to some structural element. When the structural element is stressed, it either elongates or shortens, depending upon whether it is in tension or in compression. The filament of the strain gauge follows the structural element to which it is attached, and its cross-sectional area is reduced or increased, with consequent stretching or compression along its length. The electrical resistance is thus increased or decreased from the normal or zero-load position. By suitable electrical magnification and instrumentation, and with proper initial calibration, instantaneous changes in load can be measured and recorded.

The Capacitor. Another device for measuring loads or forces directly is the capacitor, a small capsule consisting of a dielectric material between two layers of electrical conducting material. When a voltage is applied across a capacitor, an electric charge is stored. The capacitance of the unit varies directly as the area of the surface plates and inversely as the thickness of the dielectric. When pressure is applied across the faces of the capacitor, the thickness of the dielectric is reduced and the capacitance is changed.

Pressure gauges based on this principle have been developed at the Franklin Institute *(29).* In these instruments, the construction is loose so that appreciable changes in spacing between the plates, and hence in capacitance, occur with changes in loading. Springiness is achieved by impressing a waffle pattern of indentations into the steel discs which serve as the plates of the capacitors. The gauge is used as one arm of a bridge circuit in which a high-frequency signal is supplied and the unbalance is amplified and recorded on an oscillograph. The degree of unbalance is calibrated in terms of load on the gauge.

Other Force-Recording Devices. Still other techniques for the measurement of loads have been used widely. For example, the principle of equal distribution of pressure in pneumatic and hydraulic systems has resulted in the development of various types of pressure gauges. The property of springs—leaf, helical, or torsion types—in maintaining, within certain limits, a direct ratio of load to deflection has been used in other force-measuring units. Still other devices have been developed making use of other known physical phenomena to obtain data desired in specific problems.

EXPERIMENTAL ADAPTATIONS

Many of these principles, techniques, or devices have been applied in the basic research program to obtain the data needed to develop new and better prostheses. The same applications also have been used to evaluate the prostheses on the amputee, and in some instances special adaptations of certain of these principles have been used as aids in amputee training. Some of the more important experimental units merit further elaboration.

The Lower Extremity

In 1945 the Prosthetic Devices Research Project at the University of California, Berkeley, initiated a program of basic research directed toward the gathering of information on locomotion, both in normal subjects and in leg amputees. It was desired to obtain data on the individual factors which contribute to the pattern of human gait—the displacements of the head, arms, and torso; the displacements and rates of displacement of the thigh, shank, and foot; the moments at the hip, knee, and ankle joints; the pressure at the point of ground contact; and the shift in apparent point of pressure application. Using the techniques already described, the engineers participating in this program developed a variety of ingenious devices *(18,56)*.

To record the displacements of the segments of the body, motion-picture techniques were adopted. The appropriate control points on the body were identified by targets, in some instances the motions of small magnitude were magnified by target extensions, and in other instances the pattern of locomotion was photographed at intervals varying up to 3000 per second. To obtain the components of motion along the three axes of space, a glass walkway and tilted mirror were used. By this expedient, side and plan pictures were taken simultaneously on one film, thus minimizing the time required for reduction of data and also reducing the possibility of error as compared to the use of two synchronized cameras. From these photographs the motions of the leg segments, heel and toe rise, degree of knee flexion, phasing of the step, and all other desired details could be analyzed. Forces during the swing phase could be determined, as could also the moments at the joints.

To measure ground reaction, two force plates were designed using strain gauges in various combinations to measure vertical, fore-and-aft, and lateral components of foot pressure at ground contact. Through appropriate electronic combinations, the strain pickup also could give the apparent instantaneous center of pressure and the torsional moments exerted by the rotation of the foot at ground contact. In a similar study conducted by the Research Division, College of Engineering, New York University, the same elements, strain gauges, and structural beams were combined in another variation of the force plate *(42)*. Both the UC and the NYU force plates represented a refinement of those conceived and used by Elftman *(20),* who, in his earlier studies in human locomotion, had used springs and dial gauges to record components of forces.

The Upper Extremity

The University of California at Los Angeles, through its Engineering School, was entrusted with basic research in the upper extremity. To study the range of movement required by arm prostheses in the performance of selected daily activities, a photographic procedure was established. A subject was placed within an enclosure composed of vertical, horizontal, and lateral grids. Two mirrors permitted views in the horizontal and lateral planes (Fig. 8). When the subject was photographed, the motion of the targets on the joints could be pictured simultaneously in all three planes, together with the coordinate grids, thus permitting rapid data reduction. An ingenious mannikin enabled the duplication of motions photographed for further study of particular combinations of angular displacement of segments.

Adaptations to Evaluation

It is difficult to indicate clear boundaries between the basic research and the evaluation stages in the Artificial Limb Program, for many of the tools used to obtain basic data also are useful to the group at New York University engaged in the evaluation of prostheses. These techniques and others now being used in the evaluation program are discussed later (page 65). As the measuring and recording instruments become more generally applied, scientists other than engineers will become equally proficient in their use. When the need arises, the engineering profession undoubtedly will produce even more refined devices for measuring more complex performances.

PROSTHETICS DESIGN

Important as is the role of engineering in the development of instrumentation and equipment for basic research in human motion, it is in the second stage of any prosthetics program—the design of the prosthetic device—that the engineer is pre-eminent. Among the many factors he must consider in the design of

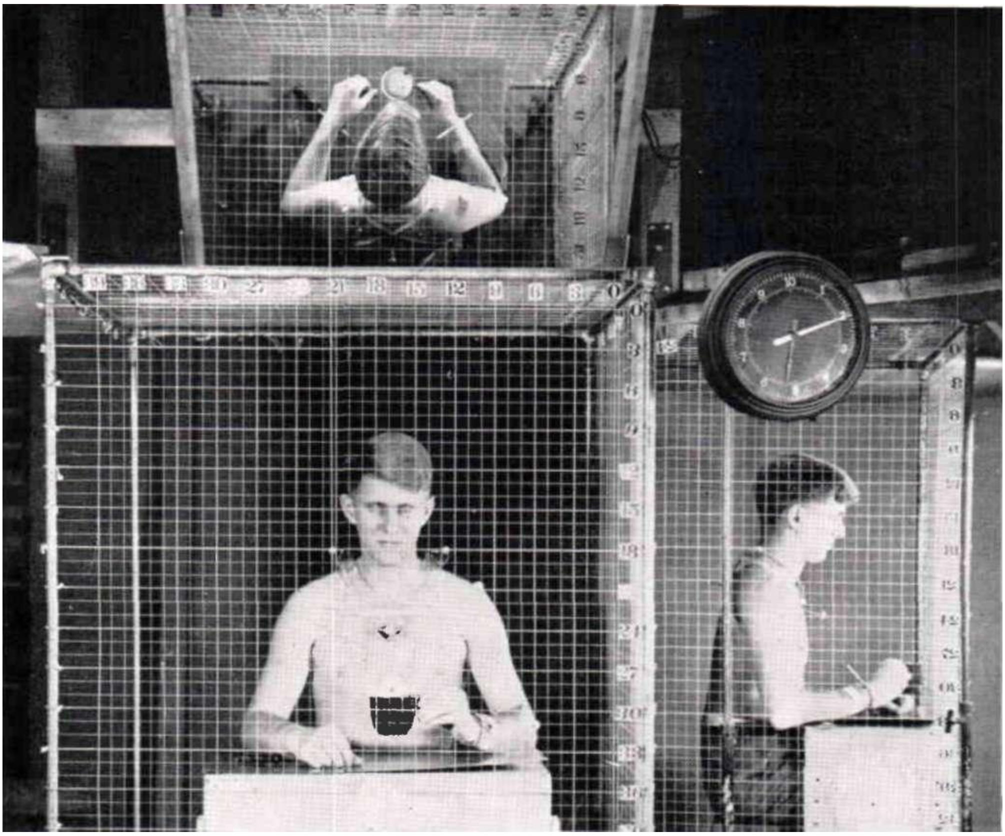

Fig. 8. Three-dimensional grid system for analyzing motions in the upper extremity. From an NRC report *(13).*

a prosthetic device we may include safety, function, control, efficiency, appearance, comfort, simplicity, and durability. These features can scarcely be assigned any order of importance; since they are all interdependent, the design usually must end up as a compromise.

Safety, function, control, efficiency, and appearance require a knowledge of the means—mechanical, pneumatic, hydraulic, or electrical—by which the desired performance can be accomplished and also a knowledge of the forces available, of the forces applied, and of the proper distribution of masses in the device. Comfort requires a knowledge of the limits and distribution of pressure that can be tolerated by body tissues and vessels without damage and without distress to the amputee. Simplicity and durability, both important in the cost and maintenance of the device, require a knowledge of the breakdown that may occur owing to perspiration and body acids, continuous use, temperature changes, and abrasion and chemicals from external sources and, in addition, knowledge as to what materials and combinations of materials may be used to minimize such deterioration.[4]

This kind of problem is the true test of en-

[4] **In press as of this writing is a large collaboration on the general subject of deterioration prevention. Prepared by the Prevention of Deterioration Center, National Research Council, under the joint editorship of Glenn A. Greathouse and Carl J. Wessel, and titled** *Deterioration of Materials—Causes and Preventive Techniques,* **it is to be available this autumn from the publishers, Reinhold Publishing Corporation, New York. Many of the techniques described may find application in the field of prosthetics.**

gineering. All the physical sciences which contribute to the substance of engineering may be called upon in evolving the final product. The mechanical engineer contributes his knowledge of mechanisms—cams and gears and linkages, which together may reproduce a motion. With the hydraulic and electrical engineer, he devises means for the operation or control of the prosthesis, for damping a swing, or for magnifying the power available within the amputee. The metallurgical engineer develops the alloys which go into the joints and prescribes methods of treatment to bring out the maximum qualities desired—strength or ductility or resilience or wear. The chemical engineer makes available the new synthetic substances which so handsomely replace the natural substances heretofore the only materials available. Plastics, whether they be the strong, structural resins used in the lamination of shanks and arms *(11,44),* or whether they be the plastics used for cosmetic purposes *(36),* have radically changed the appearance, weight, and sanitary properties of prostheses.

The design engineer must combine all this knowledge into the most effective whole. He must bring to the job all of the experience and ingenuity he possesses so that the ultimate product will not only produce the desired function, be strong enough, and last an adequate period but will also be relatively inexpensive and simple enough to be maintained locally with a minimum of special tools. The making of artificial limbs can now be based on well-established scientific principles; it can cease to be empirical and can become a branch of engineering and medical activity. But without the necessary technical skills, progress in prostheses will return to the trial-and-error system from which it has so recently emerged. Some of the specific problems to be solved, and the methods for their solution, which have occurred in the design of upper- and lower-extremity prostheses, deserve to be discussed in some detail.

THE LOWER EXTREMITY

The scientific basis for lower-extremity prostheses is provided by biomechanical investigation of the functions of the lower limb in human locomotion. Man is an erect biped, that is, he has two supporting limbs and the mass of his body is carried in a vertical plane. The human body, then, may be represented as an upper mass upheld by two supporting columns. The upper mass consists of the head, arms, and trunk. The supporting columns are the two lower limbs. Of complex character, they each consist of three segments, superposed and movable on each other. To meet the needs of standing, the three movable segments form a quasi-rigid column by virtue of their superposition.

The standing position includes standing on both feet and standing on one foot, as in the stance phase during locomotion when the weight is borne on one foot only. The vertical line passing through the center of gravity of the body passes behind the line connecting the centers of the two hip joints and in front of the axes of the knee joints. Extension of the trunk relative to the thigh and of the thigh relative to the shank is thus maintained by gravity and limited by powerful ligaments. The two lower limbs therefore remain rigid with a minimum use of active muscle groups. But locomotion demands that the lower limbs be composed of movable, superposed segments. This requirement appears irreconcilable with the demands imposed by the standing position, but the natural arrangement of the lower limbs meets both requirements. Mobility of the hip and knee joints is essential in performing a normal step, a motion which can be divided into four alternating phases, two phases of support on both feet and two phases on each foot alternately.

During single support on one foot, the supporting leg bears the weight of the body while the other swings in the sagittal plane like a pendulum suspended from the trunk. Since the two lower limbs are of precisely the same length, the swinging leg must become shorter than the supporting one, or else the swinging foot would drag on the ground. Shortening of the swing leg is effected by flexion of the thigh on the trunk, of the shank on the thigh, and of the foot on the shank.

The geometry of the hip joint, and particularly that of the knee and ankle joints, is very complex. Not all authorities are in agreement as to the movements of the segments of the lower limb in flexion and extension, but enough is known to provide information as to how stability and mobility are provided both in standing and in walking. In the manufacture of artificial legs, it is desirable to reproduce insofar as possible the static and dynamic characteristics of the sound limb.

The Above-Knee Case

With notably rare exceptions, the design of artificial legs proceeded along a fairly well-defined pattern. Generally, until the middle of the nineteenth century, and now still so in many underprivileged countries, it was considered adequate to supply the leg amputee with a peg-leg. For above-knee amputations, it consisted of a pylon supported below a pad, corset, or socket, which in some fashion was attached to the stump or suspended from the shoulders. For below-knee amputees, the stump was flexed and the peg-leg attached below the flexed knee.

Such an artificial leg satisfied completely one of the two functions of the normal leg. It provided a column which, together with the sound leg, allowed the individual to stand erect. It also enabled the wearer to walk, although, since there was no knee joint, it affected the amputee's gait considerably. In the swing phase, the wearer was required to raise the hip on the amputated side in order to swing through; in the stance phase he necessarily had to vault over the pylon. Although such a device is simple, strong, inexpensive, and quite serviceable, the amputee is subjected to excessive stress during walking, his gait is asymmetric and unnatural, his performance in walking is inefficient, and his physical appearance is far from cosmetic.

Next in order of development was the so-called "conventional" leg (Fig. 6, page 11). In general, this prosthesis was made to look like the sound leg, that is, it possessed some cosmetic appearance. The knee was hinged and could be flexed, although in the earlier devices a knee lock was provided to assure stability in standing. The foot was attached to the shank with either a rigid or a jointed ankle.

This order of devices had many advantages over the peg-leg, but it introduced other problems. Because of the knee hinge, it was possible to sit or kneel or to perform in a more natural manner other activities requiring knee flexion. Moreover, because of the knee joint, when not provided with a knee lock, the amputee was able to walk with a better gait. Knee flexion permitted a certain amount of leg shortening in the swing phase, thus reducing the amount of hip elevation required to clear the ground. But the knee and ankle joints introduced instability in the stance phase, particularly at heel contact. The free-swinging leg resulted in an exaggerated back swing and forward swing with a pronounced shock at each stop. Later compromises were effected by setting the knee bolt forward of the weight line of the body, by addition of check straps to decelerate the shank at toe-ofi and to provide some assistance at the beginning of the forward swing, by introducing friction devices at the knee bolt, by a combination of both, and by limiting ankle motion through the use of bumper blocks.

With minor and individual exceptions, this was the general state of development at which the above-knee prosthesis had remained until the end of World War II. As a result of the research initiated thereafter, engineers began to devote time to the application of old and new knowledge to the design of lower-extremity prostheses. Among the features which had been demonstrated as desirable were flexion at the knee but with some stabilizing control at the time of heel contact and immediately thereafter, some measure of support in an emergency situation such as in stubbing the toe, a controlled swing of the leg, an ankle joint which would permit rotation in a horizontal plane as well as in the sagittal and transverse planes and yet not be so flexible as to increase instability, and a toe-lift device for ground clearance in the swing phase. All this was to be accomplished without substantially increasing weight, sacrificing durability, or increasing initial and maintenance costs of the device. By combining known engineering principles with newly developed materials, a substantial gain was achieved in the above-knee prosthesis, with consequent improvement in the performance of many leg amputees.

The U.S. Navy above-knee leg *(12,57,58)* developed at the U.S. Naval Hospital, Oakland, California, is an example of such an improved prosthesis. Controlled swing with terminal deceleration was achieved by the use of friction devices which come into operation in the last portion only of the forward and backward swings. New plastics and molding techniques provide a much more natural appearance. New methods of bonding rubber and a new method of attaching the foot to the shank allow for greater flexibility at the ankle without serious problems of instability.

Proper application of mechanical and hydraulic engineering principles have resulted in two improved devices, the Stewart-Vickers and the Henschke-Mauch hydraulic legs, both for above-knee amputees. The Stewart-Vickers leg (Fig. 9) provides some resistance to knee flexion and hydraulic damping or deceleration at the terminal portion of the forward and backward swings. By a controlled cycle of operation of valves and cylinders, it provides coordinated hip-knee-ankle flexion in the swing phase so that adequate ground clearance is obtained, gives to the gait a more natural appearance, and apparently results in less effort on the part of the amputee. Whenever it has been tried by an amputee, it has generally resulted in favorable acceptance.

The Henschke-Mauch leg (57), which most nearly duplicates the swing pattern of the sound limb, has been designed to provide stability at heel contact, both at the beginning of the stance phase or in the event of a sudden forward acceleration as in stumbling. A carefully designed, pendulum-type valve controls the passage of hydraulic fluid within a cylinder, the added stability being maintained long enough for the amputee to regain his balance but not long enough to impede knee flexion in the stance phase or to increase the risk of a fall. By other valving arrangements the hydraulic cylinder also controls the leg in the swing phase by providing adjustable constant friction in the full cycle plus terminal deceleration.

The human knee joint flexes by a combination of rotation and sliding, so that a simple, single-axis joint cannot duplicate the relative positioning of the tibia and femur. A number of attempts have therefore been made to duplicate this articulation in so-called "anatomical" knees by means of various complex mechanical devices, of which one is the four-bar linkage. In Figure 10, links *AD* and *BC* attach thigh to shank. Links *AB* and *CD* are formed by the shank piece and the thigh piece, respectively. *A* is the center of rotation of the ankle; *K* is the center of rotation of the knee; *H* is the center of rotation of the hip joint. The locus of the instantaneous center of rotation of the knee is 0-5-10-20-30-45-90, the

Fig. 9. The Stewart-Vickers hydraulic leg incorporating knee lock, swing-phase control, and coordinated motion between ankle, shank, and thigh. *Courtesy Prosthetic Devices Study, New York Unhersity.*

centers being at the point of intersection of projections of the links *AD* and *EC.* Each number indicates the angle of knee flexion which places the instantaneous center at the point shown. As extension takes place, the effect is as if the shank were lengthened and the thigh shortened, a feature which aids stability in the stance phase and reduces the force required to start flexion at the beginning of the swing phase.

In the design shown, maximum elevation of the center of knee rotation occurs prior to full extension, so that initial knee flexion at toe-off is difficult. An improved design, with maximum knee elevation at full extension, is to be found in the University of California four-bar-linkage knee (57). It attempts to simulate the path of the instantaneous centers of rotation of the knee joint so as to provide maximum stability and maximum flexibility at the proper times in the walking cycle.

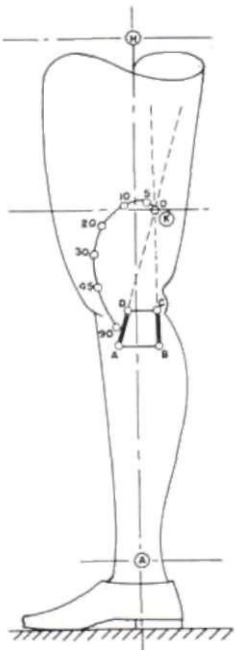

Fig. 10. Polycentric knee based on a four-bar linkage.

The Below-Knee Case

It is this complex articulation of the knee joint that poses a major problem in the design of an adequate below-knee prosthesis. Since the below-knee amputee retains his natural knee, and since each individual knee follows an individual pattern in flexion, it has thus far been impossible to provide between the thigh corset and the below-knee socket an articulation that will not introduce some displacement between the stump and the socket.

Methods of Suspension

The suspension of the above- or below-knee prosthesis has been another area for research and design. Above-knee prostheses had been suspended either by shoulder harness or by some sort of pelvic band. The former did not maintain an adequate positioning between the stump and the socket, since by its very nature it could not adjust to the varying relationship between the shoulder and the leg in different activities. Although the pelvic band retained the leg more securely, it in turn imposed an artificial restriction on possible thigh movements, especially rotation and abduction.

A novel method of suspension by suction was patented by Parmelee *(45)* in 1863, but the idea apparently was abandoned in this country although it continued to be used occasionally in Europe. Increasing experience with the suction socket in Germany after 1933 brought it to the attention of medical and engineering scientists in other countries, including the United States. After World War II, in a coordinated program sponsored by the Veterans Administration and directed by the Advisory Committee on Artificial Limbs of the National Research Council, all aspects of suction-socket suspension were studied carefully. The results of this study proved the merits of the suction-socket method of suspension, and it is gradually being adopted for all above-knee prostheses *(19,31)* where the limbmaker is certified to make such a socket and where there are no medical contraindications. A similar method of suspension is being worked out for below-knee prostheses with increasing evidence of success.

THE UPPER EXTREMITY

The upper limb is the limb of contact. It consists of three segments—the hand, the forearm, and the arm. Of these, the hand is the most highly differentiated and the most important, since the essential upper-extremity function is grasp, which is mobile and variable in quality, power, and duration. Although its primary function is that of prehension, the hand is also one of our major sense organs. Through it we sense temperature, pressure, surface quality, and the shape of objects. For the blind it serves as substitute for the eyes by providing a sense for discriminating form and texture and, together with the forearm and arm, for determining spatial relationships. The forearm and arm serve merely as mobile attachment for positioning the hand in space. Since most of the hand movements and its different articulations are dependent on arm and forearm muscles, they provide a reserve of active power for hand activation. A detailed analysis of the functional mechanism of grasp *(9,50,53)* furnishes the basis for construction of the more scientifically conceived artificial hands.

The Mechanism of Prehension

The natural grasp and manipulation are wholly dependent upon the muscular action controlling movement of the fingers. The nature of muscular action therefore determines the nature of the grasp, and the two properties governing the mechanical phenomena of muscular function are contractility and elasticity. Contractility of the muscle is controlled at will. It can be graduated voluntarily in power, extent, and duration, so that the fingers can be closed firmly or gently, as in holding a tool or an egg, or partially or wholly, as in holding a book or a sheet of paper (Fig. 11). Similarly, the fingers can be moved or closed for very short or very long increments of time, as in fingering the violin or in holding a telephone receiver. Muscle normally is in a state of tone, which may be defined as the property possessed by muscle of preserving, either by voluntary or by reflex action, a state of contractility. This contractility may be long or short in duration, greater or less in extent, strong or weak in power. By means of muscle tone, the hand can be kept in a convenient position for long periods of time.

Since the hand is so important in everyday activities, and since its functioning is so complex and so dependent for mobility on the two other segments of the upper limb, surgical and orthopedic treatment of the upper-extremity amputee is extremely important in restoration of functional loss. It should be directed toward preservation of the maximum amount of nat-

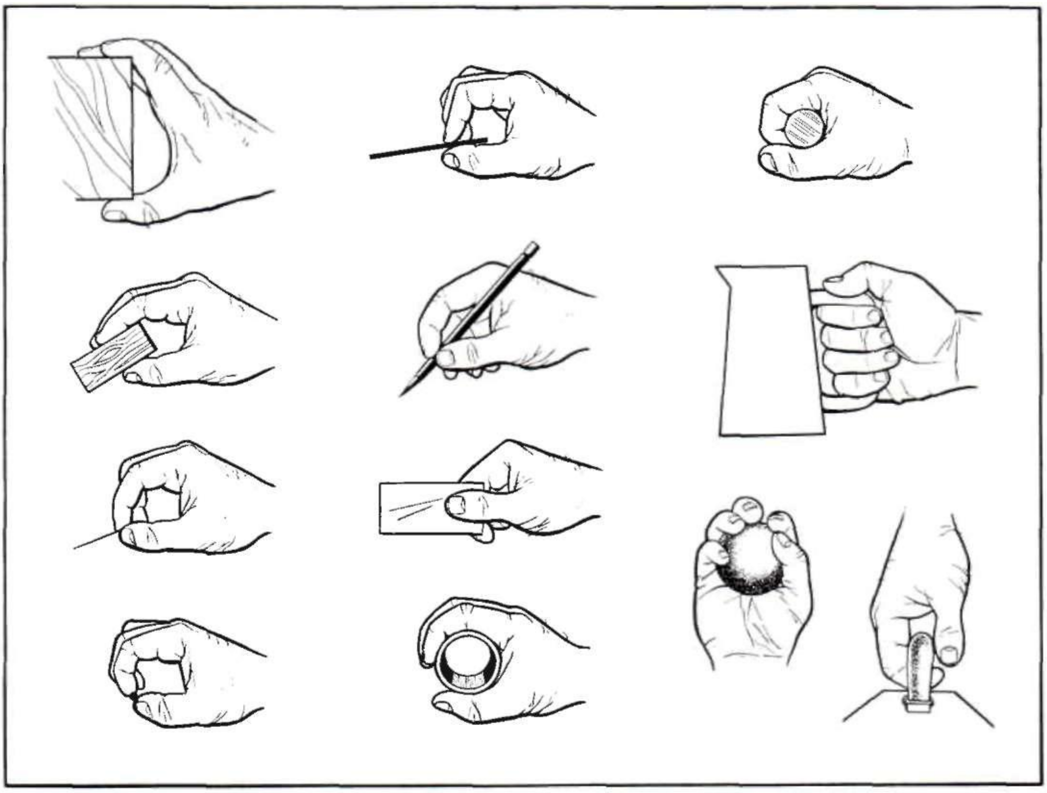

Fig. 11. Twelve basic types of grasp After Schlesinger *(50).*

ural mobility. Since it is not yet possible to create artificial muscle, it is necessary to reproduce as well as possible by indirect processes the effects of normal muscle action on the fingers. Prostheses for this purpose are successful in such proportion as the mechanical effects produced approximate those of the natural limb.

Substitute Power Sources

Until the present, and even now with all the currently available technology, the most adequate substitutes for the lost muscle activators are muscular substitutes, self-powered agents which induce the movement of the artificial fingers by means of artificial tendons, that is, by control cords. The latter are, as a rule, attached by some appropriate means to the shoulder on the amputated side or on the normal side or both. The movement produced by them is thus entirely dependent upon the shoulder group of muscles. Improvements in surgical techniques *(3)* and extensive research in muscle physiology *(34)* recently have reawakened interest in the use of cineplastic procedures to provide other muscle motors (Fig. 12). Both the biceps and pectoral muscle groups have been used for this purpose.

Since the action of the controlling muscles must continue for such periods as required for the particular grasp function concerned, the muscular substitute can become heavily burdened. It is therefore absolutely necessary to arrange for release of the muscular substitute once the fingers have been placed in the appropriate position. This is achieved by mechanisms which produce in the artificial fingers the same effect as that produced by muscle tone in the natural fingers.

Prior Art in Upper-Extremity Prosthetics

Although the basic concept of an artificial arm and its terminal device has not changed materially from that of the first arms made many years ago, recent technological developments in materials of construction and a better application of known mechanical principles have together resulted in arms of improved appearance and greatly improved function. As in the artificial leg, the materials most commonly used for the artificial arm and forearm have been wood and leather. Control was achieved by shoulder harness operating through control cords, usually leather, connected to the terminal device, which was usually a split hook, that is, a pair of iron or steel fingers bent in the shape of a hook and so hinged as to close on each other. For different applications the shape of the hook was modified as appropriate. Since in general the closed position required for grasping an object is of longer duration than is the open position for

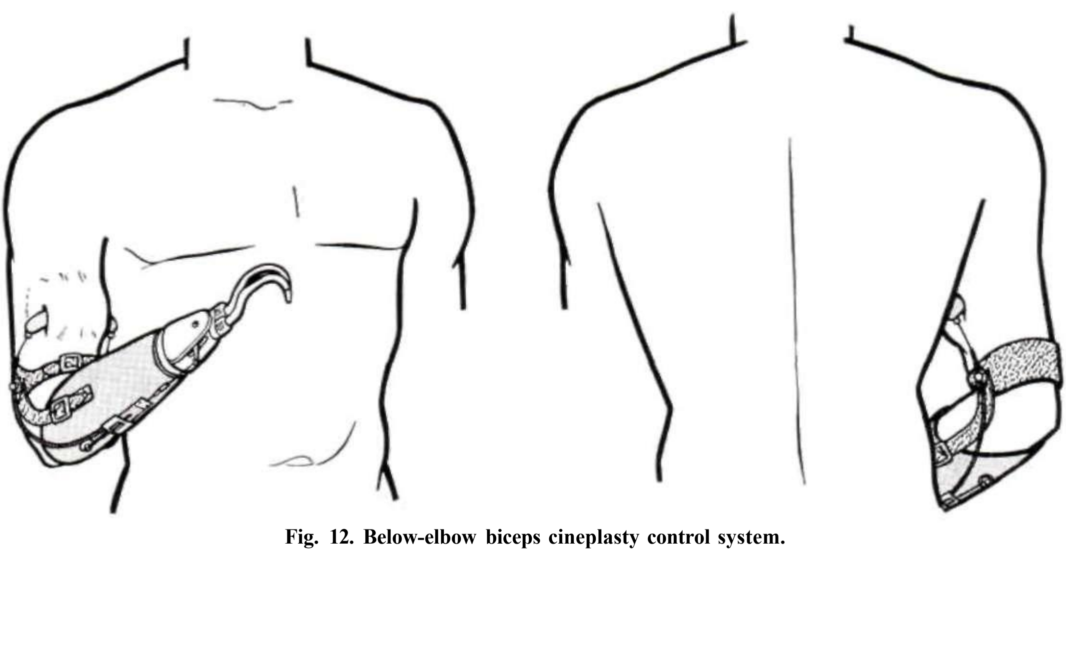

Fig. 12. Below-elbow biceps cineplasty control system.

approaching the object, opening was effected by the shoulder muscles and closing was brought about by some spring or elastic medium. Cosmetic appearance was neglected or, in those few cases where it was attempted, a passive hand was the usual result.

To return to the arm amputee some measure of productive capacity, there were devised a great many one-function terminal devices, each intended for some particular occupational need (Fig. 13). Such "tools" could be inserted and attached to the distal end of the artificial arm. The practice was predominantly European, and we see in their "armamentaria" hooks, rings, hammers, knives, brushes, and a multiplicity of other designs intended to enable the amputee to function in his customary occupation as smith or carpenter or metal worker *(9,50,54).*

Present-day technology and a formal approach to the design of both arms and terminal devices has since effected vast improvements in upper-extremity prostheses. Although most of the newer designs have been described in detail in available literature *(26,27,28),* it is appropriate here to review these developments in a very general way as they relate to engineering practice.

WORK ARM / OCCUPATION		GENERAL TOOLS						SPECIALIZED TOOLS			
		RING	HOOK	CRANK	HAMMER	BRUSH	WOODEN HAND				
1	TURNING OPERATOR							DRAWING POINT	HAND VISE		
2	MILLING OPERATOR										
3	PRESSING and PUNCHING OPERATOR										
4	METAL FITTER							HAND VISE	FILE HANDLE	CHAIN CLAW	
5	LOCKSMITH							HOLDER for HEAVY HAMMER	HAND VISE	CHAIN CLAW	FILE HANDLE
6	CARPENTER							WOODEN HAMMER	DOUBLE BALL SUPPORT	SCRAPER	FILE and RASP HANDLE
7	WHEELER							WOODEN HAMMER	DOUBLE BALL SUPPORT	SCRAPER and DRAW HOLDER	FILE and RASP HANDLE
8	SADDLER							CLAMP JAW	BALL SUPPORT	AWL HOLDER	
9	SHOEMAKER (HAND)							CLAW		AWL HOLDER	
10	SHOEMAKER (MACHINE)										
11	TAILOR							KNIFE	CLAW	SEWING HAND	FLATIRON HOLDER
12	UPHOLSTERER MATTRESSMAKER							KNIFE	BALL SUPPORT	AWL HOLDER	
13	PAINTER PAPERHANGER							KNIFE	SPATTLE HOLDER	AWL HOLDER	PATTERN or STENCIL HOLDER
14	LACQUERER							CLAW	DOUBLE BALL SUPPORT	SPONGE BANDAGE	SPATTLE HOLDER
15	BAKER							KNIFE	PEEL HOLDER (FLAT HANDLE)	PEEL HOLDER (ROUND HANDLE)	
16	FARMER							KNIFE		SPADE HOLDER	PLOW HOLDER

Fig. 13. Typical occupational-aid terminal devices, all European. The screened boxes indicate the devices recommended for the various activities. From a German report ***(54).***

New Arm Substitutes

The developments in plastics and in methods of fabrication have resulted in greatly improved arms. By proper lamination, molding, and coloring, arms and forearms can be made lighter, stronger, and with much better cosmetic value *(11)*. Shoulder caps for high above-elbow amputations and for shoulder disarticulations (Fig. 14) can be molded successfully to provide a good base for attachment of the prosthesis. Similarly, plastics of a different character and with other molding methods produce the flexible artificial gloves which cover the active hand to provide natural appearance *(36)*.

With regard to elbow and wrist articulation, basic research had indicated the desirability of certain ranges of arm motions *(53)*. To provide the necessary mobility, multipositioning elbows and wrists have been devised. The use of ratchet mechanisms, friction clutches, and alternator devices enable the above-elbow amputee to position the forearm by voluntary control through the shoulder harness. Wrist units have been designed both for positioning the terminal device in flexion and rotation and for quick disengagement of the terminal device.

New Hand Substitutes

The improvements effected by sound engineering approach are particularly evident in the terminal device (Fig. 15). Since control resides in the shoulder muscles, it appears logical that voluntary control should be available for closing the fingers rather than for opening the device. Such an arrangement, characteristic both of the APRL hook and of the APRL hand *(26,27,59)*, permits some measure of control of the force applied. An alternator mechanism provides for alternate opening and closing of the fingers, locks the fingers in the closed position with the desired pressure, and thus relieves stress on the shoulder muscles while an object is held. The extent of opening of the fingers can be set in either of two positions, depending upon the particular operation being performed, and in repetitive operations the lock can be eliminated, thus reducing the amount of work to be done by the shoulder muscles. The development of these voluntary-closing devices has, moreover, permitted the more successful fitting of cineplasty cases *(52)*.

For other situations, where an amputee may prefer a voluntary-opening hook, the Northrop two-load hook *(27)* is available. Using springs

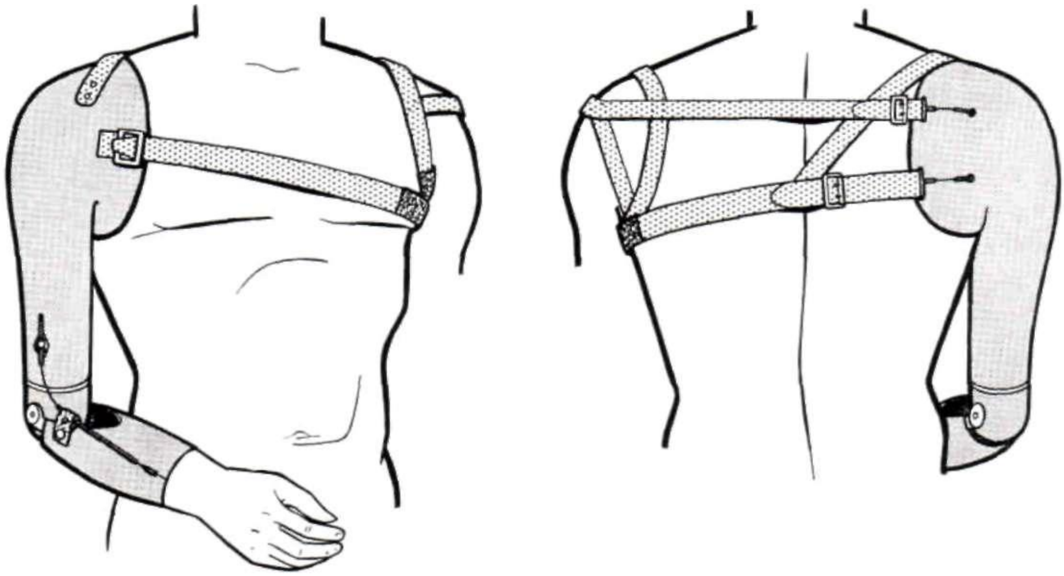

Fig. 14. Shoulder-disarticulation harness.

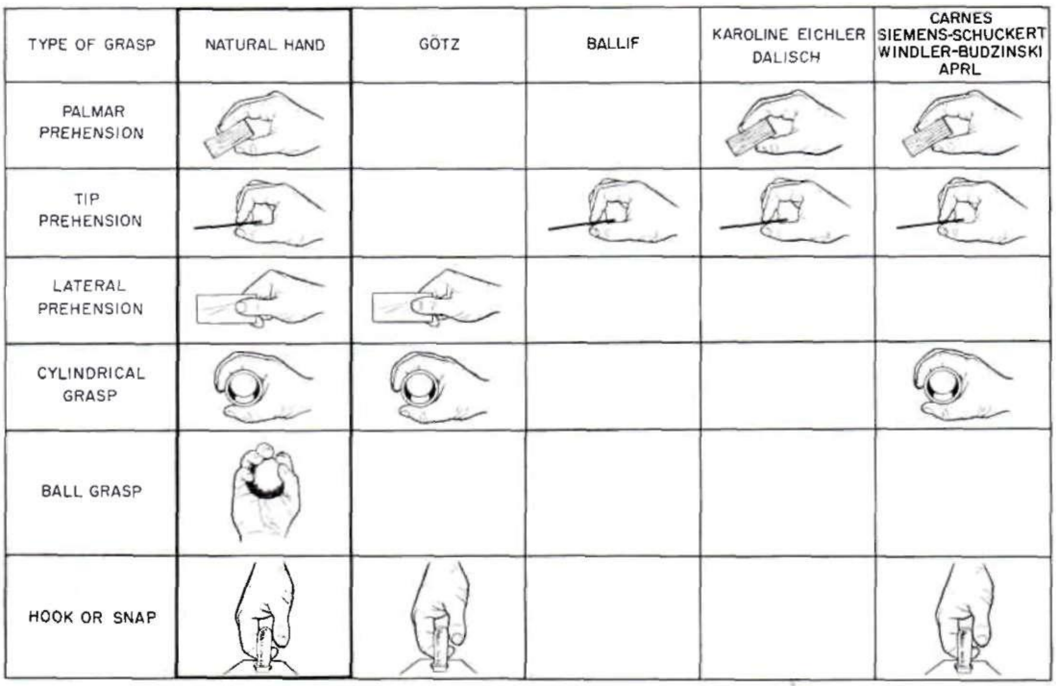

Fig. 15. Types of grasp possible with the natural hand and those available in various designs of artificial hands. After Schlesinger *(50).*

rather than elastic bands, it permits the fingers to close with either one of two available spring loads. The hook fingers of this terminal device as well as of the APRL hook were shaped in accordance with the findings of basic research into the frequency of hand prehension patterns *(53).*

Harnessing

The whole technique of harnessing has undergone extensive revision as a result of applied engineering principles *(11,53).* One feature concerns the fact that the power available at the shoulder should be transmitted to the terminal device with a minimum of loss, that is, with maximum efficiency. Replacing the older leather thongs is the Bowden cable adapted from the aircraft industry. The cable is attached to the harness, directed along the arm by an appropriate number of suitably located cable-housing retainers, and ends at the terminal device. In this circuitous path are friction losses owing to passage of the cable through its housing, especially at points of flexion around joints. Proper selection of points of load application, however, and judicious design of various components make it possible to reduce frictional losses to a minimum (Figs. 14 and 16).

The successful harnessing of cineplasty cases requires the intelligent use of applied mechanics and biomechanics *(52).* The terminal device and the control system by which it is operated must be adapted both to the end-uses desired by the amputee and to the physiological characteristics of his muscle motor.

External Power Sources

A more or less radical departure in the design of upper-extremity prostheses has been the application of engineering science to the utilization of external power sources for activation of arms and terminal devices. Although pneumatic and hydraulic applications have been attended with little success, the development of miniature, compact, and powerful electrical components has made it possible to develop an electrically actuated arm *(1,2)*. Elbow flexion, wrist rotation, and prehension can all be operated electrically, but thus far it has not been possible to develop completely suitable methods of control. The individual components, such as the electric elbow lock, may, nevertheless, have useful application in more conventional arms *(1,2)*. Study of such possible applications is now under way. There can be little doubt that, in some future study, with even newer materials and more advanced methods, externally powered arms, discretely controlled and respondent to the will of the amputee, may be developed.

TECHNIQUES OF EVALUATION

The real merit of a prosthesis cannot be judged solely on the basis of mechanical and cosmetic elegance of the design or by the number of functions it incorporates. It can be evaluated in true perspective only when it is fitted to the amputee and when his over-all performance with and acceptance of the device is appraised. In the Artificial Limb Program, the Prosthetic Devices Study, Research Division, College of Engineering, New York University, has been charged with the evaluation of prosthetic devices. To conduct this work, the roster of personnel includes physicians, psychologists, physiologists, therapists, and engineers, and the evaluations consider both the subjective and objective aspects of the biomechanical relationship.

Although in much of ordinary engineering practice the objective evaluation of a mechanism is the only valid criterion, in prosthetics practice, because of the close relationship between the human and mechanical elements, the importance of subjective evaluations cannot be discounted *(43)*. As has been demonstrated repeatedly, what appears to be a very distinct and sound advance in a prosthesis may not in fact be acceptable to the amputee. A proper understanding of the attitudes of amputees, how they are affected by their own experience and by the characteristics of a device, and how these factors can be translated into the design is altogether necessary. The psychologist therefore has an important role in the evaluation process. So, too, the therapist, trained to observe human performance, and with a knowledge of the physiology and function of the human organism, can render a sound opinion with respect to the relative merits of various amputee-prosthesis combinations.

But these methods of evaluation are subject to all the limitations of personal judgment. The experience and acuity of the particular observer, the relationship between the ob-

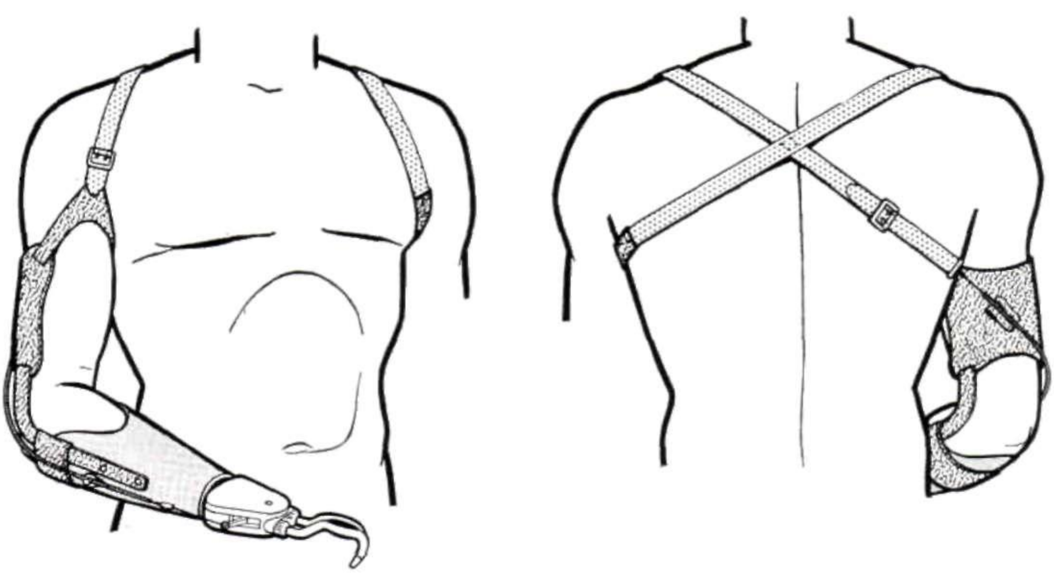

Fig. 16. Below-elbow figure-eight harness.

server and the amputee, and other individual factors will in some way affect the evaluation. To a certain extent these variables are controlled by a comparison and correlation of judgments of different observers, but even under the most favorable conditions there may always be areas of disagreement as to what has been observed.

When positive criteria of performance with a prosthetic device can be established, it becomes very important to be able to measure and record accurately those factors which constitute the criteria. Instrumentation and methods developed on the basis of engineering knowledge provide the tools for obtaining objective data. They enable the investigator to compare the performance of a particular amputee with different prostheses, of a given amputee with the same prosthesis at different times, or of different amputees wearing identical prostheses. The recording instruments and techniques available can record more rapidly, more accurately, and more permanently than can any human observer. All the devices useful in the basic research program are equally useful in the evaluation program.

THE LOWER EXTREMITY

Symmetry in the Walking Pattern

In establishing criteria for the evaluation of lower-extremity prostheses, it has been postulated that the pattern of normal locomotion is symmetrical and, therefore, that the behavior of the normal side may be the legitimate measure of performance of the affected side. That is to say, the more nearly the amputee achieves a symmetrical pattern of locomotion the better the prosthetic device and the better the adjustment to it. Further, it is assumed that, in the performance of activity, the human organism adjusts itself to perform at a minimal level of stress. The measure of performance of normals, then, can be a guide to the relative merits of amputee-prosthesis combinations. Such criteria as stability in the erect position, variability of stride time, and other biomechanical factors may be used as indices of performance. Lacking proper instrumentation, no objective evaluations of this character could be made.

Energy Costs

The investigations of Hettinger and Miilier *(33)* indicate that the walking cadence favored by a normal human being is usually that which requires the minimum expenditure of energy. Deviations from this optimum cadence require increasing amounts of energy. Psychologists indicate that, in a repetitive operation which may be performed at varying tempos, the average person will perform the operation with least deviation at some one tempo best suited to him. On the strength of these two premises, the variations in stride time at different cadences were recorded and curves plotted (Fig. 17). The assumption is made that the nearer the curve of the affected leg approaches that of the normal leg, and the nearer the two curves approach those of a normal subject, the better the prosthetic device. Such data can be taken with the tachograph (Fig. 18), force plates, and interrupted-light photography.

Figure 19 represents a typical plot of ver-

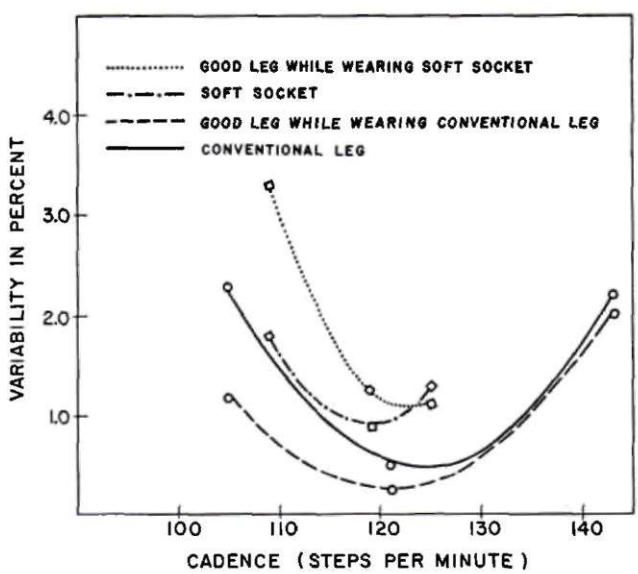

Fig. 17. Variability in stride time. *Courtesy Prosthetic Devices Study, New York University.*

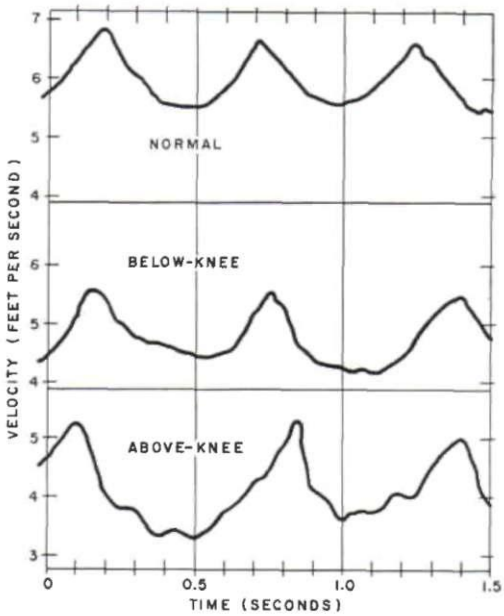

Fig. 18. Velocities in level walking at normal speed (from tachograph records). *Courtesy Prosthetic Devices Study, New York University.*

tical load versus time during ground contact from heel contact to toe push-off. By means of stick diagrams and force-plate records, this over-all curve may be resolved into one for heel-contact impact and another for toe push-off momentum. When the separation is correct, the area C should be equal to the area *D*. Used in conjunction with other criteria, these curves give useful information regarding the effect of a prosthesis on the amputee's gait.

Double-Support Time (At)

Marey and Demeny *(38,39)* determined that the time of double support in the walking cycle is inversely proportional to cadence. The NYU studies indicate that it is also related to the ratio of swing-phase time to stance-phase time *(r)* and that, moreover, at optimum cadence the stance-phase time in normals is approximately twice the swing-phase time. A criterion was established that, given the relationship between double-support time and cadence, plotted against a family of curves for varying ratios of swing-phase time to stance-phase time, that amputee-prosthesis combination was best which enabled the amputee group more nearly to approach the normal group.

Figure 20 shows the average trend line for a group of normals and for a group of above- and below-knee amputees. From the equation indicated, a series of hyperbolas may be plotted for varying values of *r*. The observed double-support times for normals, for below-knee amputees, and for above-knee amputees at three different speeds were plotted, and straight lines were fitted to these observed

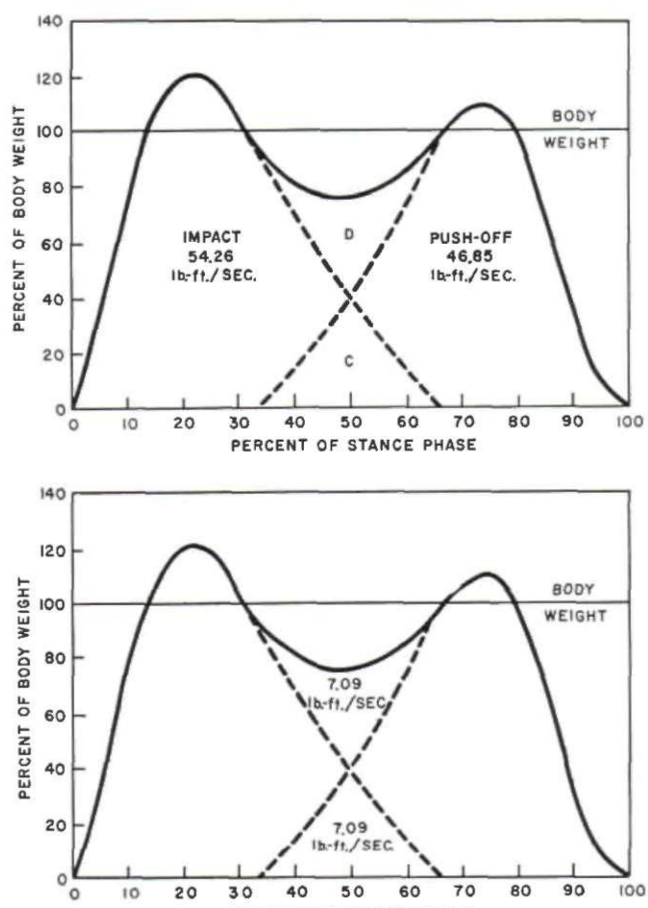

Fig. 19. Components of vertical force. Normal speed, level walking, mean of eight subjects.

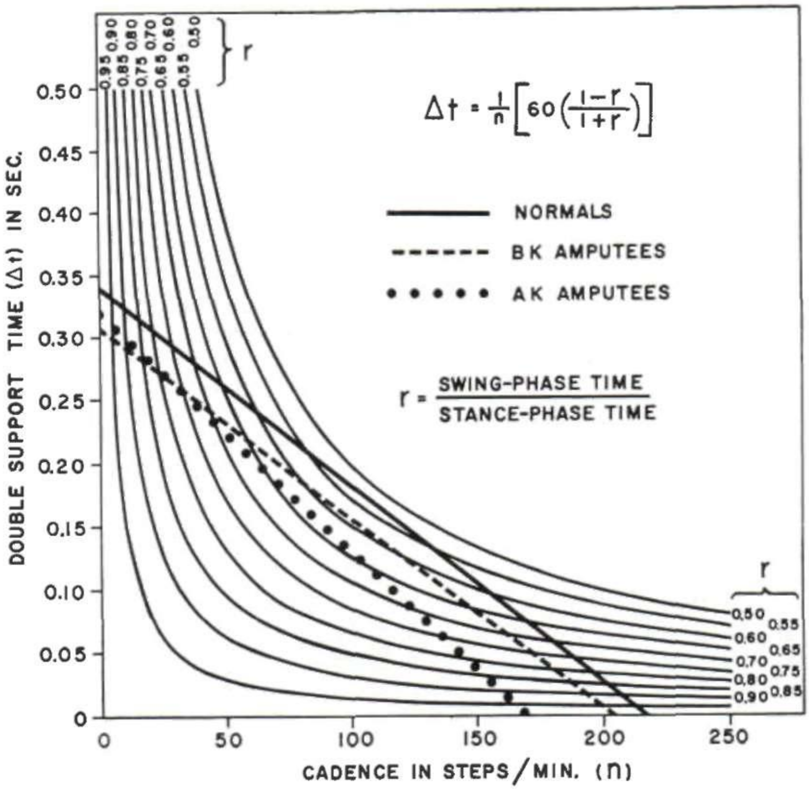

Fig. 20. Analysis of optimum cadence.

points. A line for double-support time crosses each of the hyperbolas at two points. The mean abscissa of these points indicates optimum cadence. Since a deviation from this optimum causes an increase in energy consumption, the increase in the value of r can be used as an indicator of higher energy requirement. The validity of this criterion appears to be borne out, since the below-knee group, having more of their natural limbs, more nearly approach the normals. Again, such data can be obtained only because adequate instrumentation, force plates, tachograph, and camera are available.

Vertical Stability

Stability in the erect position is used as another criterion *(17)*. The normal individual keeps himself erect by the interaction of muscle and skeletal groups responding to sensory cues. In the amputee some of the normal cues have been destroyed and new ones, such as pressure on the stump, or pain, have been introduced. Besides this, the amputee has fewer muscle groups available with which to compensate for the effect of external forces tending to throw him off balance. Because the human anatomical structure is not truly rigid, the equilibrium of a normal erect subject will be disturbed by a force of lower magnitude than that which will unbalance a rigid body of the same general mass distribution and with the same general support base (Fig. 21). Since the amputee cannot compensate for the effect of unbalancing forces as readily as can a normal, and since in fact poor alignment or fit of the prosthesis may exaggerate the unbalancing effect, the measure of stability is highly important.

Three methods are used for obtaining information on stability. In one, the subject is placed in a known position on one force plate, and the center of the base of support on the force plate is determined geometrically. The extent and frequency of deviation in the sagittal and transverse planes are recorded simultaneously (Fig. 22). Mean values of recorded

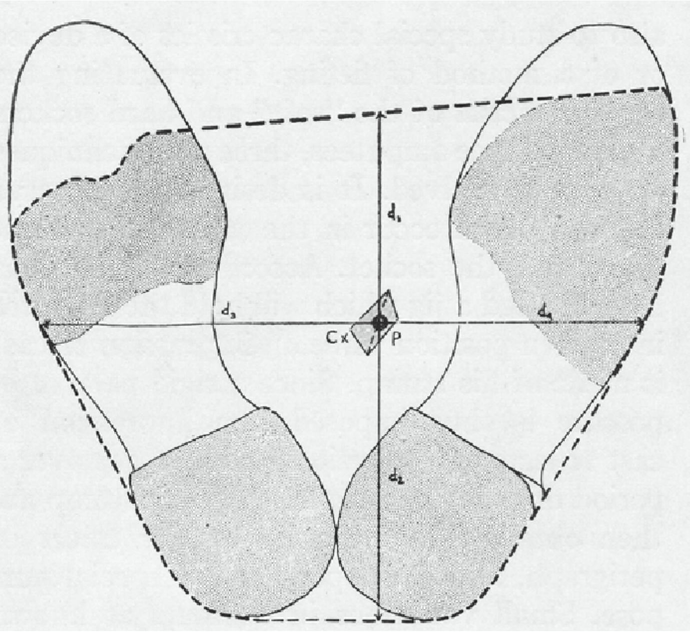

Fig. 21. The base of support. ***C*** **represents the center of the support base. Shaded areas show the contact zones of feet and ground. The small trapezoid defines the limits of travel of the projection of the center of gravity.** ***P*** **represents the mean of all the readings of center-of-gravity projection. The distances** ***d1, d2, d3,*** **and** ***d4*** **are the respective distances from the center** ***P.***

oscillations determine the location of the center of pressure, which at the same time is also the projection of the center of gravity on the force plate. Distances measured from the center of pressure of the axis of each foot give an indication as to how the body weight is distributed between the two legs.

Since the reduction of force-plate data alone is not sufficient for the purpose of determining stability constants, a simple device, the stability platform shown in Figure 23, has been fabricated for imposing upon a subject known accelerations and recording that one

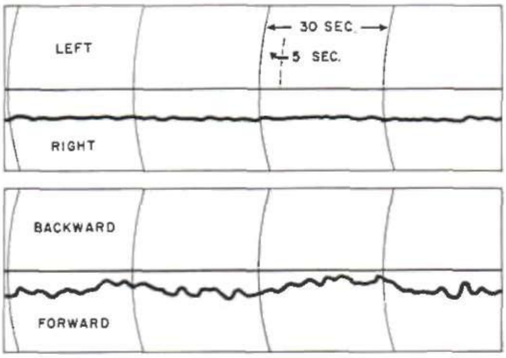

Fig. 22. Record of stability in standing.

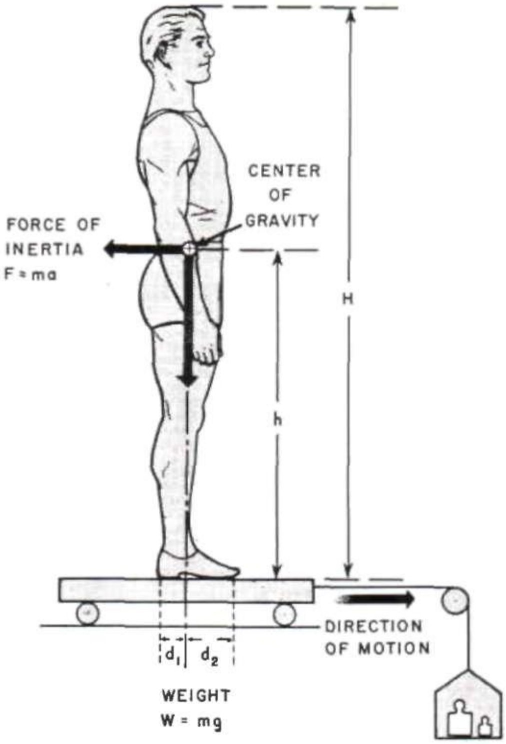

Fig. 23. The stability platform.

at which he is unbalanced. The support base is known, the center of mass of the subject vertically above the platform can be established, the acceleration when the platform is suddenly released can be controlled by the known weights in the suspended basket, and thus it can be determined at what acceleration the subject is unbalanced. Stability trapezoids for normals and for above- and below-knee amputees (Fig. 24) have been prepared on the basis of available data. It will be noted that thus far only four positions have been recorded—accelerations tending to unbalance the subject in the forward, rearward, right, and left directions. No positions along intermediate axes have been studied, but it seems likely that, if more positions were measured, the envelope would assume some oval shape. This criterion too seems validated by results, since, although there are differences between individual amputees as well as between normals, as a group the below-knee amputees more nearly approach the normal group.

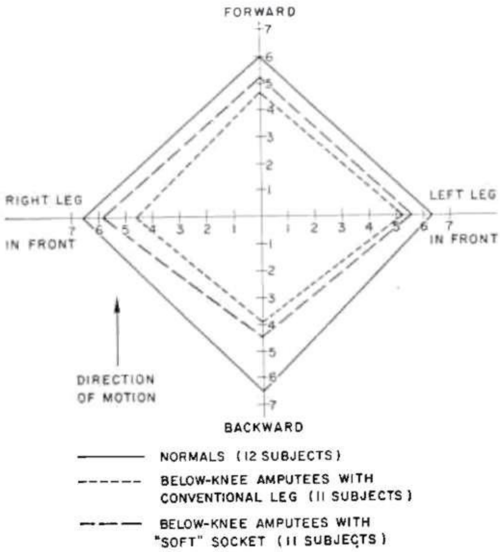

Fig. 24. Stability polygon; mean values in percent of *g. Courtesy Prosthetic Devices Study, New York University.*

Another simple device which has been used to corroborate acceleration data is the inclined platform. A kymograph records the increasing angle of tilt, and the recording is interrupted when the subject topples.

Standardization of Fit and Alignment

It is not amiss at this point to mention two devices, developed at the University of California, which are indispensable in the evaluation procedures. The alignment devices for above- and below-knee prostheses and the transfer jig *(47,48)* are tools useful in assuring that different prostheses on the same amputee are alike in physical dimensions and positioning, and they make it possible to measure the effects of known changes in position or alignment in the same prosthesis. A third device, developed at the Prosthetic Testing and Development Laboratory of the Veterans Administration, makes it possible to duplicate sockets, a matter of importance when shanks requiring different sockets are needed. The internal contours of the socket can be maintained and their effect on changes in performance thus minimized.

Measurement of Force Distribution

Engineering knowledge makes it possible also to study special characteristics of a device or of a method of fitting. In evaluating the relative merits of the "soft" and hard sockets for below-knee amputees, three new techniques have been evolved. It is desirable to observe changes which occur in the stump as a result of wearing the socket. Accordingly, there has been devised a jig which will hold the amputee in a given position while an impression or cast is made of his stump. Since a rigid pattern of posture is thus imposed, the impression or cast reflects only physiological changes over a period of time. The contours of the stump are then obtained by using a contour tracer or perigraph, also developed for this special purpose. Small variations in contours at known levels can be recorded and compared.

The second technique involves the use of the capacitance gauges previously described. In a study at New York University, in cooperation with the Prosthetic and Sensory Aids Service of the Veterans Administration, they have been applied in an attempt to answer once and for all the question among limbmakers as to the proper distribution of forces within a below-knee socket. Several gauges are attached at points of particular interest on the stump of a below-knee amputee (Fig. 25). The subject then walks at different speeds for a distance of 30 to 40 feet while the unbalance of the gauge bridges is recorded. In this way, simultaneous indications of pressure are obtained at six points on the stump. Although it is still too early to make a general statement, it is evident that great differences exist in the forces exerted by the stump on the socket wall at different points. A composite record of the forces involved during a single stride (Fig. 26) shows the relative magnitudes of forces at a number of points. The maximum observed pressure was 65 lb. per sq. in. at the relatively insensitive patellar tendon. Eventually it is intended to map the total stump contact area for pressure distribution during different phases of the walking cycle.

In addition to the research applications of the pressure gauge, it is likely to find use in the routine fitting of sockets. For this purpose, gauges would be attached to the stump at critical points, such as weight-bearing areas, sore spots, or relieved areas, when a new socket

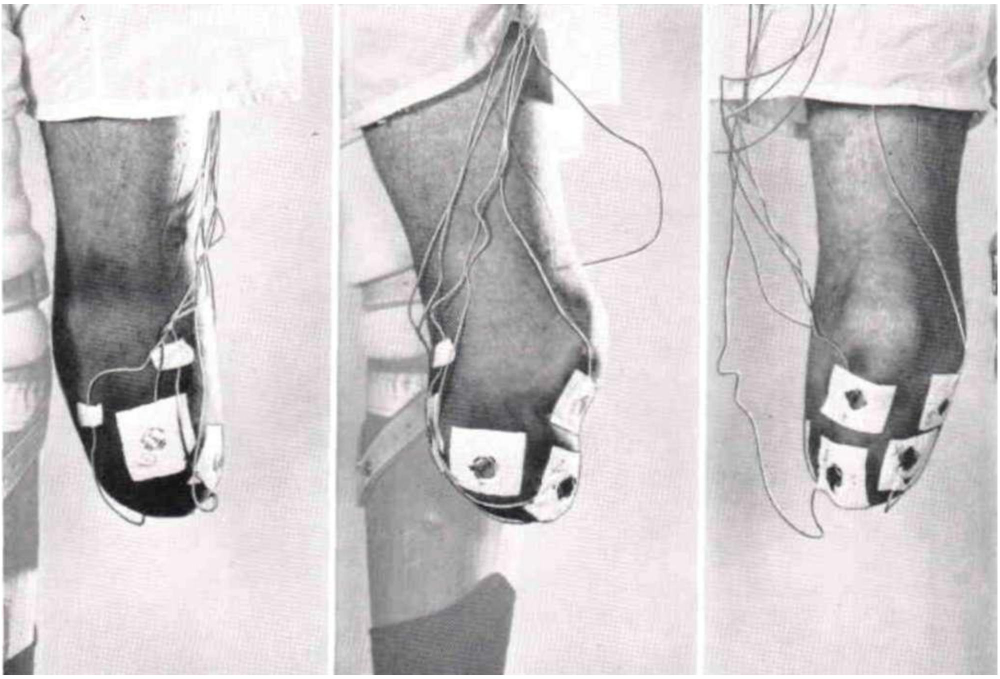

Fig. 25. Experimental arrangement for pressure measurement using capacitors. *Courtesy Prosthetic Devices Study, New York University.*

were tried on. A meter reading would give the magnitude of the pressure at the points in question and would tell objectively whether the pressure were excessively concentrated or well distributed when the subject stood or walked.

The third technique specially developed makes use of the strain gauge also described previously. By means of this instrument it has been possible to attack the problem of determining the relative distribution of body weight between the sidebars and the socket of the below-knee amputee. In the experimental procedure developed, modified sidebars (Fig. 27) are substituted for the original ones of the test subject. So constructed that the subject's gait is unaffected by the substitution, these modified sidebars permit the mounting of the strain gauges so as to simplify determination of axial and bending strains. In the test procedure, wires are run from the gauges on the bars to a recording oscillograph by means of an eight-conductor cable. Stick diagrams and force-plate records are taken simultaneously with the recording of the dynamic sidebar strains (Fig. 28). Thus, at any particular instant, the position of the leg in space, the forces it exerts on the ground, and the strains in the sidebars all are known. From the knowledge of the axial sidebar loads, plus some logical assumptions and some simple kinematic relationships, the components of socket load along the axis of the shank and normal to the shank axis can be found. At the present time, runs have been made on two test subjects, one unilateral and one bilateral, both wearing conventional wooden sockets *(35).*

THE UPPER EXTREMITY

Engineering techniques have been employed in the evolution of upper-extremity prostheses also, though not to the same extent. The refinements in lower-extremity prostheses are such as to require discrete, fine, and rapid measurements, while those in the upper extremity are comparatively gross and subject, in many cases, to visual observation and judgment. Moreover, the increased performance with the newer arms and terminal devices can be appreciated quite readily by both the am-

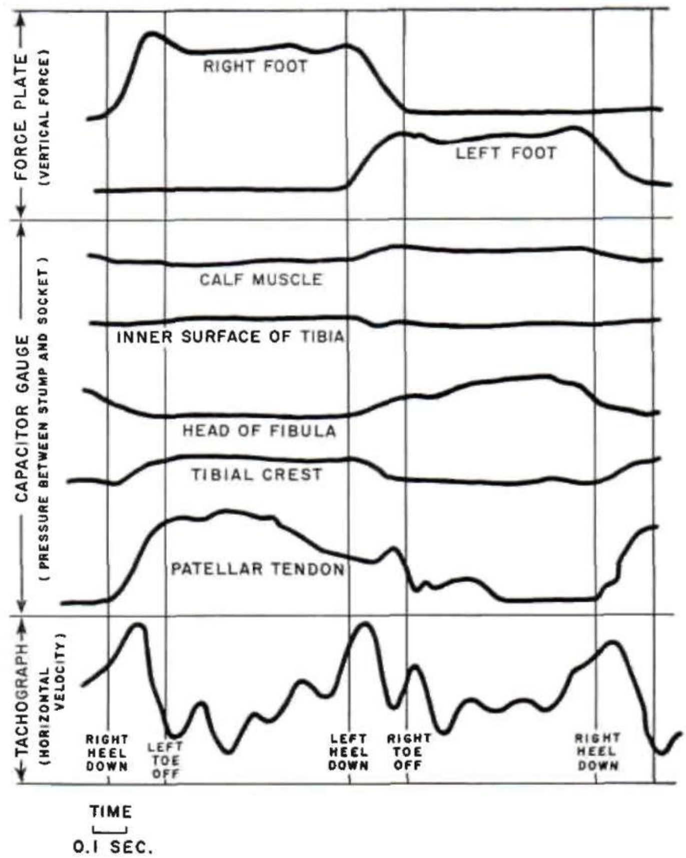

Fig. 26. Typical oscillograph record of forces in walking. *Courtesy Prosthetic Devices Study, New York University.*

putee and the observer. In the upper extremity, therefore, the employment of measuring devices is required only in those special situations where human observations fail.

Control Systems

The efficiency of an upper-extremity control system, from the point of load application at the harness to the point of pressure applied by the terminal device, cannot be obtained other than with measuring instruments. For such measurement, the strain gauge, applied to appropriately designed devices, can be used to measure the pressure at the tips of the fingers or the force applied at any point along the cable of an actuating system. In the course of some of the NYU studies, a channel-shaped structural element was designed in such a way that it could be inserted as a link in the cable system at different points along the cable. Tension in the cable causes deflection in the elements, and the extent of deflection is recorded as a change in voltage through strain gauges cemented to the crossbar of the channel.

Finger Forces

A similar principle has been used for measuring hook-finger pressures. Elements resembling tuning forks were designed, the beams being so shaped as to accommodate different grasps. Strain gauges cemented to the crossbar measure the bending stress in the fork, the stress being proportional to the pressure applied by the amputee at the tips of the hook fingers. With knowledge of the linkages involved in the system, it is possible to determine what harness combination is most efficient.

At the Army Prosthetics Research Laboratory, a "grip" meter has been developed for

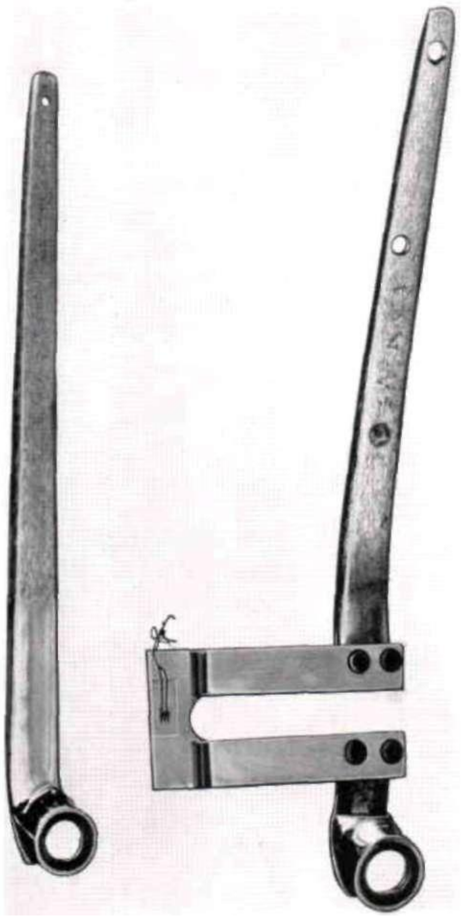

Fig. 27. Conventional sidebar (left) and experimental modification for measurement of bending forces. *Courtesy Prosthetic Devices Study, New York University.*

the purpose of measuring normal grips and the grips that can be achieved by amputees with artificial hands. The grip is resisted by a spring calibrated to be read directly on a dial gauge.

Range of Stump Motion

During the course of development of the electric arm, an unusual instrument was developed by Alderson *(2)* to measure the range of motion of the various muscle groups which later were to actuate the controls of the electric arm. The *simul"arm"ator* permits the designer and fitter to estimate the range of control available to the amputee in the various muscle groups—biceps, triceps, pectoral, etc.—

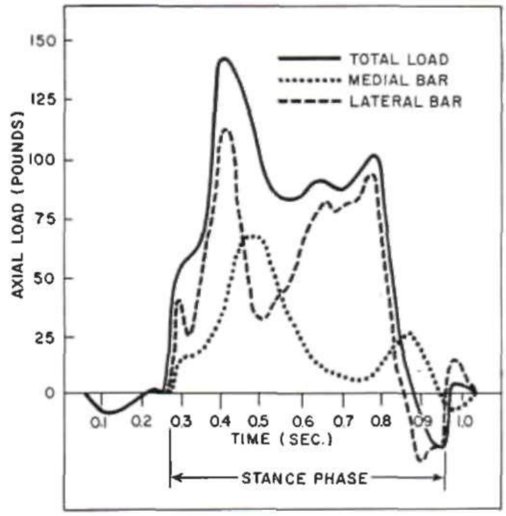

Fig. 28. Axial load on sidebars. Body weight, 250 lb.; cadence, 120 steps per minute. *Courtesy Prosthetic Devices Study, New York University.*

and to allow for this range in designing the control switches of the prostheses.

THE FUTURE IN PROSTHETICS EVALUATION

As more and more improvements are incorporated into upper- and lower-extremity prostheses, the relative merit of one prosthesis as compared to another will become more and more difficult to evaluate without appropriate instrumentation and recording. The development of recording and measuring devices must therefore keep pace with the combinations to be evaluated. Hence the engineer must continue to function in his role in the evaluation phase of the program.

CONCLUSION

The contributions of engineers and the role of engineering in all stages of prosthetics design and application now have been well established. But this turn of events could scarcely have materialized without the cooperation of the Government. The program established by the U.S. Congress *(46),* supervised by the Veterans Administration, and coordinated by the Advisory Committee on Artificial Limbs of the National Research Council assured a continuity of operations—of research, design, and evaluation—in which engineers and engineering groups could become interested.

Theretofore engineers had been interested in prosthetics in a desultory fashion only, and engineering principles had been applied only to the extent that that knowledge was available to the individual limbmaker concerned. Engineers have brought to the Artificial Limb Program a curiosity as to the physical principles involved in human performance and an appreciation of the scientific method in approaching the problems. They have contributed their knowledge of measurement and of instrumentation to obtain necessary data, they have translated the results into terms of new needs, and they have applied their knowledge of materials and of mechanisms toward the fulfillment of those needs.

It cannot be expected that the present program, born of World War II and under the pressure of veterans' demands, will continue indefinitely. And yet it may be anticipated that more and more amputees will continue to need truly functional artificial limbs. Records indicate that annually there arise from disease and other natural causes—industrial and traffic accidents and accidents in the home—many times more amputees than were produced in all Service-connected activities throughout World War II. And these include the weak and the old and the very young, not alone the average, healthy male represented by the veteran amputee. As in all science, the problems which yet require solution are much more numerous than are those already solved. Programs must therefore be established which will be broad enough in scope and long enough in duration to attract engineers. The limb industry must continue to upgrade itself, to create the positions which require engineering skills, and to offer commensurate rewards. Rehabilitation agencies and all those groups interested in the welfare of the disabled should consider how the role of the engineer and of the physical scientist can be integrated into their work.

As an alternative it has been suggested that a cross-discipline should be evolved, with courses of instruction available to the engineer, the physician, and the rehabilitation specialist to enable each to understand each other's problems. Such a curriculum in biotechnology could offer the engineer instruction in physiology and psychophysiology useful as well in applications other than prosthetics. It could offer the physician and rehabilitation specialist instruction in the physical sciences, instrumentation, and measurement. For such an integrated course of instruction there are already precedents. Physicians have studied engineering for a better understanding of orthopedics. Engineers have studied the physiology of human activity to develop better operational methods in industry. In Europe, particularly in Germany, Russia, and the Scandinavian countries, a whole new science of "work physiology" or "work science" is being developed. In England the Ergonomics Society brings together physiologists, psychologists, and physical scientists interested in the problems of human performance, and their contributions are having effect on the design of equipment and operational processes.

A scientist from whatever field, trained in biomechanics, can bring to a prosthetics program a much greater appreciation of the problems to be solved. He will be better equipped to evaluate the solutions that will be offered. But it seems inevitable that the solutions in their final development will be offered only by the engineer.

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Digest of Major Activities of the Artificial Limb Program

Human Limbs and Their Substitutes

The 840-page collaboration, *Human Limbs and Their Substitutes,* prepared, under the supervision of ACAL, by Paul E. Klopsteg, Philip D. Wilson, and more than a score of other contributors, went to press in mid-August. Bound volumes are scheduled to be available in bookstores or directly from the publisher, McGraw-Hill Book Company, by the first week in October. The price will be $12, a conservative one considering the size and complexity of the work, its 450 illustrations, and the steeply rising costs in the entire publications field. Full content of the volume is as follows:

HUMAN LIMBS AND THEIR SUBSTITUTES

CONTENTS

Upper-Extremity Prosthetics Training Center and Field Study

The tenth session of the Upper-Extremity

Prosthetics Training Center, University of California at Los Angeles, was completed on July 2. A total of 93 prosthetists, 108 therapists, and 134 physicians have now been trained in the latest techniques and developments involved in the management of upper-extremity amputees. These graduates form 77 prosthetics clinic teams throughout the United States. Of this group, 24 are Veterans Administration Regional Office Orthopedic Clinic Teams, seven are Veterans Administration Hospital Orthopedic Clinic Teams, four are Army clinics, two are Navy clinics, and 40 are private clinics.

Of the 77 clinic teams trained, over 50 are participating in the Upper-Extremity Field Study being conducted by New York University. By July 2, 358 arm amputees had been prescribed for, of which 143 cases had been completed. Pertinent information from the field clinic is being transmitted to the research and development laboratories by means of a series of Field Technical Reports initiated by NYU.

The staff of the Training Center is preparing a revision of the *Manual of Upper Extremity Prosthetics,* since the present edition is out of print and new developments have made certain sections obsolete. A preliminary printing of the new edition will be made to ensure a text for the eleventh session, which is scheduled to begin October 11 and to run for the customary six weeks.

Louis Edward Levy Medal (Franklin Institute)

It has been announced that Dr. Craig L. Taylor and Alfred C. Blaschke of the Artificial Limbs Project, University of California, Los Angeles, will be awarded Louis Edward Levy medals by The Franklin Institute in recognition of their outstanding paper, *The Mechanical Design of Muscle-Operated Arm Prostheses,* which appeared in the *Journal of The Franklin Institute* for November 1953.

Dr. Taylor and Mr. Blaschke, through their scientific analysis of harnessing the potential of the cineplasty tunnel, have contributed substantially to the success that has been obtained with the cineplasty procedure. Dr. Taylor has directed the Artificial Limbs Project at UCLA since its inception in 1946, is Chairman of the Upper-Extremity Technical Committee and of the Upper-Extremity Research and Development Panel, and is a member of the Advisory Committee on Artificial Limbs. Mr. Blaschke was a member of the staff of the UCLA project and an instructor in mathematics at UCLA.

European Tour by Dr. Eugene F. Murphy

On August 6 Dr. Eugene F. Murphy, Chief, Research and Development Division, Prosthetic and Sensory Aids Service, U.S. Veterans Administration, sailed for Europe aboard the *United States.* Dr. Murphy represented the VA at the technical session of the meeting of the World Council for the Welfare of the Blind in Paris, August 12-14, and at the meeting of the Expert Committee on Prosthetics, World Health Organization, at Copenhagen, August 23-28. After visiting the various artificial-limb research centers in Great Britain and on the Continent, Dr. Murphy attended the Sixth World Congress of the International Society for the Welfare of the Crippled at The Hague, September 13-17. Dr. Murphy is scheduled to return September 28 in time to report his observations to the Scientific Assembly of the Orthopedic Appliance and Limb Manufacturers Association in Atlantic City, September 26-30.

DR. MURPHY

ACAL Demonstrations

At the invitation of the American Legion, the Advisory Committee on Artificial Limbs gave a demonstration before the New York State American Legion Convention July 29 in the Grand Ballroom of the Hotel Commodore in New York City. Dr. Sidney Fishman of New York University and Dr. Eugene F. Murphy and Mr. William Bernstock of the Prosthetic and Sensory Aids Service, Veterans Administration, were the principal speakers. Assisted by several amputees, this group discussed the latest developments evolving from the Artificial Limb Program.

On Tuesday, September 7, in the South American Room of the Hotel Statler in Washington, a number of persons prominent in ACAL activities participated in a presentation before the annual scientific session of the American Society of Physical Medicine and Rehabilitation. The subject matter was concerned with prosthetics restoration techniques for upper- and lower-extremity amputees and with the general management of the amputee patient. Under the chairmanship of Dr. Fishman, the program was as follows:

INTRODUCTORY REMARKS

F. S. Strong, Jr.
Executive Director

Advisory Committee on Artificial Limbs

AMPUTATION SURGERY: Recent Developments
Charles O. Bechtol, M.D.
Assistant Professor of Orthopedic Surgery
Yale University

PREPROSTHETIC THERAPY

Sidney Fishman
Prosthetic Devices Study
New York University

PRESCRIPTION :

Development of the "Armamentarium" for Upper-Extremity Amputees

Maurice J. Fletcher, Lt. Col., MSC, USA
Director, Army Prosthetics Research Laboratory
Walter Reed Army Medical Center

Development of the "Legamentarium" for Lower-Extremity Amputees

Renato Contini
Research Coordinator
College of Engineering
New York University

PROSTHETICS FABRICATION: Latest Upper-Extremity Techniques

R. A. Beales
Prosthetist
J. E. Hanger, Inc.
Washington, D. C.

CHECKOUT PROCEDURES: Upper- and Lower-Extremity Prostheses
Edward R. Ford
Laboratory Supervisor
Prosthetic Devices Study
New York University

PROSTHETICS TRAINING: Upper- and Lower-Extremity Prostheses

Frederick E. Vultee, Jr., Capt, MC, USA
Department of Physical Medicine & Rehabilitation
Walter Reed Army Medical Center

FOLLOW-UP PROCEDURES
Sidney Fishman

Amputee demonstrators included George J. Barthel, Albert P. Clark, Joseph J. Cochran, Robert H. Gomersall, and Alfonso Spencer from the Washington, D. C, area and Robert DiZefalo, Herbert Kramer, Vito Minelli, and Vincent Wagner from the New York City area.

OALMA Prosthetics Day

Wednesday, September 29, will be "Prosthetics Day" at the Scientific Assembly of the Orthopedic Appliance and Limb Manufacturers Association, Chalfonte-Haddon Hall, Atlantic City. Preliminary planning calls for presentations by a number of persons of whom many have long been closely associated with the Artificial Limb Program. Tentatively, the day's agenda includes motion-picture films, to be shown by Mr. Charles A. Hennessy of the Peerless Artificial Limb Company, Los Angeles; the first detailed report on the clinical study of amputees at the University of California, Berkeley, to be given by Professor Howard D. Eberhart and Dr. Verne T. Inman; a report on the field-testing of prosthetic devices, to be offered by Dr. Sidney Fishman of New York University, assisted by an active clinic team; and an appraisal of the upper-extremity training program, by Mr. Chester C. Haddan of Gaines Orthopedic Appliances, Inc., Denver.

Following these presentations, there is to be a panel discussion of recent European developments in prosthetic devices. Serving as discussion leader will be Dr. Craig L. Taylor of UCLA. Other panel members will be Mr. Carlton Fillauer of Fillauer Surgical Supplies, Chattanooga; Dr. Eugene F. Murphy of the VA's Prosthetic and Sensory Aids Service, New York; Mr. Basil Peters of B. Peters Company, Philadelphia; and Mr. William Tosberg of the NYU-Bellevue Medical Center, New York. All of these people have recently returned from extensive travels on the Continent.

Autumn Meetings

On Thursday, September 30, at the National Academy of Sciences, Washington, there will be a meeting of the Lower-Extremity Research and Development Panel. Since the previous meeting in February at the U.S. Naval Hospital, Oakland, where lower-extremity clinical studies and development work now are largely centered, considerable progress has been made in this difficult field. These and other matters will come before the Panel for consideration. On the following day, the Upper-Extremity Panel will take up problems growing out of research, development, and application in upper-extremity prosthetics, particularly as a result of experience at the UCLA Training Center and in the field work being supervised by the NYU group at Veterans Administration and civilian clinics throughout the country. Finally, on Saturday morning, October 2, there will be a combined session of the Upper- and Lower-Extremity Technical Committees to review over-all progress for the preceding year and to make such recommendations as seem indicated.

These meetings are of special interest at this time because they mark the end of the first year's experience with a new idea in coordination and guidance in the two areas of upper- and lower-extremity prosthetics. Under this plan, small committees or "panels" of specialists, in the fields of medicine, prosthetics, engineering, and other professions related to the problem of amputee rehabilitation, study results of research, development, and application under the Artificial Limb Program while keeping in constant touch with activities through monthly reports and periodic meetings. Since the various contractors and cooperating laboratories of the Veterans Administration and of the Armed Services, as well as the prosthetics profession, are represented on the panels, collaboration is facilitated, duplication of effort is avoided, and action can be taken to expedite translation of tangible results of the Program into actual application in the amputee clinic and limbshop. In this undertaking, the combined technical committees, meeting annually at the time of the OALMA Assembly, assist by giving general direction to the Program and by making appropriate reports to ACAL for its information and guidance in presenting recommendations to the Veterans Administration, the Armed Services, or to medical and prosthetics groups concerned with the problem of amputee rehabilitation in general.

Prosthetics Bibliography

The Advisory Committee on Artificial Limbs has undertaken to compile a comprehensive and fully annotated bibliography of all important published material on the broad subject of amputations, prostheses, and amputee rehabilitation in general. The intent is to include in the listing all significant books, pamphlets, manuals, motion pictures, research reports, journal articles, patents, and related material as appropriate. All aspects are to be covered, including the surgery of amputation; preoperative and postoperative care; physical therapy; psychological problems; investigations of pain, real and phantom; studies of the anatomy, physiology, and biomechanics of human limbs of importance in prosthetics design; engineering studies; design and construction of prostheses themselves; matters concerned with fitting, training, and evaluation; cineplasty; and all other subjects related to amputee management in whatever way. Accordingly, all readers of ARTIFICIAL LIMBS are invited to submit lists of items published by them or by their groups within the last 20 years. Contributors of such material will be furnished copies of the completed bibliography without cost.

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

The National Academy of Sciences—National Research Council is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare.

The Academy itself was established in 1863 under a Congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the Federal Government in scientific matters. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency.

The National Research Council was established by the Academy in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the Academy in service to the nation, to society, and to science at home and abroad. Members of the National Research Council receive their appointments from the President of the Academy. They include representatives norninated by the major scientific and technical societies, representatives of the Federal Government designated by the President of the United States, and a number of members-at-large. In addition, several thousand scientists and engineers take part in the activities of the Research Council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the Academy and its Research Council thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the Government, and to further the general interests of science.