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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

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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

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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 Paré (*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, limb-making 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 side-bars and molded leather corsets similar to those used in braces. At the time of the Napoleonic Wars, the wooden leg, used from earliest times, was provided, for example, by Potts of London for the Marquis of Anglesey and others (*40,86*). Wood reinforced by rawhide was used customarily in the United States, although a variety of other structural materials has been suggested in the journal literature and in patents.

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

WORLD WAR I

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

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

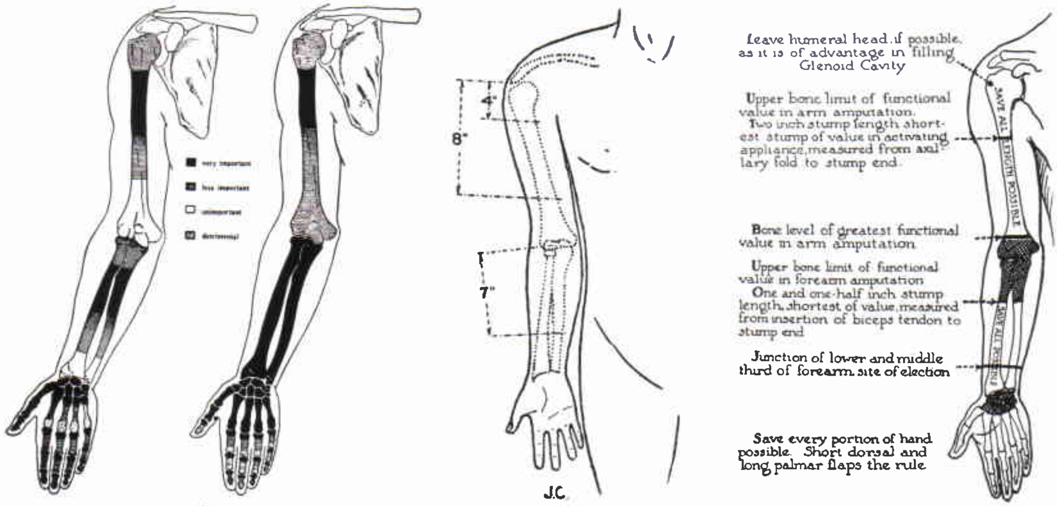
For the upper extremity, a great many artificial arms, hands, and working tools were developed during World War I, as can be seen from the major books on prostheses of the period (*17,50,58,59,80*). American designers generally used the split mechanical hook closed by rubber bands and separated from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

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

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

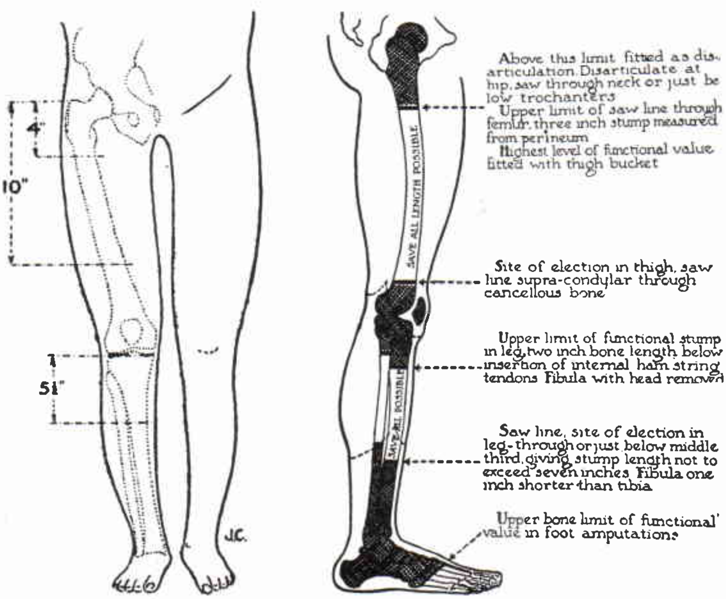
WORLD WAR II

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



A *B* *C*

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.



A *B*

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.

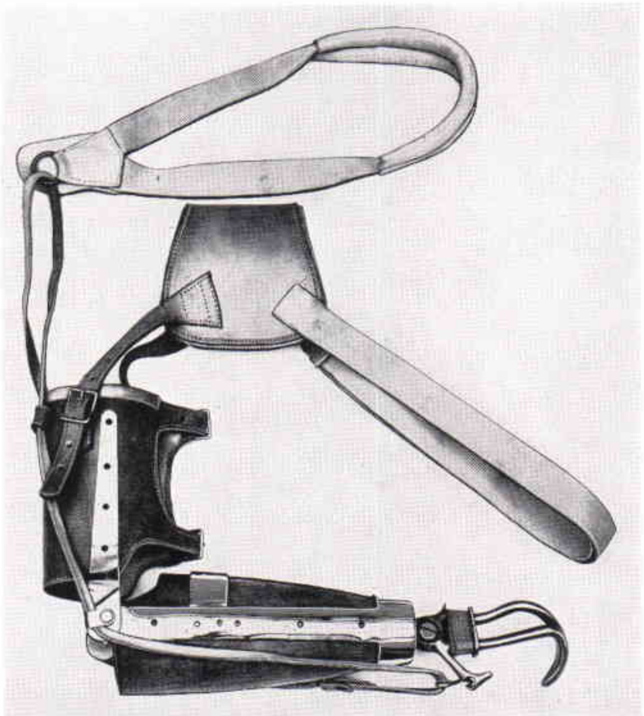


Fig. 3. Typical prosthesis for amputation below the elbow, made about 1945–47. Note modled leather socket, steel sidebars and single-axis joints permitting elbow flexion only, full upper-arm cuff with two straps, heavy leather shoulder saddle and webbing cheststrap, and double leather thong passing over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

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.

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

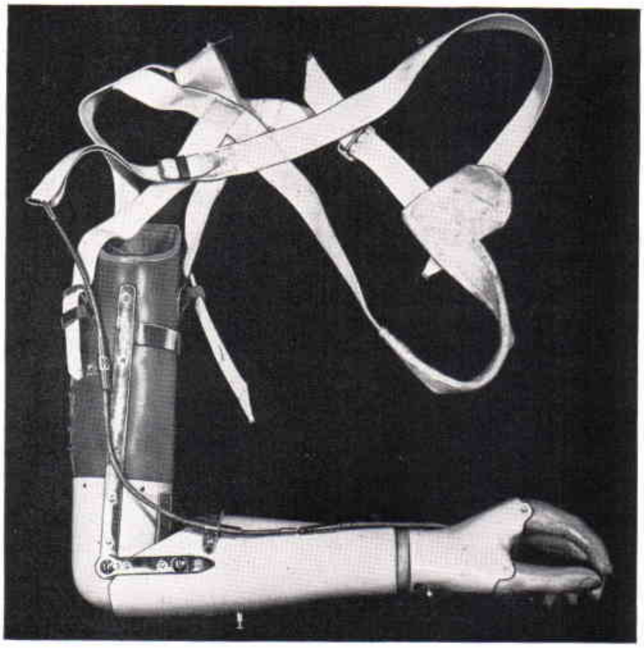


Fig. 4. Conventional prosthesis for amputation above the elbow, made about 1945–47. Note the molded leather socket (with the unusual rear opening and laces), wooden elbow shell and forearm, and push button projecting from lower surface of forearm to control elbow locking by pressure on table top through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