The Lower-Extremity Clinical Study—Its Background and Objectives[1]

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IF IT may be postulated correctly that the most satisfactory artificial leg is the one which most nearly simulates the static and dynamic behavior of the natural limb it replaces, the successful practice of lower-extremity prosthetics poses a twofold requirement. The first is an intimate and detailed knowledge of the characteristics of the normal leg in all common activities, and the second is the ability to reproduce as nearly as possible, by a combination of design and fit of the substitute limb, the kinetic and kinematic features essential to normal locomotion. In the Artificial Limb Program, principal responsibility for fundamental studies in normal and amputee gait and in lower-extremity prosthetics has, since 1945, resided in the Prosthetic Devices Research Project at the University of California, Berkeley Campus.

But the problems facing the leg amputee are not wholly prosthetic. Many, indeed, are clearly medical. For the amputee, being no longer the whole normal individual, manifests gross structural and physiological changes to be dealt with successfully only by the physician. The Lower-Extremity Clinical Study being conducted jointly by the Department of Engineering, University of California, Berkeley, and the University of California Medical School, San Francisco, and in cooperation with the U. S. Naval Hospital, Oakland, has as its chief objectives the analysis of medical problems inherent in the amputated state and the application of fundamental knowledge to practical problems in the management of lower-extremity amputees. Current techniques and practices in the fitting of leg amputees still are so varied from place to place and from prosthetist to prosthetist that some orderly means has been wanting for establishing what is, everything considered, the best prosthetics practice in the lower extremity. Designed to close the gap between basic work in the laboratory and work in the field, the Clinical Study is an outgrowth of the fundamental research in locomotion conducted earlier by the Berkeley Project.

THE BACKGROUND

For a number of years during World War II a group at the University had been conducting research in the field of biomechanics and had published data relating to the behavior of the upper extremity. In the autumn of 1945, therefore, the University was approached by a representative of Northrop Aircraft, Inc., a company which at that time was already engaged in prosthetics research *(70)* under contract with the then Committee on Artificial Limbs of the National Academy of Sciences—National Research Council. It was requested that the University group undertake an investigation aimed at providing information that

[1] Based on two lectures delivered September 29, 1954, before the Scientific Assembly of the Orthopedic Appliance and Limb Manufacturers Association, Chalfonte-Haddon Hall, Atlantic City, New Jersey. Produced here through the courtesy of OALMA.

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could be utilized in the design and construction of lower-extremity prostheses.

The suggestion having been taken under advisement, the entire Committee on Artificial Limbs met at the University shortly thereafter to consider the proposal and to evolve details of contractual arrangement. Out of this meeting came two basic observations. One was that, inasmuch as the financial support for the work was to come from public funds, any information derived from the contract would have to be shared with all other contractors participating in the Artificial Limb Program as well as with the general public. The other was that, in the opinion of the conferees, between five and seven years of study would be required before sufficient detailed and quantitative information could be accumulated to effect substantial improvement in lower-extremity prostheses *{113)*. At the outset, the University group insisted that it be kept free of the task of developing prosthetic devices—that it simply be permitted to investigate normal human locomotion and to furnish the collected data for others to use. The original concept of the scope of the project—as a program of basic research in human locomotion—has been adhered to up to the present time, the only deviations having involved development of experimental devices *(24,25,80,81,82,95,102, 112)* needed to assist in the locomotion studies.

The early years, then, were spent in working out techniques suitable for recording objectively the motions and the forces involved in the gait of man *(22)*. Of course, the investigators took advantage of all the previous work in this field, not only that done by other contractors *(1,12,49,51,67,71)* participating in the Artificial Limb Program but also that contained in material, particularly that of Elftman*(26,27,28,29,30,31,32,33,34,35,36,37,38,39, 42,43,44)*, published in the United States and in foreign countries over a period of many years. By 1947, enough data had been accumulated to publish a comprehensive report *(102)* on the walking pattern of normals and of leg amputees.[4]

Attempts to translate the results of basic research into criteria for the improvement of prosthetic devices led to the second phase of the project, that is, to developmental research, an area that involves engineering and prosthetics technology. During the last few years, this phase of the project has been conducted on a relatively small scale. As devices were prepared for trials by amputees, the problem of fit and alignment had to be attacked, and hence fundamental studies were undertaken in this area in order to establish a set of basic principles and techniques *(103,104,106,108,110)*. Because fitting and alignment contribute most to the comfort and therefore to the success of any artificial leg, the validation of these principles and techniques formed the basis for embarking on the third phase of the project, the Lower-Extremity Clinical Study, an activity that provides a laboratory where medical and prosthetic problems can be handled under controlled conditions. It offers an opportunity to see how individual solutions may be obtained by applying a set of general principles based on biomechanical considerations. Until recently, the study group has been concentrating on the problems of the above-knee amputee because that case appeared to offer neither the most difficult nor simplest set of circumstances.

THE LOCOMOTION STUDIES

Muscle Physiology

When the Prosthetic Devices Research Project first was organized, man was viewed as a machine, the object being to measure the displacements, accelerations, and forces required in human locomotion *(4,7,14,15,18,19,21,47, 48,96,105)*. But man is more than a single machine. He is powered by a complicated system of many internal engines served by muscles. Accordingly, the study was broadened to include the field of muscle physiology *(73,74,75,76,77,92,100)*. Investigation of the behavior of the musculature during normal locomotion (Fig. 1) revealed the basic action of the various muscles involved *(8,52,111)*. It was

[4] The 1947 report *(102)* contains an extensive bibliography of earlier work, mostly German, on the mechanism of human locomotion and on related matters. It is available, either in photostat form or on microfilm, from the U. S. Armed Forces Medical Library, 7th Street and Independence Ave., S. W., Washington 25, D. C

shown that in locomotion each muscle acts when it is near its rest length but that it acts for a very short period of time in each walking cycle *(60).* This action makes the contraction essentially isometric and limits the activity of each muscle fiber to a few twitches. Under these conditions the muscle works with minimal energy and maximum tension, which helps to explain why a person can walk considerable distances without tiring.

Upon working out the speed of contraction, it was found that, if muscles are halved, their contractile velocities likewise are halved (Fig. 2). Utilizing a profile electromyographic recording (electromyogram rectified and dampened to give a relatively smooth line), and taking the maximum amplitude in a given cycle as 100 percent, the average durations with an amplitude greater than 75, 50, or 25 percent are approximately 0.04, 0.1, and 0.2 second, respectively *{55,56,58,61,62,89, 116).* Since it seems probable that the profile electromyographic amplitude largely indicates relative numbers of active motor units, it would appear that most of the units participating in this phasic action are active during bursts of 0.1 to 0.2 second only. According to Weddell *{115),* at a repetition rate of 20 per second or less most motor units would fire in each cycle one to four times only. In such a case, any temporal summation taking place at neuromuscular junctions would not be effective fully, and the action of a motor unit, at least in a normal phasic pattern like locomotion, would not have the character of a sustained tetanus.

As a result of these investigations, in 1947 the group at Berkeley, noting the earlier work of Blix *{11),*

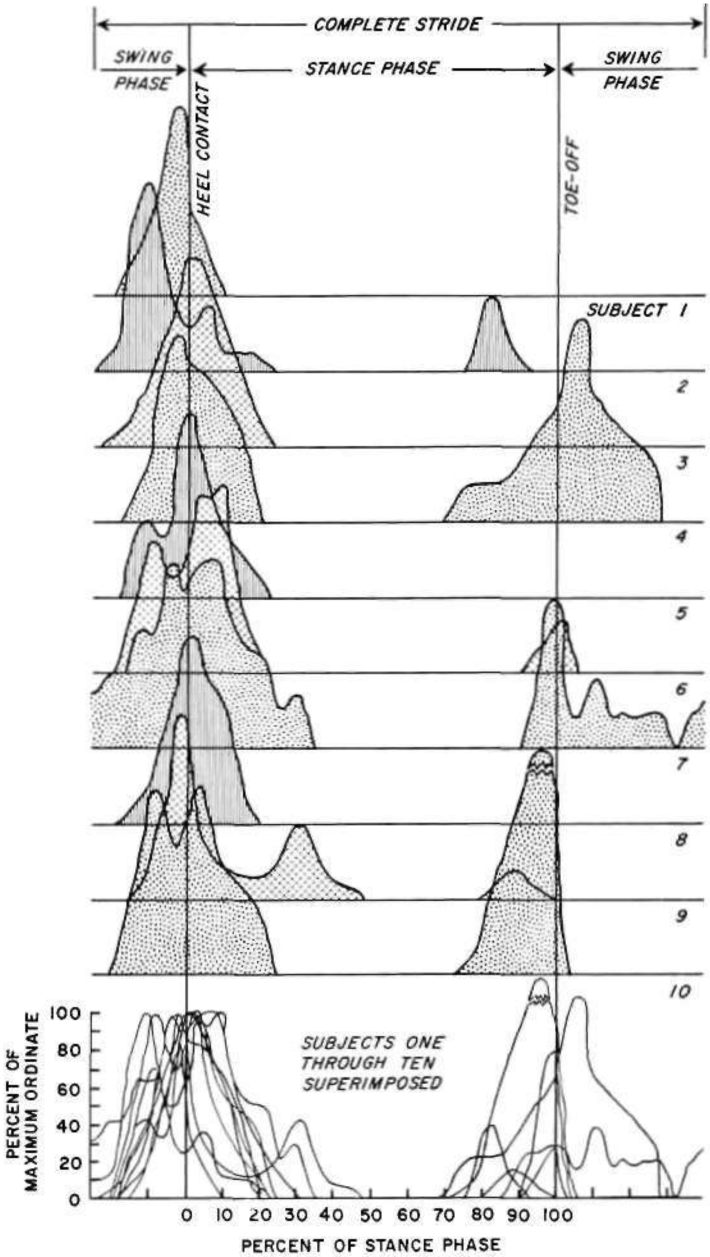


Fig. 1. Typical electromyographic summary curves, in this case for the hamstring group. Ten subjects. Cadence: 95 steps per minute, level walking. Data from UC studies *{102).*

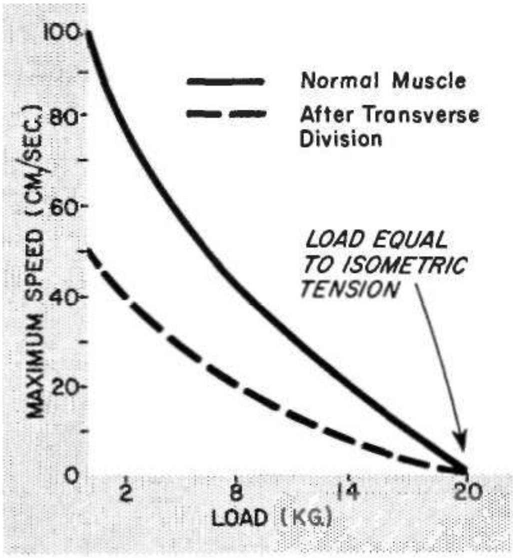


Fig. 2. Relation between the maximum speed with which a muscle can contract and the weight with which it is loaded. When the length of the muscle is halved, its speed of contraction is also halved.

was first to call attention to the length-tension relationships existing in human muscles *(57,63, 64,83,84,85,86,87,90,91,93,94)* and thus laid the basis for the decision to use certain muscles for the cineplastic technique *(2,3,9,99).* The characteristics of the length-tension diagram have since proved to be of fundamental importance in devising prosthetic aids for upper-extremity amputees *(10,101,107).* The cineplastic muscle tunnel, comprising a skin-lined tube placed through the distal end of a muscle, permits an amputee to utilize effectively his own muscle forces for activating an artificial arm or hand. But in order to operate a cineplastic prosthesis efficiently, it is necessary that the muscle be near its rest length, so that it can generate a force sufficiently large and so that it can shorten enough to carry out necessary movements *(17).* Appearing in publications as early as 1949, the work conducted at the University of California has been recognized by Buchthal *(17)* of the University of Copenhagen as the best so far done on normal human muscle dynamics.

Energy Requirements

In another study, an investigation was made of the dissipation of energy (Fig. 3) in human locomotion *(13,14,15).* Results showed that approximately 50 percent of the energy consumed in walking is used simply in bouncing up and down, that is, in vaulting over one leg and then the other. The other half is used in the oscillations of the legs. It is therefore apparent that, if the amputee is not to be subjected to unduly large energy demands, he must have a smooth pathway of displacement of the center of gravity of the body *(23,40,41).* Any deviation from the smooth, natural locus of the center of gravity means excessive dissipation of energy and consequent degradation into heat *(53,97).*

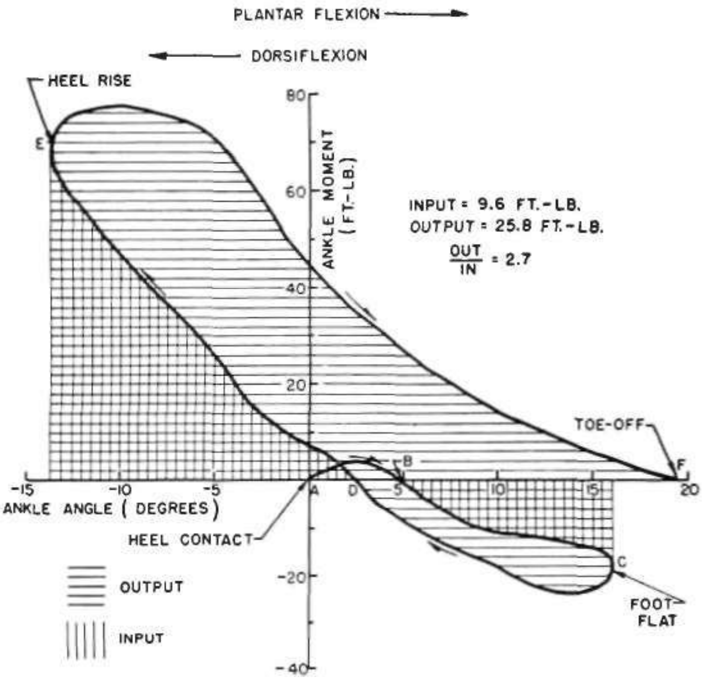


Fig 3. Typical moment-angle diagram for the leg of a normal subject during level walking. From Bressler *[sic]* and Berry *(14).*

Contrary to much popular belief, man not only pushes his way through space. He also *pulls* his way *(15,102,105)*. Indeed, deceleration of the swinging leg, not push-off from the other toe, provides the greater part of the energy for locomotion, the proportion attributable to deceleration of the swinging leg being about 4, that attributable to push-off only 3. Energy is absorbed by the knee to decelerate the leg and foot during the swing phase, but not all of the energy so absorbed is lost *(4)*. A considerable portion is stored and returned to the system in the later part of the swing phase to impart continued forward acceleration at the time when most of the body's potential energy is lost *(48)*. Thus locomotion is due not only to the push of the member in support but also to the pull of the deceleration in the swinging knee.

Because the above-knee amputee has no calf group, and therefore cannot contribute the equivalent of this force at push-off, it was suggested that some conservation of energy might be effected in a prosthetic device without an ankle joint *(78)*. That this was a correct deduction has since been demonstrated (Fig. 4) in the Stewart-Vickers leg *(20,69,112)*, in which the ankle is locked at toe-off until 20 deg. of knee flexion has occurred *(114)*. It has the highest net output and the lowest total input of all legs tried to date (Fig. 5).

AMPUTEE PAIN

Intimate contact with amputees led to the early investigation of pain as related to the amputee patient *(65)*. In 1946 a team of interviewers set out to question amputees in various hospitals, particularly in the Veterans Administration Hospitals and in the Naval Hospital then at Mare Island. Over a period of a year and a half, detailed histories were obtained from 80 patients. As a result of this review, further funds were provided by ACAL to establish a Pain Clinic at the University of California, primarily to evaluate pain as found in the amputee. Established in August 1949, the clinic functioned until January 1953.

In June 1952, an analysis of 218 amputees was reported *(109)*. In this study, which constitutes one of the largest series on record, the type and frequency of pain in the amputee were explored. Because it was thought that perhaps deficiencies in stump circulation might contribute to the pain experienced by the amputee, circulatory studies were undertaken. Concurrently, innervation of the deeper tissues was studied *(54)*. Sections of tissue were taken from periosteum, muscle, and skin, and the

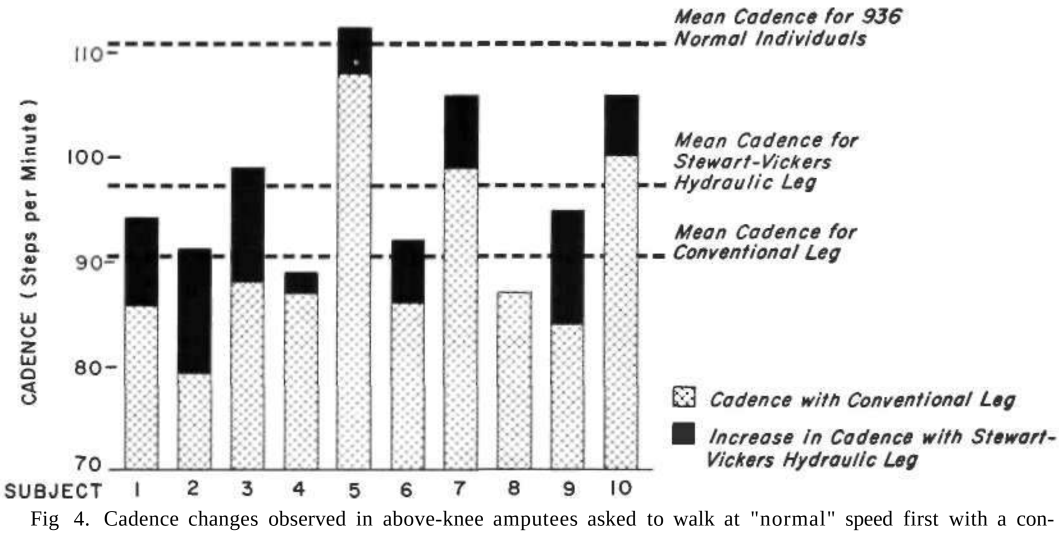


Fig 4. Cadence changes observed in above-knee amputees asked to walk at "normal" speed first with a conventional limb and then with the Stewart-Vickers (locked ankle) prosthesis *(114)*.

nerve supply to these tissues was demonstrated by a methylene blue technique.

One of the most intriguing aspects of this investigation was the work with normal individuals in whom irritative lesions purposely were produced in the deeper tissues *(45,46,109)*. With the authors, some 75 medical students, and three laboratory assistants serving as subjects, 0.5 to 1.0 cc. of 6-percent saline solution was injected systematically into the paravertebral muscles at each intervertebral level from the atlanto-occipital area to the lower sacrum. Five subjects were used in the testing of each injection site, a total of 140 individual observations being made. Although the distribution of pain approximated a segmental plan, it also overlapped considerably and differed in location from the conventional dermatomes. It was found that, in any irritation of deep somatic tissues, pain did not restrict itself to the area of injection but tended to radiate distally into the extremities. Injection of 6-percent saline into any given interspinous level produced in the normal a characteristic pain distribution that was remarkably constant from subject to subject.

The distribution of pain referral from deep structures in the normal suggested similar investigations in the amputee. To elicit the sensation of the phantom limb, it was necessary to inject the salt solution into the appropriate interspace. In the normal, radiation of pain into the lower limb was most marked when the interspinous tissue between L4 and L5 was affected, and in the above-knee amputee the L4-L5 interspace also gave the best response. The immediate reactions of amputees resembled those reported by normals—a rapid onset of pain close to the site of injection and then, in the case of L4-L5 injection, radiation into the buttocks and the posterolateral aspect of the thigh. In nearly all instances there occurred a rapid "filling" of the absent areas of the phantom limb, the subjects usually evidencing surprise at the sudden totality of a

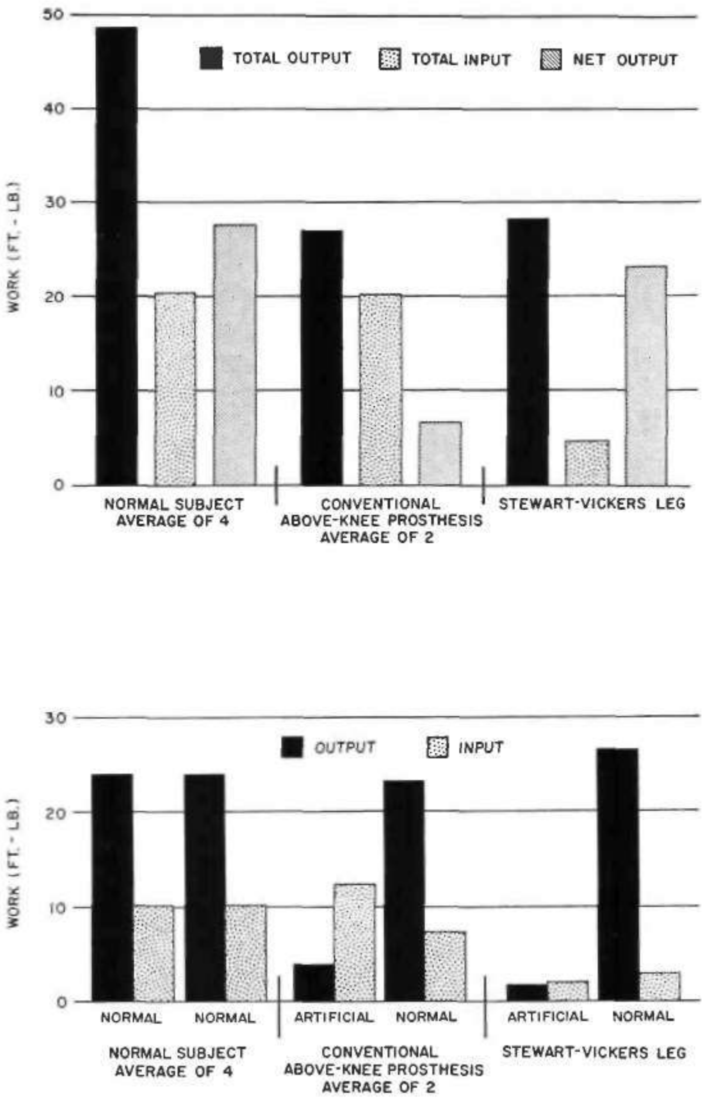


Fig. 5. Energy characteristics of the normal ankle compared with those of the conventional leg and the Stewart-Vickers leg. Top, total input, total output, and net output of both ankles per stride. Bottom, input and output of each ankle per step.

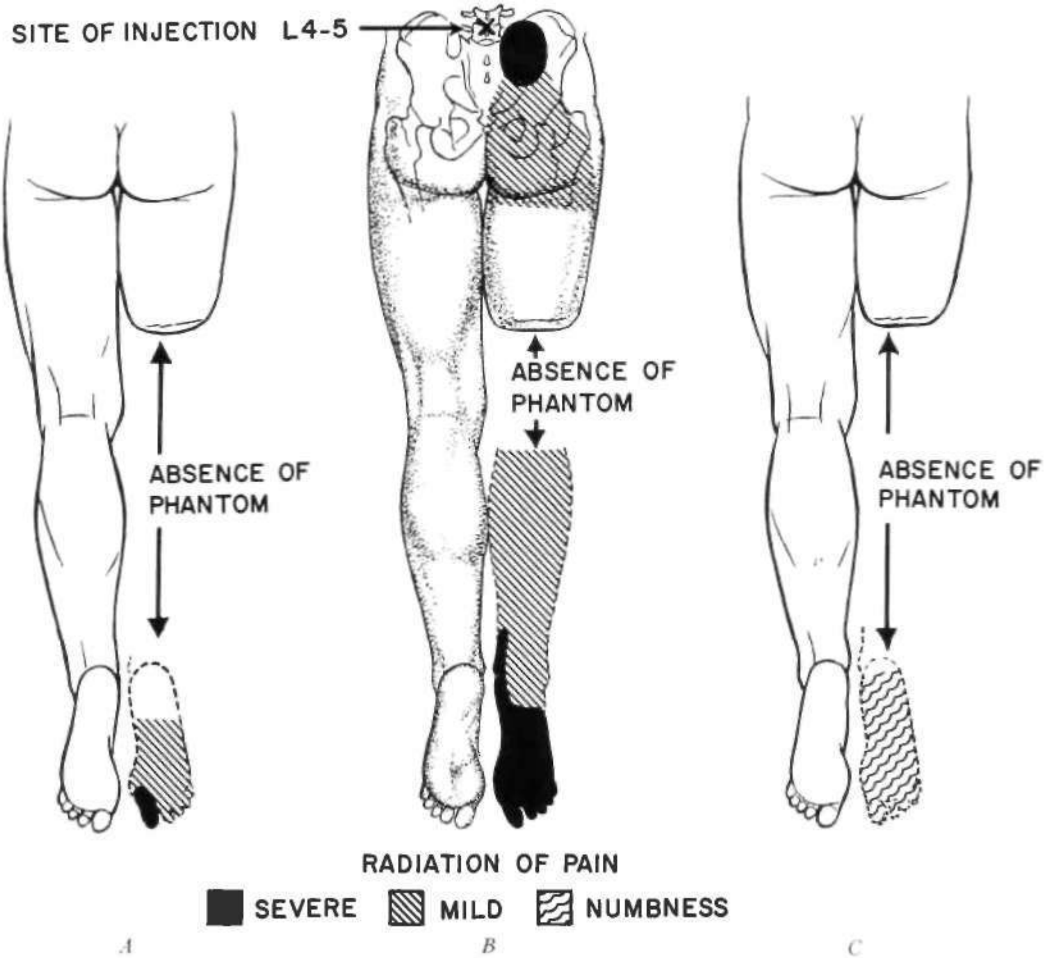


Fig. 6. Effect of interspinous injection of saline on the painful phantom limb of one subject. *A*, Phantom before injection. *B*, Radiation of sensation induced by injection of 6-percent sodium chloride solution. *C*, Residual sensation following injection.

phantom limb even though the new portions were seldom, if ever, immediately painful.

Severe pain was a frequent feature in the portion of the phantom present before injection. After injection the pain often spread into the newly "filled in" portion of the phantom limb. Transient pain following injection occurred in phantom limbs regardless of the existence of preinjection pain. But in many cases involving pre-existing phantom pain, a secondary decrease in the amount of pain followed the injection, in some but not in all instances the decrease being preceded by a transitory accentuation of the pre-existing pain. Occasionally, the decrease reached the point where no pain was felt, so that the amputee experienced the first complete relief in many months.

The decrease in pain is even more remarkable when one considers that it is brought about by the application of a noxious stimulus to a tissue remote from the phantom itself. For example, in an above-knee amputee who had undergone amputation two months before the investigation, there was a phantom sensation of the "foot" only, the phantom being very painful with the sensation of severe constriction of the great "toe" (Fig. 6). When saline was injected into the L4-L5 interspace, much of the intervening phantom limb was filled in almost immediately, the anterior aspect of the "leg" becoming the most prominent part. Soon after the phantom was "completed," the preexisting pain in the "foot" increased in intensity and area. This state continued for five or six minutes, whereupon the pain began to decrease and continued to do so until, in another five minutes, it had disappeared completely. Numbness, but not pain, remained in the "foot" only. In some instances even phantom awareness disappeared after saline injection.

In general, the saline injections had greater effects on phantom limbs than on real ones, a peculiar susceptibility best illustrated by the effects of mid-line injections. An accurately placed mid-line injection in a normal subject produces very little radiation, the severe pain being confined to a rather small area in the immediate vicinity of the injection. In the case of the amputee, however, such minimal radiation in the trunk is accompanied by profound effects on the phantom extremity. Every conceivable change in phantom form and phantom pain can result from interspinous injection of an irritating hypertonic saline solution, the changes probably stemming from the sudden increase in the sensory inflow at the particular segmental level.

Out of these observations came, then, one method of treating phantom pain, for when a small amount of hypertonic saline was injected into the appropriate segmental interspinous ligament, the phantom experience was changed and pain occasionally was relieved. This finding led to the use of hypertonic saline for the treatment of various painful conditions. Although permanent cures resulting from such techniques are not numerous, the method may prove to be a valuable addition to the modern medicine chest, which is by no means rich in effective pain palliatives *(98)*.

It deserves to be noted that, in seeking the origin of the phantom experience, one must look not only for direct involvement of the nerves of major nerve trunks. The entire segment of the extremity must be investigated for any irritative skeletal lesions arising from the joints, the muscles, or the connective

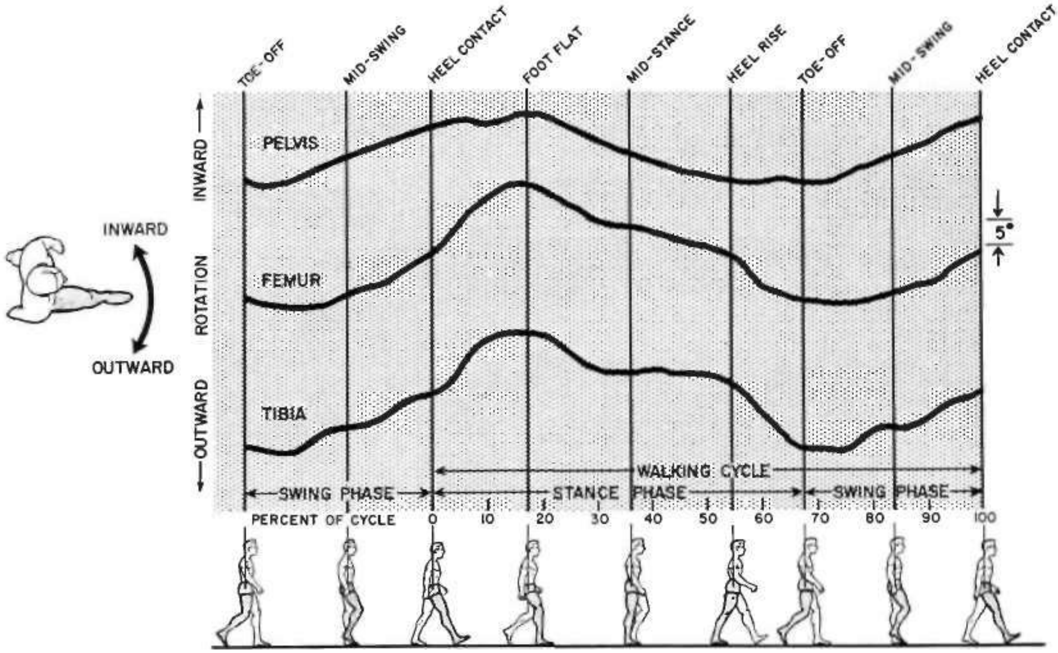


Fig 7. Typical relative rotations of the pelvis, femur, and tibia in normal, level walking. Data from UC studies *(102)*.

tissues of the stump or from portions proximal to the stump.

EVOLUTION OF BASIC DATA

From the basic studies now has come much information of value in prosthetics. As early as 1947 it was determined *(59)* that in normal walking the leg rotates in space internally and externally about 15 deg. on the average (Fig. 7). That this horizontal rotation of the extremity might be of some importance in human locomotion has since been known as the "Berkeley fetish," and as far as is known no one has yet taken cognizance of the fact in any successful limb design. In 1950 it was suggested *(79)* that it would be of considerable value if deceleration at the end of the swing phase could be incorporated through some sort of variable-cadence knee joint. This has been done in at least one device, the U.S. Navy above-knee leg *(68,112),* now available commercially (see *Digest,* this issue, page 65). Several others currently are under development.

At the same time it was suggested that, inasmuch as the above-knee amputee can obtain no forward propulsion by contraction of the calf group, the ankle joint is of little use—that, indeed, if an ankle joint with rubber bumpers is used, energy is lost by hysteresis of the bumpers. As already mentioned, the improved performance of the Stewart-Vickers leg, in which the ankle is locked at toe-off up to 20 deg. of knee flexion, proves the validity of the original observation. Similarly, it was pointed out that, because of the interrelationship between the ankle-foot function and the knee-joint function, greater stability would be required of the knee joint were the articulated ankle to be abandoned.

In 1953, Saunders, Inman, and Eberhart *(97),* summing up the results of all the basic studies, pointed out that there is an interrelationship between all displacement patterns of all segments of the lower extremity, that there are six major determinants in locomotion, that modification of one results in modification of the others, and that any changes in the knee or ankle, either in normal or in amputee, are necessarily accompanied by compensatory changes in the remaining joints. Basically, locomotion is the translation of the center of gravity through space along a pathway requiring the least expenditure of energy (Fig. 8). The six major determinants of the pathway are pelvic rotation, pelvic tilt, knee flexion, knee extension, knee and ankle interaction, and lateral displacement of the pelvis. Serial observations of irregularities in these determinants provide insight into individual variation and a dynamic assessment of pathological gait, which may be viewed as an attempt to preserve the lowest possible energy consumption by exaggerating motions at unaffected levels. Compensation is reasonably effective with the loss of one determinant, that at the knee being the most costly. Loss of two determinants makes effective compensation impossible, the cost of locomotion in terms of energy then being increased threefold, with an inevitable drain upon the body economy.

With regard to the surgery of amputation, the studies in muscle physiology suggested that considerable improvement might be effected in lower-extremity prosthetics were muscles fixed in the distal end of the stump so that they could not retract *(88).* As previously pointed out, retraction of these muscles means shortening, and shortening means an inability to develop natural tensions. More recently the studies have suggested that, in order to retain normal weight-bearing through the shaft of the femur, more attention should be paid to the possibility of end-bearing rather than to the more conventional method of weight transmission through the ischial seat. All of these ideas, derived from the results of the early studies on locomotion, were offered to the limb industry by the University group in the hope that designers or manufacturers would incorporate the recommended features into new prostheses.

THE CLINICAL STUDY

In the spring of 1953, after years of basic study, the question arose as to what might be done toward applying to the amputee problem some of the knowledge gained. After several months of discussion, the UC Prosthetic Devices Research Project accepted a proposal to institute the so-called "Clinical Study," the principal objective being to draw upon the

Fig. 8. The sum of the effects of the six determinants of gait. The pathway of the center of gravity is a smooth curve in both horizontal and vertical planes. From Saunders, Inman, and Eberhart *(97),* by permission of *The Journal of Bone and Joint Surgery.*

pool of fundamental knowledge, to attempt to apply it toward the solution of practical problems, and to see whether or not there would emerge certain definite devices or methods which could be passed on to the artificial-limb industry and to prosthetists. Last year, then, the clinical program was established, and currently it is the center of attention.

To organize such a clinical study obviously required a limbshop and examining rooms. Through the kindness of the Navy, space was afforded at the Navy Prosthetics Research Laboratory at the U.S. Naval Hospital at Oakland, California. There the setup includes a small limbshop where prosthetics work is done, a medical examination room, fitting and training rooms, an evaluation and photography room, and conference rooms, the entire operation being conducted in cooperation with the limb industry. Through the Industry Advisory Committee, amputees are selected on the basis of referral by limbshops, by physicians, by rehabilitation agencies, by the Veterans Administration, and by direct personal contact. After preliminary screening by the Clinical Study Group, an individual is selected only with the approval of the Industry Advisory Committee, and all of the work is done with the knowledge, assistance, and cooperation of the artificial-limb industry.

Because it is concerned primarily with research, the Clinical Study is not a commercial operation, and consequently production is not high and is not supposed to be. Thus far only 16 subjects have entered the clinic. Of these, 10 are unilateral above-knee amputees ranging in age from the teens to the seventies, two are bilateral above-knee cases, one is a bilateral above-knee/below-knee case, two are hip-disarticulation cases, and one is a unilateral below-knee case. Five are in the follow-up stage, six in the postfitting adjustment stage, three in the fitting stage, and two in the pre-prescription stage. All save one have been complicated cases, presenting difficult problems that nobody else wished to tackle. From particular cases such as these have come practical answers for other difficult cases.

A thorough and complete study—from the medical, biomechanical, and prosthetic points of view—is made of each case, and individual problems are diagnosed and corrected. To find the best possible solution in any particular case requires a knowledge of what attempts have been unsuccessful and why they failed, for sometimes a great deal more is learned by determining why one proposed solution failed than by determining why another was successful.

THE CLINIC TEAM

The clinic team consists of an orthopedic surgeon, a prosthetist, a physical therapist or amputee instructor, and sometimes an engineer (5). This group makes the initial evaluation and provides a prescription *(6)* based on complete data including a medical history, an analysis of existing condition of the stump and of the rest of the body, and an evaluation of the old prosthesis. The prescription is reviewed by the Clinic Study Panel, including several orthopedic surgeons, a psychiatrist, a prosthetist from industry, and an engineer familiar with prosthetic problems. Once the prescribed device is fitted, the results are viewed by the Panel, and the reasons for success or failure are documented fully so that the case may serve as an example for future reference. No experimental devices are used in the clinic program. Only those devices available commercially are fitted to the subjects.

INDUSTRY PARTICIPATION

Active participation by individual members of the artificial-limb industry has not yet started, but plans are now being made for such activity in the immediate future. That part of the program will involve working with prosthetists, screened by the industry, who will visit the clinic for a period of orientation. They will follow cases through the clinic study and then be assigned a shop case on a cooperative basis. The clinic team will act initially as a review committee in preparing the prescription, but the individual prosthetist will fill the prescription in his own shop. After fitting, the amputee and the prosthetist will return to the clinic for evaluation. This procedure provides a twofold check. It evaluates the prosthetist's degree of efficiency and tests the validity of the clinic's method of prescription.

PROSTHETIC PROBLEMS

Crotch Pressure

Because enough time has now elapsed to be sure that more than temporary success has been achieved, some general ideas can be discussed with a fair degree of confidence. The most common complaint heard by the group relates to crotch pressure. In every instance, however, the condition has been eliminated. Correcting for excessive crotch pressure involves two things—the right socket shape and correct alignment (page 35). Proper socket shape is ensured by providing for ischial-gluteal bearing (which prevents sinking into the socket), by controlling the anteroposterior dimension, and by raising the height of the socket brim.

Localized Socket Pressure

The next most common complaint relates to edema. Rarely has there been a case of the suction socket where edema could be traced to high negative pressure alone. Excessive crowding or tightness invariably were contributing factors. Edema may result principally from a high rate of pressure change at any point along the length of the stump. Because emphasis has been placed on socket shape near the top brim, not enough attention has been given to good fit throughout the length of the stump. Any constrictions or ridges, including those formed by muscle groups, cause pressure changes that interfere with venous return. The inside finish of the socket also may be a factor. In one instance, for example, a severe case of edema was alleviated by providing the socket with a smooth, high-gloss finish.

Socket Brim

Skin irritation around the socket brim also is a source of annoyance and discomfort. Accordingly, dermatologists are cooperating in the program. They examine amputees having skin problems and outline procedures for therapy, including the taking of biopsies of the skin. Pigmentation is evaluated to determine whether or not it is due to capillary hemorrhage caused by decreased suction or whether it is merely a pigmentation that often occurs in areas of friction. Out of this study should come a routine test and a new modality of skin care for the leg amputee.

Again, the condition can be eliminated by controlling the shape and height of the anterior and lateral brim above the ischial seat. Medial width also is a controlling factor because it determines the total amount of pressure exerted by the front of the socket to maintain stability on the posterior weight-bearing surface. And, as in the case of edema, the inside finish is important in preventing skin damage. Sitting discomfort, a complaint often heard, usually is relieved by using a flat back, by not having the inside edge of the seat too sharp, and by ensuring that any channel for gluteal relief is not too large.

Alignment

Alignment is a continuing problem, and the development of guiding principles is most important. Although general principles are comparatively simple to state, to understand them fully and to apply them to individual cases is difficult. One of the objectives of the clinical program is to apply to typical problem cases the alignment principles developed through fundamental research and to develop examples showing how these principles can be applied, why they work, and the end-results that can be obtained. Naturally, the best results are obtained when the stump is so oriented as to take full advantage of the remaining hip musculature. There is a growing body of information relating to a number of common problems—problems associated with changing from a pelvic belt to a suction-socket leg; problems concerning the very muscular stump with prominent hamstrings or with some particularly firm muscle or muscle groups isolated in the stump; problems of the short and the long above-knee stump; problems caused by the flabby stump; and problems of inside finish.

MEDICAL PROBLEMS

Often the problems of the amputee, both in the lower extremity and in the upper, stem not from an ill-fitting prosthesis. More often the problems can more properly be termed medical. Accordingly, the Clinical Study includes investigation of those aspects of amputee rehabilitation related to physiological changes associated with loss of limb.

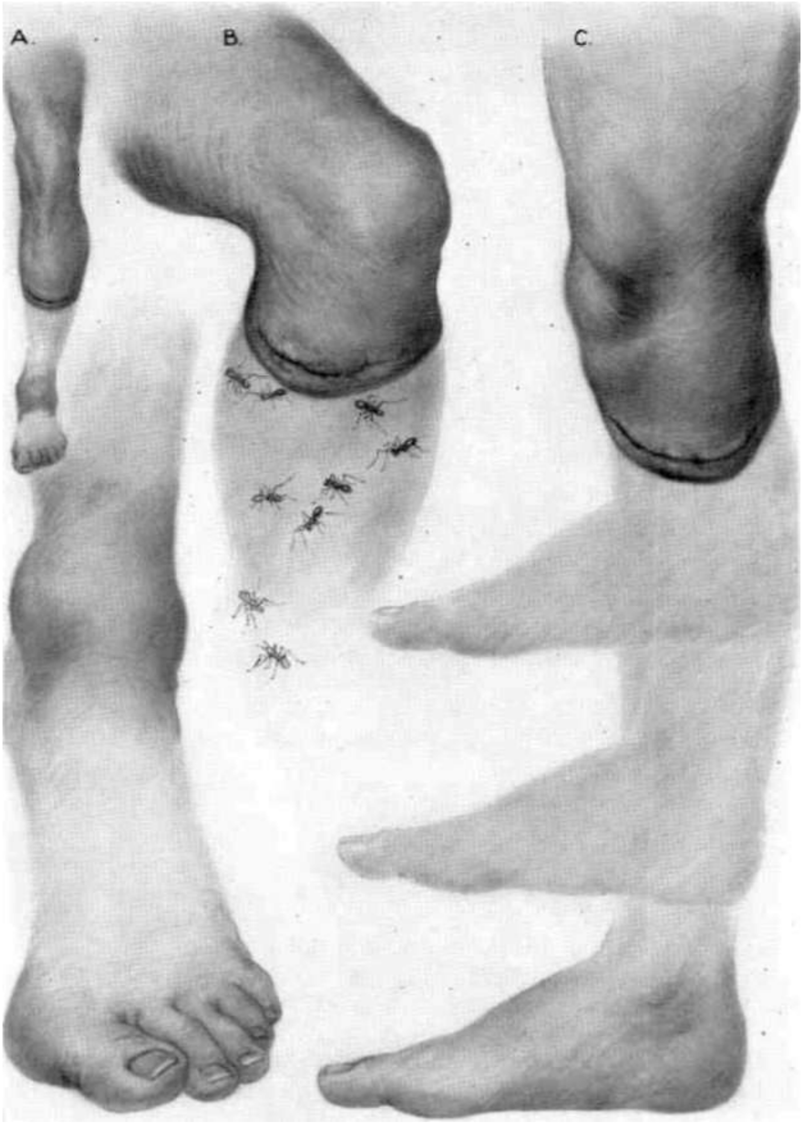
Pain—Phantom and Real

As pointed out long ago *(66.72),* loss of the normal limb so often is followed by the appearance of some form of phantom limb that, when a patient does not acknowledge one, it is suspected that he is withholding information or that the phantom has been repressed. Statistics show that the phantom is a normal phenomenon in the sense that most amputees have it. It is pathological, however, in the sense that the amputee perceives something that actually does not exist.

In general, awareness is a matter of degree and, to some extent, a matter of verbal conventions. Some amputees say that the phantom has the same unobtrusive quality as does the material counterpart, that it appears only when called upon. Sometimes the amputee has difficulty in remembering that the phantom is unreal and that it does not serve in the capacities of its living predecessor. The normal person is not particularly aware of his limbs unless his attention is drawn to them in some way. Except under the impact of a sudden stimulus, or when a special effort is made, preferably together with a movement, our awareness is potential and shadowy in nature. With the eyes closed, and with the limb at complete rest, awareness is, in fact, not too far removed from mere imagination. To make certain that the limb exists, we move it, look at it, or rub some part of it. The amputee cannot conduct such an empirical test.

Sometimes the patient can sense his lost limb as acutely as he can the remaining real one, and he often can imagine that he can "move" the phantom. More often, however, the phantom draws attention to itself by some "abnormal" sensation which makes the amputee more aware of it than he is of his real limb. Fortunately, only a small percentage of all phantoms habitually are painful. Some typical ones are shown in Figure 9.

Frequently the "foot" seems to shorten and approach the end of the stump. The patient illustrated in Figure *9C* experienced "telescoping" of the phantom, a phenomenon which, contrary to the observations of most other writers on the subject, was found infrequently in the Berkeley series. It is true that relatively undifferentiated parts like the calf and the forearm commonly are not felt. Some phantoms of distal parts are, from their onset, situated at the normal distance from the trunk. Others always seem to be located closer to the stump than normal. A few patients experience a gradual shrinkage of intermediate phantom parts, as has occurred over a period of years in the subject illustrated in Figure 10. In this case, all that remains of the shrunken ghost are the "toes," and these have come to lie not in empty space, as is the rule, but inside the stump. Not infrequently a phantom which has shortened may, on application of a prosthesis, lengthen and actually become identified with



[Fig. 9. The phantom limb, a phenomenon of almost universal occurrence among amputees. *A*, Phantom toes and ankle, reported more frequently than are other phantom parts of the amputated lower extremity. *B*, Mild "tingling," characteristic of the painless phantom, is often described in terms of "crawling ants." C, The "telescoping" phantom, in which the foot, over a period of time, gradually approaches the stump and finally disappears within it.

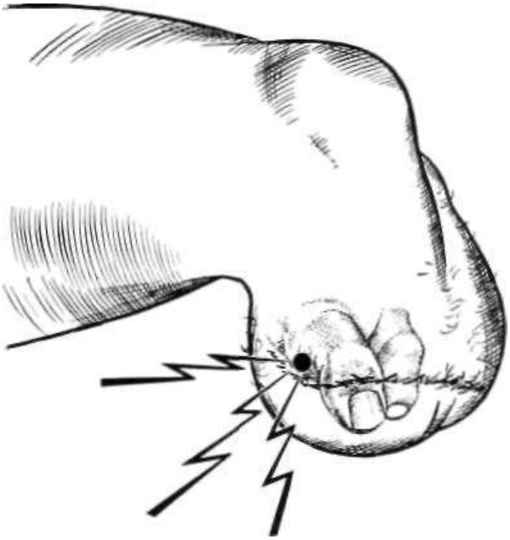


Fig. 10. A rare and peculiar form of phantom experience. Here the two "toes" seem to reside within the stump itself.

the artificial limb. Thus, in one instance, a young above-knee amputee felt as though the shortened "foot" were appended to the stump. When he wore his prosthesis, however, the phantom foot felt as though it were in the position corresponding to that of the artificial foot.

Awareness of the missing member may or may not be described as basically unpleasant, but it is subject to intermittent unpleasant sensations—itching, tingling, or pain (Fig. 11). As pointed out by Livingston *(65),* the pattern of the painless phantom bears no resemblance to the areas of distribution of the major peripheral nerves. Thus the partial nature of the phantom cannot be ascribed to the affection of certain nerve lesions in the stump. Rather, the pattern of the phantom seems to relate to the most mobile parts and to those serving the highest degree of sensory function. But a substantial number of amputees experience, at one time or another, some sort of painful phantom of varying duration (Table 1).

How many amputees have pain? Taking into consideration the inadequacies of follow-up information, the subjective character of the pain experience, and the semantic difficulties beclouding the term "pain," a conservative estimate would be that 80 percent of all amputees are substantially free of pain and are either being trained for useful work or else are already actually so engaged. It is likely that, of the remaining group, possibly half are faced with severe intermittent or persistent pain. Because of persistent, incapacitating pain, approximately 10 percent of all amputees never get into a limbshop, never get out of the doctor's office. They become narcotic addicts and often commit suicide. Where pain enters the phantom syndrome, it may assume large clinical importance. If it is excruciating and persists for long periods, it may take a devastating toll of the whole personality and physical well-being.

In describing severe pain, we all use a vocabulary taken from common objects known to produce injury. Lesser pains are described in terms of cutaneous and deep sensations. Thus we speak of "pressure," of "pins and needles," of "sharp" pains and "dull" aches, of "stabbing" and "shooting" pains. It seems unlikely that man at his present stage of evolution ever will devise a specific terminology for pain because he has no special organ for observing his discomforts. No matter how introspective a person may be, his account of pain always is phrased in imagery taken from other fields of experience. Nothing could be more real than these sensations, but we say "as if" to give them intelligible expression. The vocabulary is metaphorical.

It is not surprising, therefore, to find am-

Table 1

INCIDENCE AND SEVERITY OF PHANTOM PAIN IN A BERKELEY SERIES OF 80 AMPUTEES

Pain Characteristics	No. of Patients	Percent of Total
No phantom pain at any time	24	30
Moderate pain at one time, now gone entirely	18	22
Moderate pain which still occurs	32	40
Severe pain at some time but now gone entirely	3	4
Severe pain which still occurs	3	4
Total	80	100

putees using language akin to that of the torture chamber when they try to do justice to their agonies. They hardly go further than anyone else in telling about physical suffering, Nor do they hallucinate when they talk about "ropes" and "vises," for they remain aware of the imaginary character of these similies. It is possible, however, that, as the tearing and

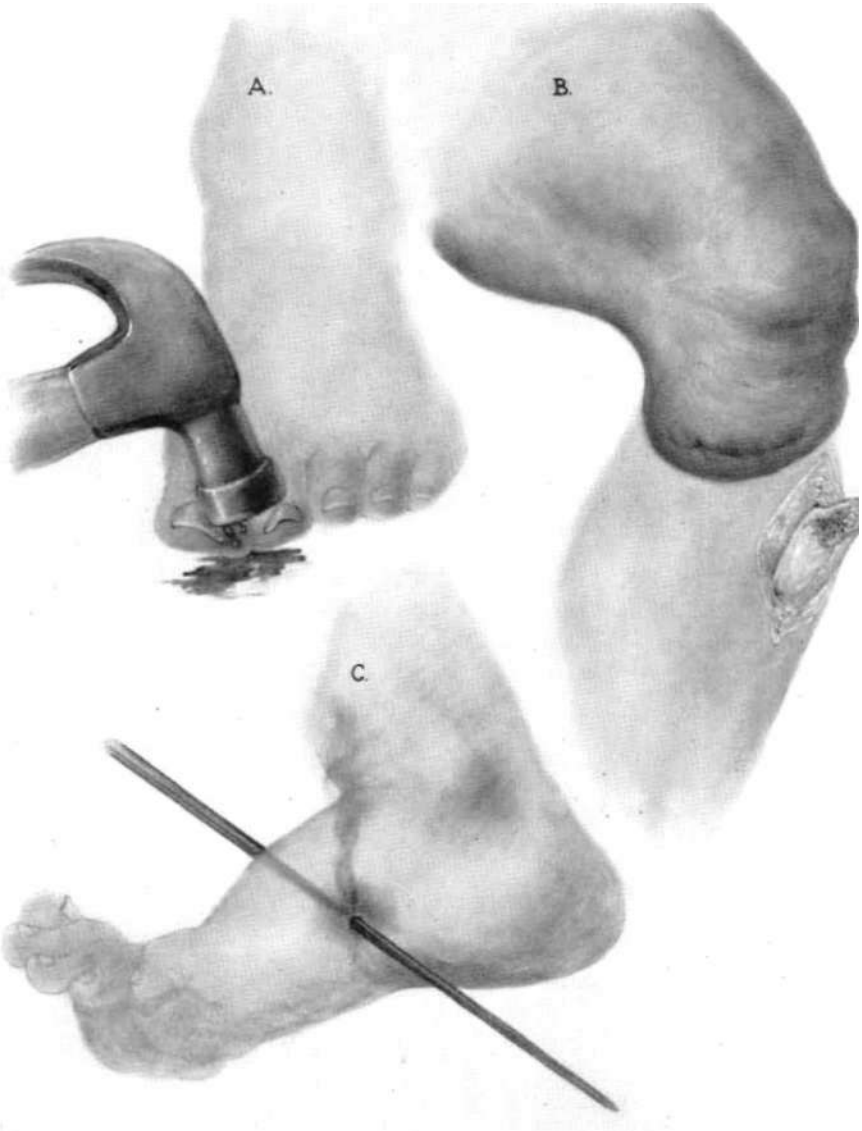


Fig. 11. The painful phantom, of fairly common occurrence among amputees at one time or another. Only some 30 percent experience no phantom pain at any time. Probably about 10 percent face persistent and sometimes incapacitating pain. *A*, Among the similes used to describe a phantom pain is "as if my toes are being crushed by a hammer." *B*, Pain experienced at the site of an injury leading to amputation, such as a fracture, often persists as a part of the phantom pattern. C, The "hot wire" sensation and involuntary cramping of phantom toes are among the other frequent manifestations.

squeezing sensations are felt in a part of the body known to be missing, the suffering is heightened and the imagery made more vivid by the ghostly character of the phantom.

It has been argued that phantom sensations are hallucinations because they entail a belief in the reality of an absent object, or that they are illusions because irritations of the stump are being misinterpreted, or that they are normal sensations because the cerebral representation of the once-present member still is intact. Some workers have correlated the type of sensation with the "level" of its origin in the nervous system, painful sensations being ascribed to pathological conditions of the cut nerve end in the stump or to mental aberrations. But classifications of either the amputee's descriptions or of the presumptive causes bringing about the sensations have thus far been unsatisfactory. The various frames of reference used in the statistical survey at Berkeley do, in fact, overlap. Duration and frequency of pain have some influence on the complaint of severity. Tingling and burning seem to be more superficial and, however annoying, more tolerable than do tearing, stabbing, cramping, squeezing, and crushing. It should be understood, however, that there are degrees of each of these and that, as such, intensities may, to a point, be compared with each other.

It is obvious that a patient's account of his painful feeling is colored by his personality. The way a person describes such experiences depends not only on the abnormal processes causing them but also on his imagination, his previous experience, his learning, his cultural inheritance, and his vocabulary. But any view which discounts the abnormal physiological processes and credits only their "mental" interpretation is probably in error. The complexity of the nervous system and its integration into one functioning whole does not favor the idea that there is one chief recipient and executive who sorts out the messages from the various parts of the body and, in the case of pain, edits them as writhings and groans or as sentences made up of more or less colorful language. It seems improbable that there is simply one stimulus arising somewhere in the organism and that the ego reacts to this stimulus in a more or less stoic way. A so-called "neurotic" or "imaginative" disposition is likely to pervade the most "bodily" of processes, while a steadfast person is apt to have a stomach and blood vessels no more stable than his emotional display.

Regardless of individual personalities, however, there is a certain uniformity in the complaints of pain-stricken amputees. Although the matter has not been explored from the point of view of psychophysiological typing, it appears that pain phenomena cannot be predicted either from the age of the patient or from the age of his phantom. By the same token, racial or cultural background and physical or mental make-up cannot be used to predict pain phenomena. Nor have the local pathological factors before, during, and after amputation—the factors that might be held responsible for the appearance of pain—been elicited.

Aside from the problem of the painful phantom is that relating to painful stumps (Fig. 12). Amputees may have spontaneous stump pain. Or they may have so-called "trigger points," certain areas which, on slight pressure, tend to produce a flash of pain persisting for various intervals of time. Patients have complained of circumscribed areas of pain in the stump even though palpation revealed no corresponding point of tenderness. These two conditions usually are found together. Nodularities in the stump often are palpable, as indeed they are, on a minor scale, in other subcutaneous parts of the body. Some of these are tender, some are not; some are and some are not connected with phantom pain. In fact, separate places in the same stump may represent exclusive triggers—one for stump pain, the other for phantom pain.

But the conditions prevailing at the end of the stump, including such nodules as the famous "amputation neuroma," do not provide a basis for intelligent speculation. The mere fact that stimulation of a presumptive neuroma often produces pain in the phantom is no proof for the theory that the "cause" of this pain lies solely in the periphery. In order to be disabused of such a notion, one has only to look at certain cases of known diseases of the central nervous system or at. complete transections of the spinal cord. In the latter, the brain receives no communications from the stump. In cases of painful diseases of the central nervous system, stimulation of the normal peripheral tissues having their nervous connections with the diseased part of the central nervous system often produces an abnormal sensation, including pain. This phenomena always is referred to the periphery. Nobody sounds convincing when he says that

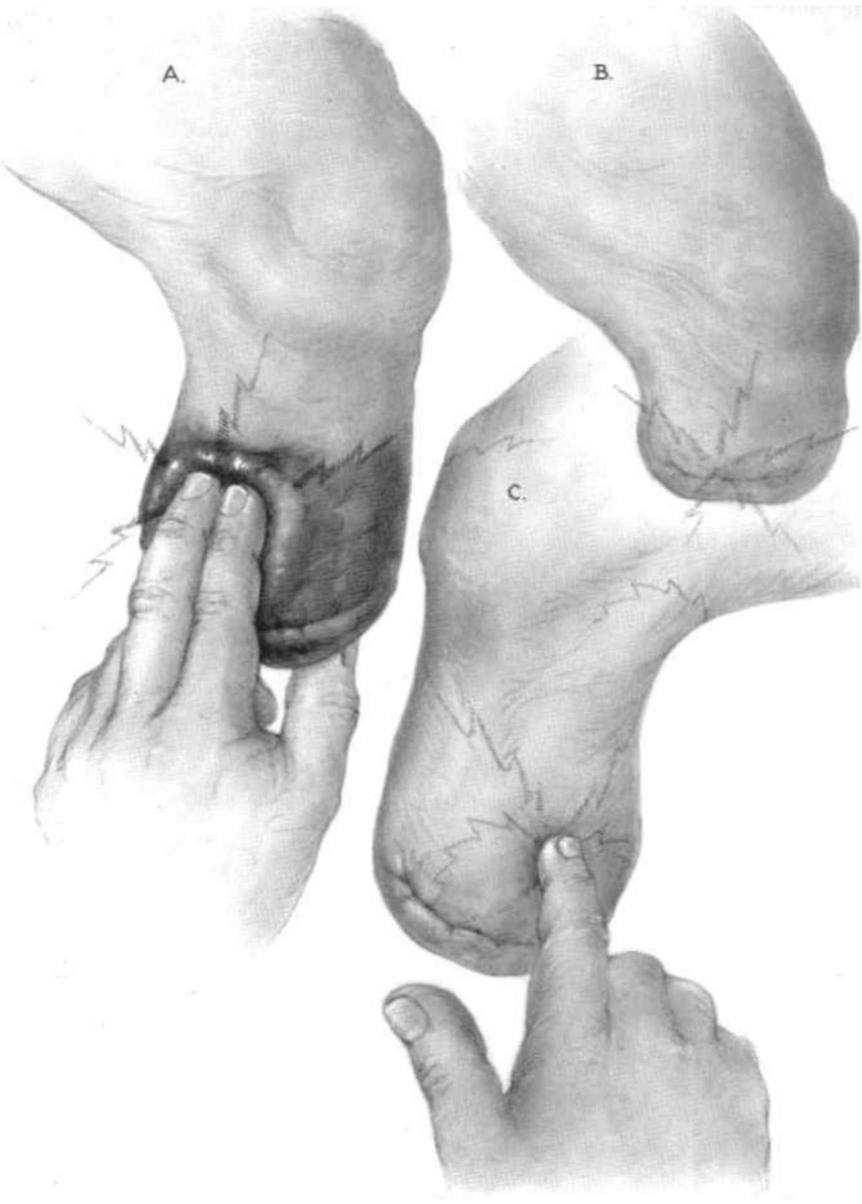
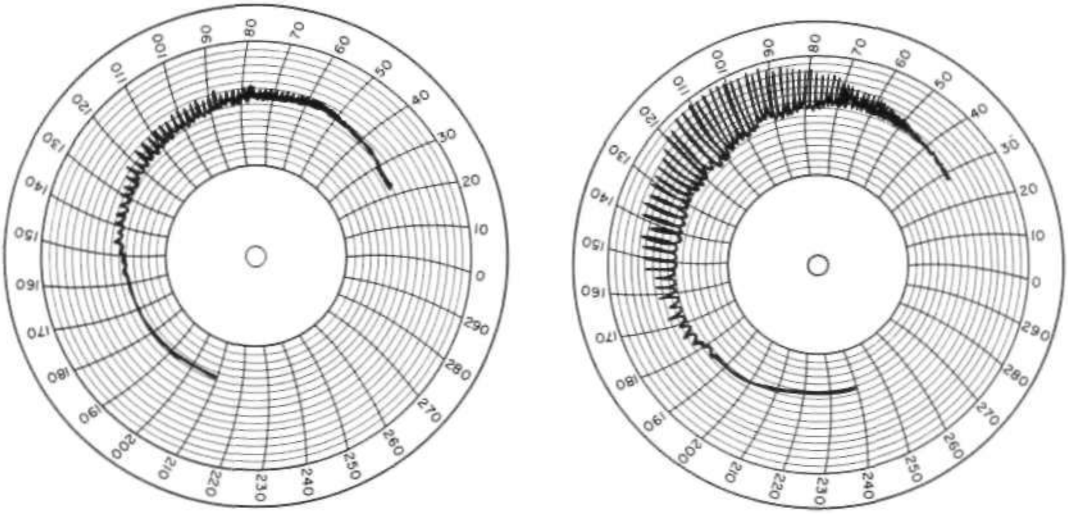


Fig. 12. Types of stump pain. About a third of the clinical reports of pain refer to discomfort in the stump rather than in a phantom part. Stumps may be painful to the touch *(A)* or spontaneously *(B).* Frequently present are "trigger points," pressure upon which gives rise to pain over a larger area, either in the stump or in a phantom or both (C).



A B

Fig. 13. Pulsations recorded during generalized vasodilatation in a below-knee amputee. Oscillometric records show a smaller amplitude of pulsation in the blood vessels supplying the stump *(A)* than in those supplying the sound limb *(B).*

he feels pain in the brain or spinal cord. The central nervous system has no conscious sensory representation of itself. The mere description of a painful sensation does not permit detection of its origin. The origin has to be deduced from circumstantial evidence which, in the case of amputees, is lacking. Even where sensations are "triggered off" from the periphery, they can be completed only by participation of the central nervous system, and disturbances may occur anywhere along the line.

We are confronted with the anomaly that stimulation of a certain trigger point within the stump arouses not a distant, painful phantom but one incorporated in the flesh of its own trigger. The specificity of this trigger further is illustrated by the fact that, on the opposite side of the same stump, there may be another tender spot, stimulation of which sets up increased local stump pain.

Circulatory Problems

Investigation of circulation in the amputee reveals that the stump acts as though it were poikilothermic, that is, it has no ability to change its temperature. Rather, the temperature of the stump matches that of the surroundings, as occurs in a cold-blooded animal. Studies concerning the relationship of the vascular system to pain in amputees have been conducted along three general lines. First has been evaluation of the status of the circulatory system in amputation stumps, both in patients suffering from phantom or stump pain and in amputees free of pain. The second has involved clinical and laboratory studies of selected nonamputee patients suffering from pain syndromes possibly related in pathophysiology to phantom pain. And finally tests have been conducted with various sympatholytic drugs and blocking procedures, first with respect to their effects on phantom-limb pain and related pain syndromes and second in regard to their effects on the circulation of blood in stumps and in painful limbs.

Studied in detail were 43 amputees, 31 without known vascular disease (Group A) and 12 suffering from vascular disease either as the underlying cause of amputation or as a concomitant to the amputation (Group B). Pain in the stump or phantom limb was an important problem for 15 of the patients in Group A and for 8 of those in Group B. The remainder described varying degrees of phantom awareness but denied that pain existed or, if it did exist, that it was disturbing.

One method of investigation was simple

clinical examination. In that survey, stumps appearing to have an adequate blood supply were found, when exposed to air at room temperature, to be almost uniformly cold to the touch as compared with the opposite extremities. In oscillometric tests, the pulse of arterial blood into the stump was found to be significantly smaller than that into the normal limb (Fig. 13). In skin tests with histamine, the appearance of normal flares and wheals indicated that local denervation could not account for the failure of the skin to warm during generalized body warming.

Figures 14 and 15 indicate graphically the results of surface-temperature measurements on the normal extremities and on the stumps of two amputees *(16).* Skin temperature was measured after initial exposure of the body to cool air in a room with controlled atmosphere, the subject being exposed until finger and toe temperatures were stabilized. Recordings were made by means of thermocouples taped to the skin of the stump and to the contralateral extremities at multiple points along the length of the limb, the thermocouples being applied symmetrically so that points equidistant from the trunk could be compared. All such measurements were made with the subject in a basal state and exposed to room air between 17° and 21°C, conditions leading uniformly to constriction of the cutaneous vessels of the extremities in normal subjects. Under such circumstances, a temperature gradient exists between the proximal and distal portions of a normal arm or leg, so that the surface temperature of a finger or toe is several degrees lower than the temperature at points near the trunk.

Temperatures then were recorded during maximal vasodilatation induced by oral administration of whiskey and wrapping the trunk in an electric blanket. After vasodilatation, the gradient is abolished or reversed in the normal limb, finger and toe temperatures rising to 30°C or higher.

At the end of the initial cooling period, when subjects had been exposed to cool room air for periods of from 30 to 150 minutes, the surface temperature at the distal end of the stump almost invariably was cooler than was the skin at a symmetrical point on the corresponding intact limb. Analysis of the temperature gradients found after cooling showed further that, in at least a third of the Group A amputees and in half of the Group B amputees, the stumps were cooler than were the opposite extremities, not merely at the distal ends but for distances of from 20 to 55 cm. from the ends.

In one instance a patient was put in a room at 18°C with nothing across his body except a towel. Over a period of two hours the body temperature was lowered to a point just above that at which shivering occurred. The temperature of the toe in the normal extremity dropped to a low level. When the patient suddenly was given 2 ounces of whiskey and warm water and had an electric blanket placed across his chest, the temperature of the normal extremity rose rapidly. But the temperature of the stump remained constant during the entire procedure, a phenomenon characteristic of all amputation stumps.

A total of 40 amputees (28 Group A, 12 Group B) were subjected to one or more vasodilatation tests, and the responses of 45 stumps were observed. Of these, nearly two thirds failed to warm significantly at a time when the skin temperature of the normal extremities had risen to 30°C as a result of indirect or "reflex" vasodilatation. Only occasionally did stumps show evidence of significant vasodilatation. It occurred with higher frequency in those patients with underlying or concomitant vascular disease than in amputees of Group A. Thus, of 11 stumps in which the temperature rose to the same level as the corresponding point on the contralateral limb, or even to levels reflecting "ceiling" blood flow for skin, only six were among the 32 stumps of Group A patients, and five were among the 13 stumps of Group B patients. In brief, a smaller proportion of stumps showed vasodilatation in Group A patients (one fifth) than in Group B patients (two fifths).

In the majority of trials, experiments with other methods of inducing vascular relaxation were equally ineffective in causing a rise in stump temperature. In a total of eight intravenous injections of vasodilator drugs, the temperature of the stump increasedonlyslightly on two occasions (2.5°C or less). A rise in ternperature was effected once with Priscoline (2-benzylimidazoline hydrochloride) and once with tetraethylammonium chloride. Injections of prccaine in the region of the lumbar sympathetic ganglia produced a significant warming of the stump in one of two cases only. No correlation was found between the degree of phantom or stump pain experienced by these patients and the extent to which slump temperature fell during the initial period of exposure or the extent of stump warming during generalized vasodilatation. Amputees rarely complained of stump or phantom pain during these experiments, even though they were subjected to extremes of temperature requiring rapid vasomotor adjustments.

The ease with which stumps become cool on exposure to a cold environment can be attributed to two factors. First, surface-volume relationships in stumps favor cooling. Second, less blood passes through the stump than through comparable portions of the intact limb because, in the stump, distal tissues are absent. Apparently the shunts between the arterial and the venous side, which permit an increased volume of blood to flow through the extremity, are located distal to the wrist joint and to the ankle joint. In amputations at or above the wrist or ankle, therefore, flow of blood to the extremity is impaired. Normally, body heat is lost chiefly through radiation from hands, head, and feet. When the body is deprived of one of these radiating "fins," the remaining stump cannot be warmed. Neither can excess heat be radiated away, and for that reason an amputee often finds intolerable an environmental temperature that is quite acceptable to the normal. The amputee is distressed in a heated room, while the normal subject suffers no discomfort. Since the radiating mechanism is lost with amputation of an extremity, and since the only other means of cooling is through evaporation of sweat, the amputee is more likely to be troubled with problems of perspiration.

Skeletal Changes

In addition to problems of pain and changes in circulation, the amputee sometimes is troubled by decalcification of the stump and adjacent portions of the pelvis, a change that occurs when the body weight no longer is borne along the axis of the major articulations but along the prosthetic weight line (page 36). Because in an osteoporotic extremity the covering of the bone is more sensitive than is that in the normal, a decalcified bone often becomes exceedingly tender and develops spontaneous pain.

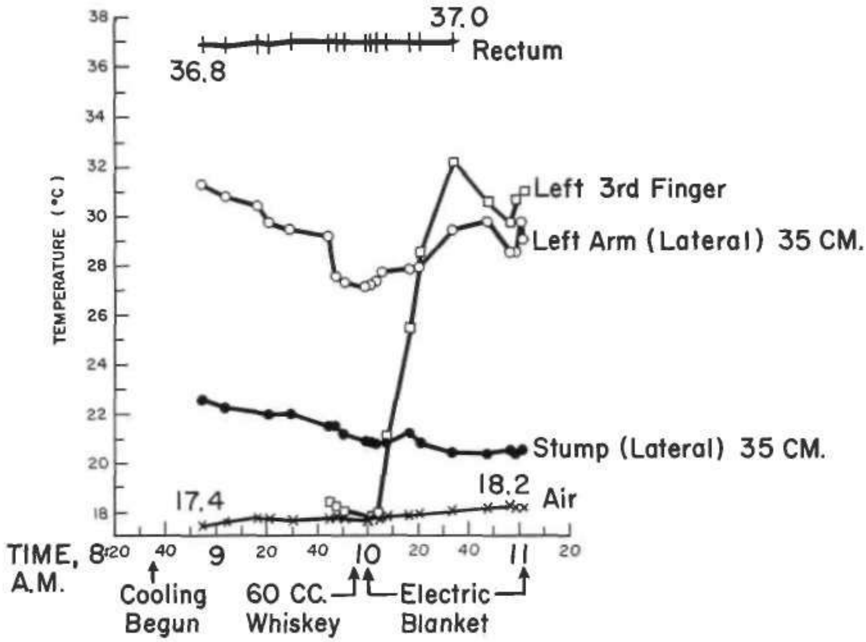
An interesting fact is that the joint itself, in Figure 16 the hip joint, begins to show early degenerative changes because it no longer transmits weight. In future studies it should be possible to evaluate more closely what changes are to be expected in the proximal articulations of an amputation stump, and more particularly in the joint cartilage covering the articulations, as a result of elimination of normal weighi-bearing through thesearticulations. Obviously, the only way la preveni osteoporosis and increased sensitivity is to resort to some type of end-bearing.

In the younger leg amputee, moreover, especially in growing children, other bony deformities develop (Fig. 17). Instead of the normal curvature of the neck of the femur, there develops a valgus deformity as is seen in polio and in dislocated hips. And finally, of course, because of loss of the mass of the limb, one must expect to find scoliosis and other abnormalities in the spine (Fig. 18).

SUMMARY

In summary, it may be said that, first, amputation produces changes in musculature, not only the familiar contractures and atrophy *(50,88)* but other changes as well. If a muscle is cut in half, its ability to shorten is decreased. A mid-thigh amputation decreases the effective normal range of motion of the hamstring group. If the hamstring group is cut in half, the velocity of contraction is halved, and an amputee thus afflicted cannot therefore perform certain functions with any degree of facility.

The mechanism of normal level walking requires the expenditure and distribution of considerable energy, for which the body depends largely upon the leg musculature. Thus, the handicap resulting from loss of any part of the leg is due not only to the loss of support but also to the loss of power available from



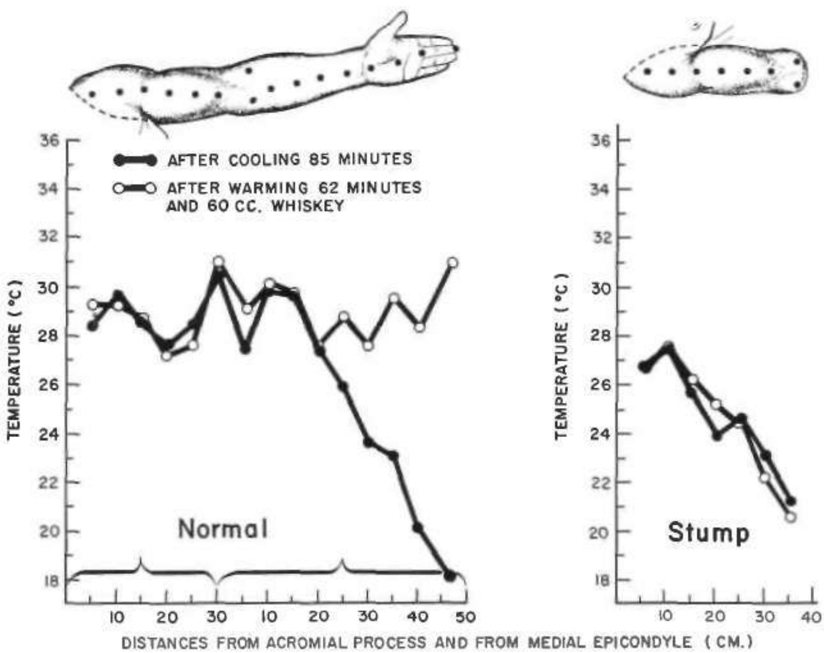


Fig. 14. Surface temperatures in the upper extremities of a below-elbow amputee during cooling and subsequent warming and vasodilatation. Above, time-temperature relations. Below, length-temperature relations. Points along the extremities indicate the locations of thermocouples. Relative humidity constant at 65 percent.

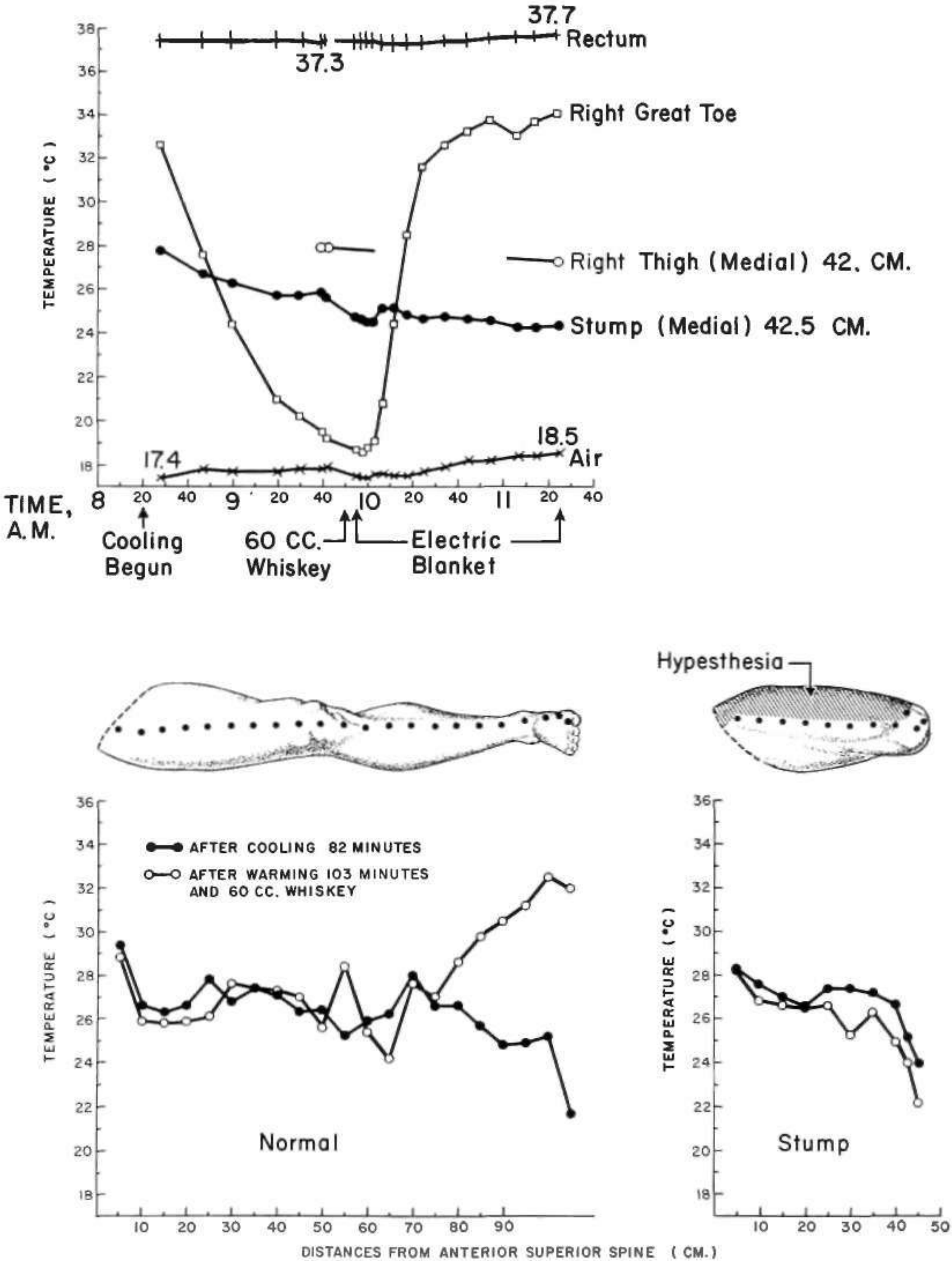


Fig. 15. Surface temperatures in the lower extremities of an above-knee amputee during cooling and subsequent warming and vasodilatation. Above, time-temperature relations. Below, length-temperature relations. Points along the extremities indicate the locations of thermocouples. Relative humidity constant at 74 percent.

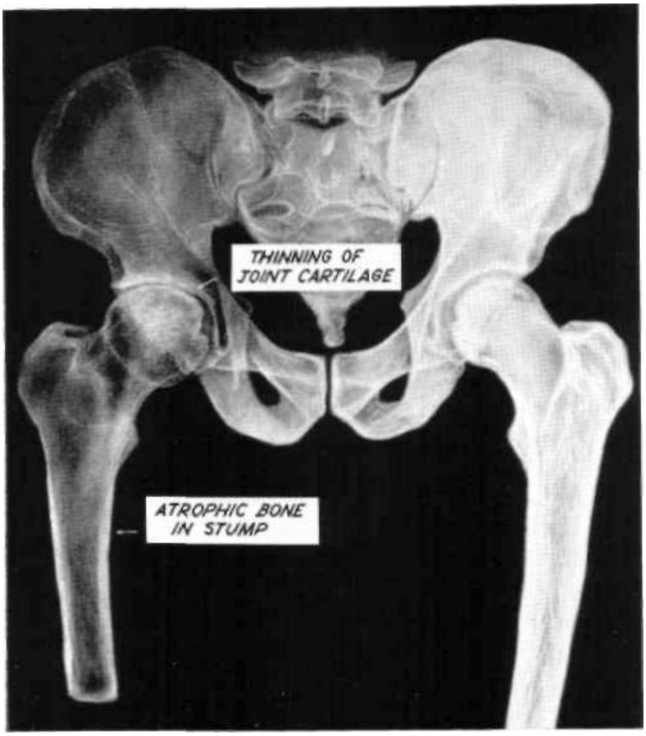


Fig. 16 Roentgenogram of an above-knee amputee, showing skeletal changes that occur when the hip and the remainder of the leg on the amputated side are deprived of the normal stimulation of weight-hearing

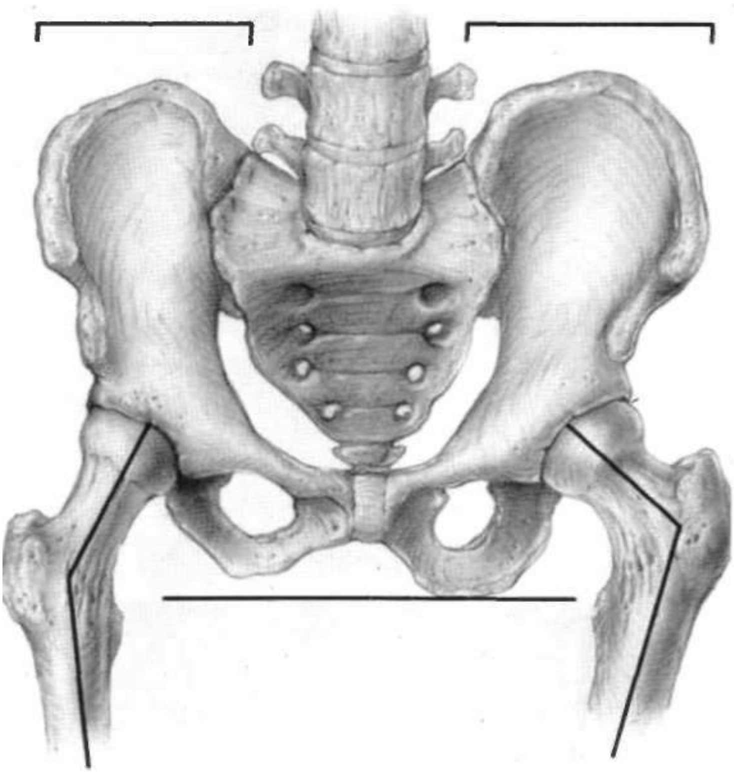


Fig. 17. Complicating deformities in juvenile amputees. When amputation is necessitated in childhood, defects often occur in the subsequent growth of related bony structures. Here, for example, the pelvis is smaller, and the pelvic-femoral angle larger, on the amputated side than on the sound side.

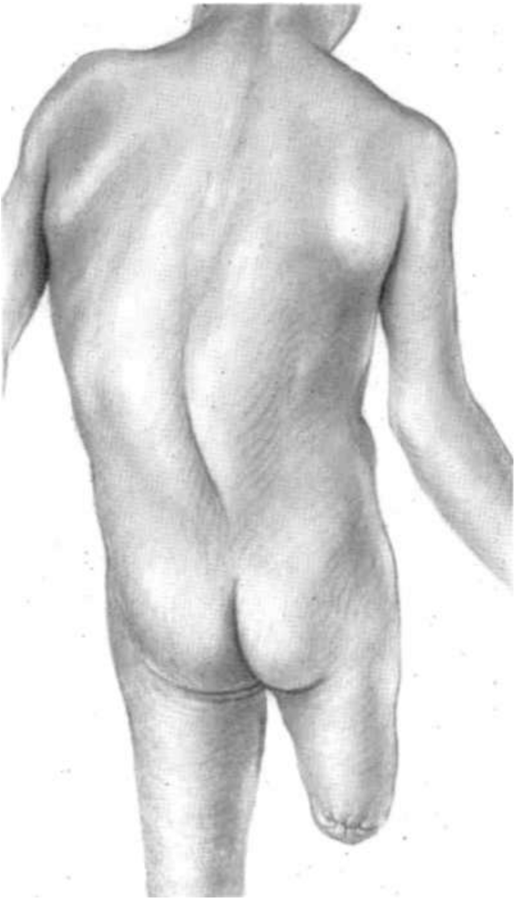


Fig. 18. Scoliosis, a postural defect often a sequel to amputation of the lower extremity. Loss of the weight of the amputated limb leads to habitual compensatory positioning of other body elements and thus complicates rehabilitation.

the muscles. The skeletal structure of a normal limb can more or less easily be simulated in a prosthesis, but such a device has little value without simultaneous provision for the necessary power. Accordingly, an understanding of the energy characteristics of normal level walking is important in considering the design criteria for artificial legs. Judging from the results of the energy studies at Berkeley, at a given pace an above-knee amputee uses two and a half to three times as much energy as does the normal. The adverse effect of this overexertion is only further complicated by the fact that heat production is increased at a time when the radiating mechanism has been impaired. In the manufacture of any lower-extremity prosthesis, then, an important consideration, is to design the substitute limb for maximum energy conservation.

Medical problems are common to all amputees. Some of them, for example those related to circulation, cannot be solved, but proper surgical procedures help to preserve the musculature and skeletal structures of adjacent joints. Moreover, many things can be done to relieve pain, both spontaneous phantom pain and the tender trigger points occurring in stumps. All amputees suffer some discomfort at one time or another. They are bothered by skin changes occurring over the bony prominences, by edema at the distal end of the stump, and by attritional lesions occurring in the folds of the groin (Fig. 19). A minor skin lesion can disable a leg amputee completely, especially when it means staying off the leg or going on crutches. Increased perspiration and poor ventilation of the stump in the prosthesis may close the sweat glands and make the skin susceptible to fungal diseases, and contact dermatitis may result if the patient is allergic to certain materials used in the manufacture of the prosthesis. Such problems must be solved by socket fit, by alignment, or by other procedures.

From the Clinical Study have come valid recommendations concerning fit, alignment, and functional characteristics. As already noted, some horizontal rotation (between 9 and 15 deg.) is desirable in an artificial leg. Further, increased stability in the knee joint increases the leg amputee's sense of security. Some conservation of energy can be effected by eliminating the articulated ankle joint. And finally, the matter of appearance deserves consideration. In this regard, attention must be given to the color, contour, and texture of the artificial leg.

In the last analysis, the problem of the leg amputee is more than that of providing him with a prosthetic device. He has many medical problems, including pain, abnormalities in circulation, heat intolerance, and skeletal and muscular changes. The prosthetic device itself raises other problems—conservation of energy, proper alignment, comfort, and cosmetic ap-

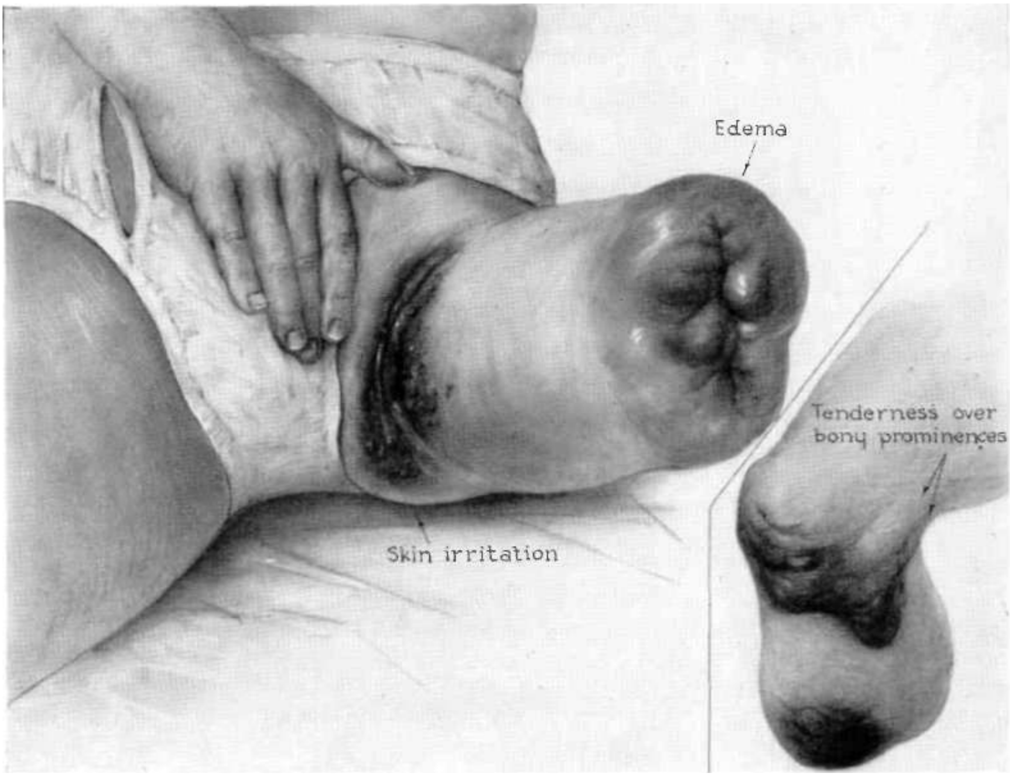


Fig. 19. Problems of fit. Among them are irritation and swelling in the crotch area, edema at the stump end, and tenderness at pressure points. Because such problems are more or less readily corrected by proper fit and alignment, they are less medical than prosthetic, although chronic skin irritation may need the attention of a dermatologist.

pearance. The Lower-Extremity Clinical Study is concerned with the solution of all these problems. The manner in which solutions are sought is shown in Figure e 20, where the central area represents the pool of fundamental knowledge accumulated over a period of nine years. As the amputee moves around the circle, each problem is studied and solved before he is allowed to move into the next phase of processing.

To date, pain and skin irritation have been the predominant problems, and study groups are being organized to investigate these areas in detail. Study groups also have been organized to investigate skeletal and muscular changes. At each step in the process, the panel itself often is faced with difficult problems. For example, the question of evaluation always is present, and it is not easy to determine whether or not the amputee actually has benefited from the time and effort devoted to his case. But as each difficulty is solved, the information derived is placed at the disposal of all those concerned, not only those within the Clinic Study Group but also all others whose interests lie in the field of amputee management. Seminars are held weekly to ensure that the information is brought to the attention of all interested persons. Eventually, all of the problem-solving data stemming from the investigations will appear in educational publications and will be available to members of the artificial-limb industry.

Finally, it may be said that the University group has no intentions of producing prosthetic devices and, indeed, makes excursions into that field only when it is necessary to develop experimental models pertinent to the study.

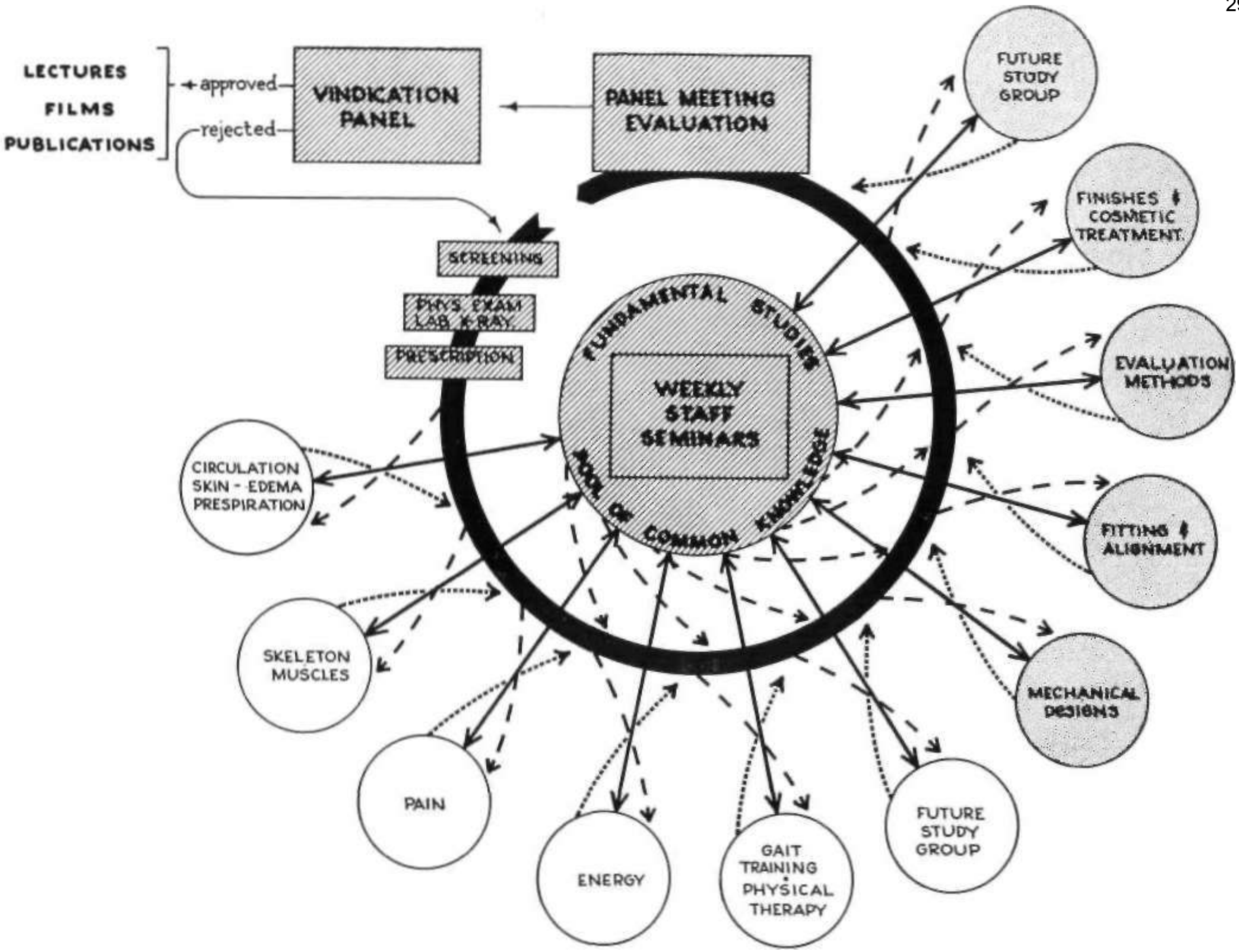


Fig. 20. Functional organization of theLower-Extremity Clinical Study:

The only function is to produce sound ideas that can be used by the artificial-limb industry in the manufactuie and fitting of improved prostheses. The study must, however, continue to be active until the basic scientific information can be translated into useful guides for the professions involved in the rehabilitation of the amputee.

ACKNOWLEDGMENTS

For the illustrations appearing in this article, the authors are indebted to two people in particular. Thomas Raubenheimer, of the Department of Medical Illustration, University of California Medical Center, San Francisco, prepared the charcoal halftones. With the exception of Figure 8, all line drawings were worked up by George Rybczynski, free-lance illustrator of Washington, D. C.

LITERATURE CITED

1. Adel Precision Products Corp., Burbank, Calif., Subcontractor's Final Report [to the] Committee on Artificial Limbs, National Research Council, *The development of a hydraulically operated artificial leg for above knee amputations,* 1947.
2. Alldredge, Rufus H., *The cineplaslic method in upper-extremity amputations,* J. Bone & Joint Surg., 30A:359 (1948).
3. Alldredge, Rufus H., Verne T. Inman, Hyman Jampol, Eugene F. Murphy, and August W. Spittler, *The techniques of cineplasty,* Chapter 3 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
4.'Bartholomew, S. H., *Determination of knee moments during the swing phase of walking and physical constants of the human shank,* University of California (Berkeley), Prosthetic Devices Research Project, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, January 1952.
5. Bechtol, Charles 0., *The prosthetics clinic team,* Artificial Limbs, January 1954. p. 9.
6. Bechtol, Charles O., *The principles of prosthetic prescription,* Chapter 6 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
7. Berry, F. R., Jr., *Angle variation patterns of normal hip, knee and ankle in different operations,* University of California (Berkeley), Prosthetic Devices Research Project, [Report to] the Advisory Committee on Artificial Limbs, National Research Council, Series 11, Issue 21, February 1952.
8. Blaschke, A. C, *General energy considerations and determination of muscle forces in the mechanics of human bodies,* University of California (Los Angeles), Department of Engineering [Contractor's Memorandum Report No. 9 to the Advisory Committee on Artificial Limbs, National Research Council], September 1950.
9. Blaschke, A. C, and C. L.Taylor, *Biomechanical considerations in cineplasty,* University of California (Los Angeles), Department of Engineering, Special Technical Report 18, 1951.
10. Blaschke, Alfred C, and Craig L. Taylor, *The mechanical design of muscle-operated arm prostheses,* J. Franklin Inst., 266:435 (1953).
11. Blix, Magnus, *Die Lange und die Spannung des Muskels,* Scandinav. Arch. f. Physiol., 6:150 (1894).
12. Bradley, C. C, and Son, Inc., and Catranis, Inc., Syracuse, N. Y., Subcontractor's Final Report to the Committee on Artificial Limbs, National Research Council, *Artificial limb development for above-knee amputees including mechanical and hydraulic knee locks; suction socket and suction socket controls; knee lock controls operated by hip motion, stump muscles and foot position; toe pick up and foot providing lateral, plantar and dorsal flexion,* July 1947.
13. Bresler, B., *Use of energy methods for evaluation of prostheses,* University of California (Berkeley), Prosthetic Devices Research Project, [Report to] the Advisory Committee on Artificial Limbs, National Research Council, September 1951.
14. Bressler *[sic],* B., and F. R. Berry, *Energy characteristics of normal and prosthetic ankle joints,* University of California (Berkeley), Prosthetic Devices Research Project, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, April 1950.
15. Bresler, B,, and F. R. Berry, *Energy and power in the leg during normal level walking,* University of California (Berkeley), Prosthetic Devices Research Project, [Report to] the Advisory Committee on Artificial Limbs, National Research Council, May 1951.
16. Brown, E., and N. Foreman, *Studies of skin temperature and of indirect vasodilatation in amputation stumps,* Am. J. Med., 10:112 (1951).
17. Buchthal, Fritz, and E. Kaiser, *Optimum mechanical conditions for work of skeletal muscle,* Acta Psychiat. et Neurol., 24:333 (1949).
18. Close, J. R., and V. T. Inman, *The action of the ankle joint,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, April 1952.
19. Close, J. R., and V T. Inman, *The action of the subtalar joint,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, Series 11, Issue 24, May 1953.
20. Contini, Renato, *Prosthetics research and the engineering profession,* Artificial Limbs, 1(3):47 (September 1954). p. 58.

21. Cunningham, D. M., *Components oj floor reactions during walking,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, November 1950.
22. Eberhart, Howard D., *The objectives of the lower-extremity prosthetics program,* Artificial Limbs, May 1954. p. 4.
23. Eberhart, Howard D., Herbert Elftman, and Verne T. Inman, *The locomtor [sic] mechanism of the amputee,* Chapter 16 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
24. Eberhart, H. D., and V. T. Inman, *An evaluation of experimental procedures used in a fundamental study of human locomotion,* Ann. N. Y. Acad. Sci., 51:1213 (1951).
25. Eberhart, Howard D., Verne T. Inman, and Boris Bresler, *The principal elements in human locomotion,* Chapter 15 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
26. Elftman, H., *A cinematic study of the distribution of pressure in the human fool,* Anat. Rec, 69:481 (1934).
27. Elftman, H, *The measurement of the external force in walking,* Science, 88:152 (1938).
28. Elftman, H., *The rotation of the body in walking,* Arbeitsphysiol., 10:219 (1938).
29. Elftman, H., *The force exerted by the ground in walking,* Arbeitsphysiol., 10:485 (1938).
30. Elftman, H., *Forces and energy changes in the leg during walking,* Am. J. Physiol., 125:339 (1939).
31. Elftman, H., *The function of muscles in locomotion,* Am. J. Physiol., 125:357 (1939).
32. Elftman, H., *The function of the arms in walking,* Human Biol., 11:529 (1939).
33. Elftman, Herbert, *The work done by muscles in running,* Am. J. Physiol , 129:672 (1940).
34. Elftman, H., *The action of muscles in the body,* Biol. Symposia, 3:191 (1941).
35 Elftman, H., *Experimental studies on the dynamics of human walking,* Trans. N. Y. Acad. Sci., 11:1 (1943).
36. Elftman, H., *The bipedal walking of the chimpanzee,* J. Mammalogy, 25:67 (1944).
37. Elftman, H., *The carrying angle of the human arm as a secondary sex character,* Anat. Rec, 91:49 (1945).
38. Elftman, H., *The orientation of the joints of the lower extremity,* Bull. Hosp. Joint Diseases, VI-.139 (1945).
39. Elftman, H., *Torsion of the lower extremity,* Am. J. Phys. Anthropol., N.S. 3:255 (1945).
40. Elftman, H., *The basic pattern of human locomotion,* Ann. N. Y. Acad. Sci., 51:1207 (1951).
41. Elftman, Herbert, *The functional structure of the lower limb,* Chapter 14 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
42. Elftman, Herbert, and John T. Manter, *The axis of the human foot,* Science, 80:484 (1934).
43. Elftman, Herbert, and John Manter, *Chimpanzee and human feel in bipedal walking,* Am. J. Phys. Anthropol., 20:69 (1935).
44. Elftman, H., and J. T. Manter, *The evolution of the human fool, with especial reference to the joints,* J. Anat., 70:56 (1935).
45. Feinstein, Bertram, John N. K. Langton, R. M. Jameson, and Francis Schiller, *Experiments on pain referred from deep somatic tissues,* J. Bone & Joint Surg!, 36A:981 (1954)
46. Feinstein, Bertram, James C. Luce, and John N. K. Langton, *The influence of phantom limbs,* Chapter 4 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
47. Felkel, E. O., *Determination of acceleration from displacement-time data,* University of California (Berkeley), Prosthetic Devices Research Project, [Report to] the Advisory Committee on Artificial Limbs, National Research Council, Series 11, Issue 16, September 1951.
48. Felkel, E. O., *Determination of accelerations of the human leg during locomotion,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, Winter 1951.
49. Goodyear Tire & Rubber Company, Akron, Ohio, Subcontractor's Final Report [to the Committee on Artificial Limbs, National Research Council], *The development of a foot prosthesis incorporating a metal structure and a bonded rubber to metal ankle joint,* 1947.
50. Gordan, G. S., B. Feinstein, and H. J. Ralston, *Effect of testosterone upon atrophy of denervated skeletal muscle,* Exper. Med. & Surg., 7:327 (1949).
51. Hosmer Corp., A. J., Santa Monica, Calif., Subcontractor's Final Report to the Committee on Artificial Limbs, National Research Council, *Hydraulic weight bearing knee lock for knee disarticidation amputations; work arms for wrist disarticulations, below and above elbow amputations; work tools and devices for vocational rehabilitation; hydraulic control to actuate hooks and hands used on work arms; improved design hook,* 1947.
52. Inman, V. T., *Functional aspects of the abductor muscles of the hip,* J. Bone & Joint Surg., 29:607 (1947).
53. Inman, V. T., *Theoretical requirements of a lower-extremity prosthesis,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, December 22, 1950.
54. Inman, V. T., *Innervation of the extremities,* 3rd Biennial Western Conference on Anesthesiology, The California Society of Anesthesiologists and the Northwestern Society of Anesthesiologists, Los Angeles, 1953. p. 22.
55. Inman, V. T., B. Feinstein, and H. J. Ralston,

Some observations on electromyography, Am. J. Physiol., 155:445 (1948).

56. Inman, Verne T., H. J. Ralston, J. B. deC. M. Saunders, Bertram Feinstein, and Elwood W. Wright, Jr., *Relation of human electromyogram lo muscular tension,* University of California (Berkeley), Prosthetic Devices Research Project, and UC Medical School (San Francisco), Report to the Advisory Committee on Artificial Limbs, National Research Council, November 1951.
57. Inman, Verne T., and H. J. Ralston, *The mechanics of voluntary muscle,* Chapter 11 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954.
58. Inman, V. T., H. J. Ralston, J. B. deC. M. Saunders, B. Feinstein, and E. W. Wright, Jr., *Relation of human electromyogram lo muscular tension,* Electroencephalog. & Clin. Neurophysiol., 4:187 (1952).
59. Levens, A. S., V. T. Inman, and J. A. Blosser, *Transverse rotation of the segments of the lower extremity in locomotion,* J. Bone & Joint Surg., 30A:859 (1948).
60. Libet, B., *Neuromuscular facilitation by stretch, and the duration of muscular activation in locomotion,* Proc. 19th Internat. Physiol. Cong., Montreal, 1953. p. 563.
61. Libet, B., and B. Feinstein, *Analysis of changes in electromyogram (EMG) with changing muscle length,* Am. J. Physiol., 167:805 (1951).
62. Libet, Benjamin, and Bertram Feinstein, *Human electromyogram,* Surg. Forum, W. B. Saunders Co., Philadelphia, 1952. p. 415.
63. Libet, Benjamin, H. J. Ralston, and Bertram Feinstein, *The effect of stretch on action potential in muscle,* Biol. Bull., 101:194 (1951).
64. Libet, B., and E. W. Wright, Jr., *Facilitation at neuromuscular functions by stretch of muscle,* Fed. Proc, 11:94 (1952).
65. Livingston, Kenneth E., *The phantom limb syndrome: a discussion of the role of major peripheral nerve neuromas,* J. Neurosurg., 2:251 (1945).
66. Mitchell, S. Weir, *Phantom limbs,* Lippincott's Mag. Pop. Lit. So, 8:563 (1871).
67. National Research and Manufacturing Company, San Diego, Calif., Subcontractor's Final Report [to the Committee on Artificial Limbs, National Research Council], *An investigation of low pressure laminates for prosthetic devices; design and fabrication of above-knee and below-knee artificial legs; preparation of a production survey for manufacture of artificial plastic legs,* 1947.
68. New York University, Prosthetic Devices Study, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, *Shakedown lest of the Navy above-knee prosthesis,* May 1951.
69. New York University, Prosthetic Devices Study, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, *The functional and psychological suitability of an experimental hydraulic prosthesis for above-the-knee amputees,* March 1953.
70. Northrop Aircraft, Inc., Hawthorne, Calif., Subcontractor's Final Report [to the] Committee on Artificial Limbs, National Research Council (Contract VAm-21223), *A report on prosthesis development,* 1947.
71. Northwestern Technological Institute, Evanston, III., Subcontractor's Final Report to the Committee on Artificial Limbs, National Research Council, *A review of the literature, patents, and manufactured items concerned with artificial legs, arms, arm harnesses, hands, and hooks; mechanical testing of artificial legs,* 1947.
72. Pare, A., from T. Johnson, *The works of that famous chirurgion, Ambrose Parey, translated out of the Latine and compared with the French,* Richard Cotes and Willi: Du-gard, London, 1649.
73. Polissar, M. J., *Concentration and potential pattern within the membrane and its relation lo penetration of ions and lo time constants of electrolonus and accommodation,* Fed. Proc, 11:124 (1952).
74. Polissar, M. J., *Physical chemistry of contractile process in muscle. I. A physiochemical model of contractile mechanism,* Am. J. Physiol., 168:766 (1952).
75. Polissar, M. J., *Physical chemistry of contractile process in muscle. II. Analysis of other mechanochemical properties of muscle,* Am. J. Physiol., 168:782 (1952).
76. Polissar, M. J., *Physical chemistry of contractile process in muscle. III. Interpretation of thermal behavior of stimulated muscle,* Am. J. Physiol.. 168:793 (1952).
77. Polissar, M. J., *Physical chemistry of contractile process in muscle. IV. Estimates of size of contractile unit,* Am. J. Physiol., 168:805 (1952).
78. Radcliffe, C. W., *Flexion stiffness of prosthetic ankle joints,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, May 1949.
79. Radcliffe, C. W., *Information useful in the design of damping mechanisms for artificial knee joints,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, April 1950.
80. Radcliffe, C. W., *Use of the adjustable knee and alignment jig for the alignment of above knee prostheses,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, August 1951.
81. Radcliffe, Charles W., *Mechanical aids for alignment of lower-extremity prostheses,* Artificial Limbs, May 1954. p. 23ff.
82. Radcliffe, Charles W., *Alignment of the above-knee artificial leg,* Chapter 21 in Klopsteg and Wilson's *Humanlimbs andtheirsubstitutes,* McGraw-Hill, New York, 1954. Especially pp. 686-688.
83. Ralston, H. J., *Muscle dynamics,* Surgical Forum

(1951), American College of Surgeons, Clinical Congress, W. B. Saunders, Philadelphia, 1952. p. 418.

84 Ralston, H J., *Isometric tension in the intact human quadriceps,* Proc. 19th Internat. Physiol. Cong., Montreal, 1953. p. 692.

85. Ralston, H. J., *Mechanics o] voluntary muscle,* Am. J Phys. Med., 32:166 (1953).

86. Ralston, H. J., J R Close, V T. Inman, and B. Feinstein, *Dynamical and electrical features of human isolated voluntary muscle in isometric and isotonic contraction,* Fed. Proc, 7:97 (1948).

87. Ralston, H. J., H. D. Eberhart, V. T. Inman, and M. D. Shaffrath, *Length-tension relationships in isolated human voluntary muscle,* Proc. 17th Internat. Physiol. Cong., Oxford, 1947. p. 110.

88. Ralston, H J., B. Feinstein, and V. T. Inman *Rate of atrophy in muscles immobilized at different lengths,* Fed. Proc, 11:127 (1952).

89. Ralston, H. J., V. T. Inman, B. Feinstein, and B. Libet, *Human electromyogram,* Am. J. Physiol., 163:743 (1950).

90. Ralston, H. J., V. T. Inman, L. A. Strait, and M. D. Shaffrath, *Mechanics of human isolated voluntary muscle,* Am. J. Physiol., 151:612 (1947).

91. Ralston, H. J., B. Libet, and E. W. Wright, Jr., *Effect of stretch on action potential of voluntary muscle,* Am. J. Physiol., 173:449 (1953).

92. Ralston, H. J., and B. Libet, *The question of tonus in skeletal muscle,* Am. J. Phys. Med., 32:85 (1953).

93. Ralston, H. J., M. J. Polissar, V. T. Inman, J. R. Close, and B. Feinstein, *Dynamic features of human isolated voluntary muscle in isometric and, free contractions,* J, Appl Physiol., 1:526 (1949).

94. Ralston, H. J., E. W. Wright, Jr., B. Feinstein, and V. T. Inman, *Effect of stretch upon action potential of voluntary muscle,* Am. J. Physiol., 159:586 (1949).

95. Ryker, N. J., Jr , *Glass walkway studies of normal subjects during normal level walking,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, Series 11, Issue 20, January 1952.

96. Ryker, N. J., and S. H. Bartholomew, *Determination of acceleration by use of accelerometers,* University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, September 1951.

97. Saunders, J. B. deC. M., Verne T. Inman, and Howard D. Eberhart, *The major determinants in normal and pathological gait,* J. Bone & Joint Surg., 35A(3):543 (1953)

98 Schiller, F., *Pain—controlled and uncontrolled,* Science, 118:755 (1953).

99. Spittler, A. W., and I. E. Rosen, *Cineplaslic muscle motors for prostheses of arm amputees,* J. Bone & Joint Surg , 33A:601 (1951).

100. Strait, L. A., V. T. Inman, and H. J. Ralston, *Sample illustrations of physical principles selected from physiology and medicine,* Am. J. Physics, 15:375 (1947).

101. Taylor, Craig L., *Control design and prosthetic adaptations to biceps and pectoral cineplasty,* Chapter 12 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York. 1954.

102. University of California (Berkeley), Prosthetic Devices Research Project, Subcontractor's Final Report to the Committee on Artificial Limbs, National Research Council, *Fundamental studies of human locomotion and other information relating to design of artificial limbs,* 1947. Two volumes.

103. University of California (Berkeley), Prosthetic Devices Research Project, Preliminary Report [to the] Committee on Artificial Limbs, National Research Council, *The suction socket above-knee artificial leg,* September 1947.

104. University of California (Berkeley), Prosthetic Devices Research Project, |Report to the] Committee on Artificial Limbs, National Research Council, *The suction socket above-knee artificial leg,* revised edition, April 1948.

105. University of California (Berkeley), Prosthetic Devices Research Project, Supplementary Report 2, *The forces and moments in the leg during level walking,* revised August 10, 1948.

106. University of California (Berkeley), Prosthetic Devices Research Project, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, *The suction socket above-knee artificial leg,* 3rd edition, April 1949.

107. University of California (Berkeley), Prosthetic Devices Research Project, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, *Biceps cineplasty and prosthesis for below-elbow amputations,* April 1950.

108. University of California (Berkeley), Prosthetic Devices Research Project, [Report to the] Advisory Committee on Artificial Limbs, National Research Council, *Functional considerations in fitting and alignment of the suction socket prosthesis,* March 1952.

109. University of California (Berkeley), Prosthetic Devices Research Project, and UC Medical School (San Francisco), Progress Report [to the] Advisory Committee on Artificial Limbs, National Research Council, *Studies relating to pain in the amputee,* June 1952.

110. University of California (Berkeley), Prosthetic Devices Research Project, [Report to the] Advisory Committee on Artificial Limbs, *Functional considerations in fitting and alignment of the suction socket prosthesis,* 2nd ed., August 1953.

111. University of California (Berkeley), Prosthetic Devices Research Project, Report to the Advisory Committee on Artificial Limbs, National Research Council, *The pattern of muscular activity in the lower extremity during wilking,* September 1953.

112. Wagner, Edmpnd M., *Contributions of the lower-extremity prosthetics program,* Artificial Limbs, May 1954. p. 8.
113. Wagner, Edmond M., and John G. Catranis, *New developments in lower-exlremity prostheses,* Chapter 17 in Klopsteg and Wilson's *Human limbs and their substitutes,* McGraw-Hill, New York, 1954. p. 482.
114. Wagner and Catranis, *op. cit.,* p. 511.
115. Weddell, G., B. Feinstein, and R. E. Pattle, *Electrical activity of voluntary muscle in man under normal and pathological conditions,* Brain, 67:178 (1944).
116. Wohlfart, G., B. Feinstein, and J. Fex, *Uber die Bieziehung zwischen electromyographischen und anatomischen Befunden in normalen Muskeln und bei neuromuskularen Erkrankungen,* Arch. f. Psychiat. u. Ztschr. Neurol., 191:478 (1954).