Reports, Prosthetics Research Board
1955

Indexed

January 1955

24,1

Artificial Limbs

A Review of Current Developments

ADVISORY COMMITTEE on ARTIFICIAL LIMBS

National Academy of Sciences
National Research Council

Artificial Limbs

VOL. 2 JANUARY 1955 NO. 1

CONTENTS

ADVISORY COMMITTEE on ARTIFICIAL LIMBS

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

2101 Constitution Ave. Washington 25, D. C.

Artificial Limbs is a publication of the Advisory Committee on Artificial Limbs, National Academy of Sciences—National Research Council, issued three times a year, in January, May, and September, in partial fulfillment of Veterans Administration Contract VAm-21223. Library of Congress Catalog Card No. 55-7710.

Prelude, Prophecy, and Promise

JOHN B. DEC. M. SAUNDERS, M.B., F.R.C.S.(Edin.)[1]

IT HAS become almost axiomatic to say that the effective and rational treatment of human ills is dependent upon a knowledge of the normal structure and function of the human body and its response to the abnormal. But application of this dictum to the development of prosthetic apparatus as a substitute for loss of an extremity has been long delayed, and consequently improvement in artificial limbs has been extraordinarily slow. Almost to the immediate present, design of artificial limbs has been characterized largely by empirical developments and has depended little on fundamental investigation.

The reasons for this state of affairs are many and complex. Among them might be mentioned the late appearance, in the nineteenth century, of the humanitarian movement which was to provide much of the stimulus and the monetary support from private philanthropist and, later, from the public purse. Tradition too has had its influence, for initially the development of prostheses lay in the hands of the armorer, an association reminiscent of the relationship between amputation and warfare, and thence it passed to his lineal heirs, the surgical-instrument maker and the skilled artisan, who, however ingenious, had no background either in anatomy or in physiology and little knowledge of mathematics or of engineering.

Replacement of hand and arm, the tool through which the highest endowments of the human mind have been expressed, offered no great possibility of complete success. This circumstance influenced the surgeon toward an extreme conservatism in upper-extremity amputation, and failure to achieve perfection in a prosthesis brought no greater disappointment than there were expectations. From the point of view of amputee rehabilitation, furthermore, it was recognized that in the unilateral arm amputee the left hand could be taught to perform the functions of the right, and vice versa, so that a partial restoration of function in supplying stability was all that was sought. Limitations in expectation provided limitations in objective.

In the lower extremity, the problem of restoration seemed, on superficial analysis, to be infinitely more simple. As might have been expected, initial concepts of replacement were in terms of support only, to be followed by development of a jointed support in mimicry of the human leg as a static rather

---

[1] Professor of Anatomy, School of Medicine, University of California, San Francisco.

than a dynamic mechanism. The degree of disappointment and measure of failure in these simple objectives, without change in fundamental concepts, is to be seen in the countless empirical modifications of initial designs which bestrew the literature on artificial limbs over the past hundred years and more.

Earlier optimisms were gradually replaced by indifference and the inertia of failure, as is well known to those associated with the problem of the amputee after World War I. Locomotion, as we ordinarily understand it, is impossible on a single extremity. But it was realized insufficiently that, unlike the upper extremities, the two lower limbs together constitute but a single organ—the organ of locomotion. Consequently, the complexity of locomotion in relationship to prosthetics design never really was understood, and even where designs were in question the available information was inadequate to support newer developments of principle.

Preliminary efforts in the study of human locomotion are to be found in the work, *De Motu Animalium*, of the Neapolitan mathematician and physician, Giovanni Borelli (1608–1679). As a pupil of Galileo, he was stimulated to take a mechanistic view of bodily function and to study locomotion as a problem in leverage, but his theories and those of his followers soon were reduced to absurdity in the attempt to apply the same mechanistic principles to the whole of medical practice. Continuation of Borelli's approach had to await the nineteenth century and the advent of the Weber brothers, Edward (1806–1871) and Wilhelm (1804–1891), physician and physicist respectively, who with primitive electrical apparatus made the first accurate measurements of gait and undertook its mathematical analysis. The development of photography as a method of recording enabled Étienne-Jules Marey (1830–1904) to avoid previous errors and to correct earlier ideas, and further improvements in photography led to the classical work of Christian Braune and Otto Fischer, *Der Gang des Menschen* (1895), which has constituted the main source in the formulation of principles for the construction of artificial legs, as in the well-known books of H. von Recklinghausen (1920) and Frederich Mommsen (1932). Over more than a decade (1933–1945) Elftman published the results of extensive locomotion studies. To these and many others we owe a great debt.

Despite all these investigations, at the end of World War II our knowledge of human locomotion was still quite incomplete, and such knowledge as existed was only poorly understood. Thus it was that, when approached in September of 1945 by the then Committee on Artificial Limbs of the National Research Council, the representatives of the College of Engineering and of the Medical School of the University of California could point to the necessity of the adoption of a long-term outlook which envisioned the study of the fundamentals of human locomotion, of the amputee who must wear a lower-extremity prosthesis, and of the prosthesis itself. It could be shown that the experience of 400 years in trial-and-error techniques had offered little and that a firm basis for progress could be established only by a systematic approach. It was predicted that at least seven years of study would be required to collect the fundamental data necessary for improved design of artificial legs.

That that prophecy was not needlessly pessimistic is revealed in the fact that only today can it be said with a degree of confidence that we are about to enter a period of practical development in the evolution of a truly satisfactory lower-extremity prosthesis. Within the next two or three years we should see the appearance of sound improvements based upon the preceding nine years of pioneering work.

But the problems of the leg amputee are not wholly "prosthetic." Such a patient presents a clinical picture of considerable significance. The whole being the sum of its parts, the amputee can scarcely be looked upon as normal in the medical sense, however good general health may be. He is, indeed, quite abnormal, for from amputation of an extremity come changes in skeletal, muscular, and circulatory systems to be dealt with in the design and application of the prosthetic replacement. Complications of pain, real and phantom, and of skin disorders are other matters needing the skills and experience of the medical profession.

Taking cognizance of this situation, the Advisory Committee on Artificial Limbs, in the spring of 1953, recommended that the University of California initiate an extensive clinical program to be integrated with the work already under way in the fundamentals of locomotion and in the techniques of lower-extremity fit and alignment. Utilizing space and services afforded by the U. S. Naval Hospital at Oakland and personnel from the University of California Medical and Engineering Schools, the Clinical Study aims to apply to the practical problems of difficult amputee cases the results of the earlier work on the Berkeley Campus.

This issue of ARTIFICIAL LIMBS is concerned with two major factors in the management of the lower-extremity amputee—the solution of medical problems associated with the amputated state, and the proper application of the prosthetic replacement on the basis of established biomechanical considerations. In the first of two articles, an orthopedic surgeon and an engineer collaborate in describing the origin, observations, and objectives of the Lower-Extremity Clinical Study. In the second, an engineer develops the principles of alignment and socket fit so indispensable to comfort and function, and hence to the success, of the above-knee artificial leg. In this cooperative effort is reflected the whole basic philosophy of the Artificial Limb Program in approaching the problems of the amputee.

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

VERNE T. INMAN, M.D., Ph.D.,[2] AND
HOWARD D. EBERHART, M.S.[3]

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.

[2] Professor of Orthopedic Surgery, School of Medicine, University of California, San Francisco; Professional Associate, Advisory Committee on Artificial Limbs, National Research Council; member, Technical Committee on Prosthetics, ACAL, NRC.

[3] Professor of Civil Engineering, University of California, Berkeley; member, Advisory Committee on Artificial Limbs, National Research Council, and of the Technical Committee on Prosthetics, ACAL, NRC.

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.

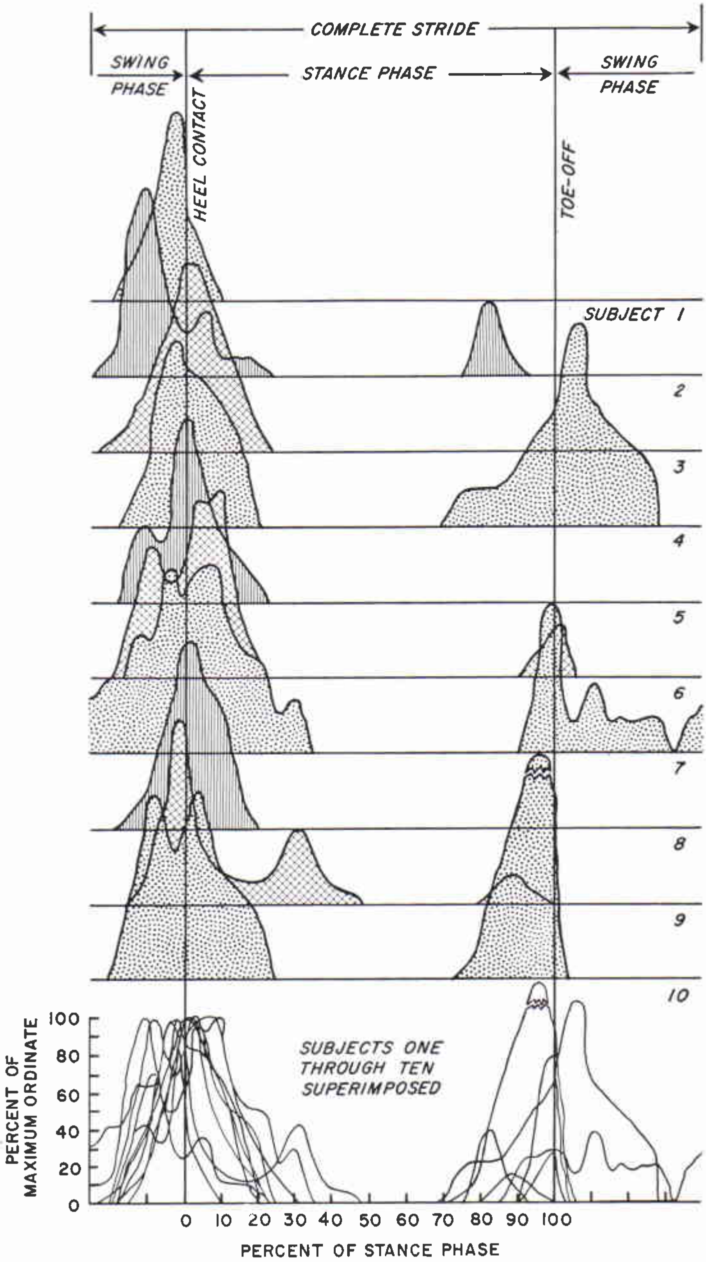

Fig. 1. Typical electromyographic summary curves, in this case for the hamstring group. Ten subjects. Cadence: 95 steps per minute, level walking. Data from UC studies (*102*).

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

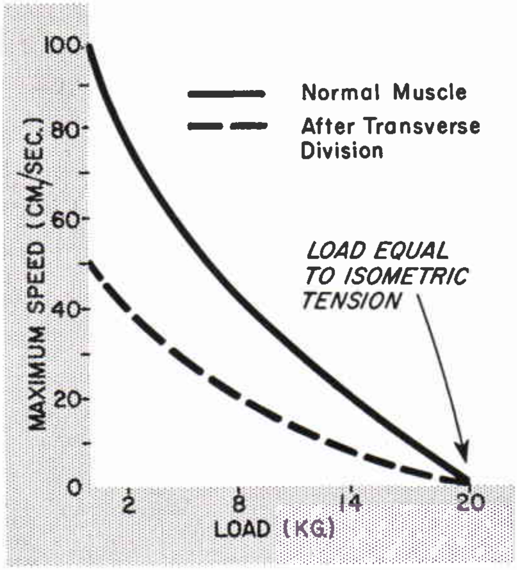

Fig. 2. Relation between the maximum speed with which a muscle can contract and the weight with which it is loaded. When the length of the muscle is halved, its speed of contraction is also halved.

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*).

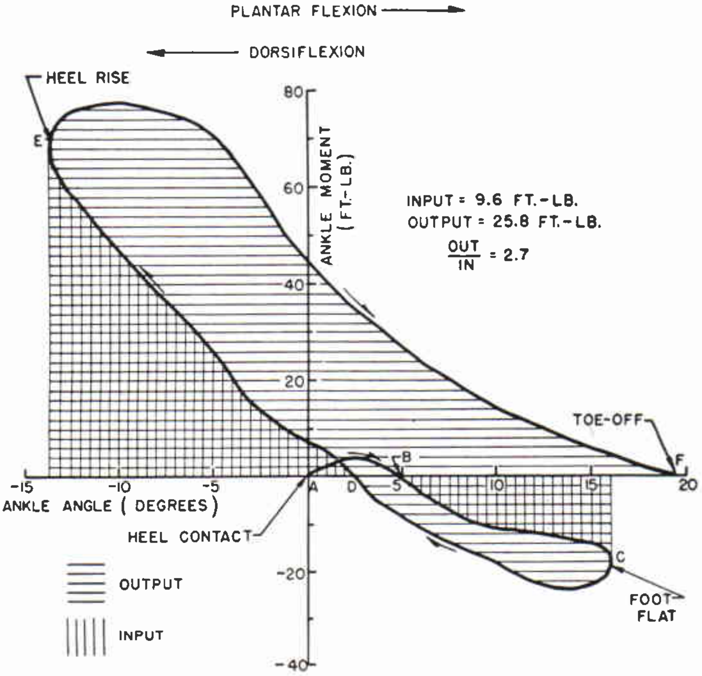

Fig. 3. Typical moment-angle diagram for the leg of a normal subject during level walking. From Bressler [*sic*] and Berry (*14*).

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

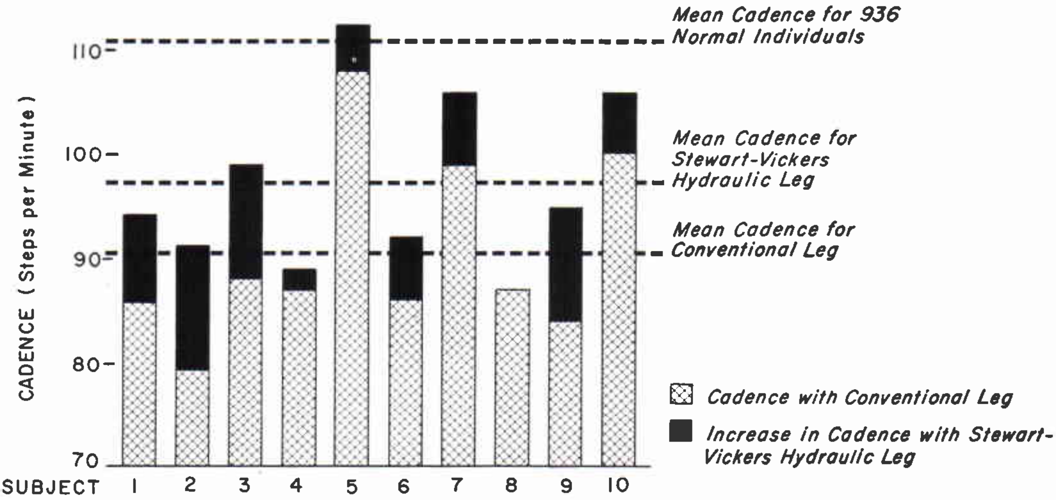

Fig. 4. Cadence changes observed in above-knee amputees asked to walk at "normal" speed first with a conventional limb and then with the Stewart-Vickers (locked ankle) prosthesis (*114*).

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

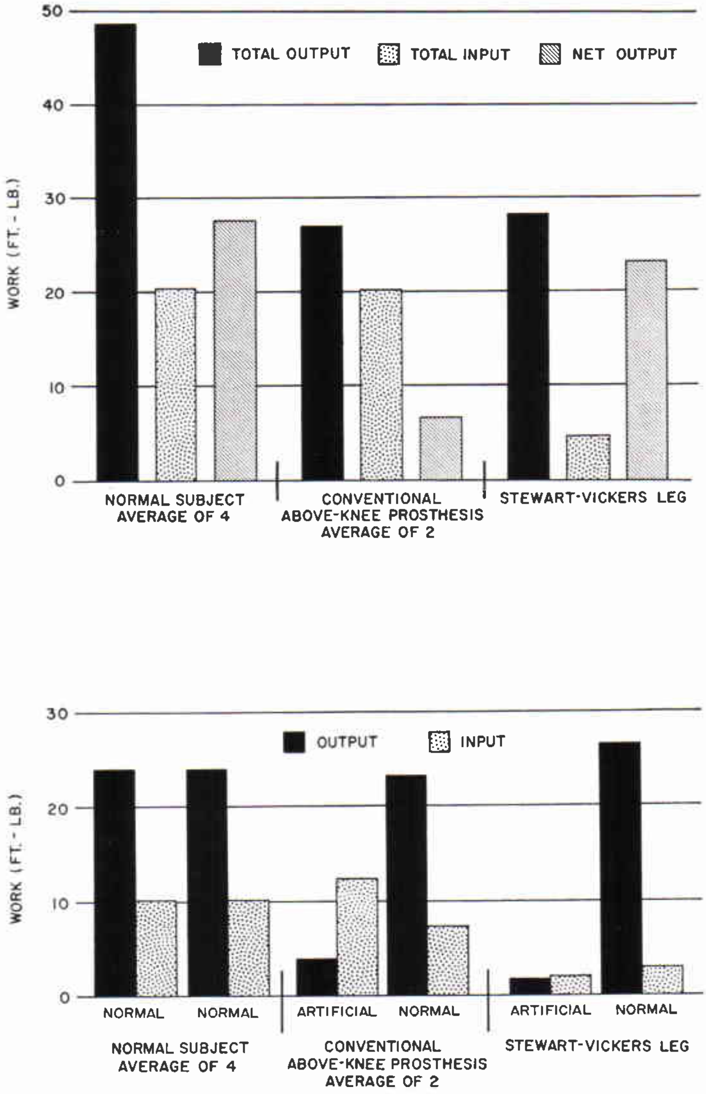

Fig. 5. Energy characteristics of the normal ankle compared with those of the conventional leg and the Stewart-Vickers leg. Top, total input, total output, and net output of both ankles per stride. Bottom, input and output of each ankle per step.