June 1962

Artificial Limbs

A Review of Current Developments

COMMITTEE ON PROSTHETICS RESEARCH AND DEVELOPMENT

National Academy of Sciences
National Research Council

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Division of Engineering and Industrial Research

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

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VOL. 6 JUNE 1962 NO. 2

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2101 Constitution Ave. Washington 25, D. C.

Artificial Limbs is a publication of the Committee on Prosthetics Research and Development, National Academy of Sciences—National Research Council, issued randomly two numbers to the volume, in partial fulfillment of Veterans Administration Contract V1005M-1914, Office of Vocational Rehabilitation Contract SAV-1000, and National Institutes of Health Grant RG-5057.
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The Patellar-Tendon-Bearing Prosthesis

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Obiously there is no "ideal" leg substitute short of regenerating or transplanting another normal leg. The surgeon, the prosthetist, and the amputee alike have long accepted major deficiencies in leg prostheses as inescapable concomitants of aid in a situation demanding drastic compromise. Substitution of an artificial leg for a natural one involves not only manual skills and the principles of inanimate mechanisms but is also dependent on anatomy, physiology, and biomechanics. Mutual application of these disciplines toward the advancement of leg prosthetics was slow in coming. As the science of astronomy emerged from the superstitions of astrology, so too there is sound reason to hope that the profession of prosthetics will continue to grow increasingly rapidly beyond the great dependence on "experience in the finger tips" of the ancient skill of limbmaking by adding to its art more general application of the discoveries of science.

Time after time, like recurrent approaches of a comet from its far-reaching orbit, dazzling prospects of improvements in prostheses for below-knee amputees have illuminated the prosthetics scene. The slip socket, the many attempts at end-weight-bearing, the "muley" leg without side joints or corset, the single sidebar, the various polycentric joints, and the several attempts at below-knee suction sockets have been spectacular objects visible for varying periods in Europe, the United States, or alternately in both regions. Unhappily, these phenomena, like comets, have often receded into outer darkness as abruptly as they appeared, leaving the typical amputee with crutches, peg leg, or the centuries-old "conventional" prosthesis.

Pads, straps, locks, and similar devices often reflect either lack of knowledge or incomplete application of such knowledge as there is to control pressure or to overcome instability. Freedom of the human knee joint, distribution of forces in proportion to tolerance of tissues, improved rather than constricted circulation, and better kinesthetic appreciation—all major goals in recent years—demand simplicity of mechanism and reduction of the false joint between the prosthesis and the body by use of an intimate fit.

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The patellar-tendon-bearing (PTB) prosthesis developed by the Biomechanics Laboratory of the University of California, to which much of this issue is devoted, combines many long-controversial features—each long used by some, yet rejected by others. PTB is almost a code name integrating a long list of elements which the prosthetist through logical principles and teachable techniques employs to distribute forces comfortably. Because of individual variations, not all so-called "PTB prostheses" contain all the major features. The name implies weight-bearing on the patellar tendon, more properly called the patellar ligament. Because in fact the nearby retinacula also share weight, perhaps the name might well be the "patellar-tendon*s*-bearing" prosthesis! Actually, as later pages of this issue describe, many other areas of the socket (notably the closed distal end) are at least in contact with the stump, and some (*e.g.*, the flares supporting the tibial condyles) share substantial portions of body weight.

Because of its typical use of cuff suspension, with consequent freedom from thigh corset, the PTB prosthesis is often erroneously identified with the "muley" leg, which has stomped the field for as much as a century and yet has so often developed complications during prolonged use. One may speculate that the common complaints of instability of the knee attributed to the "muley" principle were at least partially related to poor alignment between socket and foot, excessive extension or even hyperextension of the socket axis and hence of the human knee, and needlessly low brim levels offering less than maximum stability to the stump. Careful prescription and medical supervision, not available for the earlier "muley," should also characterize use of the PTB and greatly enhance its chances of success.

This writer's personal observations, from visits to the birthplace of PTB and to numerous clinics throughout the United States, have indicated misconceptions of the role of knee flexion in initial alignment of the socket axis. Certainly hyperextension is to be avoided and mild flexion sought. Because the *cast* is taken with the knee in substantial (possibly excessive?) flexion, some newly trained prosthetists initially aligned the socket bore similarly but with a very large angle of flexion. The horizontal components of forces on the condyles were reduced; but the resulting extreme bent-knee gait was tiring, the quadriceps were unduly stressed in their atrophied state immediately after their release from bondage within the thigh corset, and the unique mechanical stability of the extended human knee was transformed into the capability of substantial horizontal rotation of the flexed knee. In the below-knee amputee lacking an actively steerable ankle and foot, an unimpaired but controlled horizontal rotation in the knee joint must be considered of added importance. Thus neither the rigid "screw-home" of final extension nor the gross instability of major flexion will be as suitable as mild flexion with control of unencumbered hamstrings as internal and external rotators.

In many past efforts too little attention has been paid to the popliteal space.

The PTB includes logical principles allowing a higher brim in the popliteal space (and indeed on all aspects) than has been customary in a majority of cases yet freedom for action of the hamstrings and avoidance of bulging of tissue during sitting. The high brims medially and laterally, reflecting better appreciation of anatomy and of the force patterns dictated by biomechanics, should give greater mediolateral stability than was typically available with a "muley" limb. Eventual use of brims of tapering flexibility, by avoiding sharp pressure points at the very edge, may ultimately allow still better fitting.

No one, especially among its developers, would acclaim the PTB as the ultimate solution. Some of its features represent successive reincarnations over a century, each with a higher survival percentage. Yet the PTB is only an evolutionary step toward greater mechanical freedom under better neuromuscular discipline. Many apparent failures can be salvaged by careful adherence to the principles and techniques enunciated in the UCB manual and its recent revision and in the following papers of this issue of ARTIFICIAL LIMBS.

The conveniences which the PTB leg accords its wearer are so numerous that continued efforts seem assured. Though a single breaker may recede, the tide is surely coming in.

Anatomical and Physiological Considerations in Below-Knee Prosthetics

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AND
A. BENNETT WILSON, JR.[2]

ONE of the most difficult problems in the design of prostheses is the development of the best means of attaching the prosthesis to the wearer. In lower-extremity cases, transmission of forces between stump and prosthesis is of primary importance. To effect efficient transmission of forces, a stable connection between stump and prosthesis is necessary. At the same time comfort and freedom of motion must be maintained to as high a degree as possible. All of these goals are affected by anatomical and physiological characteristics of the stump and the next proximal joint, and often of the joint above that.

Stability is provided most often by encasing the stump in a socket to a point near the first proximal joint. The soft tissues of the stump are not especially ideal for providing resistance to the torques and moments imposed on them by a socket during use of a prosthesis. If the tissues are compressed in an attempt to provide maximum stability, circulation will be impaired; if the socket is too loose, a false-joint effect is produced resulting in abnormally high unit pressures at proximal and distal points, chafing, and a reduction in ability to control the prosthesis. Thus, extreme care must be exercised in socket design and fabrication if the optimum condition is to be obtained.

When weight-bearing can be achieved through the long bones, as in the case of many disarticulations and certain special types of amputation, the socket is designed to permit loads to be carried through the end of the bone in the stump. If most of the weight-bearing needed cannot be achieved through the end, some other areas must be found to provide the transmission of forces necessary during standing. For all of these reasons, then, it is extremely important that prosthetists and others responsible for the design of sockets take into consideration certain anatomical and physiological factors in the management of the amputee. In no other case is it more important than in that of the below-knee amputee.

Function of the Below-Knee Stump

Because most of the insertions of the muscles and ligaments that control the knee are located on the tibia and fibula at points close to the knee joint (Figs. 1, 2, 3), amputation below the knee rarely affects the function of the knee joint. An exception is the gastrocnemius which originates from the posterior portion of each of the femoral condyles and has for its insertion the Achilles tendon, thus acting as a flexor. Upon amputation, however, the distal end of the gastrocnemius often becomes reattached to the tibia, and the remaining musculature is thus available to assist the flexors and perhaps to aid in preventing dislocation of the fibula with respect to the tibia. Thus the moment that can be generated about the knee in the parasagittal plane by a typical below-knee amputee is approximately the same as that before amputation. Because, in general, the ligaments are left untouched, mediolateral stability of the below-knee amputee usually is not affected.

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Those muscles which have origins on the tibia and fibula, and which control ankle and foot motion, have been severed and consequently atrophy, resulting generally in a bony, conical-shaped stump (Fig. 4). The amount and type of atrophy that takes place depend of course upon surgical technique and postoperative care.

In very short below-knee stumps, removal of the fibula (Fig. 5) is sometimes performed to prevent lateral and posterior deviation with uncomfortable protrusion at the distal end. Such deviation is generally thought to be caused by frictional engagement on the socket wall (with inadequate relief) or by action of the biceps femoris. In any below-knee amputee, the distal ligamentous attachment near the ankle is missing, and in short stumps the interosseus membrane (Fig. 6) between the remnants of the tibia and the fibula is presumably inadequate, partly because the proximal opening for the vessels leaves only a small amount of the membrane, and particularly because atrophy of intervening muscles leaves some slack in the membrane. Removal of the fibular head, though, implies that the tendon of the biceps femoris, as well as the fibular collateral ligament, should be reattached with appropriate lengths and at suitable centers on the tibia. A bone bridge from fibula to tibia (p. 90) that would restore stability between tibia and fibula as well as increase the possibilities for bearing weight on the end of the stump would seem to be preferable to removal of the fibula.

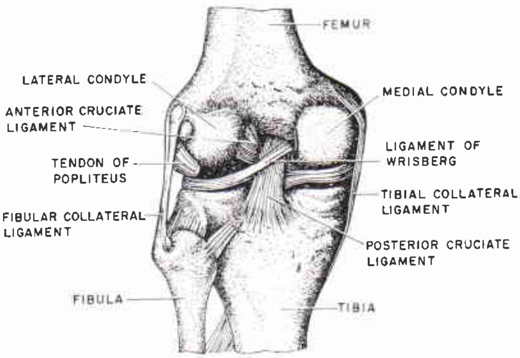

Fig. 1. Posterior view of left knee joint, showing anterior ligaments. Redrawn from Gray's *Anatomy*.

The Knee Joint

The knee joint formed by the condyles of the femur and tibia (Figs. 3, 7) allows about 160 deg. of flexion. It is classified as a synovial joint, or one that is provided with synovial fluid, and the friction developed between the moving surfaces of an unimpaired joint is of an unusually low magnitude as compared with

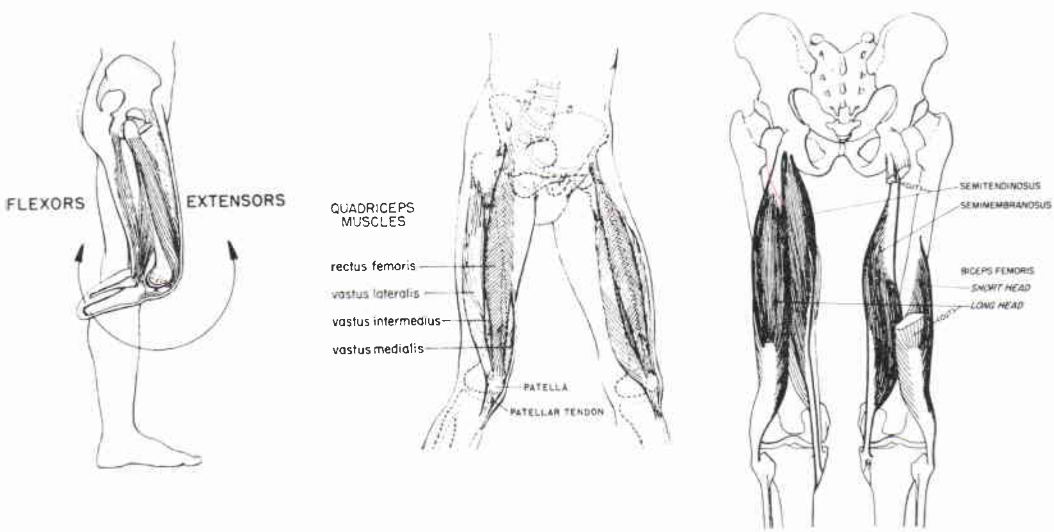

Fig. 2. The major muscles that flex and extend the knee joint. From *The Patellar-Tendon-Bearing Below-Knee Prosthesis* (4).

Fig. 3. X-rays of a typical below-knee stump. *A*, Anterior view; *B*, medial view. Courtesy *Veterans Administration Prosthetics Center.*

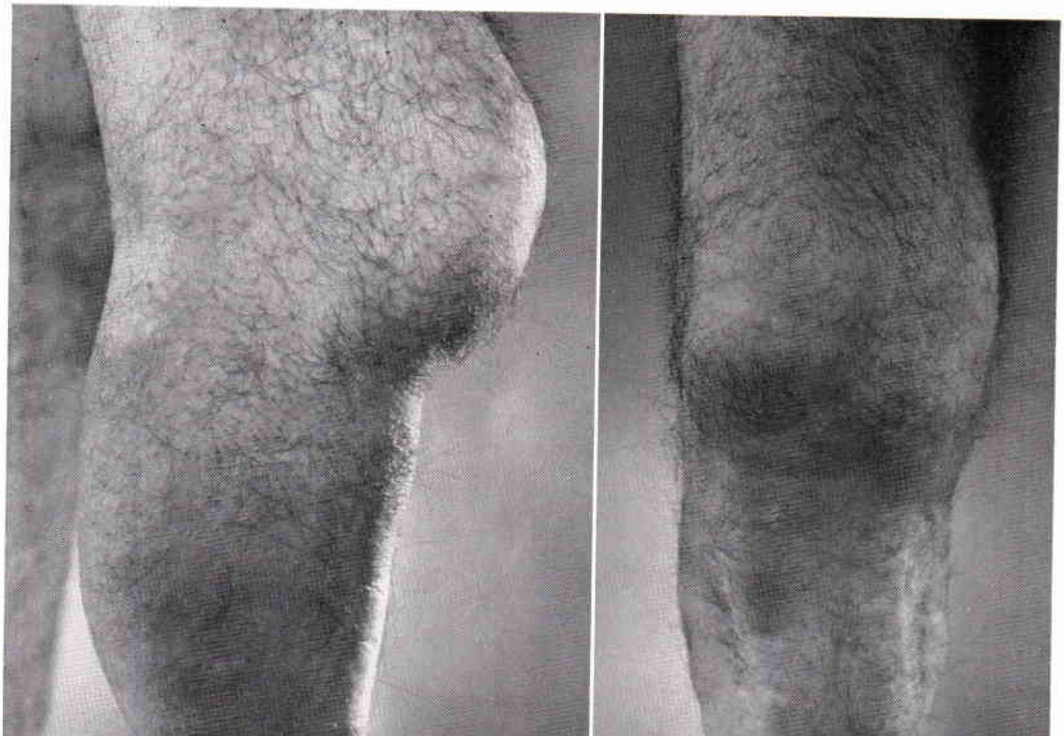

Fig. 4. Lateral and anterior views of a typical, well-formed, right below-knee stump. Courtesy *Veterans Administration Prosthetics Center.*

Fig. 5. Roentgenogram of a short below-knee stump in which lateral deviation and rotation of the fibula have taken place. *Courtesy University of California Medical School.*

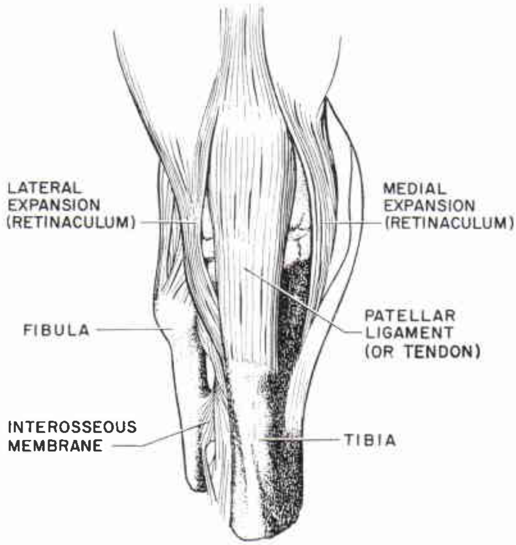

Fig. 6. Anterior ligamentous structure of the right knee.

moving joints in machinery (*1*). It is not a simple hinge joint with a single axis of rotation. Because movement of the tibia with respect to the femur is a combination of gliding and rolling actions, and because of the shape of the contacting surfaces, the instantaneous center of rotation of the knee varies with each degree of flexion. Though the exact course of the instantaneous centers for different individuals cannot be described with present knowledge, a general idea of the typical area through which they move can be had (Fig. 8).

For many years it has been common practice to divide the responsibility of weight-bearing between the below-knee stump and the thigh by use of simple hinge joints (located along the medial and lateral aspects of the knee) connecting a thigh corset to the socket and shank (Fig. 9). But, because the center of rotation of the knee moves constantly while flexion or extension takes place, any artificial joint attached on the outside of the leg and thigh that does not follow the complex pattern of the human joint will cause relative motion between the body parts and the prosthesis. Since there is not available an artificial joint that simulates normal movement, it appears highly desirable to provide the below-knee amputee with a prosthesis that does not require side joints, even though the tissues in the stump and thigh are capable of absorbing the effects of some relative motion.

Weight-Bearing

If sidebars are to be avoided, obviously all of the weight-bearing loads must be transmitted through the stump to the skeletal system. Some areas on the stump are better suited to assume these loads than others. In the light of present knowledge and technology it is necessary to design and construct the socket so that the pressures imposed on specific areas, whether by normal repeated loads encountered during walking or whether by single emergency loads, are not of values that exceed the varying tolerances of the different tissues of the stump. And just as obviously some means other than sidebars and thigh corset must be found to maintain the limb on the stump. If, however, the necessary mediolateral stability

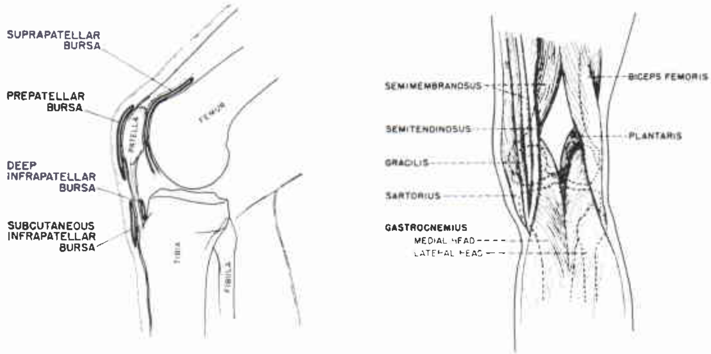

Fig. 7. Major structures that form the knee joint. From *The Patellar-Tendon-Bearing Below-Knee Prosthesis* (*4*).

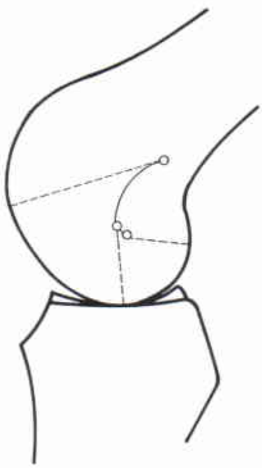

Fig. 8. Section through the medial condyle of the femur and through the tibia. The center of curvature is shown for three parts of the articular surface. As gliding occurs in the joint, the instantaneous center moves along the curve connecting these centers of curvature. From Elftman (*2*).

is not present, there is no known recourse except to use at least one sidebar and generally two.

THE PATELLAR LIGAMENT

Extension of the knee is effected by the contraction of the quadriceps muscle, so named because it has four distinct components. However, they merge into a single tendon which inserts on the anterior portion of the tibia just below its head (Fig. 6). Embedded in this tendon is the patella (Fig. 7), which is therefore a sesamoid bone, the largest in the body. Its function is twofold. While acting as a guide for the quadriceps tendon by following the vertical groove between the femoral condyles, it also tends to increase the lever arm of the quadriceps acting about the knee axis. Its cartilaginous underbody tends to produce very little friction as it slides over the anterior surface of the femur. That part of the quadriceps tendon between the patella and the insertion, frequently referred to as the patellar ligament (Fig. 10), is composed of extremely tough fibers which stretch insignificantly under normal tensile loads along the long axis and is particularly suited to take compressive loads anteroposteriorly. Because of the inextensible quality of the quadriceps tendon, there can be little or no relative motion between the patella and the tibia when the quadriceps develops tension, a condition which permits compressive loads over the quadriceps tendon, perpendicular to the fibers, up to the proximal edge of the patella. The sharp lower edge of the patella, though, is relatively unsuited for weight-bearing.

Branching out from the quadriceps tendon on each side above the patella are the lateral and medial retinacula (Fig. 6), which insert on the flares of the tibia. Like the patellar ligament, these tendons are capable of weight-bearing.

If the socket wall contains an indentation (Fig. 11) between the lower edge of the patella and the tendinous insertion, some initial tension is placed on the tendon. The upper surface of the indentation also permits the tendon to assume a load with a larger vertical component than would be the case if the indentation were not present (Fig. 12). Moreover, when the socket is aligned so that a slight amount of initial flexion is present when the wearer is in the standing position, both initial tension in the quadriceps tendon and the vertical components of load-bearing are enhanced.

Fig. 9. Some examples of the so-called "conventional" below-knee prosthesis offered by prosthetists for more than a century. Note the sidebars, corset, relatively low brim, and free space at distal end of socket.

FLARES OF THE TIBIAL CONDYLES

By virtue of its wedgelike shape and the nature of its thin, tough, overlying tissues, the upper portion of the tibia can assume part of the weight-bearing load by distribution of pressure over the medial and lateral flares of the condyles. Because part of the lateral flare of the tibial condyle is obscured by the head of the fibula, the medial flare offers most of the weight-bearing area.

Figure 13 shows horizontal cross sections of the tibia below the condyles superimposed on each other. Thus it can be seen that there is available potentially a considerable difference in horizontal area over which to distribute vertical forces to balance body weight. If the socket is aligned so that the stump is forced into a slightly flexed position when the wearer is standing erect, the horizontal components are reduced, the requirements for counterpressure over the posterior wall are less, and therefore the risk of pressure over the major vessels and nerves in the rear is reduced. Proximity to relatively sensitive zones like the head of the fibula (typically present under the lateral flare), the sharp tibial crest, and the rough tibial tubercle greatly reduces the useful area on the anterolateral portion. The medial flare, though seemingly smaller than the lateral, is quite effective in providing support.

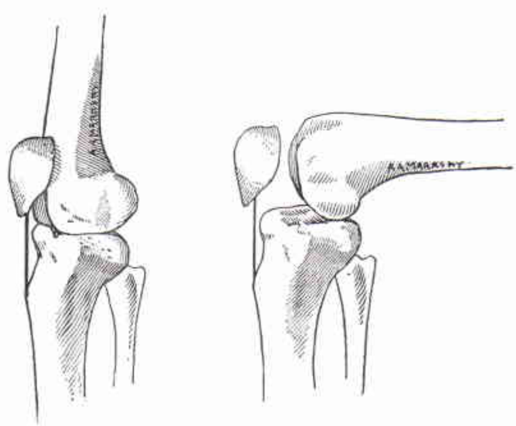

Fig. 10. Schematic drawing showing the nearly complete lack of relative motion between patella and tibia during flexion of the knee. The inextensibility of the patellar ligament prevents the patella from moving proximally with respect to the tibia. From Marks (*3*).

THE TIBIAL CREST

The shaft of the tibia is roughly triangular in horizontal section, one apex, the tibial crest, lying in the anterior portion of the leg (Fig. 13). The anteromedial wall of the tibia is covered with a thin layer of tissues and is admirably suited to assume some of the weight-bearing stresses. In the normal limb, the anterolateral wall of the tibia is covered by the tibialis anterior, which inserts in the region of the foot. Upon amputation, the tibialis atrophies but can still transmit, without discomfort, considerable load to the anterolateral wall. But the tibial crest itself cannot assume a weight-bearing load because of the high unit pressures that would necessarily develop over the knife-like ridge. For the same reason, compressive stresses cannot be tolerated either at the lateral aspect of the distal end of the fibula or at the anterior aspect of the distal end of the tibia.

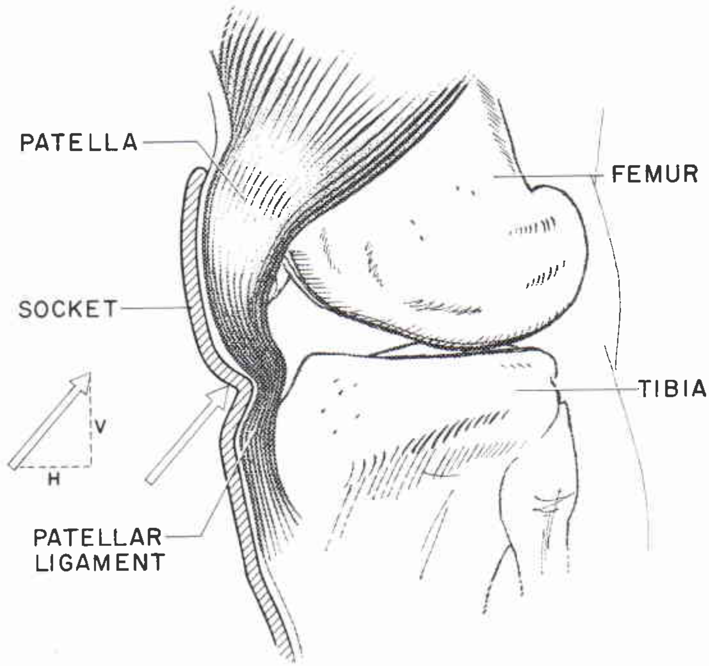

Fig. 11. Vertical cross-section of anterior portion of socket designed to take maximum advantage of patellar ligament for transmission of weight-bearing loads. Compare with Figure 12.

THE HEAD OF THE FIBULA

Because the common peroneal nerve passes on the lateral side below the head of the fibula, only very low pressure can be tolerated in that area. Also, for bony stumps it is sometimes necessary to provide a groove proximally from the region of the head of the fibula in order to permit entry of the stump into the socket. Figure 14 shows in a somewhat exaggerated way how a socket is shaped to preclude the application of pressure in tender areas.

THE DISTAL END OF THE STUMP

Few below-knee stumps will tolerate very much pressure on the distal end, presumably because of the shearing stresses developed between soft tissues and the cut end of bone. Short stumps, where amputation was made through cancellous bone, and those cases where a bridge of bone has formed between the distal ends of the tibia and fibula, accidentally or surgically (p. 90), are exceptions to the rule.

Stability

Vertical pressures on the areas projected on the horizontal plane, and hence total vertical forces, unhappily can be obtained only as *components* of the larger unit pressures and total forces exerted at right angles to the obliquely sloping surfaces of the stump, the thin but tough underlying tissues, and ultimately the bone (Fig. 15). Because these surfaces slope, there must be forces *in* the horizontal plane. Because the slowly curving surfaces slope generally *inward* toward the longitudinal axis of the tibia, in the frontal plane that fraction of the horizontal components of the sloping forces from the socket acting on the broad medial aspect of the condyles must oppose the corresponding components of the force acting on the more limited lateral aspect, resulting in over-all compression or constriction of the stump. Any net imbalance near the condyles may be counteracted by a distal horizontal force to yield in the frontal plane a moment balanced elsewhere.

Because both the medial and lateral condyles slope generally *backward*, the horizontal components in parasagittal planes would tend to force the stump backward and hence allow it to slip downward off the sloping shelves matching the tissues overlying the condyles. Similarly, forces on the patellar ligament and retinacula have components directed rearwardly. Obviously, counterpressures from the rear wall must be so distributed over the stump as to develop adequate counterforces without pressure sufficient to cause pain at any point, restrict return circulation, or interfere with adequate knee flexion during sitting. Superimposed on these forces acting in the horizontal plane as a result of vertical weight-bearing there generally are other forces, high on one aspect of the stump and low on the opposite, forming couples related to mediolateral stability, forcible knee extension, and so on. The biomechanical principles underlying these forces are discussed in the following article (page 16).

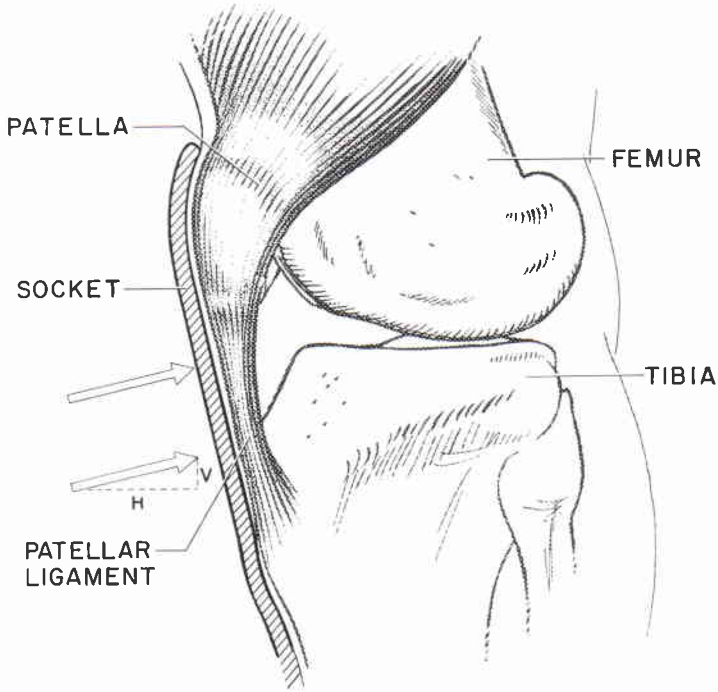

Fig. 12. Vertical cross-section of anterior portion of socket with little provision for use of the patellar ligament for transmission of weight-bearing loads. Note the small vertical component of the force between socket and stump in this area as compared to the condition shown in Figure 11.

The optimum level for the rear brim of the socket is the popliteal crease. Though as high a brim as feasible is desirable to provide greater area for horizontal counterpressure, a rigid socket brim above this level on the posterior aspect will seriously restrict knee flexion; one below results in bulging of the tissues over the brim during flexion.

The medial and lateral aspects of the socket wall should be carried to about the level of the proximal edge of the patella to enhance mediolateral stability.

The Hamstrings

The most important flexors of the knee are the hamstrings, which have two areas of insertions—one on the posterior aspect of the medial tibial condyle, the other on the posterolateral aspect of the head of the fibula (Fig. 2). As flexion occurs and the tibia and fibula rotate with respect to the femur, the hamstrings move away from the center of the femur. To prevent bunching of the tissues in the popliteal space during substantial knee flexion, especially during sitting, the brim of the socket should be brought precisely to the level of the popliteal crease. Because the two insertions of the hamstrings are below this level, interference between the hamstring tendons and the brim of the socket would occur when the knee is flexed were appropriate grooves, or cutouts, not provided in the rear portion of the brim. The medial groove is generally deeper than the lateral because the insertion of the semitendinosus is more distal on the tibia than the insertion of the biceps femoris is on the fibula.

Edema

One of the causes of edema is an unbalanced condition in the interchange of materials between blood and body cells by way of the capillary and lymphatic systems, *i.e.*, more fluid is pumped temporarily into the exchange system than is pumped out. An imbalance can be the result of either mechanical or biochemical factors. The wearing of a limb is not

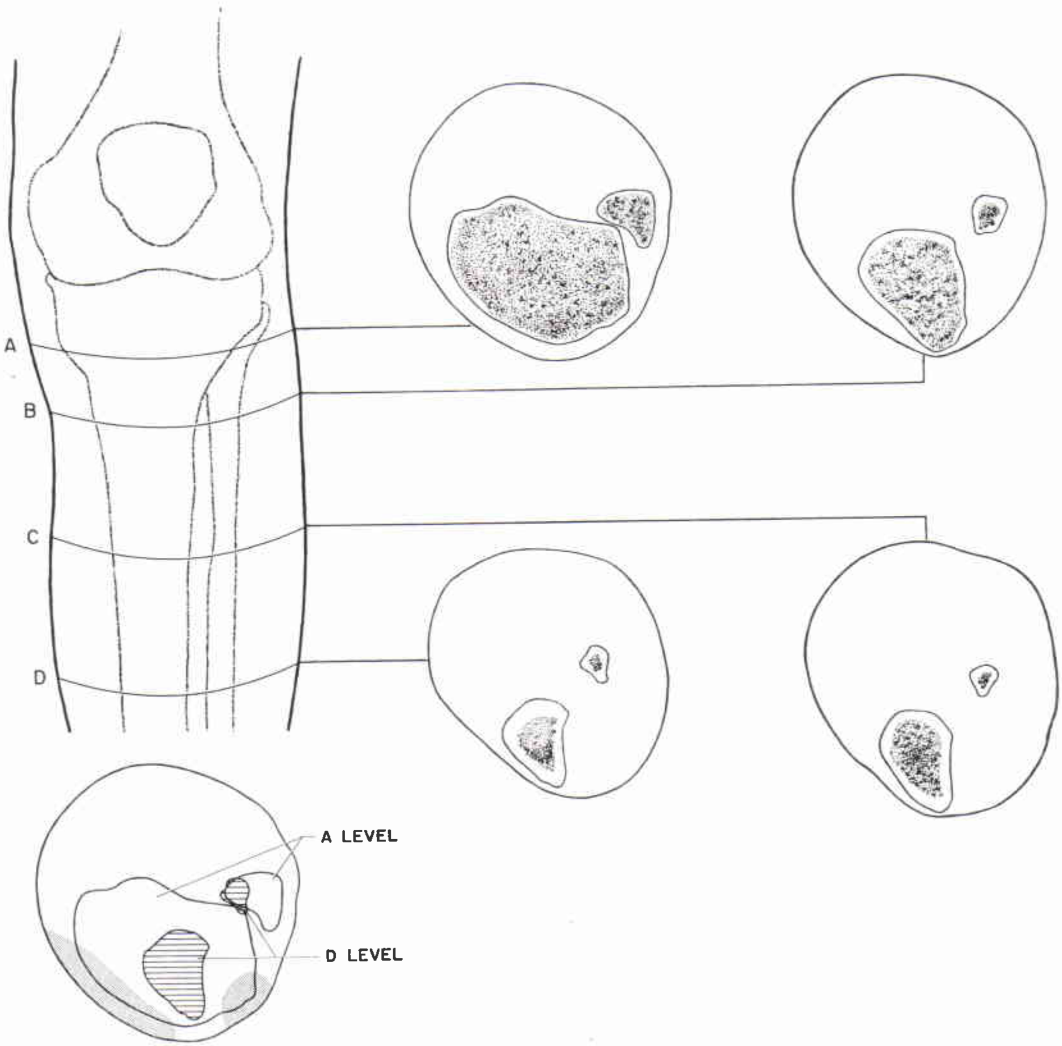

Fig. 13. Horizontal cross-sections of leg at four different levels. View below leg shows level *A* superimposed on level *D* to illustrate the horizontal area potentially available for vertical support along the sloping areas of the tibia.

likely to lead to the formation of chemicals that produce edema, but it can produce mechanical factors that do. The action of voluntary muscle working within the normally intact fascial envelope is responsible in part for the return of the blood to the venous system via the capillary and lymphatic systems, and hence factors that alter normal muscle activity can contribute to the formation of edema. Further, concentrated pressures in one area can cause edema in a distal area either by inhibiting muscle action or by restricting the low-pressure venous or lymphatic return systems and thus are to be avoided. For this reason, when relief is required for bony prominences or tender areas, the indentation in the socket wall should be flared gently. Relief should never be provided by a hole or window which removes external counterpressure from a localized area while maintaining support or even constriction elsewhere.

Also to be avoided is a combination of a

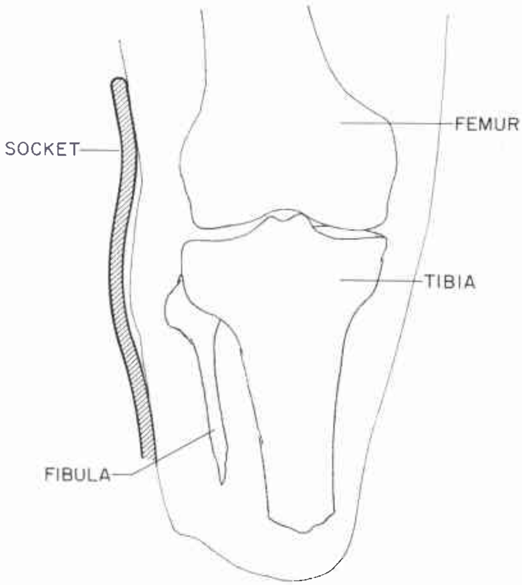

Fig. 14. Cross-section showing typical method of avoiding pressure between socket and tender areas on stump, in this case the area about the head of the fibula.

tight fit in the proximal portion of the socket and a loose fit distally. Under such circumstances the venous and lymphatic systems can be constricted to the point that edema is produced.

Gentle external pressure on soft tissues offers a mechanical aid to the return of blood to the venous system. The equivalent can be obtained by encasing the entire stump with the socket in such a manner that at least a slight amount of pressure is brought to bear over the soft tissues as the prosthesis is used.

The Composite Socket

The shape of the socket in which the anatomical and physiological factors discussed above are taken into account is shown in Figures 16 and 17. The anterior brim is brought to the level of the center of the patella; a horizontal indentation is provided at the midpoint of the patellar ligament to induce tension in the ligament and at the same time to afford a more horizontal weight-bearing surface; the lateral and medial aspects of the brim are brought about level with the proximal edge of the patella to assist in providing mediolateral

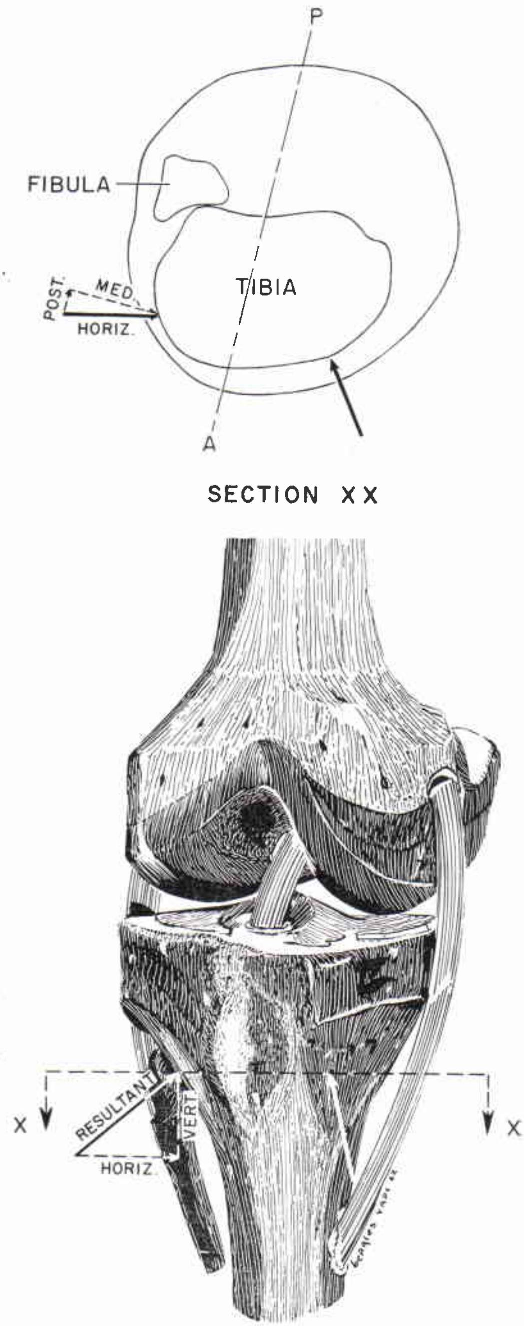

Fig. 15. Schematic drawing showing the approximate direction of forces acting on the flares of the tibial condyles. The vector representing the force on the lateral side is shown in true view in the lower sketch. Note the components developed in the horizontal plane. The components shown must of course be balanced by other forces in the horizontal plane.

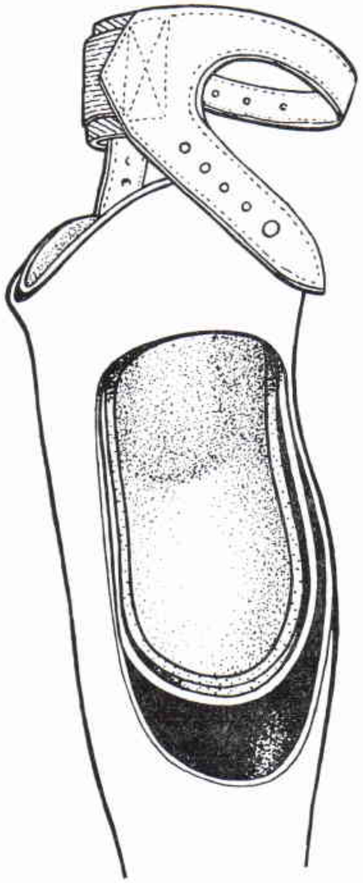

Fig. 16. Cutaway view of the patellar-tendon-bearing socket incorporated in a thin-walled plastic shank. Note especially cuff-suspension strap, high lateral and medial walls, and the total-contact feature.

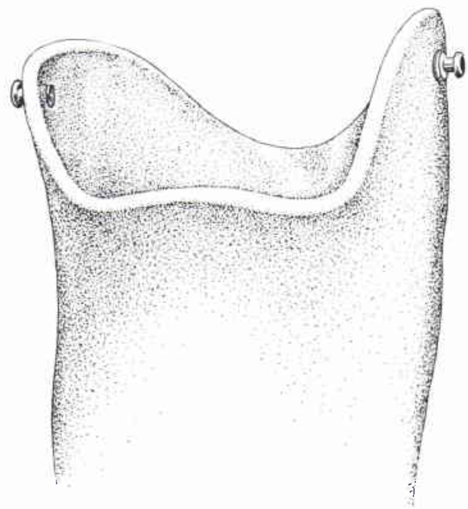

Fig. 17. Posterior view of brim of PTB socket for a right stump. Note that the medial wall is slightly lower than the lateral. Not shown is the soft inner liner commonly used.

stability; grooves are incorporated into the posterior brim of the socket to accommodate the hamstring tendons during flexion; the entire stump is encased; and areas for relief of bony prominences are flared gently to avoid radical changes in pressure.

The socket shown was developed by the Biomechanics Laboratory of the University of California (*4*) after a thorough study of previous practices and after an analysis of the anatomical, physiological, and biomechanical factors involved. The socket is installed in the prosthesis so that the knee is in some 5 to 8 deg. of flexion when the patient is standing erect. This slight degree of initial flexion not only places the weight-bearing loads on the stump in a direction that reduces the unit stresses and shearing forces but also relieves the popliteal area of some pressure as well. In addition, use of the quadriceps is encouraged, and the risk of overloading ligaments as a result of excessive hyperextension is reduced.

Because of the difficulty in achieving a truly intimate fit, and for lack of an accurate method of measuring forces between the stump and the socket, use of a soft liner is recommended. The liner, usually of sponge rubber ⅛ in. thick on the sides, slightly thicker on the end, and covered with leather, reduces the chances of abrupt changes in stress.

Suspension usually can be effected by a simple cuff above the femoral condyles attached to the shank by flexible straps, but a waist belt or sidebars and corset may be used if necessary.

The entire prosthesis has come to be known as the "patellar-tendon-bearing leg," or simply the "PTB leg," perhaps useful as a code name but an unfortunate nomenclature if taken literally, not only because it describes only a part of one functional aspect offered by the prosthesis but also because even that portion would more rightly be termed "patellar-ligament-bearing" or "quadriceps-tendon-bearing."

Sidebars and corset may be indicated in cases where rather extreme mediolateral instability of the knee is present or where muscles which control the knee have been impaired to the extent that exercise will not strengthen them. Sidebars and corset with ischial support may be indicated either for cases where bone or joint impairments prevent any of the long bones from assuming weight-bearing loads or for those where the skin is of such nature that the imposition of the required loading is simply out of the question. In addition, certain occupations might be carried out more readily if sidebars were used. Except for such limitations, virtually all below-knee amputees with healthy stumps can derive benefit from the PTB prosthesis with cuff suspension, provided the clinic team fully understands the underlying principles in the design and provided also that the prosthetist has the skill necessary to incorporate the essential features into the finished prosthesis.

Acknowledgment

The authors wish to acknowledge the gracious assistance and guidance afforded by Herbert Elftman and Gabriel Rosenkranz in the preparation of this article.

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The Biomechanics of Below-Knee Prostheses in Normal, Level, Bipedal Walking[1]

CHARLES W. RADCLIFFE, M.S., M.E.[2]

Human locomotion involves the transformation of a series of controlled and coordinated angular motions occurring simultaneously at the various joints of the lower extremity into a smooth path of motion for the center of gravity of the body as a whole. Though largely taken for granted, it is an extremely complicated process, the complexity becoming evident when one considers that the path of motion is influenced by six major factors: knee-ankle interaction, knee flexion, hip flexion, pelvic rotation about a vertical axis, lateral tilting of the pelvis, and lateral displacement of the pelvis. A thorough study of walking in the orthograde attitude would therefore include not only the influence of each of these factors on the total displacement pattern but also a complete analysis of the action of major muscle groups of the lower extremity. The present discussion is limited to a consideration of the hip, knee, and ankle joints and of their interaction during level walking—first in the normal person and then in the case of the below-knee amputee wearing the patellar-tendon-bearing prosthesis with and without additional impedimenta in the form of thigh corset and sidebars.

Phases of the Walking Cycle

The upright, bipedal walking cycle may be divided into two phases—the stance (or weight-bearing) phase and the swing phase. The stance phase of any given leg begins at the instant the heel contacts the ground, ends at toe-off when ground contact is lost by the foot of the same leg. The swing phase begins at toe-off and ends at heel contact. The two feet are in simultaneous contact with the walking surface for approximately 25 percent of a complete two-step cycle, this part of the cycle being designated as the "double-support" phase.

Figure 1 gives a graphic account of the interaction between the knee and ankle joints and of the phasic action of major muscle groups during a typical walking cycle. The particular curves shown represent the average of actual measurements recorded during studies (*3*) of four male college students considered to be representative of a larger population sample. The sequence of events is arbitrarily started at heel contact and followed until the next heel contact of the same foot. The term "knee moment" refers to the action of the muscle groups about the knee which tends to change the knee angle, either in flexion or extension. Similarly, "ankle moment" refers to the muscular action about the ankle joint which may cause either plantar flexion or dorsiflexion. The mechanics of major muscle groups of the lower extremity is indicated in Figure 2.

Events Just Prior to Heel Contact

In reference to Figure 1, and particularly to the curves in the region corresponding to the end of the swing phase (about 95 percent of a complete cycle), it may be noted that the knee joint reaches its maximum extension just prior to heel contact and that a period of knee flexion then initiated continues on into the stance phase. As seen in the curves of muscle activity, this decrease in the rate of knee extension at the end of the swing phase, in

[1] A contribution from the Biomechanics Laboratory, University of California, San Francisco and Berkeley, aided by U. S. Veterans Administration Research Contract V1005M-2075.

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preparation for the contact of the foot with the floor, is due primarily to the action of the hamstring muscle group, which is attached to the pelvis behind the hip joint and to the tibia and fibula below the knee joint. Tension in the hamstring group may cause either hip extension or knee flexion or the two simultaneously.

HEEL-CONTACT PHASE

As the heel makes contact, the hamstring action tends to bring it forcibly backward into contact with the floor, while the knee continues to flex rapidly. The activity in the hamstring group continues, but with decreasing magnitude, while the quadriceps action begins to build up quickly. The quadriceps group, acting anteriorly about the knee joint, and the pretibial group, acting about the ankle joint, serve to control the knee-ankle interaction and thus to effect a smooth motion of the forepart of the foot toward the floor. The major function of both knee and ankle during this phase is smooth absorption of the shock of heel contact and maintenance of a smooth path of the center of gravity of the whole body. Although the function of the knee as a shock absorber is often overlooked, energy studies (*1*) have shown that the knee and ankle contribute equally to shock absorption.

MID-STANCE PHASE

The controlled knee flexion of the heel-contact phase continues into the mid-stance phase (between foot flat and heel-off), and the maximum angle of knee flexion, approximately 20 deg., occurs in the first part of the mid-stance phase. As the body rides over the stabilized knee, the upward thrust of the floor reaction moves forward on the sole of the foot, thus gradually increasing the dorsiflexion of the ankle and causing the knee to begin a period of extension. In this period, control of the leg is through ankle-knee interaction, there being only minimal muscular activity in the groups acting about the hip and knee. The knee reaches a position of maximum extension about the time the heel leaves the ground, the calf group providing the resistance to knee extension and ankle dorsiflexion. As the heel leaves the ground, the knee again begins a period of flexion, chiefly because of muscular action about the hip joint. This sequence of controlled flexion at heel contact, release to allow gradual extension in mid-stance, and controlled flexion preparatory to swing is important in accomplishing a smooth and energy-saving gait in normal persons.

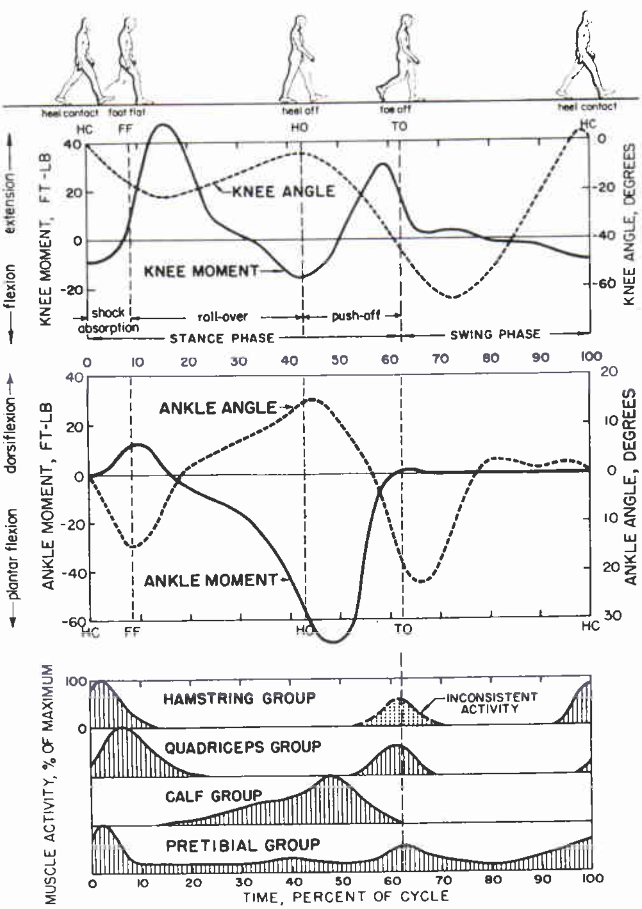

Fig. 1. Correlation between joint action and muscular activity in the lower extremity during normal, level walking.

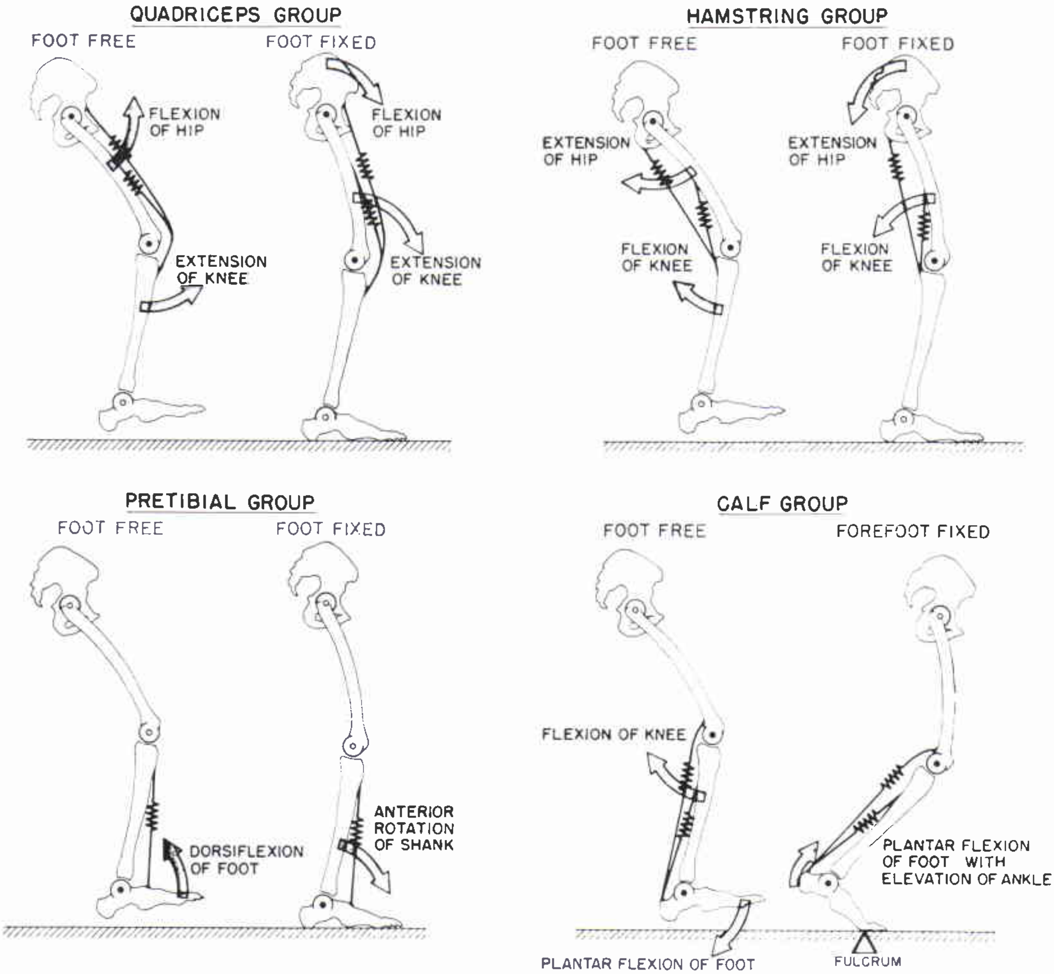

Fig. 2. Major muscle groups of the normal lower extremity (schematic), showing the major mechanics in the parasagittal plane.

PUSH-OFF PHASE

During the push-off phase, a phase complex and often misunderstood, the knee is brought forward by action of the hip joint, and a sensitive balance is maintained by interaction of hip, knee, and ankle joints. The combined action has two purposes—to maintain the smooth forward progression of the body as a whole and to initiate the angular movements in the swing phase that follows. As the knee begins to flex (about the time the heel leaves the ground), the knee musculature must first resist the external effect of the force on the ball of the foot which passes through space on a line ahead of the knee joint. Then, as the knee is brought forward by hip-joint action, so as to pass through and then anterior to the line of the force acting upward on the foot, the knee must reverse its action to provide controlled resistance to flexion by increasing quadriceps activity. Some inconsistent hamstring activity is noted as an antagonist. The calf group continues to provide active plantar flexion during the entire push-off phase. At the time the toe leaves the floor, the knee has flexed 40 to 45 deg. of the maximum of 65 deg. it reaches during the swing phase. In normal persons, knee flexion in the swing phase is not due primarily to hamstring action, as might be supposed. Complete prosthetic restoration of normal function in the push-off phase is difficult, if not impossible. A proprioceptive sense of knee position by the amputee is necessary, as well as an active source of energy in the ankle. Because of lack of an active source of ankle energy, initiation of knee flexion in amputees wearing a prosthesis must come from active hip flexion.

SWING PHASE (QUADRICEPS ACTION)

The over-all objective in the swing phase is to get the foot from one position to the next in a smooth manner while clearing the usual obstacles of terrain. At the start of the swing phase, the leg has just completed a period of rapid increase in kinetic energy caused by the active extension of the ankle and flexion of the hip during the push-off phase. The knee is flexing and continues to flex after toe-off. During rapid walking this would result in excessive knee flexion and heel rise were it not for the action of the quadriceps group in limiting the angle of knee flexion to approximately 65 deg. and then continuing to act to start knee extension. Knee extension continues as a result of a combination of pendulum effects owing both to muscle action and to the weight of the inclined shank and of the foot. Little quadriceps action is required, since other factors are of equal importance. For example, the iliopsoas muscle contributes by developing active hip flexion, which in turn accelerates the knee forward and upward.

MID-SWING

During mid-swing there is a period of minimal muscular activity, and the leg accelerates downward and forward like a pendulum with forced motion of its pivot point.

TERMINAL DECELERATION (HAMSTRING ACTION)

Near the end of the swing phase, the rate of knee extension must be reduced in order to decelerate the foot prior to heel contact. This "terminal deceleration" of the normal leg is due primarily to the extension resistance of the hamstring group.

KNEE ACTION IN AMPUTEE GAIT

In the past a common cause of difficulty in the use of the so-called "muley" below-knee prostheses (*2*) has been the "breakdown" of the stump, in particular of the knee joint on the amputated side. It has been due in part to overstraining of the ligamentous structures of the knee by excessive hyperextension under load. In order to protect these ligamentous structures on the amputated side, it is necessary to maintain within safe limits the forces and moments about the knee which tend to force it into hyperextension. In normal individuals a precise sense of knee position limits the hyperextension moment by maintaining the knee center close to the line of the force transmitted through the lower extremity. Since in many below-knee amputees the knee action is unaffected by amputation, it is reasonable to expect such an amputee to walk with a normal knee action. When this potential is anticipated and accounted for in the fitting and alignment procedure, a below-knee amputee of average-to-long stump length can make use of the controlled flexion-extension-flexion sequence of knee action required in absorbing shock and smoothing the path of motion of the center of gravity (Fig. 1). The socket must be fitted to accommodate the dynamic forces, and the amputee must contribute voluntary control of the knee by action of the musculature.

ANALYSIS OF STUMP-SOCKET FORCES

The contact pressures between the stump and socket of a below-knee amputee are influenced by a combination of factors. In the case of the patellar-tendon-bearing prosthesis (or of any other below-knee prosthesis without thigh corset and sidebars), the two major factors are the fit of the socket and the alignment of the prosthesis, *i.e.*, the location of the foot with respect to the socket. When the thigh corset is used, there are certain modifying effects even when optimum alignment of sidebars and corset with respect to the socket is obtained. In discussing the relationship between fit and alignment, it is often helpful to discuss alignment factors first, since the method of fitting a socket to an amputee's stump is dictated largely by the manner in which he

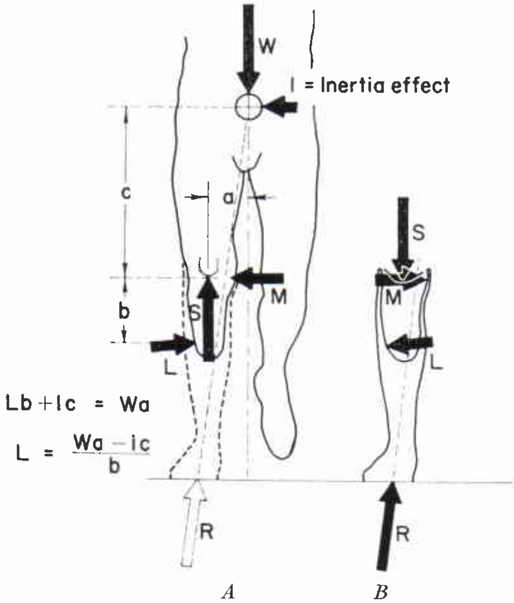

Fig. 3. Mediolateral force diagram for a below-knee amputee wearing the patellar-tendon-bearing prosthesis with supracondylar cuff only. *A*, Forces on the amputee; *B*, forces on the prosthesis.

can be expected to perform while wearing his prosthesis. His performance, in turn, is influenced considerably by the structural relationship between the elements of his prosthesis, *i.e.*, the alignment. The patellar-tendon-bearing cuff-suspension below-knee prosthesis, without side joints or corset, is here discussed first. Thereafter the modifying influences resulting from the addition of the side joints and corset are considered.

The following analysis is based on the assumption that a below-knee amputee with a stump of at least average length can be expected to walk in a manner similar to that of a normal person. That is, if the prosthetic foot is properly designed to minimize the effects of the loss of normal ankle function, the amputee can compensate by hip and knee action so as to achieve a gait which closely approximates the normal. Accordingly, he should be expected to go through the following sequence of knee motions:

1. Control of knee flexion from the time of heel contact until the foot reaches a stable position flat on the floor.

2. Control of knee flexion-extension during roll-over. The foot-shank serves as a firm base during this portion of the stance phase. The position of the knee relative to the force acting on the foot can be gauged accurately by properly trained amputees. The muscular moment about the knee required to maintain a particular knee position serves as an excellent source of proprioceptive sensation if the socket fit is intimate enough to reduce lost motion to a minimum.

3. Control of knee flexion during the push-off phase as an aid in accelerating the prosthesis forward in the swing phase.

MEDIOLATERAL FORCES, CUFF-SUSPENSION BELOW-KNEE PROSTHESIS

Figure 3 is a front view of a below-knee amputee in a position corresponding to the mid-stance phase. Two force systems are shown. Figure 3*A* shows the forces exerted on the amputee. These forces are of two types—the body weight due to the effect of the earth's gravitational pull and the forces applied through contact with the socket. Figure 3*B* shows the forces acting on the prosthesis.

If, as seen from the front, the prosthesis is considered as a means of supporting the body, it must be capable of providing both vertical support and mediolateral balance. It is apparent that vertical components of pressure are applied against the surfaces of many areas of the stump, but for purposes of simplified analysis the combined effect of all these forces is shown as the single support force S.

Considering the point of application of the support force S as a balance point, the lateral force L times the distance b equals the body weight W times the distance a, or, in equation form:

$$Lb = Wa \quad \text{and} \quad L = \frac{Wa}{b} \qquad (1)$$

Unfortunately, the effect of the horizontal acceleration of the center of gravity cannot be ignored in this case, and hence in neglecting the horizontal acceleration equation 1 is incorrect.

As indicated in Figure 3, the horizontal acceleration of the body in a medial direction, due to the medial inclination of the total floor reaction R, results in a lateral inertia force which tends to oppose the acceleration. This inertia force must be included when consideration is given to balancing moments about the

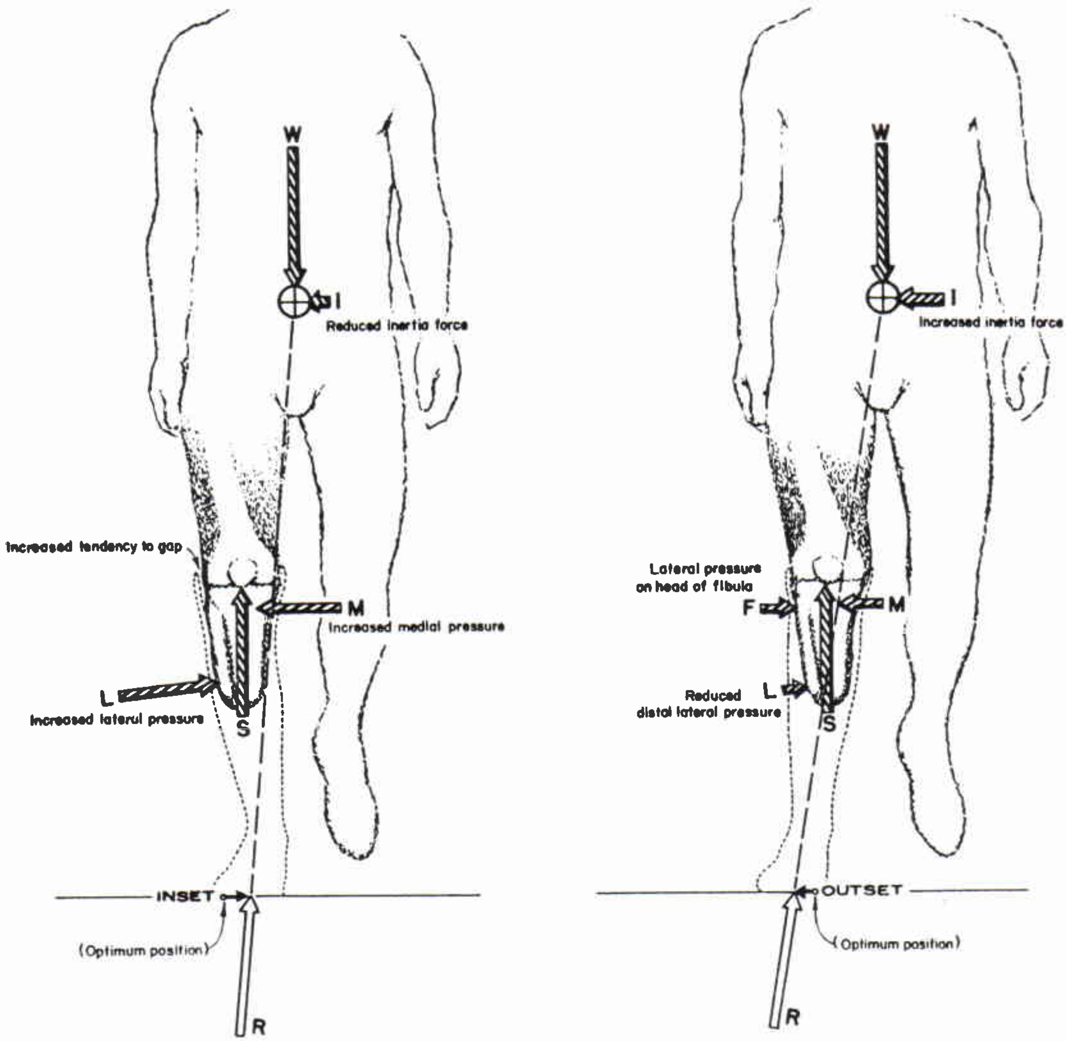

Fig. 4. Change in mediolateral force diagram owing to inset or outset of foot from optimum position, PTB prosthesis with cuff only, as in Figure 3. *A*, Inset; *B*, outset.

point of support. The correct relationship is therefore $Lb + Ic = Wa$:

$$L = \frac{Wa - Ic}{b} \quad (2)$$

Equation 2 shows that the magnitude of the required lateral stabilizing (balancing) force L can be reduced in one of two ways—by increasing the horizontal inertia force or by increasing the effective lever arm b. Increasing the horizontal inertia force requires that the horizontal acceleration be increased or, in other words, that the foot should be moved laterally so as to increase the medial inclination of the total floor reaction.

EFFECT OF FOOT INSET-OUTSET ON MEDIOLATERAL FORCES

The effect of changing the inset or outset of the foot is shown in Figure 4, where it is possible under special conditions, as shown in Figure 4*B*, to eliminate the need for the lateral

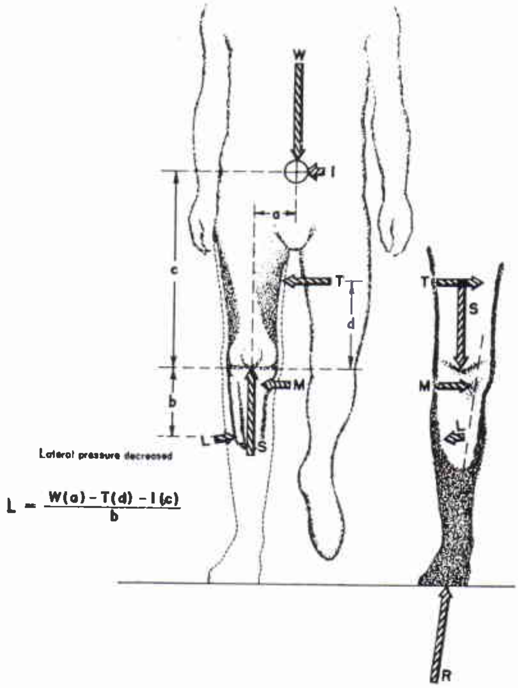

Fig. 5. Effect of thigh corset and sidebars on mediolateral stump-socket forces, PTB prosthesis. When the thigh corset applies a force against the medial side of the upper part of the thigh, the effect is similar to a force on the laterodistal side of the stump. Corset adjustment constitutes a possible means of modifying the magnitude and distribution of forces against the lateral side of the stump. This circumstance suggests that if the lateral sidebar is constructed with sufficient stiffness it may be of assistance in relieving excessive pressure on the laterodistal end of the stump.

stabilization force L, since in this case the weight and inertia force are seen to be in balance:

$$Wa = Ic \tag{3}$$

The force on the lateral aspect of the stump has shifted to the region of the head of the fibula.

Complete elimination of the lateral stabilizing force L by outset of the foot is generally undesirable, for the resulting wide-based gait is abnormal and unnecessary. Actually, a narrow-based gait with a definite need for the lateral force L (and corresponding lack of pressure on the head of the fibula) is definitely indicated for stumps 4 in. or more in length, the wide-based alignment being then reserved for very short below-knee stumps. It must be remembered, however, that planning the fit and alignment of a below-knee prosthesis to accommodate a narrow-based gait requires that the need for a definite lateral stabilizing force be recognized and accounted for in the fitting of the socket.

EFFECT OF THIGH CORSET AND SIDEBARS ON MEDIOLATERAL FORCES

Figure 5 shows the modifying effect of the thigh corset and sidebars on the pressures between stump and socket. If the sidebars are stiff enough it is possible to develop against the medial thigh a force T which acts in cooperation with the lateral-distal socket contact force L in providing mediolateral stabilization. In fact, with judicious use of bending irons the lateral pressure can be greatly reduced. In the past, this has been done to compensate for uncomfortable lateral-distal stump pressure. With a good socket fit against the lateral aspect of average-length stumps, however, the need for lateral stabilization by the thigh corset is minimized. Use of a thigh corset is indicated only for amputees with very short stumps or those in whom other medical factors require reduction in stump-socket contact forces.

ANTEROPOSTERIOR FORCES, CUFF-SUSPENSION BELOW-KNEE PROSTHESIS

Figure 6 shows a side view of a below-knee amputee and the cuff-suspension prosthesis under three conditions—at heel contact, during the shock-absorption portion of the mid-stance phase, and during push-off. At the instant of heel contact, and for a short time corresponding to about 5 percent of the walking cycle, knee stability is maintained primarily by active extension of the hip joint. The tendency of the external load on the prosthesis to extend the knee is resisted by hamstring action. During this phase, forces are acting as shown in Figure 6*A*.

Analysis of the forces acting during the shock-absorption portion of the mid-stance phase shows that it is typical for the floor-reaction force R to be acting along a line which passes posterior to the knee center. Under such circumstances, a completely relaxed knee would buckle, but the amputee is able to resist this

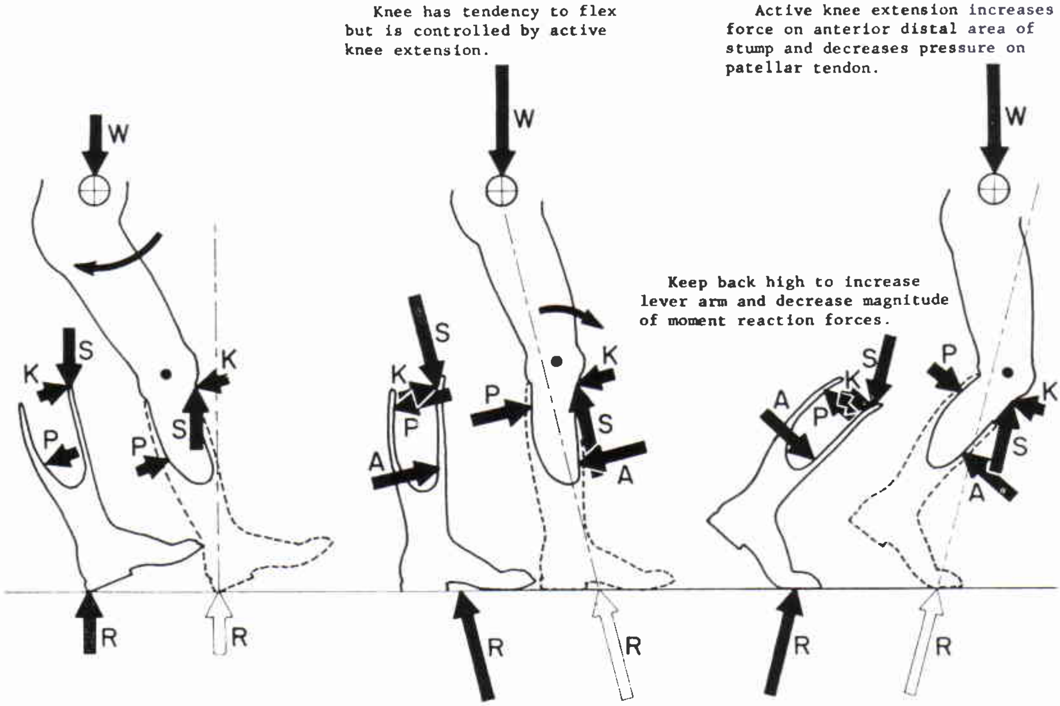

Fig. 6. Anteroposterior force diagrams for a below-knee amputee wearing the patellar-tendon-bearing prothesis with supracondylar cuff only. *A*, At heel contact; *B*, during shock absorption (foot flat in midstance); *C*, during push-off.

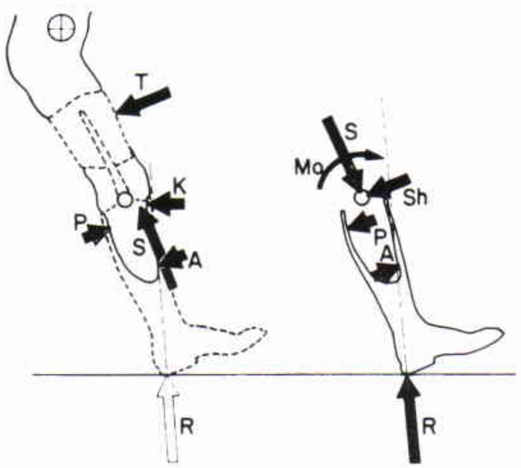

Fig. 7. Effect of thigh corset, sidebars, and back-check on anteroposterior stump-socket forces, PTB prosthesis. Shear force, *Sh*, is absorbed by mechanical side joint. Moment reaction forces on the stump are reduced through absorption of moment by knee stop. Without a knee stop, the stump would have to resist moment due to floor reaction passing ahead of knee joint. The resulting high pressure on the patellar tendon can be eliminated if the knee is allowed to flex (Fig. 6) instead of being forced into full extension.

tendency by active knee extension. The resulting force pattern on the stump (disregarding end-bearing) is as shown in Figure 6*B*, where the forces are concentrated in three areas—around the patellar tendon, on the anterodistal portion of the tibia, and in the popliteal area. The socket fit must be designed to accommodate the resulting functional pressures.

During the push-off phase, the floor reaction continues to pass behind the knee, and the anteroposterior forces are concentrated in the same three areas, as shown in Figure 6*C*.

EFFECT OF THIGH CORSET AND SIDEBARS ON ANTEROPOSTERIOR FORCES

If a below-knee amputee is fitted with a thigh corset and back-check so that he relies on the mechanical action of the back-check to resist knee extension, the force pattern is altered considerably. Figure 7 shows the effect. The floor reaction *R* must now be assumed to pass anterior to the knee, since otherwise the knee would not be extended against the back-check. If the knee joint is considered as a moment center, the effect of the force R is resisted by the back-check moment Mo and the two forces A and P exerted by the stump within the socket. Under the proper conditions, it is possible for the mechanical back-check to provide the total resistance to the floor reaction, the stump being suspended freely in the socket. This would indicate that, by proper adjustment of thigh corset, sidebars, and back-check, it is possible to modify the pattern of anteroposterior stump-socket contact pressures.

Summary

Thus it may be seen that, while normal skeletal and neuromuscular structure of the lower extremity is so organized as to accommodate the complex and precisely phased performance needed for erect, bipedal locomotion, the below-knee amputee, even though provided with a well-fitting prosthesis of the patellar-tendon-bearing cuff-suspension type, is unavoidably destined to experience in walking a continually changing set of stump-socket forces in both the anteroposterior and the mediolateral directions. Successful fitting of the below-knee amputee means, therefore, the resolution of stump-socket forces in such a way as to provide both comfortable support and adequate stabilization throughout the walking cycle. Whenever addition of thigh corset and sidebars is required, there occurs a change in the pattern of motion, and hence a change in stump-socket forces to be anticipated, and accordingly suitable modifications are required. Allowance for such factors calls in every case for the sound judgment of the prosthetist if fully satisfactory results are to be obtained.

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Construction of the Patellar-Tendon-Bearing Below-Knee Prosthesis[1]

BRYSON FLEER[2] AND
A. BENNETT WILSON, JR.[3]

THE first and most obvious requirement of any below-knee prosthesis is to furnish a suitable extension of the stump to the ground in such a way as to provide adequate support for the body weight with as little involvement as possible of other parts of the residual anatomy. In the interest of appearance as well as of function, there is a need secondarily for some reasonably faithful simulation of the normal leg, otherwise known as the "shank." Each of these requirements may be met in either of two ways. In one the structural member may be endoskeletal (the pylon), in which case the skeletal form may be covered with some suitable camouflage designed to give natural appearance. In the other, the structural element may be exoskeletal (crustacean), in which case the shell-like supporting member may itself be so shaped as to provide the desired appearance of naturalness. In either case, there is needed some acceptable means of attaching prosthesis to stump in a way that will satisfy the additional requirements of weight-bearing, comfort, and stability both in standing and in the stance phase of walking. As has been found through several centuries of observation and experiment, this is best accomplished by attaching the prosthesis via the medium of a sleeve, or socket, so shaped and so fitted as to accommodate prevailing features of local anatomy and physiology and into which the stump may be inserted.

Of all the methods, and variations of methods, that are available for the construction of sockets advantageously fitted to the irregular surfaces of the below-knee stump, most fall into one or another of three classes (*1,4*). One of these involves the forming, or shaping, of materials (such as aluminum or other metals). A second involves the negative carving, or excavation, of some suitable material (such as wood). And the third involves the molding of some material (such as leather). Because the hand-shaping of metals, like the hand-carving of wood, is at best difficult and time-consuming, and also because the skill needed for doing either may be developed only through long periods of apprenticeship, metals and wood have in recent years both been on the decline as materials of choice in the fabrication of sockets. Although the molded leather socket has persisted owing to its comparative ease of fabrication, it too is being displaced because of undesirable properties (such as its tendency to deform under load and its inclination toward perspiration absorption and consequent odor). Profoundly encouraging this transition has been the advent of plastics technology and the introduction of plastic-laminating techniques into the field of limb prosthetics. The lighter,

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[1] Compiled for the Committee on Prosthetics Research and Development, National Academy of Sciences—National Research Council, from the *Manual of Below-Knee Prosthetics* (*5*) and its successor, *The Patellar-Tendon-Bearing Below-Knee Prosthesis* (*6*), both published by the Biomechanics Laboratory, University of California (San Francisco and Berkeley). The section having to do with the use of sidebars and thigh corset in special cases (pages 60 through 63) is taken directly from the UC *Manual* (*6*), but with revisions and additions by Eugene F. Murphy, Chief, Research and Development Division, Prosthetic and Sensory Aids Service, U. S. Veterans Administration, 252 Seventh Ave., New York, 1, N. Y.

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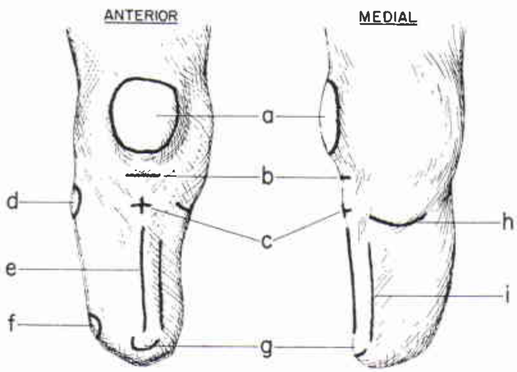


B

Fig. 1. Preparations for taking the negative cast. *A*, Patient seated with stump relaxed and knee flexed easily (about 30 deg.), cast sock applied and retained well above knee, prosthetist identifying (by palpation) bony landmarks and other pertinent features to be outlined by indelible pencil; *B*, the areas generally marked out for later use in modification of the model—some expected to be weight-bearing, some more or less pressure-sensitive and hence in need of relief. See text.

cleaner, stronger sockets of plastic laminate, much more easily made and with considerably more precision, have now all but replaced other types of sockets in new fittings of below-knee prostheses.

Fabrication of the plastic-laminate below-knee socket involves the taking of a suitable impression (the negative cast) of the particular stump concerned; the preparation of a positive model (male replica) from the negative mold; modification of the model in such a fashion that in the final socket (to be made from the rectified model) the weight of the body will be distributed over the respective areas of the stump according to their relative tolerance, or lack of tolerance, for weight-bearing; and, finally, the layup, lamination, curing, and finishing of the plastic socket itself. Should liners or other special features be wanted for particular cases, they are incorporated in the layup, as will be seen later.

While the method of construction described here is applicable in the fabrication of a variety of below-knee sockets, it is intended more specifically for the construction of the plastic below-knee socket in which the purpose is to utilize to fullest extent the patellar ligament as one of the principal weight-bearing areas (page 13).

Construction of Socket and Liner

TAKING THE NEGATIVE CAST

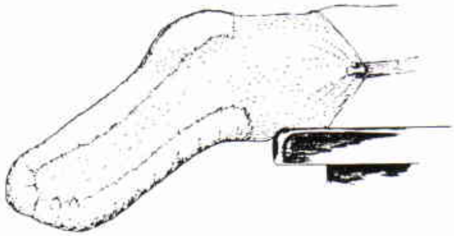
Unlike numerous other below-knee sockets heretofore recommended, the socket for the patellar-tendon-bearing (PTB) prosthesis is intended to remain at all times in intimate contact with the entire surface of the below-knee stump. The stump is therefore contained firmly in the socket throughout its length, and accordingly the cast is taken not while the patient is bearing weight on the stump (as has sometimes been done in the construction of certain "open-end" sockets) but while he is seated, relaxed, the leg hanging naturally over the edge of the support (say a table), and the knee flexed naturally about 30 deg. Whatever special effects are induced by the hands of the operator as he takes the cast are intended not to produce a "weight-bearing shape" but to emphasize the special points of weight-bearing to be anticipated in a PTB socket.

Although of possible impression materials there is available a substantial number, the most suitable, the least expensive, and the most workable for the present purpose is the old orthopedic standby, plaster of Paris. Judging from past practice, and from long usage in limb prosthetics generally, one may suppose that there are a number of satisfactory ways of taking a plaster impression, each perhaps with certain advantages and disadvantages peculiar to itself. Experience seems to suggest that for PTB sockets the most useful and practical means of cast-taking is to wrap the stump with plaster-impregnated bandage. Use of the bandage offers, among other things, the opportunity of regulating the tightness of the cast by controlling the tension applied to the bandage while it is being wrapped.

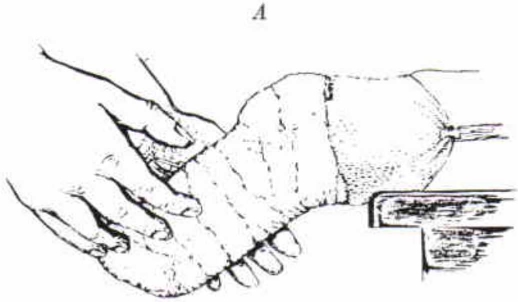
With the amputee seated appropriately, somewhat as in Figure 1*A*, there is applied to the stump a thin cast sock of such size and length as to fit snugly and to come up well over the knee. To the top of the sock on either side of the thigh are attached, by harness clamps, the ends of a piece of 1-in. webbing passing around the patient's waist and just long enough to support the cast sock under comfortable tension. As in the cast-taking technique commonly used to produce other forms of below-knee sockets, the prosthetist must now identify and outline the bony prominences and other landmarks, both those known to be unusually sensitive to pressure (and hence requiring buildup in the model in order to give relief in the socket) and those especially well adapted to weight-bearing (those requiring reduction of the model and hence buildup in the socket), in this case particularly the patella and the patellar ligament (Fig. 1*B*). To do so, the fitter moistens the cast sock and outlines the areas concerned with indelible pencil so that, subsequently, the tracings will be transferred first to the negative mold and then to the positive model.

In all cases, at least nine areas are identified. These include the patella itself (Fig. 1*B*, *a*), the mid-point (Fig. 1*B*, *b*) of the patellar ligament (approximately at the level of the medial tibial plateau), the tubercle of the tibia (Fig. 1*B*, *c*), the head of the fibula (Fig. 1*B*, *d*), the anterior crest of the tibia (Fig. 1*B*, *e*), the distal end of the fibula (Fig. 1*B*, *f*), the antero-distal end of the tibia (Fig. 1*B*, *g*), the medial flare of the tibia (Fig. 1*B*, *h*), and the medial border of the tibia (Fig. 1*B*, *i*). Marked only if they are prominent or sensitive to pressure are the anterior prominences of the lateral and medial tibial condyles, the lateral border of the tibia, and any other sensitive areas that might suggest the presence of bone spurs, adherent scar tissue, neuromas, or similar conditions.

When the necessary marking has been completed, the patient having maintained his stump as much as possible in the original position of knee flexion without external rotation of the femur, a few rolls of 4-in. plaster bandage are laid out conveniently beside a basin of clean, cool water. As needed, each strip of plaster bandage is immersed in the water for about four seconds, squeezed to remove excess water, and applied to the stump over the marked cast sock. The wrap is begun with one or two layers of bandage running lengthwise (Fig. 2*A*), beginning in front and just above the top of the patella, passing down and around the end of the stump, and continuing up the back of the stump to the posterior crease of the knee. Thereafter a series of circumferential wraps (Fig. 2*B*) is begun at the upper border of the patella and made to spiral down, then up, the stump so that half the width of the bandage (2 in.) overlaps each successive layer. Each layer is smoothed carefully as it is applied, and the wrapping is con-



A



B

Fig. 2. Taking the negative cast. *A*, Beginning of the wrap with plaster bandage, strips extending well above knee, front and rear; *B*, completion of the spiral wrap (see Fig. 3).

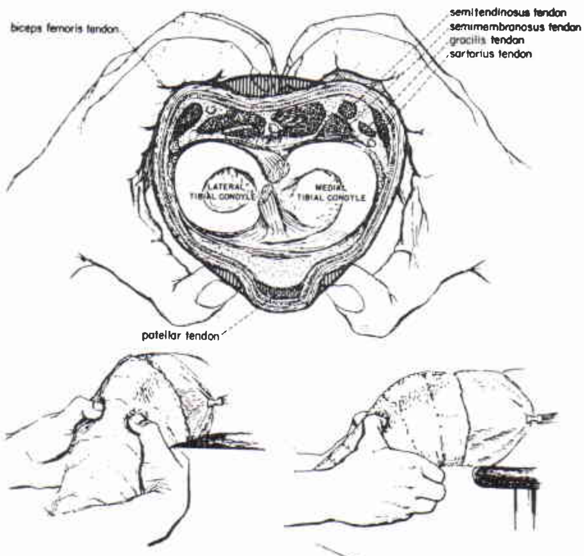


Fig. 3. Use of the hands to shape cast while plaster is hardening. Thumbs compress bandage in and around patella, fingers force cast into popliteal area.

tinued until the shell thus formed has a thickness of about ⅛ in. in the proximal third. Additional layers are applied over the distal portions until about six rounds have been completed.

While the amputee continues to maintain the original angle of knee flexion with relaxed musculature, the plaster is smoothed over the surface and worked in around the prominences and depressions by means of the hands until the plaster begins to harden. At this point, the fingers and thumbs of the operator are called upon to outline the patellar tendon and to compress the popliteal tissues, as shown in Figure 3, and considerable experience and judgment are required to establish just how much pressure should be applied and in what direction. The thumbs are placed in such a position as to make a 45-deg. angle with the long axis of the tibia, and their ends are directed upward and inward midway between the lower edge of the patella and the tubercle of the tibia. Meanwhile, the fingers, wrapped around the knee, force the cast into the popliteal area, the forefingers being at the level of the posterior crease of the knee. Contact with the sides of the knee is maintained to prevent bulging, but distortion of the sides and pressure on the hamstring tendons are to be avoided. Pressure should be firm but not so great as to cause finger fatigue (a sign that too much pressure is being exerted). Both prosthetist and patient attempt to remain as motionless as possible while the plaster hardens beyond the possibility of permanent deformation.

CASTING THE POSITIVE MODEL

When the plaster has hardened completely, finger pressure is released, but the cast is allowed to remain in place for an extra minute or two, whereupon the harness clamps are released and the cast sock is reflected down over the cast, the amputee flexes his knee to 90 deg., and the prosthetist, with his hands in the same position as when forming the cast, removes the whole cast from the stump by an anteroposterior rocking motion induced while simultaneously pulling downward (Fig. 4). The cast sock, bearing the indelible markings, is allowed to remain in the cast, and the latter is then filled to the top with fluid plaster of Paris of the usual consistency. Into the center of the still-liquid plaster is inserted lengthwise (to a depth of not more than 6 in.) an 18-in. length of ½-in. iron pipe (approx. 1 in. O.D.) to serve as a mandrel in future bench operations. When the plaster has set for 20 to 30 minutes, the wrap cast is stripped off after it has been cut lengthwise down the posterior surface, and the model is ready for modifica-

Fig. 4. Removal of the cast. Because of the depressions made in the cast purposely, a rocking motion is required to get cast off stump. Knee flexion helps.

tion in accordance with the outlines originally marked on the cast sock.

MODIFICATION (RECTIFICATION) OF THE POSITIVE MODEL

With the exception of those areas where the wrap cast was purposely distorted by the prosthetist's fingers and thumbs (around the patellar ligament, just under the lower edge of the patella, in the popliteal space, and so on), the positive plaster model now constitutes a faithful reproduction of the stump. It remains to revise the model in such a way that, when a socket is laminated over it, the shape of the socket will be that required to distribute the weight of the body over those areas best suited to weight-bearing while at the same time relieving sensitive areas from responsibility for bearing more weight than will be comfortable. This is accomplished by carefully carving away plaster where additional force transfer will be acceptable and by building up the model (with shaped patches of leather or other suitable material) in areas expected to be incapable of accommodating any appreciable part of the load. Guidance in this operation is to be had from the indelible outlines previously transferred first from cast sock to cast and then from cast to model.

Although the original compression of the cast in the vicinity of the patellar ligament and around the tibial tubercle represents a preliminary step in shifting the anticipated load in the direction of the ligament midway between the lower border of the patella and the upper margin of the tibia, further modification of the model in this area is now required to intensify the effect. Accordingly, the model is cut away, as shown in Figure 5, to form a channel at least ½ in. deep, on a radius of about 1 in., and extending horizontally across the front about 1½ in., just short of the thumb prints on either side of the tibial crest. Smooth contours are obtained by sanding rough spots with a piece of wire screen.

Another stump area normally capable of bearing a portion of the body weight is the anteromedial flare at the proximal end of the tibia. As shown in Figure 6*A*, then, the model is shaved down in this area. At the deepest point of the resulting concavity, at least ⅛ in.

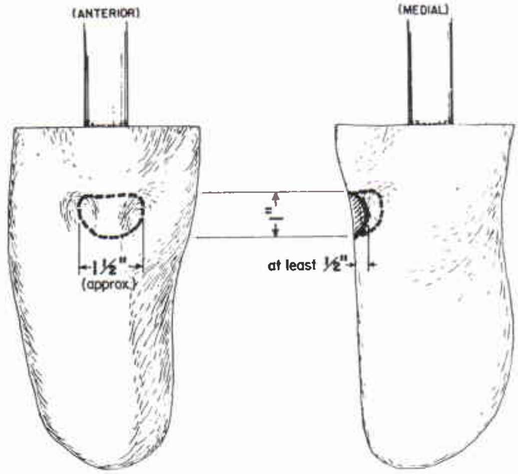


Fig. 5. Initial step in modification of the positive model—undercutting to enhance support on patellar ligament.

should be removed (depending at least in part upon the amount of soft tissue overlying the stump in this area), and the edges should be smoothed out into continuous surfaces of gentle curvature. Since adequate vector forces cannot be exerted upon the anteromedial surface of the tibial condyles without corresponding vector forces on the lateral side, and since in any event the PTB socket is designed to provide, if possible, mediolateral stability without the necessity for sidebars, knee joints, corsets, and so forth, the lateral surface of the model is now also shaved down, as shown in Figure 6*B*. Depending upon the individual characteristics of the particular stump concerned, ⅛ in. to ⅜ in. of plaster is removed, beginning about ¾ in. below the border of the head of the fibula and continuing to within ½ in. of the end of the fibula.

Just as the PTB socket is expected to furnish adequate mediolateral stability, so it also must provide enough anteroposterior stability to come under full control of the knee of the wearer on the side of the amputation. Relatively comfortable and yet adequate fixation of the stump within the socket in the anteroposterior direction is effected by trimming down the anteromedial and anterolateral surfaces of the model almost throughout the length of the remaining tibia (Fig. 6*C*). The result is a wedgelike support along both sides

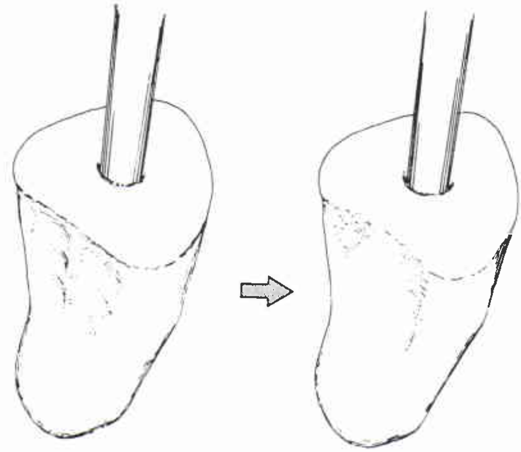


Fig. 7. Further modification of the model. Popliteal area is shaved away to provide countersupport against forces from the front, thus improving anteroposterior stability of socket.

of the front of the tibia, which, then, must be backed up by corresponding but opposite forces to the rear of the socket in the popliteal area. As seen in Figure 7, the popliteal area of the model is thus shaved down to the depth of the fingerprints, the upper portion of the model in this vicinity being rounded out to give a flare to the posterior brim of the socket.

Finally, should it be the intention that the ultimate socket provide some amount of end-bearing, thin layers, up to about ¼ in., of plaster may be shaved from the end surface of the model. If only the closed socket with no appreciable end-bearing is sought, the end of the model is simply smoothed with sandpaper, as is the whole model in any case to provide a finished job.

The model having been thus reduced to obtain the proper distribution of the loads to be anticipated in the socket, it is now equally necessary to build up those areas needing more or less relief from the pressure of weight-bearing. These ordinarily include the head and the end of the fibula, the prominent crests of the medial and lateral tibial condyles, the tibial

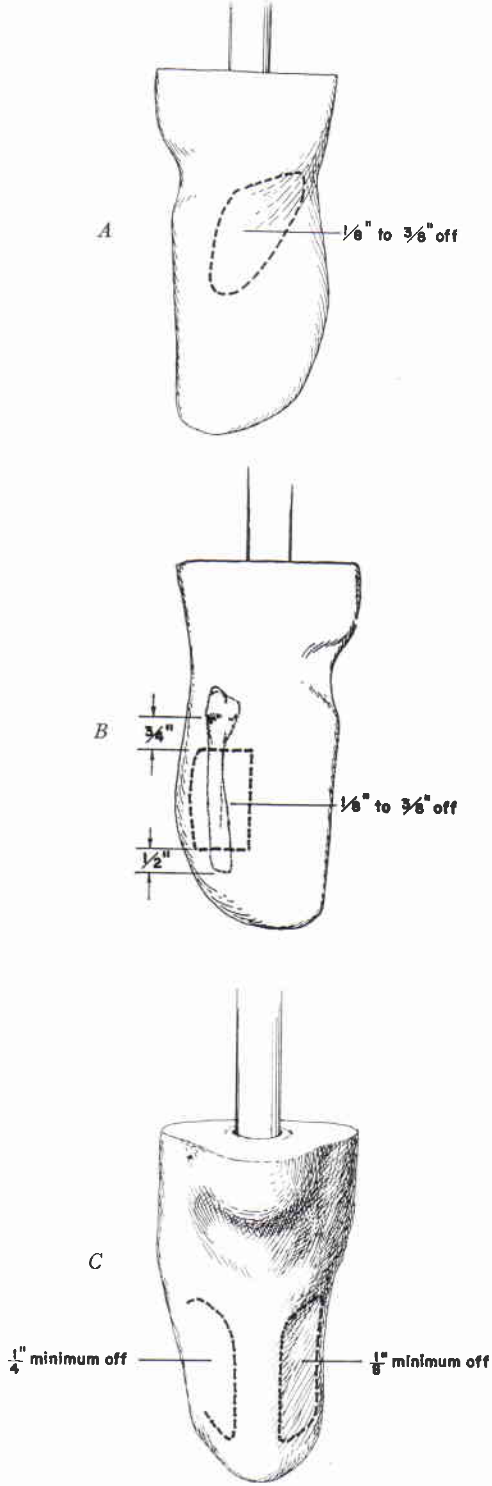


Fig. 6. Successive steps in modification of the positive model. *A*, Reduction for enhanced support on medial tibial condyle; *B*, the same to provide lateral support against fibula; *C*, the same to avoid pressure on anterior crest of tibia.

crest throughout its length, and the antero-distal end of the tibia. In general they will already be outlined on the model from the indelible markings on the cast sock. Skived patches of leather carefully trimmed to fit (Fig. 8) are used to provide the modification needed. They are bonded to the plaster in the places needed, and the rectified model is then ready for use in fabrication of the plastic-laminate socket. The drawings of Figure 9 present for comparison the shapes of stump, original stump model, and stump model after rectification.

THE SOFT INSERT

To accommodate any inadvertent irregularities in the socket, or any minor incongruities between stump and socket, and because in general it has been found desirable to provide a comparatively soft and pliable liner in below-knee fittings, lamination of the socket itself is preceded by fabrication of an insert made of medium-weight horsehide (4 to 6 oz.) and ⅛-in. sponge rubber. Although the making of the liner and the lamination of the socket may be reviewed as two separate operations, they are, as will be seen, actually carried out as two successive steps in the layup, reinforcement, and lamination of the socket. Since the socket and its liner are both prepared *over* the rectified model, the innermost layers are the ones designed first, and hence the first step is to lay up the leather insert.

The modified plaster model having been placed in the bench vise upside down and held there, in the vertical position, by means of the mandrel of iron pipe, there is cut from medium-weight horsehide a piece in the shape of an isosceles trapezoid such that the two parallel sides are 2 in. longer respectively than the proximal and distal circumferences of the model, the other dimension being about 2 in. longer than the model, and the direction of stretch of the leather being in the same direction as are the parallel sides (Fig. 10*A*). With the smooth side in, the leather is fitted to the model, the intended seam line being so placed as to follow the posterior centerline. While the leather sheet is held in place by a suitable number of harness clamps (Fig. 10*B*), the seam is marked with pencil. The sheet having then

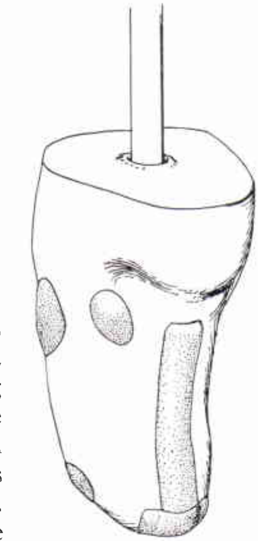


Fig. 8. Build-up of positive model to furnish relief in pressure-sensitive locations. Skiving of the leather patches provides a smooth transition from plaster to build-up.

been removed from the model, it is sewed along the mark, the clamps being removed one at a time as the sewing proceeds. After the seam has been trimmed neatly throughout its length to within ⅛ in. of the stitching, the leather sleeve is replaced on the model, the work is removed from the vise, and the proximal extension of the leather is tucked and stapled to the top surface of the model (Fig. 10*C*). An approximation of the final trim line of the socket is now drawn around the top of the leather-covered model (Fig. 11), and the whole is replaced in the vise, the mandrel again serving as the means of support.

To form an end pad for the socket, there is now cut from a ⅛-in. sheet of sponge rubber (Kemblo) a disc large enough to fit neatly over the end of the model, the diameter of the disc being usually equal to the average diameter of the stump (Fig. 12*A*). The distal end of the liner and one side of the rubber pad are now coated with cement (Stabond T-161), allowed to dry until the cement is tacky, and then placed together so that the pad will conform to the shape of the end of the model. Unless the curvature of the model is extreme, the pad will conform when pressed into place. Should it not conform well, a dart or two will suffice to correct any difficulty in arriving at a smooth transition between rubber and leather. In either event, the periphery of the Kemblo end pad is now skived with a sanding drum (Fig. 12*B*) so that the outer edge will be flush with the horsehide.

Padding of the sidewalls of the model is now undertaken by the successive application,

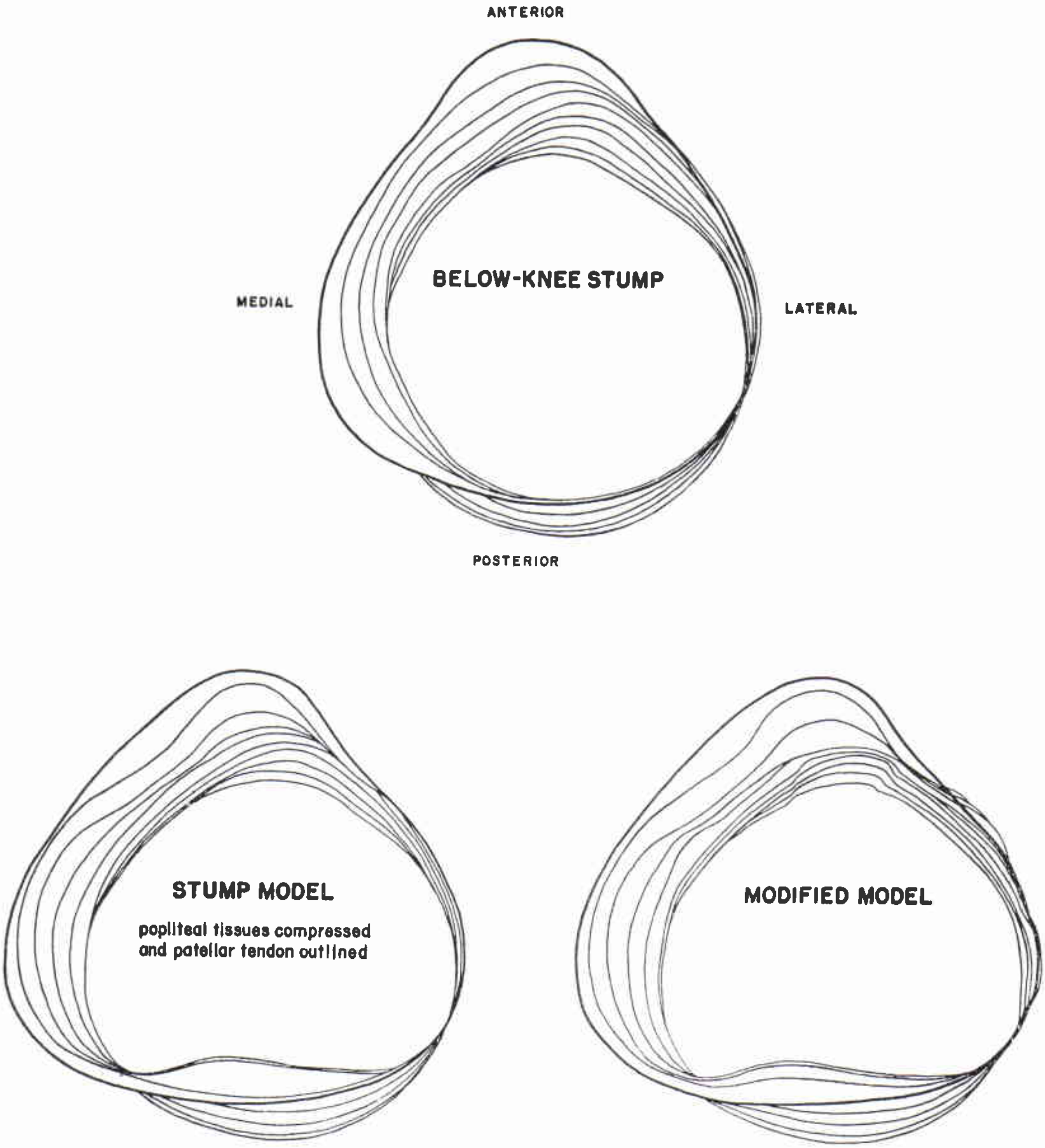


Fig. 9. Contours at successive levels overlaid to show comparative shapes of stump, of stump model as made from the cast, and of stump model after suitable rectification (modification). The specific shapes vary from patient to patient, of course, depending upon individual differences.

beginning on the anterior surface, of a circumferential series of fitted strips of Kemblo running the length of the model. To begin, there is first cut a strip of Kemblo 2 in. wide and long enough to overlap the end pad ½ in. and to extend beyond the model about an inch proximally. The anterior surface of the leather liner and of the end pad are coated with cement,[4] as is also one surface of the first strip of Kemblo. When the surfaces are

[4] Application of cement within the ½-in. border around the estimated trim line (Fig. 13*A*) is avoided at all times.

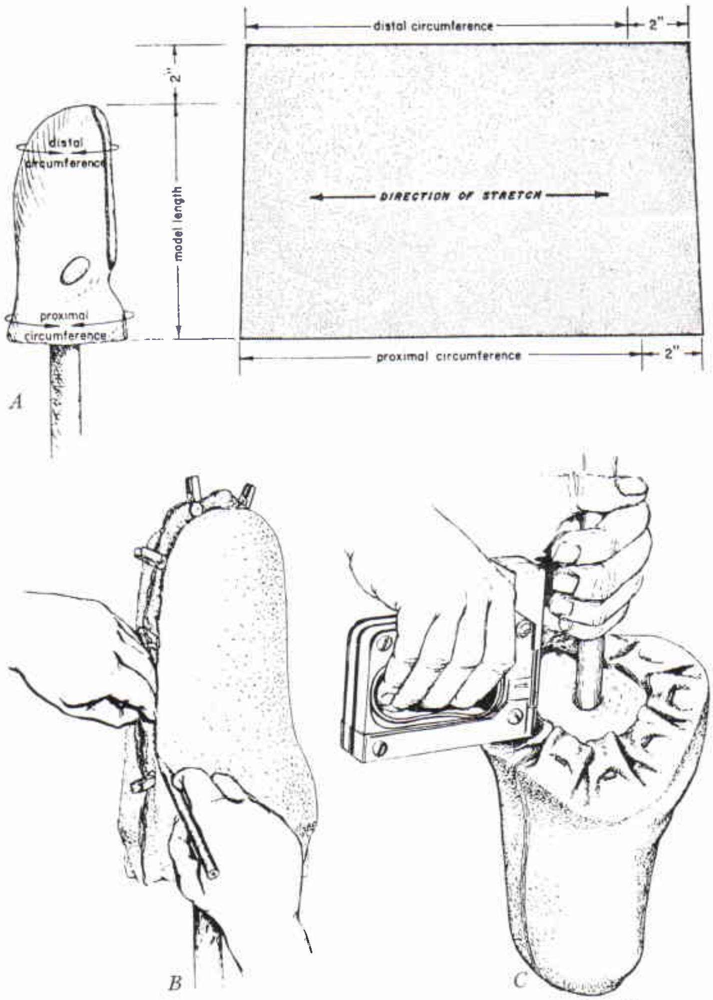


Fig. 10. Preparation and layup of the leather insert, or socket liner.

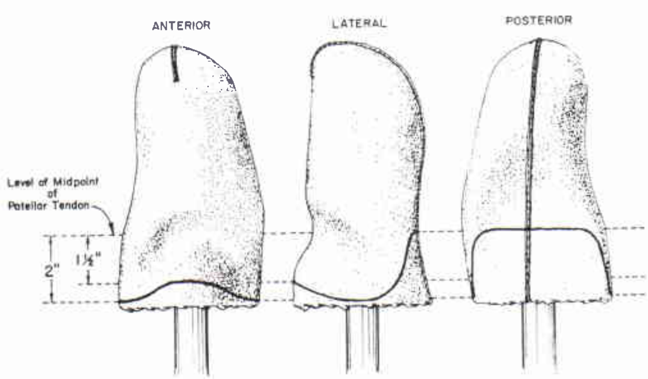


Fig. 11. Proximal trim line of the leather liner.

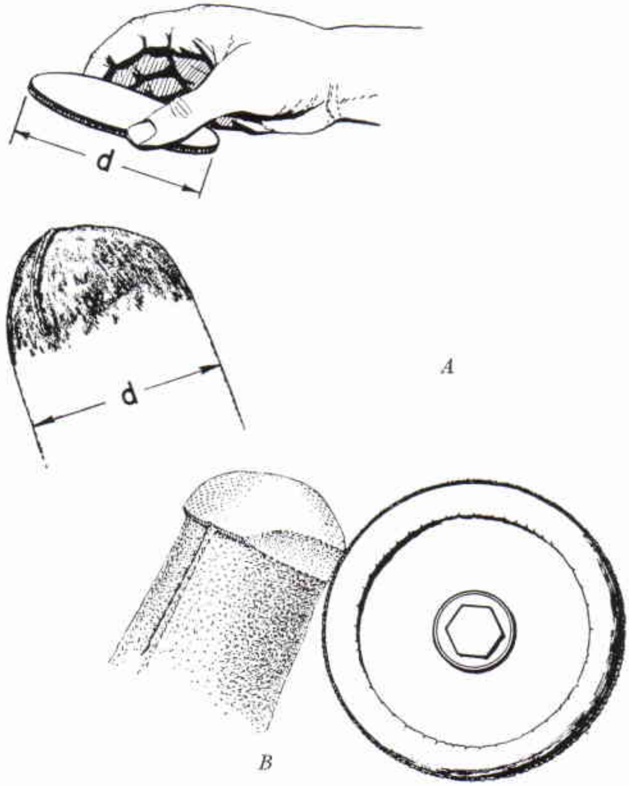


Fig. 12. Construction of the socket end pad.

tacky, the Kemblo strip is placed in the position representing the anterior crest of the tibia and allowed to extend over the end cap about half an inch (Fig. 13*A*). Carefully pressed into place so as to conform to all of the irregular areas, the edge of the first strip constitutes the pattern for one edge of the second. So that when finally cemented in place the second strip will fit as snugly as possible against the edge of the first, one edge of the applied first strip is marked with chalk (Fig. 13*B*), and the second strip is laid along the model parallel to the longitudinal axis and so that one edge just overlaps the chalked edge (Fig. 13*C*). The chalkline thus transferred to the new strip marks the trim line for tailoring to the contours of the model (Fig. 13*D*). When the new strip has been trimmed as marked, it is cemented in place, and the process is repeated until the entire surface of the liner has been overlaid with a smooth covering of Kemblo. Where the strip ends overlap the end of the model, they are skived on the sanding drum, and a second end pad, like the first, is cemented over the end of the padded model. Skiving of the second end pad to be flush with the longitudinal strips of Kemblo completes the layup and fabrication of the soft insert (Fig. 13*E*).

THE PLASTIC SHELL

The next step is the lamination of the plastic shell over the soft liner but readily separable from it after construction of the shell is complete. As in the case of plastic-laminate sockets for other levels of amputation, use is here made of sleeves fabricated from sheeting of polyvinyl alcohol (PVA). Since in the construction of the below-knee socket it is desired to keep the liner separate from the plastic shell, two sleeves are used—the first to form a separator between liner and shell and the second, as

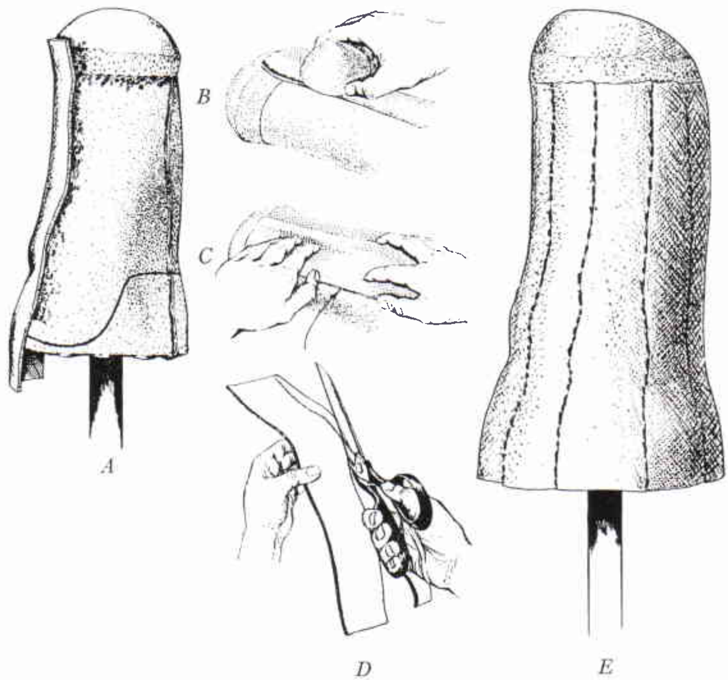


Fig. 13. Layup of the soft liner of sponge rubber (Kemblo). One edge of the first strip (*A*) becomes the pattern (*B*, *C*, *D*) for the second, and so on, until the entire model is overlaid with a smooth and neatly fitted covering (*E*).

usual, to enclose the whole layup-and-resin combination as a means of impregnating the reinforcing materials. Since neither sleeve need be more than an approximate fit for the model, two identical ones are fabricated to the dimensions shown in Figure 14. After the outer surface of the socket liner has been coated liberally with talc (to prevent sticking), the first PVA sleeve is stretched over the model and liner and trimmed around the distal end where it parts company with the surface of the liner (Fig. 15*A*). A half-inch annular area of PVA adhesive is now painted around the cut edge (Fig. 15*B*), and the open section is covered with another piece of PVA neatly bonded to form an end for the sleeve (Fig. 15*C*). At the proximal end of the model the other end of the PVA sleeve is tied tightly about the mandrel, and any loose material is trimmed away to give a neat layup (Fig. 15*D*).

The model and overlying liner, thus covered with the PVA separator, are now ready for layup of the laminations and reinforcing materials to be incorporated into the plastic shell, or socket. Three pieces of ½-oz. Dacron felt, cut to the same pattern as used for the leather liner (Fig. 10*A*), are sewed as shown in Figure 16*A* and pulled over the model one after the other, the seams lying on the posterior aspect of the model. Then, under the last layer of felt, in the vicinity of the postero-proximal margin, there are placed five rectangular pieces of Dacron felt (Fig. 16*B*) measuring 2 in. by 4 in., the purpose being to thicken and reinforce the posterior edge of the socket.

A strip of Fiberglas cloth wide enough to cover the proximal half of the model is now wrapped around the Dacron so as to overlap itself by at least an inch, and a light cotton cast sock is slipped over the distal end of the model to hold the Fiberglas reinforcement in place (Fig. 16*C*). When the second PVA sleeve has been stretched over the whole and tied tightly about the mandrel, the layup is complete and ready for application of the resin-catalyst mixture.

A quantity of the resin (200–400 grams, depending on socket size), prepared according to the recipe given in Appendix A (page 73), is poured into the open, distal end of the second PVA sleeve and thoroughly worked down into the fibers of the laminating materials. The open end of the sleeve is tied off, and working is continued to remove air and to complete impregnation by the familiar process of "stringing." To ensure that undercut areas and all other irregular contours of the model are reproduced in the final socket, the layup is now wrapped, as appropriate, with strips and pads of sponge rubber or with pressure-sensitive tape, whichever is more convenient (Fig. 17*A*). Left thus undisturbed, the resin will cure at ambient room temperature in about 30 minutes, whereupon it is allowed to lose any heat of reaction and to return to room temperature.

It remains now but to free the socket and liner from the plaster model. This is accomplished by trimming along the proximal edge of the layup (Fig. 17*B*) at a 45-deg. angle until the underlying sponge rubber is just exposed. The shell is then readily slipped off the model, as the liner in turn may be slipped out of the socket. With liner removed temporarily, the proximal brim of the socket is now trimmed as shown in Figure 17*C*.

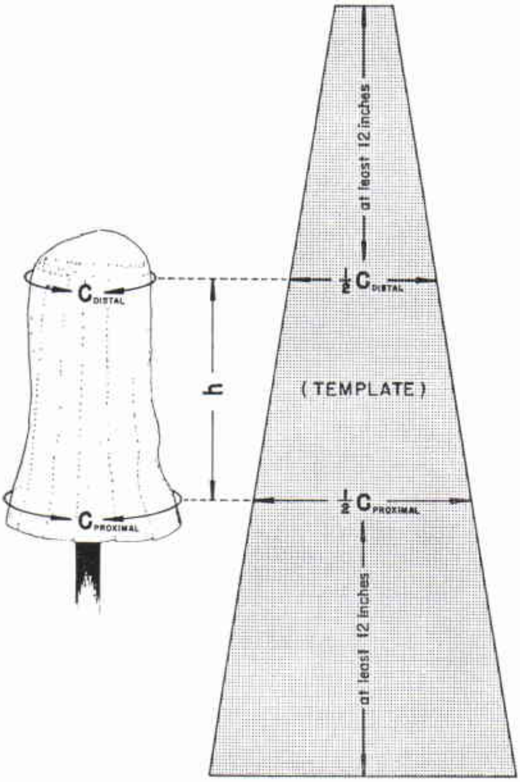


Fig. 14. Pattern for preparation of the PVA sleeves.

Preparation of Socket for Alignment

The socket thus produced must next be properly aligned with respect both to the residual anatomy of its intended wearer and to the rest of the prosthesis, including the prosthetic foot and the shoe to be worn over it. Although the below-knee prosthesis may be so aligned, as it has been for a great many years, by the simple expedient of "aligning by eye" (that is, simply by trial and error and

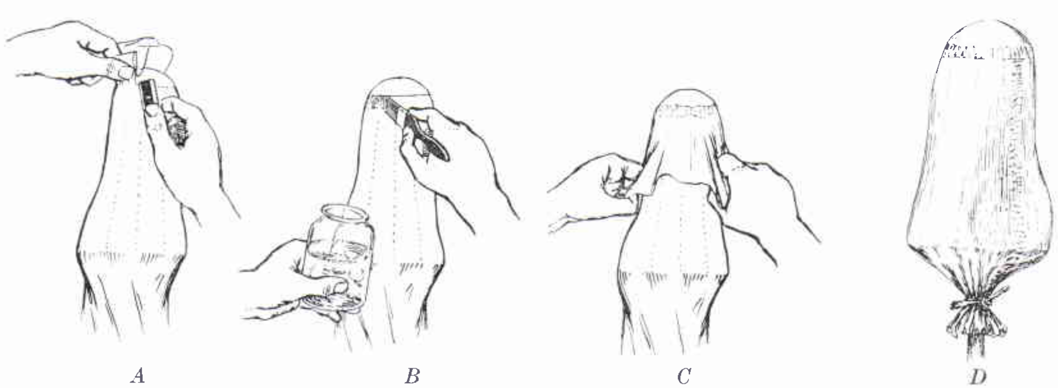


Fig. 15. Application of PVA separator over socket liner and model.

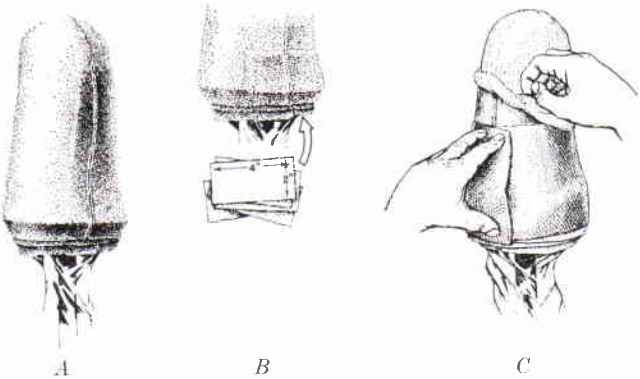


Fig. 16. Layup of reinforcing materials for plastic socket. *A*, Layers of Dacron felt in place; *B*, extra material added in posteroproximal area; *C*, application of Fiberglas cloth and cast sock over Dacron.

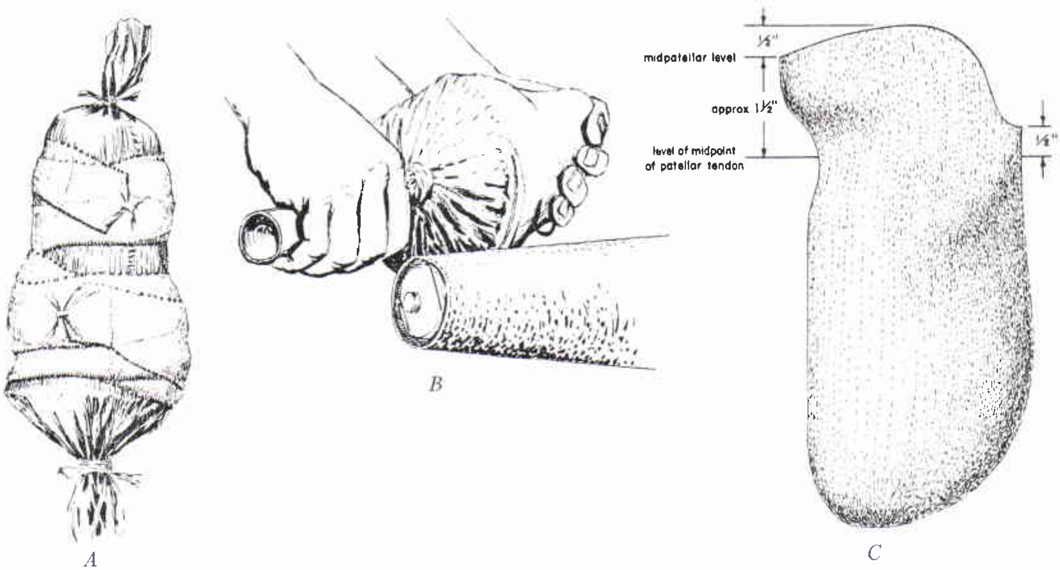


Fig. 17. Plastic lamination and initial finishing of the PTB socket. *A*, Layup encased in second PVA bag, impregnated well with resin, and undercut areas bound down by wraps of sponge rubber; *B*, removal of socket and liner from model after curing of resin is complete; *C*, specifications for trimming the top brim of the socket.

by observation of the static and dynamic behavior of the amputee-prosthesis combination), the whole procedure is made much easier (and the resulting relationships much more readily amenable to duplication if need be) by application of one of the more modern tools of prosthetics practice. Recommended for use in the present instance is the below-knee adjustable shank developed at the University of California.

As may be seen in Figure 18, the UC below-knee adjustable shank consists essentially of a steel plate perforated with a rather large number of countersunk screw holes and supported on a crossed-bar mechanism in which two identical and graduated bars cross each other back to back at a fixed angle of 90 deg. and in which each bar is capable of sliding across the other at the point of intersection, or of rotating about the longitudinal axis of the other, or of doing both simultaneously in an infinite variety of combinations of

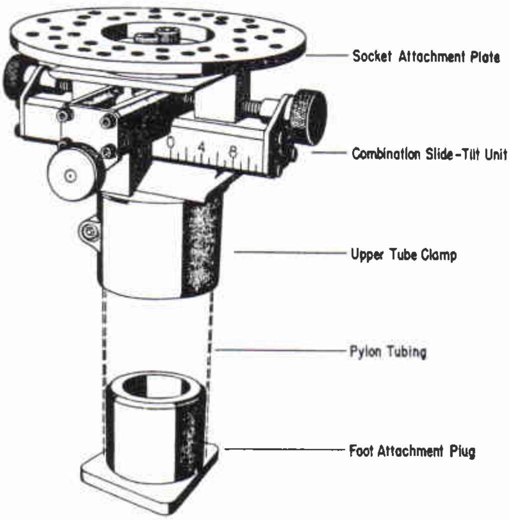


Fig. 18. The University of California below-knee adjustable shank.

sliding and tilting. Each bar is held in position by a pair of opposing setscrews, such that loosening of any one screw permits both sliding of the bar to which that screw is attached and rotatory motion about the companion bar. The net result is a kind of universal joint in which, within the limits required, any combination of anteroposterior and mediolateral shifting horizontally may be had together with any combination of anteroposterior and mediolateral tilting. Included with the device is a pylon shank for temporary service during alignment, and a clamp on the shank portion provides for attachment of the foot and for adjustable foot rotation with respect to socket orientation.

ATTACHMENT OF SOCKET TO ADJUSTABLE SHANK

Since the below-knee adjustable shank is intended for use in combination with the socket shell, and since the latter is asymmetrical in all directions on the outside as well as on the inside, there is now required some practical means of attaching the socket rigidly to the shank. Experience shows that such an attachment is best arrived at by first sinking the socket into a hollow block of wood of suitable size and shape. For purposes of reference, here and throughout the remaining stages of construction, the socket is first marked with vertical centerlines representing, respectively, the anteroposterior and mediolateral planes. As shown in Figure 19, the lines are established by connecting, in side and rear views, the estimated center points of the top and of the bottom of the socket, the proximal center point for the anteroposterior plane (Fig. 19*A*) being taken at the level of the posterior brim of the socket while the corresponding center in the lateral view (Fig. 19*B*) is taken slightly above the indentation provided for the patellar ligament.

A cylindrical socket block of willow, about 6 in. long and about 6 in. in diameter, is now drilled through along the longitudinal axis of the cylinder (parallel to the grain) with a 2-in. bit, and one end of the tubular aperture is carved out so as to receive the lower end of the socket to a depth of 3 or 4 in. and in such a way that the socket will rest easily in the block with 5 deg. of adduction (Fig. 20*A*) and 5 deg. of initial flexion (Fig. 20*B*).

The distal surface of the socket shell, roughened to improve adhesion, is now bonded into the block in the predetermined position by use of a mixture of resin and sawdust (or other filler). When the bond has hardened thoroughly, the lower end of the socket block is sawed across squarely at such a

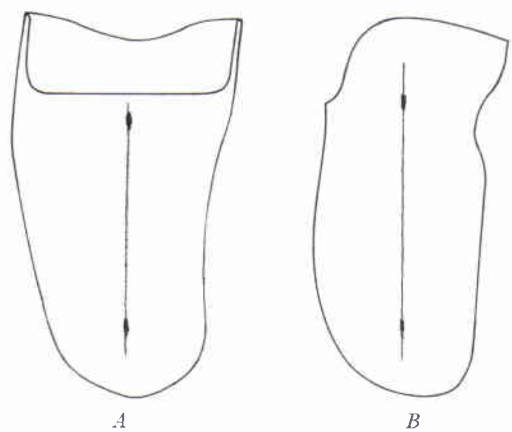
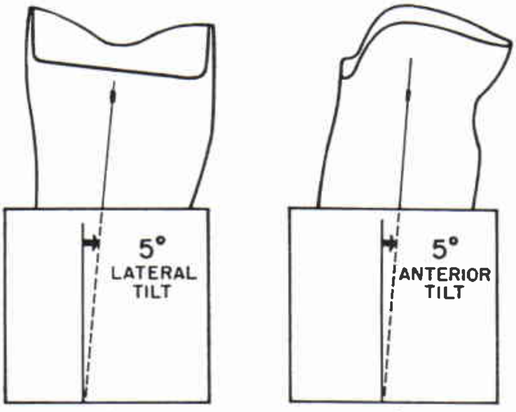
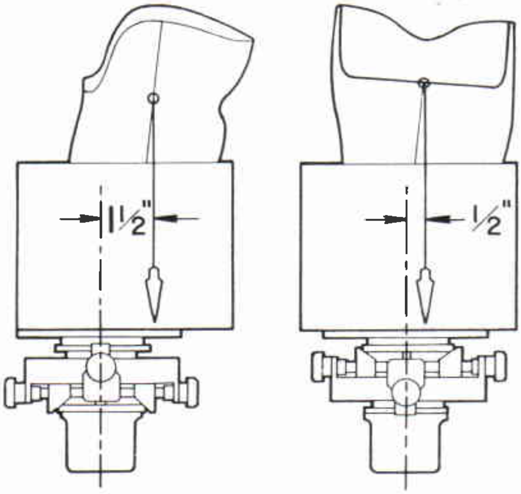


Fig. 19. Anteroposterior and mediolateral centerlines of the socket, intended for reference in alignment. In each of the two views, the approximate "center" of the brim and the estimated "center" of the bottom of the socket are connected by straight lines, except that in the lateral view the proximal center point is taken just above the level of the indentation provided for the patellar ligament.



A *B*

Fig. 20. Positioning of the socket in the socket block to give 5 deg. of adduction and 5 deg. of initial flexion.



A *B*

Fig. 21. Orientation of socket and socket block upon adjustable shank using socket centerlines for reference.

level as to leave only about an inch of wood below the end of the socket shell.

With the socket attachment plate and the slide-tilt unit of the below-knee adjustable shank (Fig. 18) centered and level, the socket block is now set upon the attachment plate in an orientation such that the mediolateral center plane of the socket (posterior reference line) lies in the same direction as the lower pair of setscrews of the slide-tilt unit (Fig. 21). Thereafter the socket block is moved upon the attachment plate in the anteroposterior direction until a plumb line dropped from the anteroposterior centerline of the socket at the level of the midpatellar tendon lies 1½ in. in front of the centerline of the upper tube clamp (Fig. 21*A*). Similarly, the block is then moved in the mediolateral direction until a plumb line dropped from the center of the posterior brim of the socket lies ½ in. lateral to the centerline of the upper tube clamp (Fig. 21*B*). While the block is held in this position temporarily, a pencil line is drawn about the attachment plate onto the base of the block, the socket and block are removed from the adjustable shank, and excess wood is cut away from the block to produce the result shown in Figure 22.

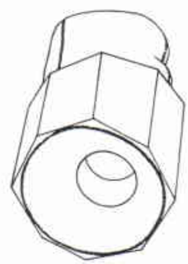


Fig. 22. Socket and socket block after removal of excess wood from the latter. Circle on base marks position of socket-attachment plate for reattachment of adjustable shank.

With the block thus partially trimmed, the adjustable shank is replaced against the bottom of the block in the same relative position as before, and the block is attached to the plate of the shank by means of not fewer than six ¾-in. flat-head wood screws (No. 10), which, incidentally, will seat nicely into the countersunk holes in the attachment plate. The particular position chosen in the individual case is, of course, as already described and as shown in Figures 20 and 21, and the net spatial relationships of socket to adjustable shank shall be such that, to begin with, all of the adjustment setscrews are near the middle of their ranges of possible adjustment.

CHOICE AND PREPARATION OF THE PROSTHETIC FOOT (WITH SHOE)

Although in the construction of the patellar-tendon-bearing below-knee prosthesis use might be made of any one of a variety of

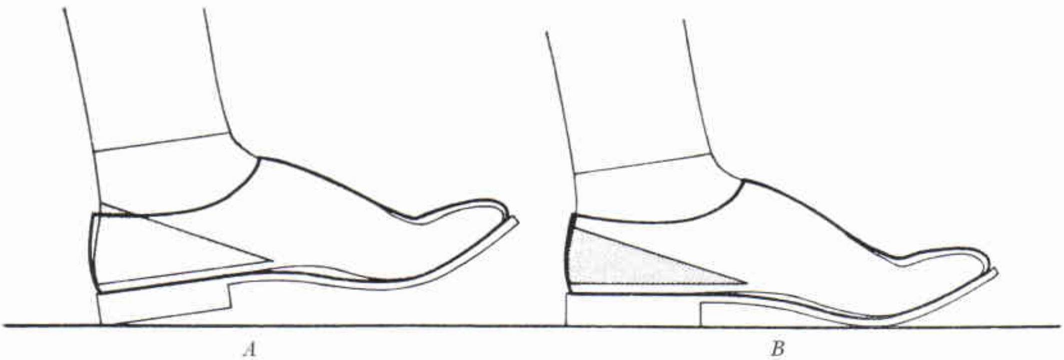


Fig. 23. The SACH foot, in transparent shoe, schematic. *A*, Heel contact; *B*, plantar flexion immediately after heel contact, heel wedge compressed. Rocker shape of keel at the ball of the foot gives support during roll-over and furnishes needed assistance at toe-off. Flexible toe piece permits normal toe-break in the shoe.

foot-ankle units commercially available, the most satisfactory results are usually obtained with the nonarticulated SACH foot (*S*olid *A*nkle, *C*ushion *H*eel), in which a heel wedge of compressible but resilient material provides shock absorption and the equivalent of plantar flexion at heel contact while a solid wooden core (or keel) properly shaped at the ball of the foot furnishes needed support during roll-over and push-off in the stance phase of walking. Figure 23 presents schematically the familiar SACH foot as seen through a transparent shoe properly fitted.

Generally, choice of SACH foot in the individual case depends on three factors—shoe size, height of the patient, and relative stiffness of the heel wedge. At present, oversize SACH foot blanks, left and right, are available in three ranges of shoe size (6–8, 8–10, 10–12) and two degrees of stiffness of the heel insert ("firm" and "medium"). As for heel stiffness, "medium" is generally recommended for below-knee amputees weighing up to 140 lb., "firm" for those exceeding 140 lb. As for Table 1, which presents the recommended size of foot blank as related to shoe size and height of patient, it should be noted that, as in most aspects of lower-extremity prosthetics, no hard and fast rules exist and that in any case borderline sizes have to be worked out as compromise. Ultimate choice of foot-blank size and heel-cushion stiffness should always be based on evaluation of the needs of the individual patient.

Table 1
Recommended Foot-Blank Sizes for Borderline Cases

Height of Patient	Shoe Size	Foot-Blank Size
Less than 5 ft. 9 in.	8	6–8
	10	8–10[a]
More than 5 ft. 9 in.	8	8–10[a]
	10	10–12

[a] Note overlap in foot-blank sizes where height of patient is not in the usual proportion to shoe size.

Once the foot blank has been selected, it remains to shape the foot (Fig. 24) until it fits properly into the intended shoe. Although in the oversize blank the general contours of the foot are provided for by the manufacturer, so that in general only slight modifications are required, certain precautions need to be exercised. For example, the portion of the foot above the top of the shoe should not be reduced until the final wooden shank has been installed. Similarly, no material should be removed from the lower third of the heel contour lest the distance from heel to toe-break be made too small for a tight fit. Conversely, certain size reductions are usually essential, especially on the lower surface of the arch of the foot, in the toe area, and in the heel cushion above the lower third of the heel, all as shown in Figure 24. In particular, the lower surface of the arch of the foot must be so reduced that it can never come into compression contact with the arch of the shoe

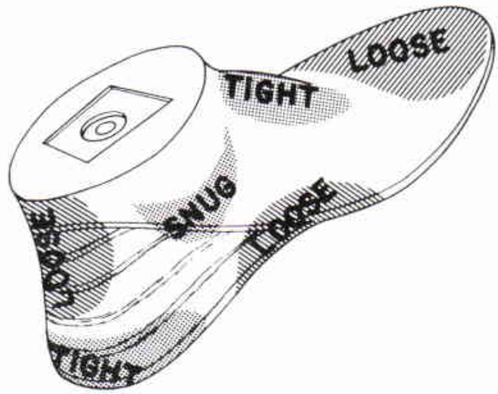


Fig. 24. Shaping of the SACH foot blank to the requirements of the shoe. Failure to maintain tightness in the areas indicated, or to provide relief in the others, leads to abnormal gait regardless of the care taken in construction of the rest of the prosthesis.

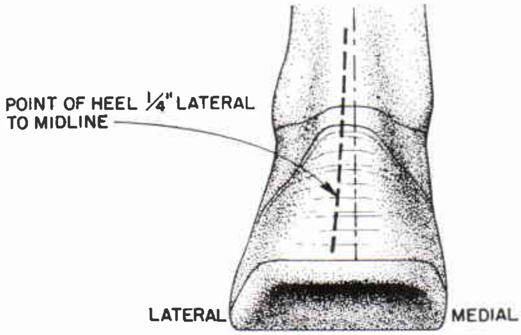


Fig. 25. Shaping of the heel of the SACH foot to accommodate proper toe-out in the finished prosthesis.

(Fig. 23). Required here is a minimum clearance of ⅛ in., for otherwise motion may be restricted or the shoe damaged. In like manner, the dorsal surface of the arch of the foot should be reduced until the lacing gap of the shoe matches that of the shoe on the remaining normal foot, but not to the extent that fitting in this area might be loose.

Just as the arch of the foot must be prevented from binding against the insole of the shoe, so the toe portion of the foot blank must be reduced so that expansion under compression will not restrict motion in the toe of the shoe. Finally, the upper two thirds of the heel insert must be shaped to give about ⅛ in. of clearance from the lateral, medial, and posterior brims of the counter of the shoe, a feature which permits the heel wedge to expand under compression without binding against the shoe (Fig. 23).

A subtle feature in the shaping of the heel wedge is that the rearmost point of the heel should be fashioned to lie ¼ in. lateral to the anteroposterior midline of the foot (Fig. 25) so that later, when the necessary toe-out is introduced, the point of the heel will automatically return to a position directly in the line of progression.

All of these shaping operations are of course best carried out by means of a cone or drum sander, the sanding being done as much as possible in a direction parallel to the direction of the laminations at all points. A spindle speed of at least 1750 r.p.m. is desirable; and in the course of fitting, a thin sock should be placed over the boot whenever the foot is inserted into the shoe for trial.

There remain now but two final adjustments—the first having to do with heel elevation (distance between bottom of heel and the surface upon which the ball of the foot rests when the top surface of the foot is parallel to the supporting surface) and the second with heel-cushion stiffness. Currently, SACH foot blanks are manufactured with a heel elevation of 11/16 in. If, when the shaped foot and companion shoe are held on a surface with top of foot parallel to that surface, there should be undue compression of the heel wedge, the heel elevation may be increased (by not more than 3/16 in.) by sanding the lower surface of the foam crepe shoe-sole material in the heel area. Should compression of the heel wedge be inadequate under the same circumstances, shims of crepe shoe-sole material, leather, or any other firm but flexible material may be shaped and bonded to the bottom of the heel.

If needed at all, the second adjustment (heel-cushion stiffness) awaits attachment of the foot (with shoe) to the rest of the assembly (*i.e.*, to the bottom of the adjustable shank). Accordingly, the foot-attachment plug of the adjustable unit is now bolted to the flat, top surface of the foot, and the distance between foot and adjustable unit is established with an appropriate length of aluminum-alloy tubing 1.625 in. O.D., 1.510 in. I.D. Attach-

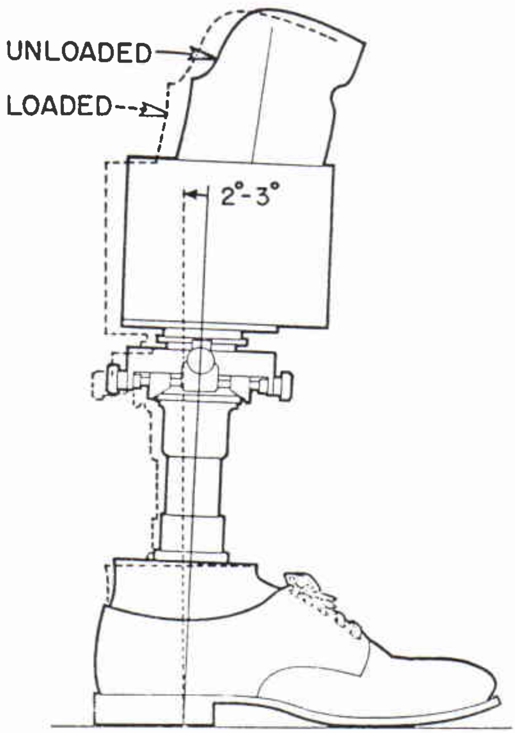


Fig. 26. Trial below-knee leg showing proper anterior tilt of shank (2 to 3 deg.) in the unloaded condition (without weight of wearer). Dotted outline shows return of the long axis of the shank to the vertical when amputee stands upon the prosthesis (initial compression of heel wedge). Should these relationships not prevail upon examination, a change in heel stiffness is indicated (Appendix B).

ment of the proximal end of the tube is by insertion into the clamp at the bottom of the adjustable unit. To clamp the distal end of the tubing about the foot-attachment plug, the lower end of the tubing is split, the tubing is slipped over the plug, and the assembly is fixed together with the tube clamp furnished with the adjustable shank. Preliminary toe-out of the foot is obtained simply by loosening the tube clamp, rotating the foot so that the line of progression is parallel to the antero-posterior (bottom) slide bar of the adjustable unit, and resetting the tube clamp. Should the unit be too short when tried on the patient, the foot is removed, annular spacers are added, the foot is replaced, and the clamp tightened again. If the unit is found to be too long, the foot is removed and a shorter length of aluminum-alloy tubing is substituted.

With the socket-and-block combination, the adjustable unit, the tubular pylon, and the foot-and-shoe combination thus assembled, the amputee dons the socket and stands upon it, weight distributed equally between heel and ball of foot. If all has been done well, the orientation in the parasagittal plane will be such that, when the prosthesis stands unloaded, the longitudinal axis of the shank will be inclined some 2 to 3 deg. anteriorly (Fig. 26, solid outline) whereas when the amputee stands upon the prosthesis the longitudinal axis of the shank will rotate posteriorly until it lies in a vertical plane (Fig. 26, dotted outline). The change in relative position brought about by addition of the wearer's weight represents of course an initial compression of the heel wedge. Over and above initial compression is that needed and acceptable at heel contact during the stance phase of walking. In general, the heel should compress about 3/8 in. at heel contact (Fig. 23*B*). Should, in any particular case, any of these values prove to be appreciably larger or smaller than the recommended compression values, the heel cushion must be replaced by a stiffer or a softer cushion, whichever applies. The procedure for so doing is set forth in Appendix B (page 73).

MAKING THE SUPRACONDYLAR CUFF

All prior conditions having been met satisfactorily, the assembly shown in Figure 26 is now ready for preliminary alignment on the amputee. But before any alignment can be undertaken it is first necessary to fabricate the means of socket suspension—the supracondylar cuff fitting about the distal flares of the femur and resting in front upon the upper margin of the patella (Fig. 27). Though in some cases it may be necessary later to resort to jointed sidebars and thigh corset, with or without still additional paraphernalia, the simple cuff, with its side tabs attached to the socket posteriorly, commonly suffices in actual prosthetic use and, in any case, serves adequately the purposes of final fitting and alignment.

To make the cuff, including the tabs, a

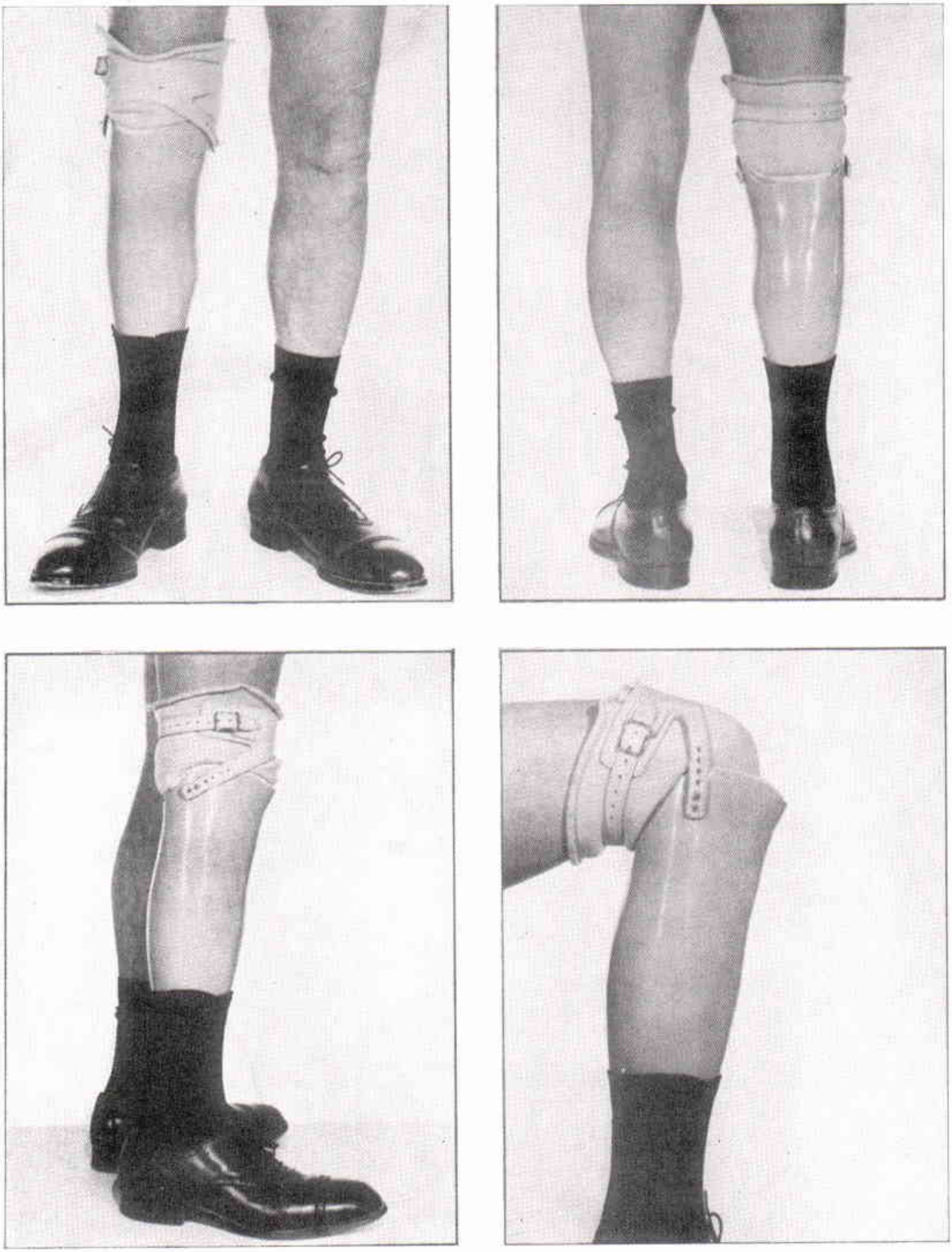


Fig. 27. Finished PTB prosthesis using supracondylar cuff as only means of suspension.

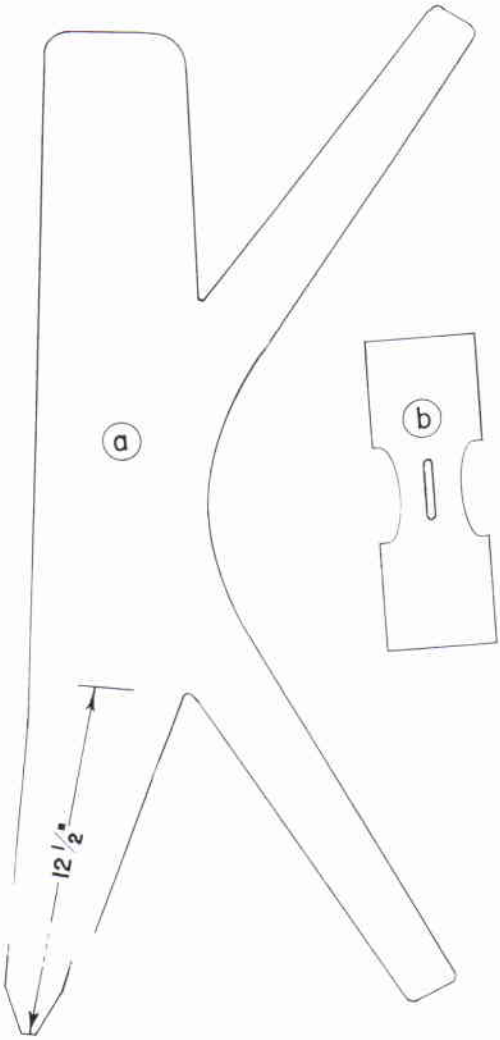


Fig. 28. Patterns (one half actual size) for preparing supra condylar cuff. *a*, Pattern for the cuff itself; *b*, pattern for the buckle billet.

suitable piece of pearled elk leather is first cut out along the pattern labeled *a* in Figure 28. Since ultimately closure of the cuff is to be by buckle on the lateral side, and since it is desired to have the smooth side of the leather outside, the orientation of pattern and material must be chosen properly. One side of the pattern is of course for right amputees, the other side for left amputees.

Rubber cement is now applied to the rough side of the leather part just cut, and two pieces of Dacron webbing 1/2 in. wide and 4-1/2 in.

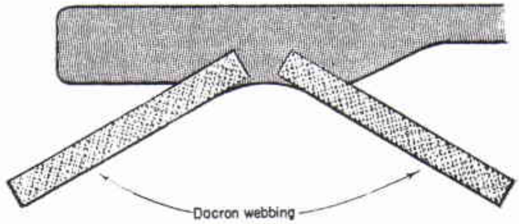


Fig. 29. Application of Dacron webbing to cuff side tabs to prevent undue stretching of the leather.

long are bonded to the leather tabs (Fig. 29) as insurance against excessive stretching. A piece of horsehide large enough to cover cuff and tabs is then selected, the rough side is covered with rubber cement, and the horsehide is bonded in place as a liner. When this laminate has set, the elk leather, Dacron webbing, and horsehide are sewed together along the edges, and the horsehide and webbing are trimmed flush with the elk leather.

When the cuff itself has been completed, a buckle billet is cut from a scrap of horsehide according to the pattern labeled *b* in Figure 28, the ends of the piece are skived on the rough side, a slot for the buckle is cut out, a 5/8-in. buckle is inserted in the slot, and the billet is lapped back on itself, rough side in, and bonded together with rubber cement. The billet containing the buckle is then glued and sewed to the pearled elk surface of the cuff, as shown in Figure 30. Finally, six or seven 3/16-in. holes are punched in the tabs at 3/8-in. intervals, and buckle holes of suitable size are punched into the strap of the cuff on 1/2-in. centers (Fig. 27).

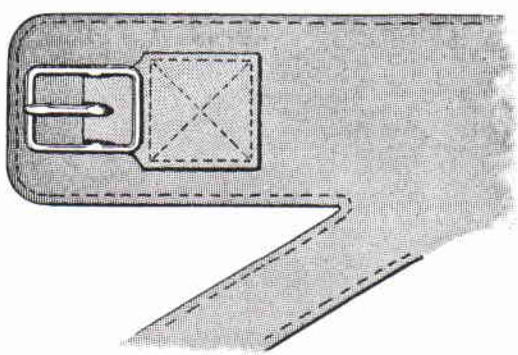


Fig. 30. Installation of buckle and buckle billet on condylar cuff.

ATTACHING CUFF TO SOCKET

As will be noted in Figure 27, one intention of the condylar cuff is that it shall bring about tension in the side tabs as the knee is extended throughout the range and that it shall permit the side tabs to relax as the knee flexes in sitting or in the swing phase of walking. Thus the points of attachment of the side tabs are pivots, the axes of rotation being behind the anatomical knee axis. Since the cuff must pull in against the patella over a full 60 deg. of knee flexion in the swing phase, while for comfort in sitting the tabs must relax throughout an additional 30 deg. to give 90 deg. of knee flexion (Fig. 31), the optimum points of attachment of tabs to socket must be arrived at by trial of the socket and cuff on the patient for whom they are intended.

The amputee first dons the cuff so that the tabs are on either side of the knee and fastens it comfortably. He then dons the socket over a stump sock, being careful to obtain proper seating of the stump, and stands on the prosthesis with weight evenly distributed on two legs. While this condition is maintained, the tabs are pulled down on either side of the knee and approximated to their natural position on the sides of the socket. The hole nearest the level of the tibial plateau but behind the average anatomical knee axis is selected on each side and the points marked through the holes with a pencil (Fig. 32). By means of self-tapping screws, the necessary buttons are attached temporarily at the points indicated, pending final alignment and walking trials. When all adjustments are complete, the buttons are attached permanently by means of rivets.

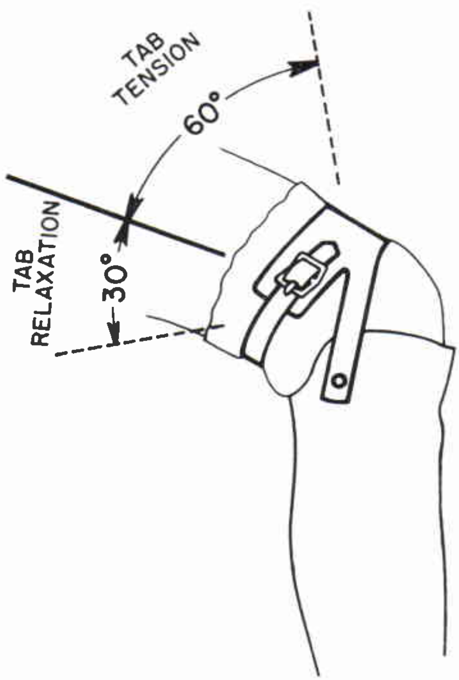


Fig. 31. Positioning of cuff side-tab attachments such as to provide tab tension throughout 60 deg. of knee flexion in the swing phase of walking and tab relaxation throughout an additional 30 deg. to accommodate comfortable sitting with knee flexed a full 90 deg.

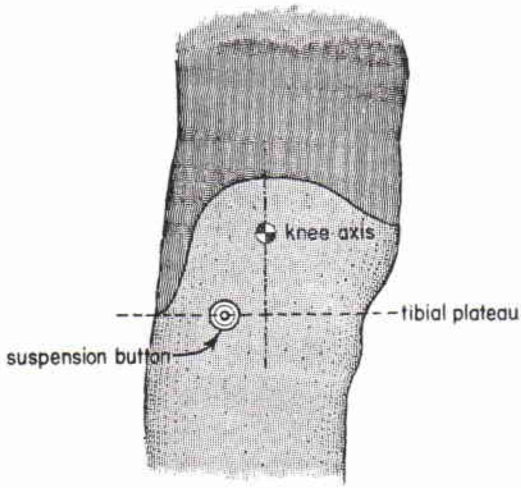


Fig. 32. Attachment of side-tab buttons at position determined in Figure 31. The usual position, arrived at by trial and error, is behind the average anatomical knee axis at the level of the tibial plateau.

Preliminary Alignment

From the alignment established at the time of assembly of socket, adjustable shank, and foot (pp. 36-42) it is now necessary to arrive at the optimum alignment for the given case, a requirement demanding ultimately the participation of the amputee himself. Since the positioning of the socket in the block, the orientation of the adjustable unit, and the characteristics of the foot are all mutually interdependent in defining the "net" optimum alignment, it is imperative that no attempt be

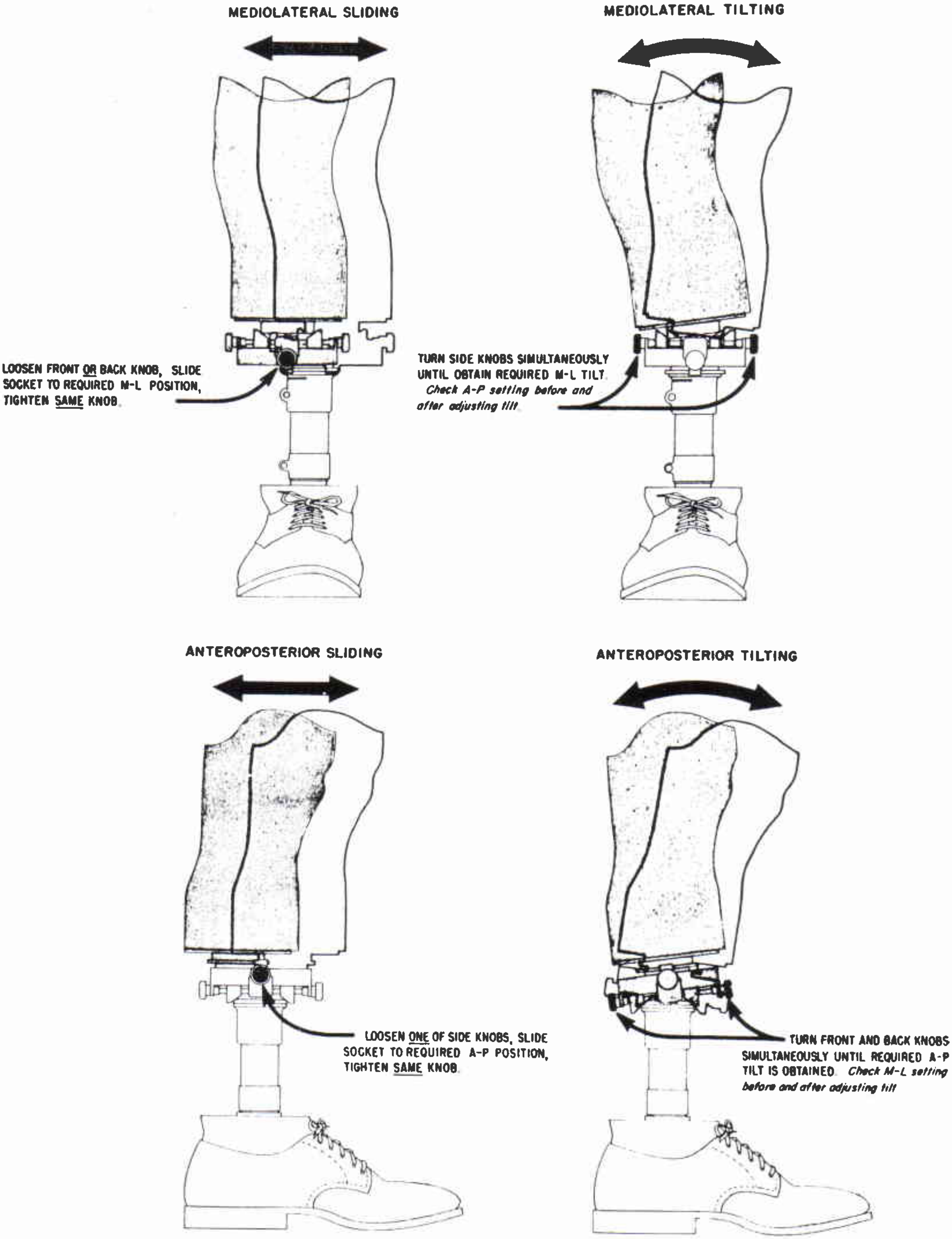


Fig. 33. Preliminary alignment of trial leg in four successive steps using the adjustment facilities of the UC below-knee adjustable shank.

made to correct a fault at a given point without considering the possibility of thus upsetting position relationships at another. The whole process of alignment is in fact a series of checks and rechecks, and it is the responsibility of the prosthetist to determine the site of faults, if any, and to make appropriate corrections as the process advances in stepwise fashion. As has been seen, use of the below-knee adjustable shank makes it possible to orient a below-knee socket to any necessary combination of fore-and-aft positioning, sidewise positioning, fore-and-aft tilting, or sidewise tilting. But because each setscrew fixes not only the lengthwise positioning of its own bar but also the rotatory positioning of the companion bar, it is essential, in the course of successive adjustments, to reset the *same* screw as was first loosened (not its opposing counterpart) and to recheck any preceding adjustment to make certain that it has not been disturbed.

The amputee having first donned the socket-shank combination (together with the condylar cuff for suspension and with the intended shoe on the prosthetic foot), a preliminary approach to alignment on the individual is made in four steps, as shown in Figure 33. While anteroposterior tilting is avoided, mediolateral sliding is accomplished. While anteroposterior sliding is avoided, mediolateral tilting at the desired angle is established. While mediolateral tilting is avoided, anteroposterior sliding is carried out to the extent desired. While mediolateral sliding is avoided, anteroposterior tilting is accomplished. To avoid any unintentional disorientation, each operation is followed by a check of the previous setting. Additional minor adjustments are made as needed until the alignment of the prosthesis upon the wearer is such that the toe-out of the prosthesis matches that of the normal foot, that the amputee can stand erect, hips level, with weight equally distributed between the two feet and with heels not more than 4 in. apart, and that in standing in one position between parallel bars (or with the aid of crutches) he can shift his weight comfortably with adequate control of both mediolateral balance and of knee flexion-extension.

Of the principal faults sometimes en-

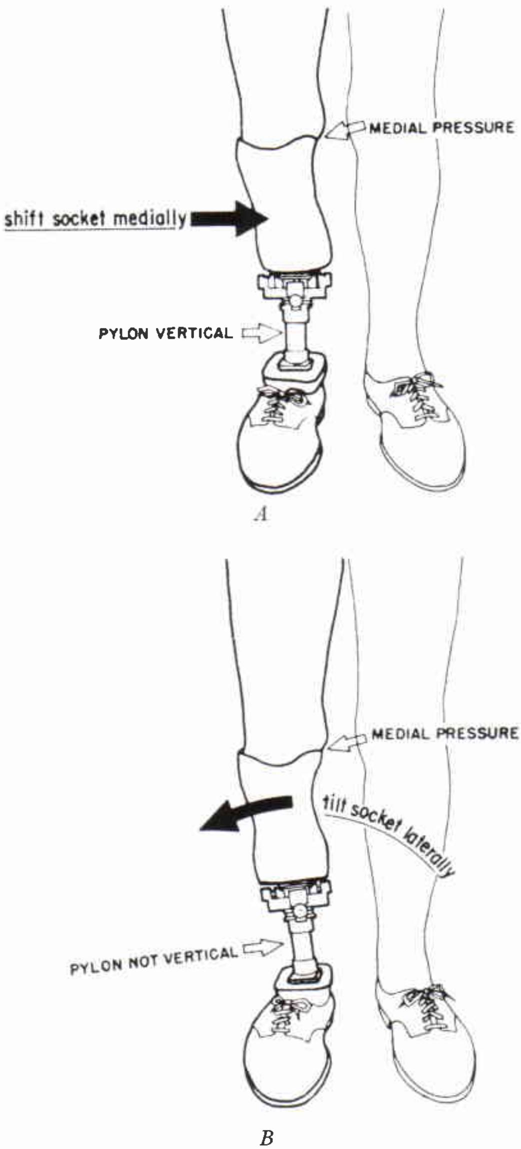
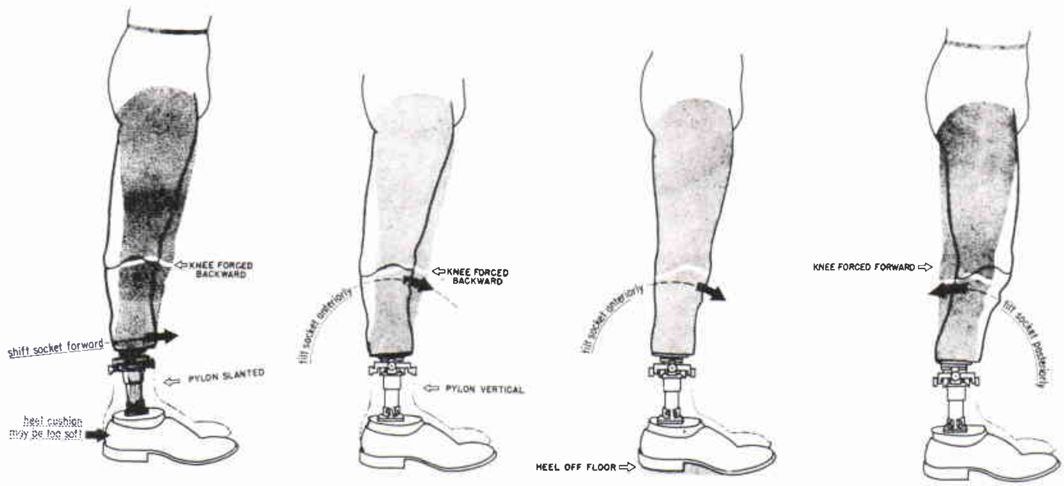


Fig. 34. Two faults in mediolateral alignment sometimes found during initial trials of prosthesis on amputee. *A*, Pylon vertical (foot flat on floor) but socket too far lateral; *B*, same situation but with pylon tilted laterally so that foot rests on outside edge of sole only.

countered at the time of preliminary alignment of the trial prosthesis on the patient, some have to do with spatial relationships in the frontal plane (Fig. 34), others with relative positioning of parts in the parasagittal plane (Fig. 35). If, for example, there should be a gap at



A *B* *C* *D*

Fig. 35. Faults in anteroposterior alignment sometimes found during initial trials of prosthesis on amputee. *A*, Knee forced backward, shank pylon tilted posteriorly so that too much weight is borne on heel; *B*, knee forced backward but with shank pylon vertical (foot flat); *C*, heel off floor, all weight borne on ball of foot; *D*, knee forced forward by virtue of too much anterior tilt in socket.

the brim of the socket on the lateral side, accompanied by undue pressure at the medial brim, the pylon of the adjustable shank may be found to be either vertical (Fig. 34*A*, foot necessarily flat on the floor) or tilted laterally (Fig. 34*B*, foot resting incorrectly on lateral edge of sole). In the first case, the remedy consists in shifting the socket medially by means of the adjustable unit (Fig. 34*A*). In the second, elimination of the trouble is to be found in tilting the socket laterally, again by means of the adjustable unit (Fig. 34*B*). When, in Figure 34*B*, the pylon shall have assumed a vertical position in the mediolateral plane, the socket will have settled into a satisfactory fit near its proximal end. Similar, but opposite, corrections are made should undue pressure be found to prevail on the lateral brim of the socket, it being kept in mind that the long axis of the shank pylon must always lie in a vertical plane (foot flat on floor).

In the parasagittal plane, a number of faults may be observed from time to time with individual patients (Fig. 35). For example, it may be found that application of the wearer's weight forces the knee backward, the shank pylon tilting posteriorly in one case (Fig. 35*A*), standing vertical in another (Fig. 35*B*). Should a shift of the socket block forward on the adjustable shank prove not to correct the difficulty shown in Figure 35*A*, it may be that the heel cushion in the foot is too soft, in which case the heel wedge must be replaced by stiffer material according to the procedure outlined in Appendix B. When, on the contrary, the knee is forced backward while the pylon remains in a vertical plane (Fig. 35*B*), then adequate correction should be obtained simply by tilting the socket-block combination anteriorly upon the adjustable unit. Occasionally, the weight of the amputee forces the socket forward while the pylon remains vertical (Fig. 35*D*). When such a relationship prevails, it is usually corrected by tilting the socket posteriorly. And finally it may happen that, when the amputee stands erect in the prosthesis, the heel is not in contact with the base of support (Fig. 35*C*), which of course means that all of the weight is borne on the ball of the foot instead of being distributed equally between heel and ball. Tilting the socket anteriorly usually corrects this undesirable arrangement.

It should now perhaps be noted that, in the process of preliminary trials on the patient, none of the indicated adjustments should be more than a minor adjustment. The necessity for any gross adjustment at this point in the procedure reflects some inadvertence in the conduct of the preceding steps of construction, and in such a rare case it may be better for the prosthetist to start over, or at least to retrace his own performance from socket casting to assembly of the adjustable leg. In any event, it will be obvious that the orientation of the socket in the wooden block, the position of the block with respect to the adjustable shank, the orientation of the adjustable unit itself, and the design of the SACH foot are all interdependent and that each of these factors contributes to the final result, so that a change in any one feature affects the behavior of all the others. Accordingly, successful alignment of the PTB prosthesis is still partly a matter of art and thus calls for extraordinary skill and judgment on the part of the prosthetist. Throughout the preliminary tests it should be remembered that the wearer of the PTB prosthesis is expected to walk with the knee on the side of the amputation flexed some 5 to 8 deg. and with weight borne over the middle third of the prosthetic foot in midstance. If any major changes are made in the initial alignment, then over-all height should be checked, since an increase in anterior tilt reduces the effective length of the prosthesis while an increase in posterior tilt tends to increase it.

Dynamic Alignment

Despite the apparent implications of the nomenclature, dynamic alignment of the PTB prosthesis is less an actual alignment as such than it is a check to make certain that the alignment established in the static condition of standing is satisfactory when the amputee undertakes normal, level walking along a substantially straight line of progression. The features sought in dynamic alignment are essentially the same as those sought under static conditions, though the criteria are different. If, indeed, the requirements of static alignment have been met fully, and if the particular case involved presents no gross deviations from the characteristics of the average below-knee amputee, then the chances are that dynamic alignment will amount to no more than a confirmation, at most a minor revision, of the spatial relationships already existing.

Since, however, no amputee-prosthesis combination, however carefully worked out, can be expected to perform in an optimum way without the active and cultivated participation of the wearer, no attempt at checking out the dynamic alignment of a PTB prosthesis is apt to be valid until the amputee has become familiar not only with what is to be expected from the prosthesis but also with what responsibility he, the wearer, has in the management of the limb. Accordingly, the patient is first encouraged to experiment (at first between parallel bars) with simple weight-bearing on the limb, with active knee flexion-extension, with standing and sitting, with short and simple steps including roll-over

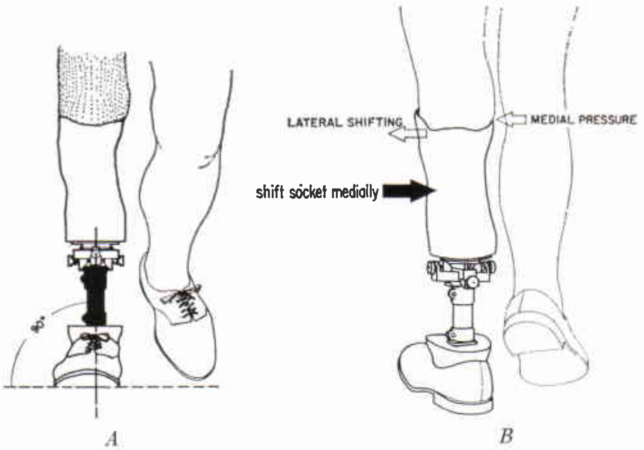
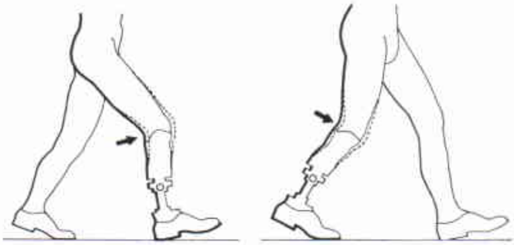
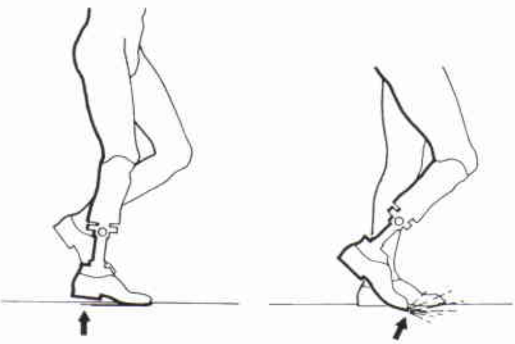


Fig. 36. Check of foot and socket in mediolateral plane during walking. *A*, Proper alignment in front view; *B*, correction for undue pressure at medial brim of socket, rear view. Compare with Figure 34*A*.



A *B*

Fig. 37. Check of anterior tilt of socket (and hence of initial knee flexion). Too much initial flexion, as here, may cause loss of knee stability at heel contact (*A*) or lack of support (drop-off) at the end of the stance phase (*B*), or both.



A *B*

Fig. 38. Check of posterior tilt of socket. Too little initial knee flexion (excessive posterior tilt of the socket) may cause early arrest of knee flexion after heel contact, or a prolonged period of unstable weight-bearing on the heel, or an excessive shift of the body weight to the ball of the foot accompanied by premature heel rise at midstance (*A*). Inadequate knee flexion may also give rise to scuffing of the toe during swing-through (*B*).

on the prosthesis, and finally, when he has gained some confidence, with straight and level walking without benefit of parallel bars or crutches. Meanwhile, the prosthetist and trainer continue to make such minor adjustments as seem indicated by observation of dynamic conditions. Thus, the indoctrination of the patient and the final details of alignment are carried out together, sometimes alternately, sometimes successively, until both patient and clinic team are satisfied that the best possible job has been done. Some of the problems that project themselves occasionally during dynamic alignment are depicted in Figures 36, 37, and 38, and the final antero-

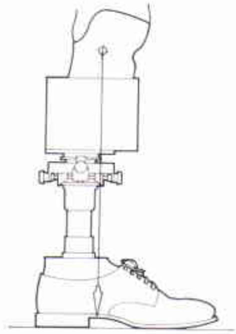


Fig. 39. Ultimate anteroposterior position of socket with respect to shoe. A plumb line dropped from the anteroposterior centerline of the socket at the level of the midpatellar tendon should pass just ahead of the breast of the heel of the shoe.

posterior position of the socket with respect to the shoe is shown in Figure 39.

Because in the practical matter of walking comfortably, effortlessly, and with acceptable appearance the details of alignment in the anteroposterior direction are more critical than those having to do with the mediolateral, it is recommended that the latter always be attended first, the anteroposterior adjustments being left until the very last. As in all other steps of alignment, each successive change should be followed at once by a check on the preceding one so that no correction coming later can upset another made earlier, except with the full knowledge of the prosthetist (as is sometimes necessitated in compromise situations where one advantage is to be gained only at the expense of another). In all cases, the patient should be allowed to walk upon the adjustable shank long enough (days, if need be) to demonstrate that all adjustments are at an optimum for the particular physico-anatomical circumstances then prevailing. When the prosthetist is convinced that he has attained the best possible set of conditions, the alignment is duplicated in the finished prosthesis by means of the UC adjustable alignment-duplication jig.

Alignment Duplication

The so-called "alignment-duplication jig" of the University of California, intended originally for duplication of the alignment of above-knee prostheses, consists of two ad-

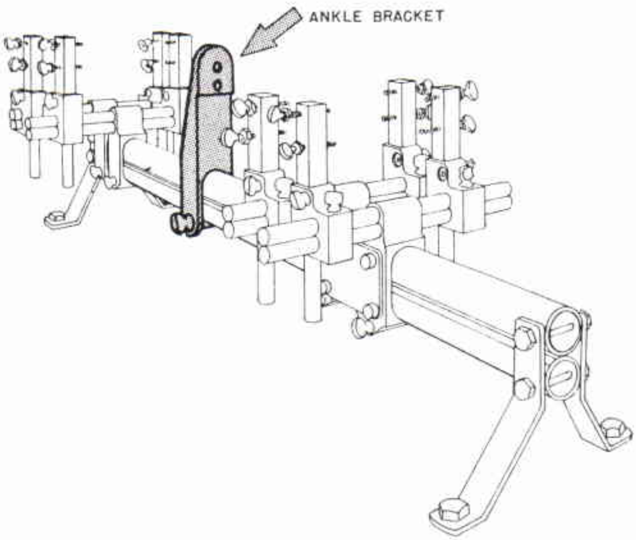


Fig. 40. University of California alignment-duplication jig for above-knee prostheses, as adapted for below-knee alignment duplication through substitution of the ankle bracket (cross-hatched) for one of the adjustable clamps.

justable, viselike clamps so mounted side by side upon a firmly fixed, tubular base as to be capable of being moved along the length of the base as required or of being fixed in any selected positions along the base in any chosen linear relationship to each other. One clamp is intended to position and hold the thigh portion and artificial knee of an above-knee prosthesis, while the other holds and positions the shank-foot combination. To be interposed between the two clamps, mounted on the same base, and movable along the base between the clamps, is a bracket intended as a guide for a miter saw whenever the saw is needed. When the bracket is in place, it is so oriented that the saw will make a cut normal to the long axis of the tubular base.

Once the clamps have been set so as to accommodate as precisely as possible a thigh socket, adjustable knee unit, shank, and foot in the relative positions established in alignment trials, the component parts of the final prosthesis may be substituted for the adjustable devices without upsetting the prevailing alignment. Similarly, the alignment of an existing prosthesis may be duplicated in a new prosthesis simply by setting up the alignment jig to match the first limb and then making the second limb to match the setting of the jig. When the desired orientation of socket and knee block with respect to shank and foot has been attained, the saw is used to cut the planes representing the intended juncture of the two segments.

Application of this device to the below-knee case, including the case of the patellar-tendon-bearing prosthesis, is readily accomplished by introduction of a special fixture called the "ankle bracket." Mounted on the base in the same way as the clamps, it is used in place of one of them, that one being simply shoved out

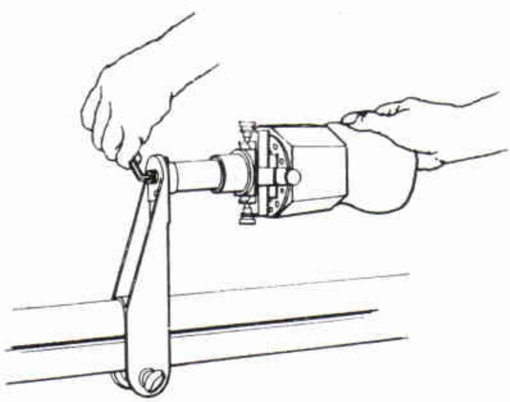


Fig. 41. Attachment of adjustable shank (with socket and socket block) to ankle bracket of alignment-duplication jig.

of the way temporarily (Fig. 40). Drilled through the top of the ankle bracket is a ⅜-in. hole whose axis is such that, when the bracket is in place, the axis is parallel to the base tubes of the jig. When, in the below-knee case, static and dynamic alignment with the adjustable leg satisfy both prosthetist and amputee, the SACH foot is removed from the adjustable shank, and the distal end of the shank is attached to the ankle bracket by means of an Allen-head screw (Fig. 41). Since

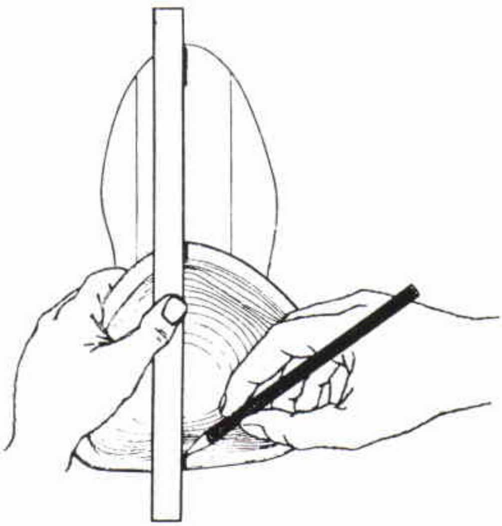


Fig. 42. Recording toe-out of foot before removing foot from adjustable shank. Same toe-out must be re-established later. See Figure 50.

toe-out of the foot must be re-established after the final shank piece has been properly substituted for the adjustable shank, the prevailing relationship of the foot to the socket is keyed before the foot is removed from the adjustable leg. Using a straightedge and one of the bonding lines of the foot for reference, the prosthetist first marks points on the front and back brims of the socket (Fig. 42). Thus later, when the final shank has been aligned and cemented into place, the foot may be replaced in the same relative position of toe-out as established in the alignment trials on the adjustable shank.

Since, when the ankle bracket is fixed to the base, the axis of the hole through the bracket is parallel to the long axis of the base, so also then is the long axis of the shank parallel to the base tubes when subsequently the shank has been bolted to the ankle bracket. The orientation of the socket being thus established, the socket clamp is brought up into position alongside the socket (Fig. 43), care being taken to see that the clamp is then not less than 10 in. from the end of the base tubes (so that later it can be backed out of the way). The socket clamp is there locked to the base tubes, and the clamping thumbscrews are run down carefully but firmly so as to clamp the socket without at the same time placing any distorting strains upon the shank. The relative positions of shank and socket are thereby established in the jig for later repro-

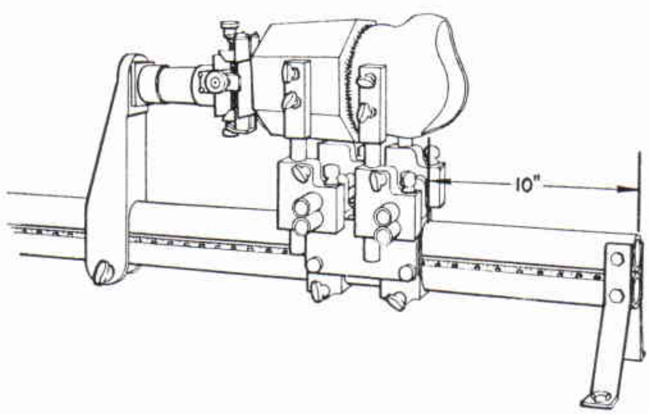


Fig. 43. Setting of socket clamp to the orientation previously established by the ankle bracket. At least 10 in. should be allowed at socket end so that socket clamp and socket may later be moved out of the way. See Figure 45.

duction in the finished prosthesis. To establish the over-all length of the final prosthesis, the positions of the ankle bracket and of the socket clamp are then recorded from the scale running the length of the base tubes of the jig.

With the socket thus fixed in the clamp and with the clamp and ankle bracket secured to the base of the jig, the adjustable shank is now removed, first from the ankle bracket and then from the wooden base of the socket (Fig. 44). The saw guide is mounted near the base of the socket (Fig. 45), and a cut (not more than ¼ in. from the end of the base) is made (Fig. 46) so as to produce a surface normal to the axis of the jig. The clamp holding the socket is moved out of the way, a partly hollowed, wooden shank block is now attached to the ankle bracket by means of the same Allen-head screw as before (Fig. 47), and a cut is made to produce a surface which, like the bottom surface of the socket base, will be normal to the long axis of the jig (Fig. 48). When the sawing is completed, the saw guide is removed from the jig, and shank and socket block are brought together by sliding the socket clamp back to its original position on the tubular base.

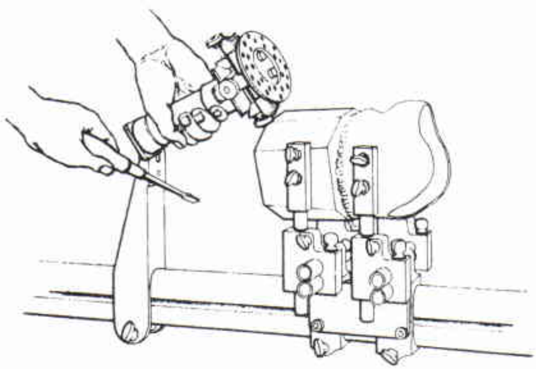


Fig. 44. Removal of the adjustable shank.

If all has been done properly, the top surface of the wooden shank and the bottom surface of the socket block will now meet comfortably all around the periphery. When that is the case, the mating surfaces are spotted with glue, brought together firmly, and held in place by locking the fixtures to the base tubes (Fig. 49). To avoid inadvertent dripping of glue onto the equipment, the base of the jig may be draped loosely with scraps of paper, rag, or waste. When the glue has set firmly, the whole unit is removed from the jig, and the foot is attached to the shank (Fig. 50) in the same position (with respect to the socket) as before (reference lines match). Thereafter the leg is ready for final shaping and finishing (Fig. 51).

Finishing the Prosthesis

Since it is inconvenient, if not actually impossible, to determine in advance exactly how the shank block and the socket block are

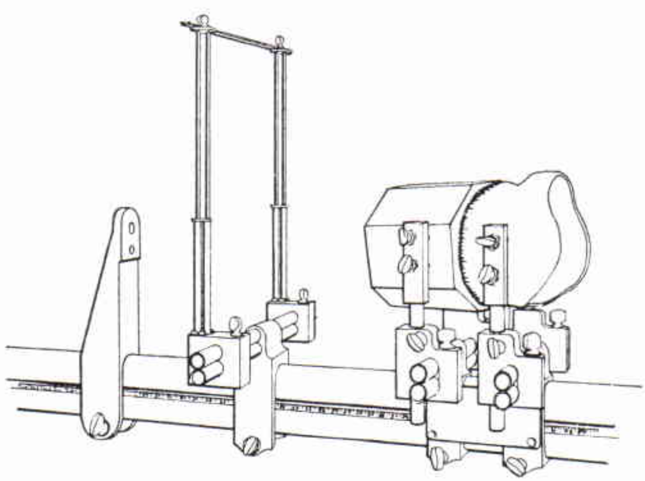


Fig. 45. Installation of saw guide on same base as other fixtures.

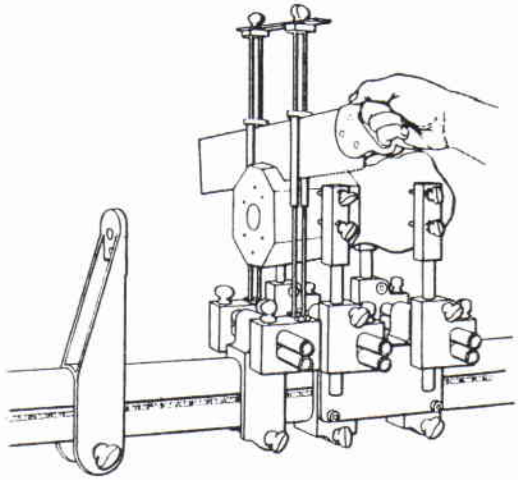


Fig. 46. Making saw cut on bottom of socket block. Remove not more than ¼ in. at thinnest point about periphery.

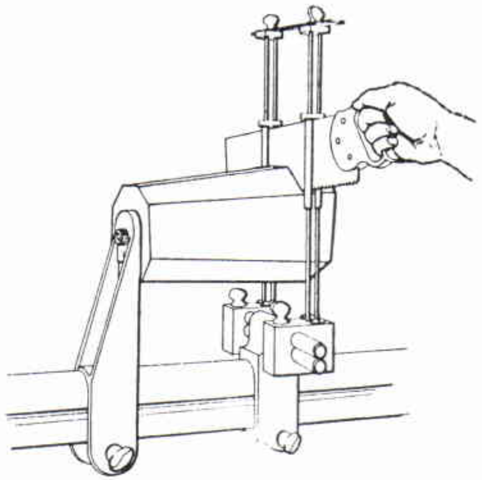


Fig. 48. Making saw cut on top of shank block. Length of block after cutting shall be such that it may be substituted for the adjustable shank and pylon without significant change in over-all length of the prosthesis.

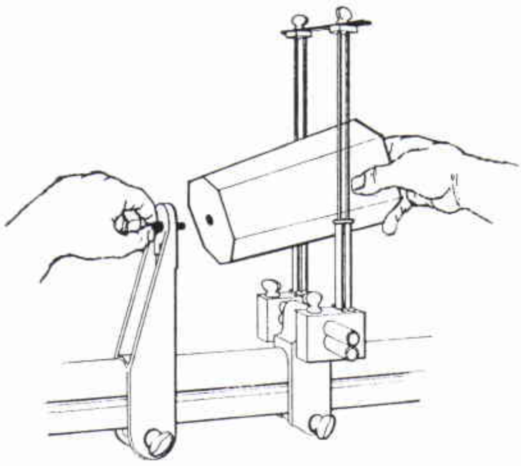


Fig. 47. Attachment of shank block to ankle bracket.

going to line up in the finished prosthesis, and since ultimately, in the interest of weight-saving, it is desirable to carve out the shank block to the thinnest possible shell compatible with strength requirements, it is necessary to break apart the temporary attachment of shank and socket, but not until essential landmarks have been recorded for the purpose of later reassembly in the same relative positions as established in the alignment jig. Similarly, finishing the foot and ankle (distal part of shank) requires another removal of the foot, but not until the necessary reference position has been recorded on the work itself.

To begin, the toe-out of the foot is marked with pencil, as shown in Figure 52*A*, and the foot is removed by unscrewing the attachment bolt. Because in the shaping of the distal end of the shank, and in its preparation for the lamination to follow (page 56), some material usually has to be shaved off the outside of the shank in the ankle area, the pencil mark on the anterior aspect is carried onto the base with a sharp tool, such as an awl or a penknife (Fig. 52*B*). In order that the later plastic-laminate covering may form a smooth transition from shank to foot, a line is now scribed around the periphery of the bottom of the shank about $\frac{1}{16}$ in. from the edge (Fig. 52*C*), and the shank is ground down smoothly to the line.

The rest of the external surface of shank and socket block are now ground down to approximate the contours of the natural counterpart (preferably to match the shape of the remaining leg of the particular individual for whom the prosthesis is intended), and reference marks are made front and rear to indicate the established relationship of socket and shank (Fig. 52*D*). The temporary, glued attachment of socket block and shank

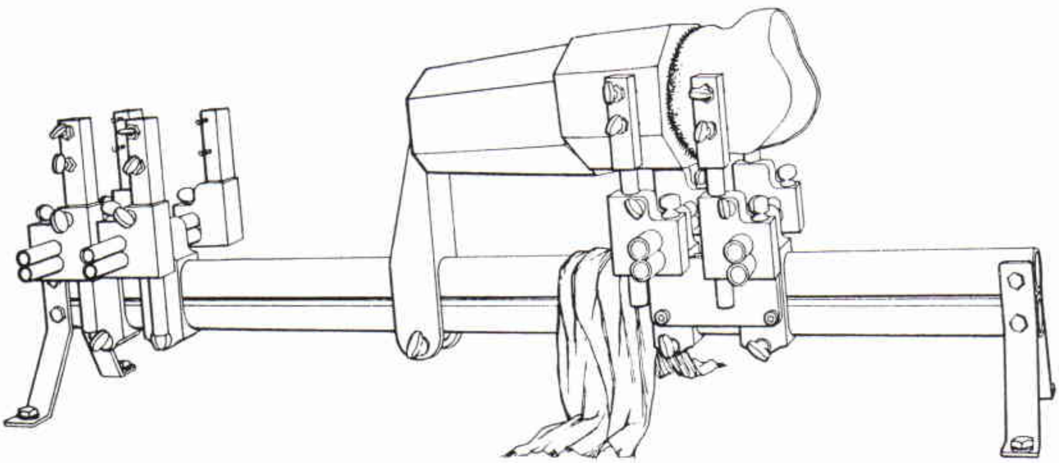


Fig. 49. Shank and socket block glued together in relationship established by jig fixtures. Dripping glue is caught by waste thrown over jig base.

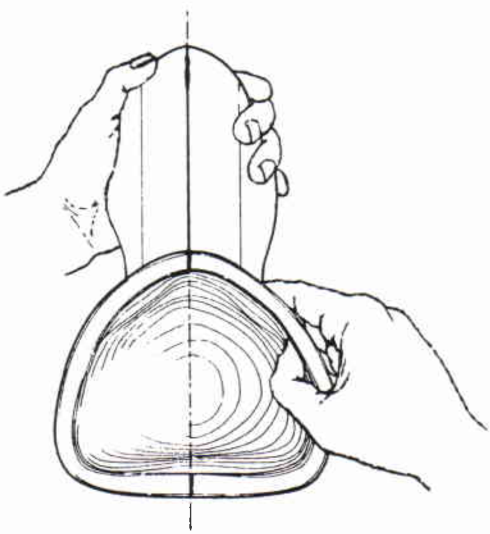


Fig. 50. Attachment of foot to shank with same relative toe-out as existed in trial leg using adjustable shank. Compare with Figure 42.

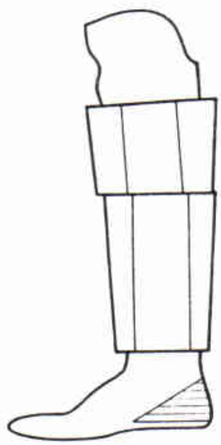
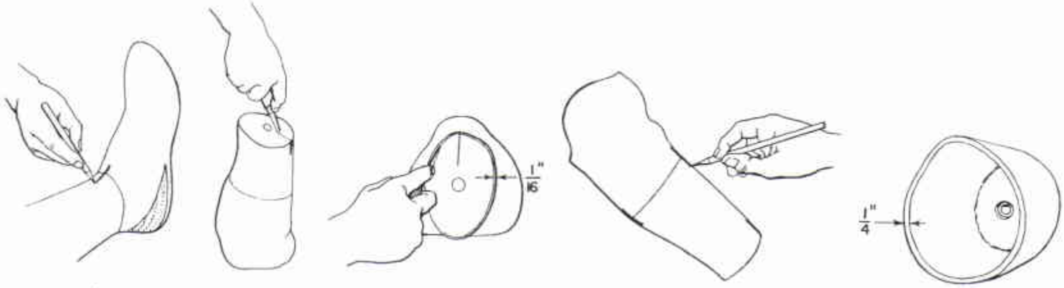


Fig. 51. Assembled prosthesis ready for external finishing. Orientation of parts is that established in trials of static and dynamic alignment.

is now carefully broken apart by a sharp knife, and the inside of the shank is routed out (by routing machine or by hand) until the walls are uniformly only ¼ in. thick (Fig. 52*E*). Thereafter socket block and shank are glued back together, this time with intent of permanency, the front and back reference lines being made to match up as in the original attachment.

To provide additional strength and at the same time to give the prosthesis a pleasant, perhaps even realistic, finish, the whole socket-shank combination is now covered with a suitable plastic laminate of Fiberglas cloth, nylon stockinet, and polyester resin, the latter appropriately tinted to simulate the color of the human skin. The technique is essentially the same as in other plastic-laminating procedures now in widespread use in prosthetics, for example in the making of the PTB socket itself (page 73).

The socket-shank unit, less the foot, being supported on a mandrel held in a vise (Fig.



A B C D E

Fig. 52. Preliminary steps in the finishing of the PTB prosthesis. *A*, Marking the established toe-out of foot with respect to shank; *B*, foot removed, reference mark transcribed to bottom surface of shank to avoid obliteration in next step; *C*, 1/16-in. annular ring marked about bottom surface of shank block as guide line for shaving down ankle area; *D*, ankle area shaved down, reference lines marked to record orientation of shank and socket block (after whole limb has been shaped on outside to match contours of the remaining leg of patient); *E*, shank block removed from socket block and routed out to form shell uniformly 1/4 in. thick all around.

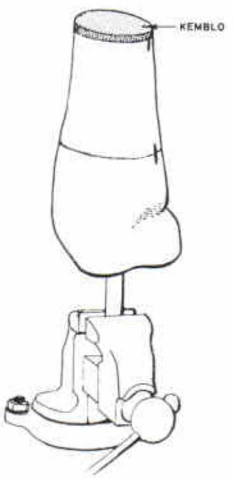
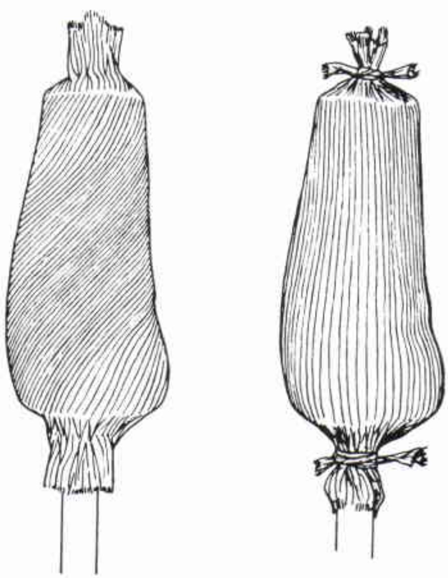


Fig. 53. Application of disc of Kemblo to end of shank prior to layup and lamination.

53), a disc of Kemblo is first bonded to the bottom of the shank to protect it from resin and to close the foot-bolt hole. Then a sheet of Fiberglas cloth wide enough to extend from the foot base to within 2 in. of the socket brim is wrapped around the unit and is in turn covered with two layers of nylon stockinet, the first being made to spiral in the interest of increased strength (Fig. 54). A PVA sleeve made in the usual manner is now pulled over the layup, and the fibrous layers are impregnated with polyester resin in the fashion described earlier (page 36). When the resin has cured, the excess (including the ends of the PVA sleeve) is trimmed off at top and bottom



A B

Fig. 54. Layup for lamination of socket-shank combination. *A*, First of two layers of nylon stockinet twisted over layer of Fiberglas cloth; *B*, second layer of nylon stockinet applied and tied off at both ends.

(at ankle and at socket brim), and the foot is replaced with the same degree of toe-out as before.

As a final finishing touch, the superior plane of the foot (which will now be somewhat larger than the end of the shank) is scored around with a pencil (Fig. 55), and the foot is sanded down in the vicinity of the ankle to give a smooth transition to the shank. The result is a finished prosthesis ready for trial on the amputee to determine, among other things, the necessity, if any, for further support, or added stability, or improved suspension in the form of conventional sidebars and thigh corset. Should the supracondylar cuff already prepared (page 42) prove adequate, the amputee should be able to perform with an optimum of comfort, function, and appearance both in standing and in normal walking on a level surface. In the event it should *not* for any reason, the prosthetist proceeds with the construction of additional equipment.

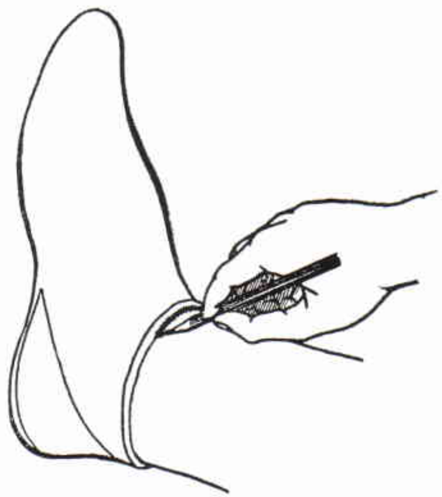


Fig. 55. Scribing foot at ankle line for sanding to provide smooth transition between foot and shank.

The PTB Prosthesis in Special Cases

The design of the so-called "patellar-tendon-bearing" below-knee socket is such that, ordinarily, the socket itself provides adequate stability in both the anteroposterior and the mediolateral directions and is itself adequately suspended from the limb of the wearer by no more than the supracondylar cuff already described. With proper relief in the rear for the hamstring tendons, and with high enough side and front walls, there develops no insurmountable problem in knee flexion-extension, either in walking or in sitting, and the amputee is thus free of all impedimenta otherwise characteristic of the articulated below-knee prosthesis. In a comparatively small percentage of cases, however, special anatomical and/or physiological circumstances invalidate the simple cuff suspension and the equally simple means of support and stabilization typical of the true PTB prosthesis. In such cases there is no alternative but to resort to the thigh corset and metal sidebars, and sometimes even to the ischial seat and the waist belt, despite the known advantages of the PTB socket. Since improvement of weight-bearing characteristics and inherent stability as offered by the patellar-tendon-bearing socket in no way alters the problem of the moving center of rotation of the normal knee, and since single-axis mechanical knee joints are for various reasons still found to be the most satisfactory under all conditions of use, introduction of the thigh corset and sidebars to improve stability, or to assume some of the weight, or both, presents the same problems as have prevailed heretofore. To date the most useful approach to this problem, when corset and sidebars are unavoidable, has been the development of an improved and simplified method of arriving at the best compromise location of single-axis joints with respect to the moving axis of the normal knee.

USE OF SIDE JOINTS AND THIGH CORSET

Theoretical Considerations

Single-axis side joints must be aligned on the shank and corset of the below-knee prosthesis so that they effectively stabilize the prosthesis on the stump and allow the amputee to sit comfortably. This is a complicated problem, first because the anatomic joint is not a single-axis joint and, second, because the exact path of a series of "instant centers," degree by degree, during knee motion is impractical to determine in each specific case. Even an average anatomic center may be estimated only roughly in the posterior portion of the femoral condyles. Thus at any one position of the single-axis mechanical joints, the center of rotation of the joints and the center of rotation of the knee will inevitably be incongruent during part or all of knee flexion and will give rise to some relative

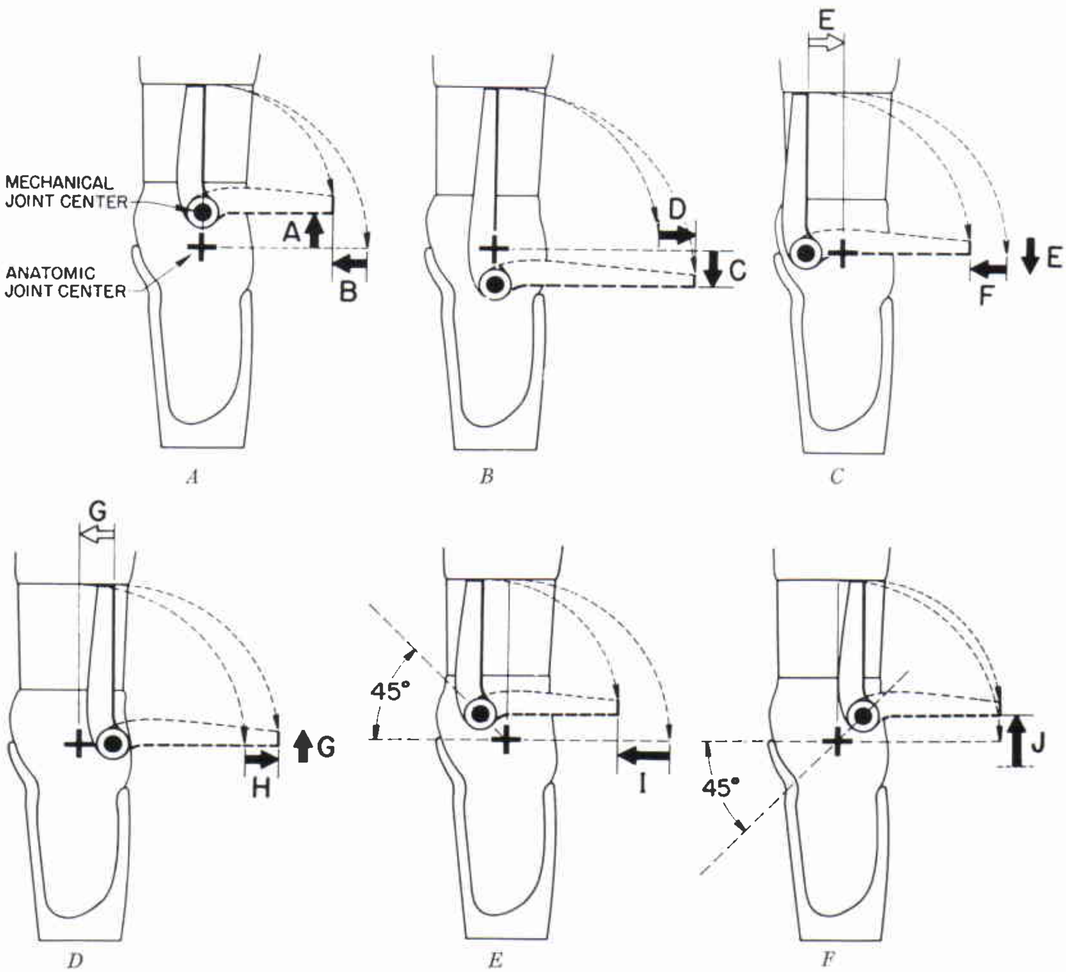


Fig. 56. Relative motion to be expected between thigh and thigh corset (stump fixed in socket) during 90 deg. of knee flexion when single-axis mechanical joints are placed in any of six positions relative to a hypothetical average anatomic joint center.

movement between the stump and the components of the prosthesis as the knee and side joints move from full extension to flexion at 90 deg. The task is to place the joints in a compromise position that will offer the best function and eliminate discomfort resulting from this relative motion. This may be done either by reducing the motion or by having the motion relieve pressures which would otherwise cause discomfort.

The effect of a particular position of the side joints with respect to the socket and corset can best be understood by investigating the effect of making a change from a position assumed to be the optimum one. Since movements result from a combination of several factors, total motion is a complex problem. In a hypothetical situation, it would be possible to have knee flexion occur either with the stump held tightly in the socket[5] and all motion occurring between thigh and corset or with the thigh fixed in the corset and motion occurring between stump and socket. Of these two extreme hypothetical situations, and the many possible variations in between, the one which will be considered is that in which the

[5] Particularly if the socket wall were rigid and lacking a soft lining.

stump is fixed in the socket and in which relative motion occurs between the thigh and upper side arms of the joints. This condition most nearly approximates the real situation and forms the basis for the joint-location procedure described below.

Figure 56*A* shows a hypothetical situation in which the socket is held fixed and the stump is not allowed to move relative to the socket. In the fully extended position, the upper sidebar is parallel to the shaft of the femur, and the mechanical joint center is placed directly above the average position of the anatomic center. The anatomic center, although it actually varies in position from high in the thigh during hyperextension to near the center of the femoral condyles at 90 deg. of flexion, is assumed to maintain a single axis of rotation for comparison with the mechanical center during this analysis. Alternatively, one may consider the effect of a tiny range of motion and study the slight motion of the thigh corset on the thigh caused by a mechanical joint center higher than the instant center of rotation during this tiny knee motion. As the thigh flexes, the mechanical sidebar tends to move relatively anteriorly on the thigh (for 90 deg. of flexion, distance *A*) and to be drawn distally along the thigh (distance *B*). As a result, pressure is created between the thigh corset and the posterior aspect of the thigh because the stump is fixed in the socket. The stump might be forced against the anterior part of the brim (the patellar-tendon area of the stump), though by assumption the stump cannot move in the socket. Thus the conical thigh corset moves distally away from the conical thigh, thereby releasing pressure by allowing a greater perimeter of corset for a given level and perimeter of thigh.

Figure 56*B* shows the effects of placing the mechanical joint below the average anatomic center (or instant center for a tiny motion). With flexion, the sidebar tends to move posteriorly on the thigh (for 90 deg., distance *C*) and to move proximally on the thigh (distance *D*). As a result, pressure is created anteriorly between corset and thigh, or else by reaction forces the socket is pressed upward against the stump. In this case, the conical corset is forced proximally, engaging the thigh more tightly and thus further increasing pressure on the thigh. Because such motion is sharply limited, the reaction on the sidebars in effect attempts to push the socket forward and thus increases pressure on the posterior popliteal area of the stump. Clearly this situation is unsatisfactory.

Figure 56*C* shows the effect of placing the mechanical joint in front of the average anatomic center. With flexion, the sidebar tends to be forced posteriorly (distance *E*) and distally (distance *F*) with respect to the thigh. As a result, pressure tends to be created anteriorly between corset and thigh, but the corset is withdrawn distally down the thigh so that its fit is loosened and hence the anterior pressure on the anterior portion is partially or wholly relieved.

Figure 56*D* shows the effect of placing the mechanical joint behind the average anatomic center. With flexion, the sidebar tends to be forced anteriorly (distance *G*) and proximally (distance *H*) with respect to the thigh. As a result, pressure is created posteriorly between corset and thigh, and the conical corset is forced proximally until it can go no farther, whereupon reaction forces the socket forward to cause pressure in the popliteal area.

Figure 56*E* shows an interesting special case in which the mechanical joint is located on a 45-deg. anterior diagonal through the anatomic center. In this case, the sidebar is drawn distally downward on the thigh (distance *I*), but there is no tendency for the sidebar to move either anteriorly or posteriorly with respect to the thigh. Thus there is no anterior or posterior pressure between corset and thigh. The distal motion would indicate that the corset might pull the stump anteriorly and cause pressure on the patellar tendon. In practice, the conical corset merely moves distally so as to relieve pressure on the thigh.

A similar analysis of the situation shown in Figure 56*F* would indicate that in this situation (posterior diagonal) posterior pressure between corset and thigh would be created by the substantial movement *J* (anterior movement of the sidebar). There would be no tendency for the stump to be pushed anteriorly or posteriorly against the socket brim or for the corset to move on the thigh.

Optimum Mechanical Relationship Between Joint Axis and Average Knee Axis

Relative movement in the mechanical joint position as compared with that in the anatomic joint position must first be understood. The prosthetist can then establish the best position for the joint axis by deciding what motions to suppress and what motions to allow. However, when the conical corset is attached to the upper side arms of the joints, proximal motion of the side arms will be suppressed so that reaction forces on the arms will cause commensurate forward movement of the socket against the stump and lead to pressure in the popliteal area. This factor must be borne in mind when the motions of the upper side arms of the mechanical joints are considered in establishing the best position. The hypothesis above of fixation of the stump in the socket may now be modified.

There are two situations in which the motions between the prosthesis and the stump are of particular significance: when the amputee sits (a major fraction of the waking hours of most amputees) and when the prosthesis is swinging through during walking.

Sitting. When the amputee sits, some motion between prosthesis and amputee will occur because of the inevitable incongruity. This being so, it is better to permit joint movement to draw the stump slightly out of the socket, and perhaps to move it forward so that roll formation and pinching between the corset and the back of the socket are reduced; yet forward motion should not press the rigid bony areas against the socket wall. In order to lift the stump, the mechanical joints must pull the corset up against the back of the thigh as the amputee sits. This will occur when the upper joint arms move anteriorly with respect to the thigh (as in Figures 56*A*, *D*, and *F*). To move the stump forward or avoid forcing the socket forward as the amputee sits, the upper joint arms should move distally with respect to the thigh (as in Figures 56*A*, *C*, and *E*). Thus, theoretically, a satisfactory position for the mechanical joints will be directly above the average anatomic joint axis, as in Figure 56*A*, if it is assumed that the amount of forward motion and upward motion should be approximately the same.

Swing Phase. For swing-phase control, and freedom from chafing, there should be little or no motion between the stump and the socket. Thus, the mechanical joint axis should be as close as practical to the instantaneous anatomic joint axis during the 60 or 65 deg. of knee motion in the swing phase. Because the instant center seems to move substantially during full extension, and especially during hyperextension, the alignment in slight initial flexion and the training of the amputee to maintain slight flexion at heel contact are considered to be important steps in reducing incongruities between axes and thus in reducing chafing.

If the prosthesis is to function satisfactorily both during sitting and during the swing phase, the mechanical axis should be above the average anatomic axis but not so far above as to introduce too much relative motion between stump and socket during walking.

All the foregoing analyses are based on consideration of the knee as if it could be averaged over 65 deg. of swing or 90 deg. between sitting and standing to behave as a single-axis joint. But, as is shown in the preceding article by Murphy and Wilson (page 4), the knee joint is actually made up of two complex bony surfaces—the femoral condyles and the tibial condyles. The femoral condyles are two convex surfaces separated by an anteroposterior groove, while the tibial condyles are two concave surfaces which fit their femoral counterparts. Further, these bony surfaces are separated by cartilages and fluids and are connected in complex ways by ligaments, so that analysis by x-rays alone may be inadequate.

The femoral condyles roll and slide on the tibial condyles as the knee joint moves. The amount of sliding and rolling determines the axis of rotation of the knee joint at any instant. A shift in the axis of rotation may sometimes help and sometimes oppose required function. If the path of the knee axis were exactly known, the best position for the single-axis knee joint could be positively stated, and joints fully satisfying the functional requirements could be designed. As noted above, such refinements for each individual case seem impractical. However,

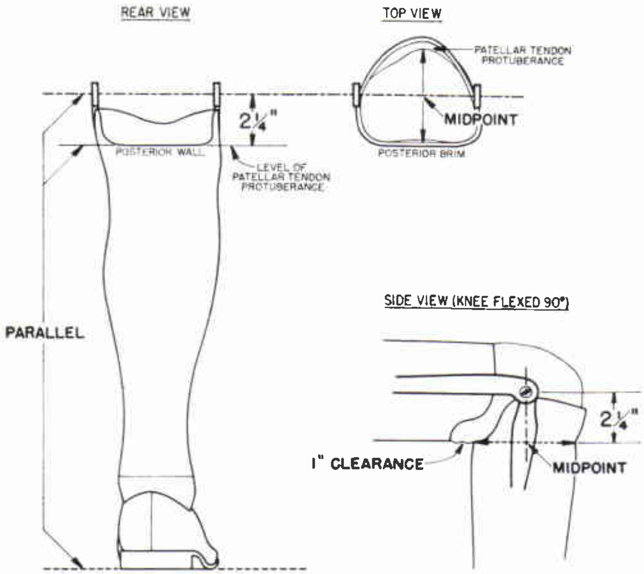


Fig. 57. Typical relationship between socket, joints, and thigh corset in a below-knee prosthesis.

experience has shown that the mechanical joints can be located accurately enough when use is made of the procedures proposed below, based on consideration of the knee as a single-axis joint at an average location.

A typical relationship between socket, joints, and thigh corset in the finished prosthesis is shown in Figure 57. The back brim of the socket will be trimmed to the patellar-tendon level. With the joints flexed 90 deg., the posterodistal edge of the thigh corset will be 1 in. behind the posterior brim of the socket and at the same level as or slightly above the posterior brim of the socket. The joints are approximately on a mediolateral axis parallel to the back wall of the socket, midway between the patellar-tendon protuberance and the posterior wall, and the axis is approximately 2-¼ in. above the level of the midpatellar tendon.

Side-Joint Locating Chart

Figure 58 is a chart based on the theoretical analysis given above. The chart can be used for correct positioning of the side joints on a below-knee prosthesis. It indicates the motion to be expected between the upper sidebar (the corset will be attached later) and the femur (Fig. 59).

Procedure:

1. After the socket is aligned on the adjustable leg and foot, the lateral lower sidebar is attached to the socket temporarily in the position indicated in Figure 57 so that the center of the joint is 2-¼ in. above the midpatellar-tendon level and midway between the patellar-tendon protuberance and the posterior wall of the socket. Only one attachment point is used, namely, at the bottom of the sidebar, the bar being secured above by wrapping masking tape around the socket. The single attachment point at the lower end of the sidebar allows the joints to be moved back and forth during trials and simplifies a change in position up or down. The upper bar is not shaped or attached to the corset at this time.

2. The amputee stands and extends the mechanical joint. The position of the front and top edges of the sidebar on the thigh is marked with a skin pencil.

3. The amputee sits on a hard chair with his knee flexed 90 deg., and a check is made to see that the posterior brim of the socket and its lining are properly trimmed and that the stump is well seated in the socket.

4. While the amputee is sitting in this position, the upper sidebar is moved until the front edge is parallel to the line on the thigh marked in Step 2. A second mark is made on the thigh along the front and top edges of the sidebar.

5. The relative motion as evidenced by the difference in position of the marks in Step 4 as compared with Step 2 is measured.

6. On the chart (Fig. 58) is entered, in accordance with the scales shown, the data obtained in Step 5. This information will indicate in true scale the approximate location of the mechanical joint center with

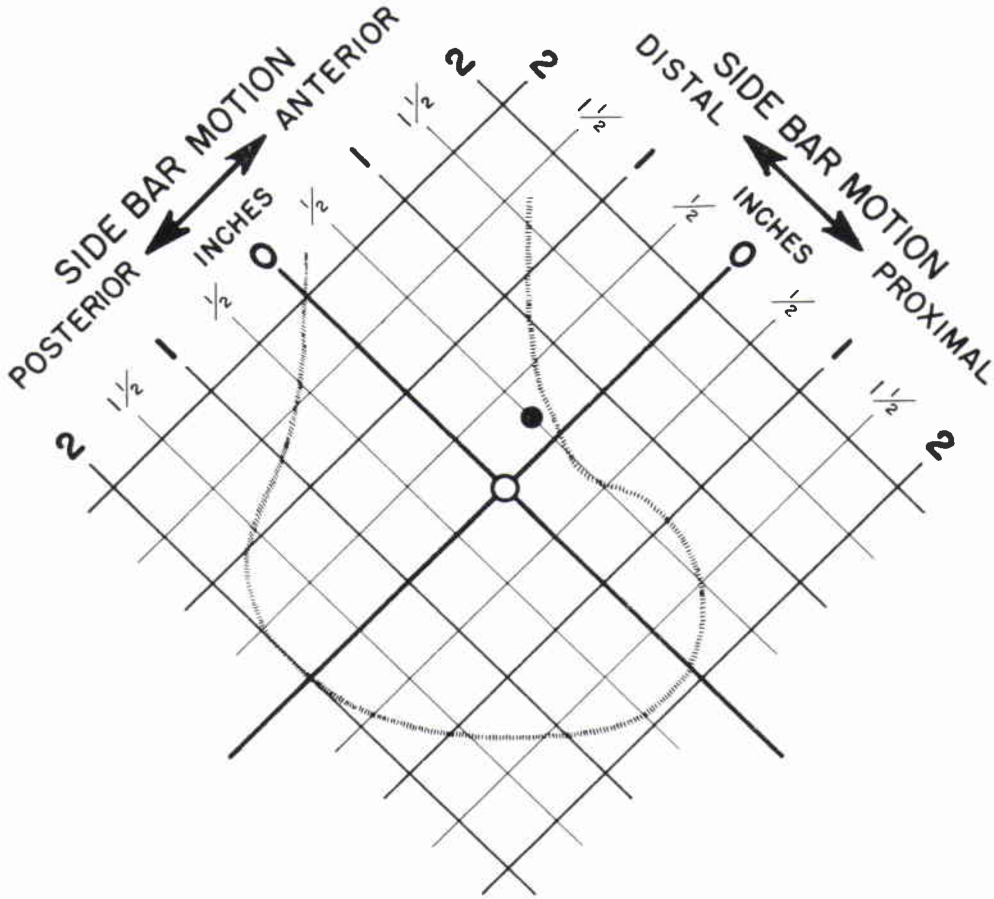


Fig. 58. Chart for determining location of joint axis of sidebars in below-knee prostheses. The motion referred to is that of the upper straps of the sidebars with respect to the thigh as the amputee sits from the standing position (Figs. 59 and 60). Outline of distal end of femur is considered to be mean actual size. The circle, ○, represents the average anatomic knee center; ● is the optimum position for the mechanical joints.

respect to the femur, as shown in typical true size by the dotted outline.

7. The direction in which to move the joint to improve its position is now estimated. The optimum compromise position is located a short distance above and slightly behind the average anatomic center. On the basis of experience with adult amputees, the upper sidebars of the mechanical joint should move distally on the thigh approximately ¼ in. with 90 deg. of knee flexion. A motion between ¼ and ½ in. is allowable. Motion greater than ½ in. results in the stump being forced forward excessively or the corset moving distally excessively after the sidebars are attached to the corset. The upper sidebars should move toward the front of the corset approximately ½ in. with 90 deg. of knee flexion. This motion is equivalent to a stump withdrawal with knee flexion after the sidebars are attached to the corset.

If the movements are not within the suggested limits, the joint is moved as indicated by the chart to bring them within these limits, and a recheck is made by the same procedures.

When the joint has been properly located, both sidebars are riveted to the socket so that a line connecting the centers of the medial and lateral joints would coincide with the axes of the joints themselves and would be parallel to the floor and to the posterior wall of the socket. The upper sidebars are shaped to fit the thigh with the joints coaxial. Particular attention should be paid to the shaping of the upper bars over the femoral condyles because a close fit here helps to suspend the prosthesis. At this point the corset is cut to shape and is temporarily attached to the upper sidebars of the joints with binding screws.

Example (Fig. 60):

1. Step 5 indicates a relative motion of 1 in. posteriorly and 1 in. distally along the thigh.
2. Enter data on chart as shown to locate point *A*. Point *A* represents the probable position of the mechanical joint relative to the femur.
3. The femur outline is actual size in Figure 58. Therefore the movement required to relocate the joint in the assumed optimum position *B* may be scaled directly from the drawing in Figure 58 (not in the reduced example, Figure 60). In this example, the joint axis shown is moved posteriorly a distance of 1-1/8 in. and proximally a distance of 3/8 in.

Fabrication of Thigh Corset and Joint Cover

Just as an encasement for any other part of the body must be made to conform to the shape of the part and must have enough elasticity and pliability to meet the requirements of necessary body activity, so the thigh corset of the below-knee prosthesis must be custom-cut to the particular size and shape of the thigh for which it is intended and it must be strong enough and yet flexible enough to meet the changing demands placed upon it. Because of its special combination of properties, leather has for many years been the material of choice in the construction of thigh corsets, almost to the exclusion of all other possible materials. Though from time to time in the history of prosthetics there have been introduced a good many variations intended to provide this or that beneficial feature, the basic construction of the modern-day thigh corset remains unchanged. It amounts to the custom fabrication of a comparatively long leather cuff, laced in the front, and furnished with the usual tongue to protect the thigh from local compression and constriction by the lacing. A common error is to make the corset too short, the amount of purchase on the thigh then being inadequate to provide the degree of stability required.

Fig. 59. Compromise location of upper sidebar straps in optimum position for comfortable walking as well as for comfortable sitting.

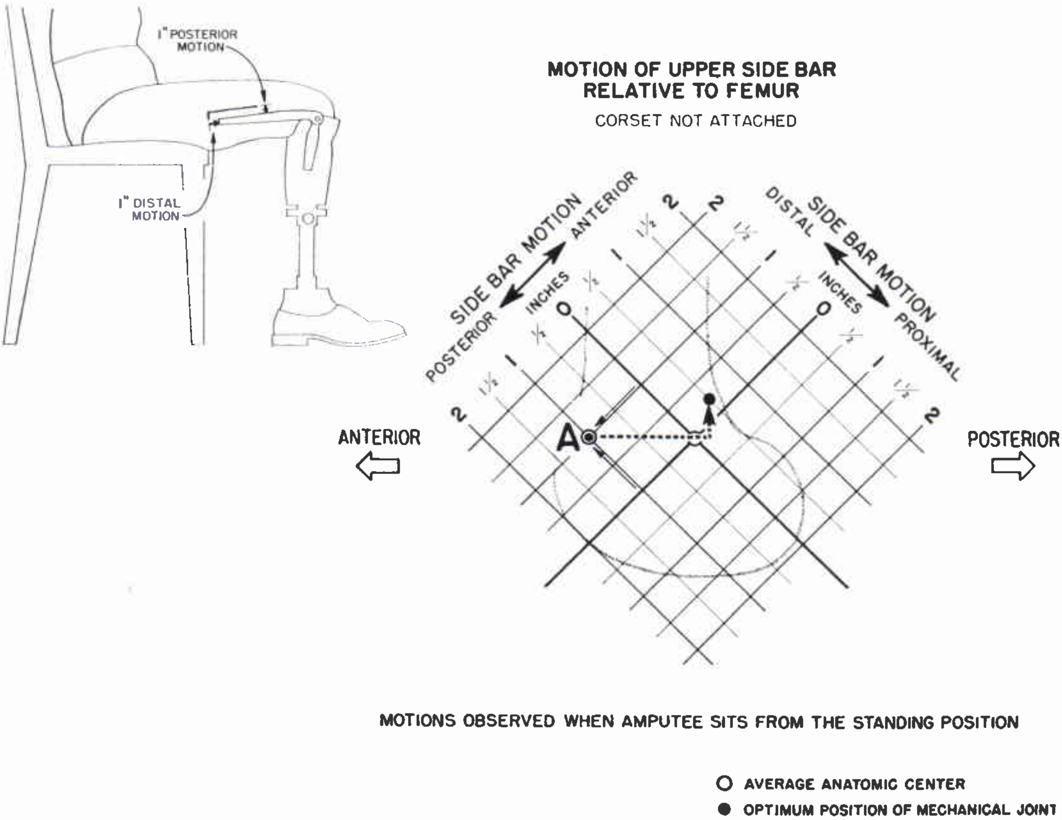


Fig. 60. Example of use of chart shown in Figure 58, chart reduced from actual size.

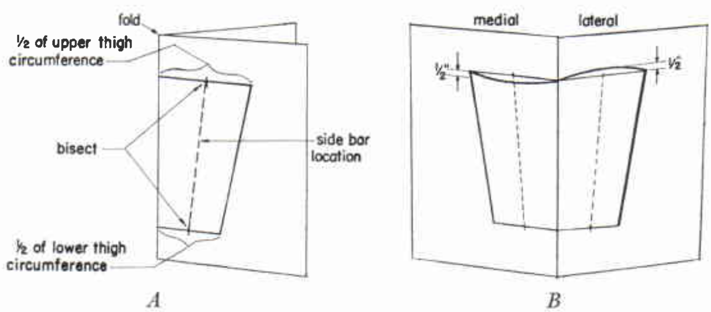


Fig. 61. Preparation of corset pattern. *A*, Paper folded in half, top and bottom margins of corset marked, lines parallel to edge projected to the extent of half the circumference of thigh at upper margin and half the circumference of thigh at lower margin respectively, ends of lines connected by straightedge, top and bottom circumferences joined by straightedge at points of bisection (broken line); *B*, paper opened at centerfold, reference lines transcribed to opposite side, proximal margin modified to match sine curve with maximum deviation of ½ in.

In the method of corset fabrication currently recommended for use when corset and sidebars are needed with the PTB prosthesis, the first step is to prepare, from appropriate measurements of the patient, a suitable paper pattern of the surface of the thigh in the area between the lesser trochanter and the condyles of the femur. While the optimum length of the corset varies somewhat with the height of the individual, in general it may be said that the pattern should extend upward some 8 in. from about 2 in. above the midpatellar level on the lower end. Accordingly, the circumference of the thigh is taken at these levels, and the corresponding measurements are carried forward to the pattern step by step.

A square of paper of suitable weight and texture (ordinary kraft wrapping paper, for example) and measuring 2 ft. on a side is first folded in half (Fig. 61*A*). Along the fold are marked with pencil the two points corresponding respectively to the top and bottom margins of the corset (distance between points corresponds to intended length of corset). From one mark there is extended, parallel to the edge of the paper, a line of length equal to half the selected circumference of the proximal portion of the thigh. From the other there is extended a similar line of length equal to half the selected circumference of the thigh in the distal area. With the ends of these two lines as reference, a third line is now drawn to join them, all as shown in Figure 61*A*, and a line (broken line in Figure 61*A*) is then drawn to connect the points of bisection of the proximal and distal circumference measurements, the latter line representing the ultimate location of the upper straps of the jointed sidebars.

The paper pattern is now opened at the fold to reveal the isosceles trapezoid shown in Figure 61*B*, and the proximal margin is cut roughly in the shape of a sine curve of ½ in. maximum deviation. Similarly, the distal margin is cut to the dimensions shown in Figure 62.

When the pattern has been completed, it is laid upon a selected piece of 7-oz. cowhide (or English bridle) in such a fashion that, when the leather has been cut out, it will fit upon the thigh (left or right as required) with the rough side in, with opening toward the front, and with the high side of the proximal margin lateral. By means of a straightedge, the locations of the upper straps of the sidebars are transferred to the leather for future reference in the construction of the corset, and the leather is cut out along the lines of the pattern.

The piece of cowhide, shaped as already described, is now applied to the thigh of the amputee smooth side out and held in place

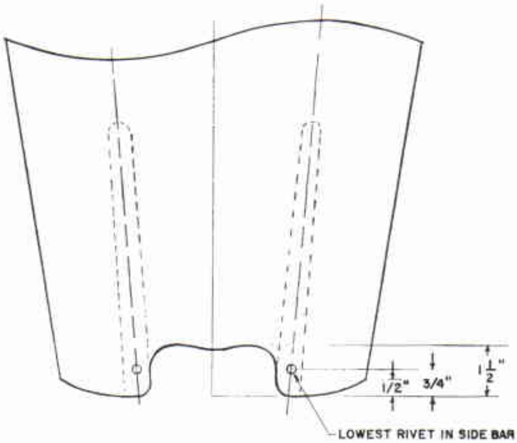


Fig. 62. Distal margin of corset pattern outlined to match requirements of popliteal space, location of upper straps of single-axis sidebars marked for future reference.

by pressure-sensitive tape or some other suitable means. The upper straps of the two sidebars are bent and shaped in such a way as to follow as closely as possible the external contours of the thigh (to assist in stabilization during the stance phase and in limb suspension during the swing phase), and the proximal ends are trimmed off as necessary so that the straps will extend to about ¾ in. below the top of the corset (thus providing maximum leverage while leaving room for finishing the top of the corset). Then, for purposes of later attachment of the upper straps of the sidebars to the corset, each upper strap is drilled with three holes ⅛ in. in diameter and so spaced along the length of each strap that the first is ½ in. from the proximal end, the second is about 2 in. above the center of the ball-bearing race on the distal end, and the third is half way between the other two (Fig. 63).

The two upper sidebar straps, thus drilled to accommodate screw-type fasteners, are now placed against the corset, one on each side and each along one of the two guide lines outside the centerline, and the positions of the two top holes are marked through to the leather. The straps are removed, ⅛-in. holes are punched through the leather at the points indicated, and the two upper straps are attached, each by means of its top hole only.

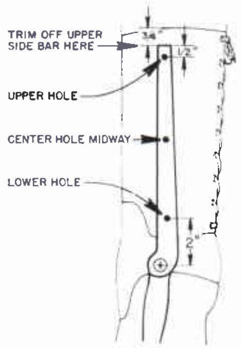


Fig. 63. Preparation of upper sidebar straps for later attachment to leather thigh corset.

To set temporarily, subject to later revision if necessary, the bottom (distal) attachment holes of the straps, the amputee stands, the prosthetist positions each strap directly over the corresponding guide lines, and the bottom hole of each strap is marked through to the leather with pencil (Fig. 64*A*). The amputee then sits with knee flexed 90 deg., the straps are once again positioned over the guide lines (Fig. 64*B*), and the bottom holes are again marked through to the leather (at the new position). The holes for the bottom attachments are now punched through the leather at the proper height but midway between the two points marked on each side (Fig. 64*C*). The process amounts to bisecting the angle between the positions of the bars in standing and their positions during sitting with knee flexed 90 deg. When the lower attachments have been completed, subject to final adjustment, the prosthetist proceeds with the remaining details of corset construction.

While the amputee stands upon the socket-shank-foot unit, the leather corset is wrapped about the thigh in the intended position, edges in front, and the edges are marked for trimming so that, thereafter, they will be 1-¼ in. apart (Fig. 65). The corset is removed from the patient, the edges trimmed as marked, and ¼-in. holes for the lacing are punched along each edge on 1-in. centers along lines ⅜ in. from the edges (Fig. 65). Now the amputee dons the corset and laces it up with a suitable length of nylon parachute cord singed at each end to prevent fraying. While he stands thus, any necessary adjustments are made in the trim lines at top and bottom, the intent being to have the front lower edge fit closely about the patella and just above it while in the back there is enough relief to avoid bunching of the flesh when the patient sits. Should the alignment of the sidebar straps prove to be faulty for any reason, re-

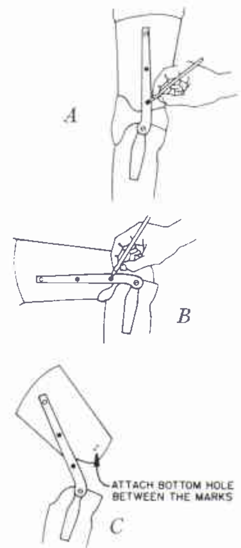


Fig. 64. Tentative attachment of upper sidebar straps to corset.

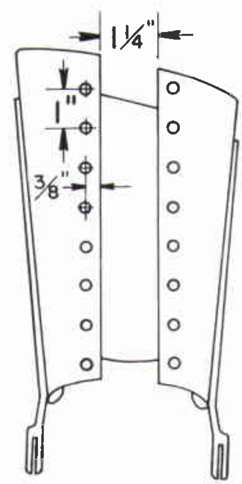


Fig. 65. Trimming of front edges of corset, placement of lacing holes in proper position.

alignment should be carried out before proceeding further.

When the fitting is thus far satisfactory, a tongue is provided out of the same kind of leather (cowhide) as was used for the corset itself, and the entire component is lined with cream horsehide of medium weight (4 to 6 oz.). To form the tongue, a piece of cowhide is cut long enough to extend from top to bottom of corset and wide enough to extend 1 in. beyond the rows of eyelets on either side (Fig. 66). One of the long edges is then skived so that, when that edge is later sewed to the body of the corset, there will be a smooth transition from corset to tongue such as not to cause any unnecessary irritation when the unit is worn. To line that portion of the corset between the fixed side of the tongue and the edge on that side (Fig. 67), a piece of medium-weight horsehide is cut 2-½ in. wide and long enough to extend from top to bottom of lacer. One of the long edges is skived, and the strip is then bonded (with rubber cement) to the inside surface of the corset, smooth side facing in and skived edge lying 2-¼ in. in from the edge (which leaves about ¼ in. of surplus horsehide for later trimming).

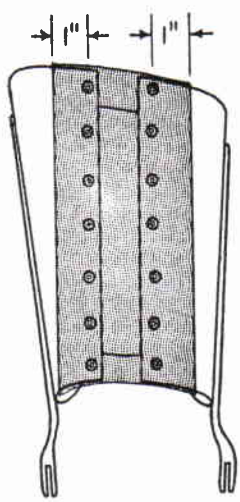


Fig. 66. Relative size and shape of corset tongue.

The tongue of cowhide is now placed smooth side out (toward the front of the corset) over the horsehide lining of the edge of the lacer and with skived edge about 2-¼ in. in from the edge of the corset. When a smooth transition has thus been attained by whatever local adjustment is necessary, both tongue and liner are sewed along the long side. The smooth side of the lacer and the corresponding smooth side of the tongue thus face each other to avoid any otherwise unnecessary bunching or wrinkling of tongue or corset.

The next step is to line with medium-weight horsehide the entire remaining internal surface of corset and tongue. To do so, the corset (together with the tongue) is laid out flat on the bench, rough side down. Thereupon is placed, rough side up, a piece of medium-weight horsehide large enough to cover the entire piece of work. Thus horsehide liner and corset-tongue combination are placed smooth side to smooth side. When the liner has been cut out to correspond roughly to the shape of the corset, the two pieces are sewed together across the top, the seam line starting where the tongue joins the corset and ending about 1 in. short of the opposite side. Thereafter the whole piece is inverted (Fig. 68) so that the horsehide falls over the cowhide corset and tongue to form a smooth liner, smooth side of horsehide in, smooth side of cowhide out. The entire facing surfaces are then bonded together with rubber cement, the edges are sewed around carefully, and any excess is trimmed close to the seams. On the side opposite the base of the tongue, a final seam is sewed down the edge of the corset just inside the row of eyelet holes, and the latter are then cut through the horsehide liner. Into the

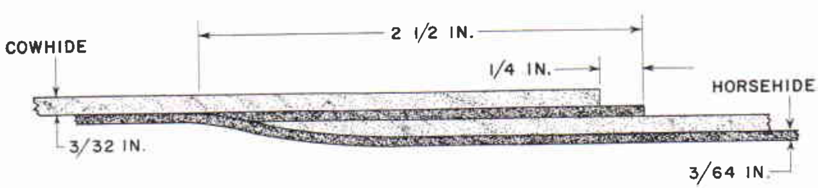


Fig. 67. Lining of corset tongue area on fixed side of tongue.

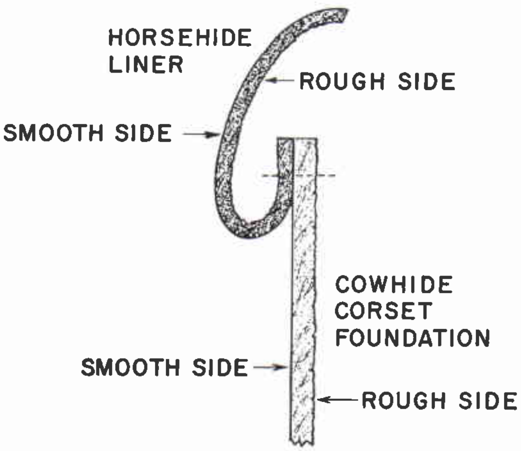


Fig. 68. Lining of entire internal surface of corset and tongue.

covers have been sewed to the corset on both sides, any excess is trimmed off, and a rivet is installed at about the point shown in Figure 70.

Finally, as protection against the effects of moisture and bacteria, all of the leather parts are coated with nylon solution according to the usual techniques (*2*, *3*).

AUXILIARY BELT SUSPENSION

In below-knee prosthetics, the conventional thigh corset (and sidebars) may serve any of three purposes to varying extents and in varying combinations. It may be needed to provide necessary additional stability not to be had from the below-knee socket alone. It may provide needed suspension over and above that furnished by the supracondylar

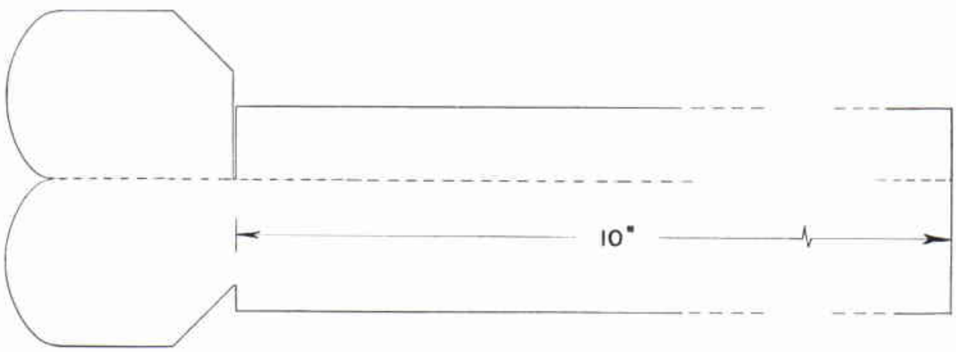


Fig. 69. Pattern for side-joint covers, half actual size.

punched holes are then installed the metal grommets for the lacing.

To protect the clothing from excessive wear, specially designed leather covers are commonly placed over the upper flanges of the sidebars and over the housings of the ball-bearing races. For this purpose use is made of cowhide one third the thickness of the leather used to make the basic part of the corset. By appropriate use of the pattern shown in Figure 69, one cover is made for each side of the corset, one medial and one lateral. When the sidebars have been riveted in place permanently through all three holes on each side (with ⅛-in. copper rivets), the covers are set in place, the distal portions being doubled back upon themselves and glued together with rubber cement. After the upper portions of the

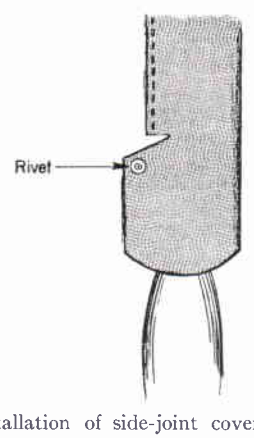


Fig. 70. Installation of side-joint covers for protection of clothing.

cuff. It may be needed to furnish additional weight-bearing over and above that provided by the PTB socket. Or it may be required for any of these purposes in one combination or another. Occasionally, additional suspension is needed for the PTB prosthesis with or without the thigh corset, and in such cases use is made of the pelvic belt in any of several forms. In all cases the belt fits about the iliac fossa on the normal side and extends downward on the side of the amputation to connect to the prosthesis itself. When, in addition to thigh corset and side joints, the pelvic belt is needed, it is attached to the prosthesis above the mechanical axes of the artificial knee joints. When the belt suspension is required on a limb without thigh corset or sidebars, it is attached to the limb either just below the brim of the socket or else to the supracondylar cuff, whichever is applicable. In general, the pelvic belt serves to reinforce the suspension provided by the supracondylar cuff, not the other way round. The supracondylar cuff is always tried first. Whenever it suffices, no pelvic belt is required.

To prepare the pelvic belt and associated suspensory attachments for the below-knee prosthesis, use is made of the patterns shown in Figure 71 and usually of one or the other of those shown in Figure 72. First there is cut from 2-in. cotton webbing a length 3 in. shorter than the waist measurement. It forms the belt component labeled "waistband" in Figure 73*A*. Next a 7-in. length of 2-in. elastic webbing is cut to form the tensile element of the vertical support (Fig. 74). Then there are cut from 6-oz. cowhide or pearled elk one piece according to pattern *A*

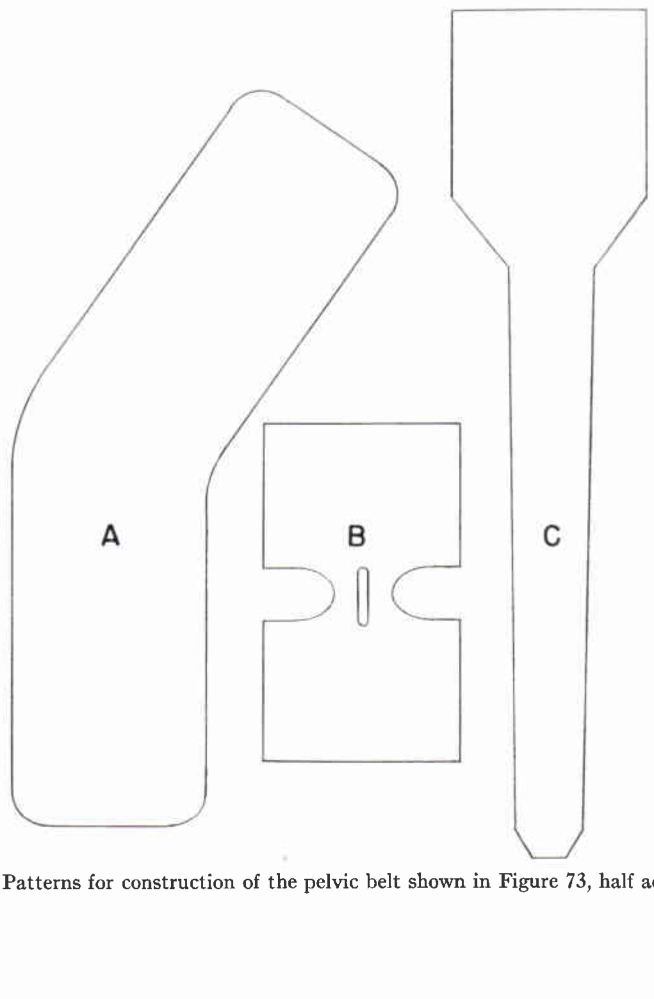


Fig. 71. Patterns for construction of the pelvic belt shown in Figure 73, half actual size.

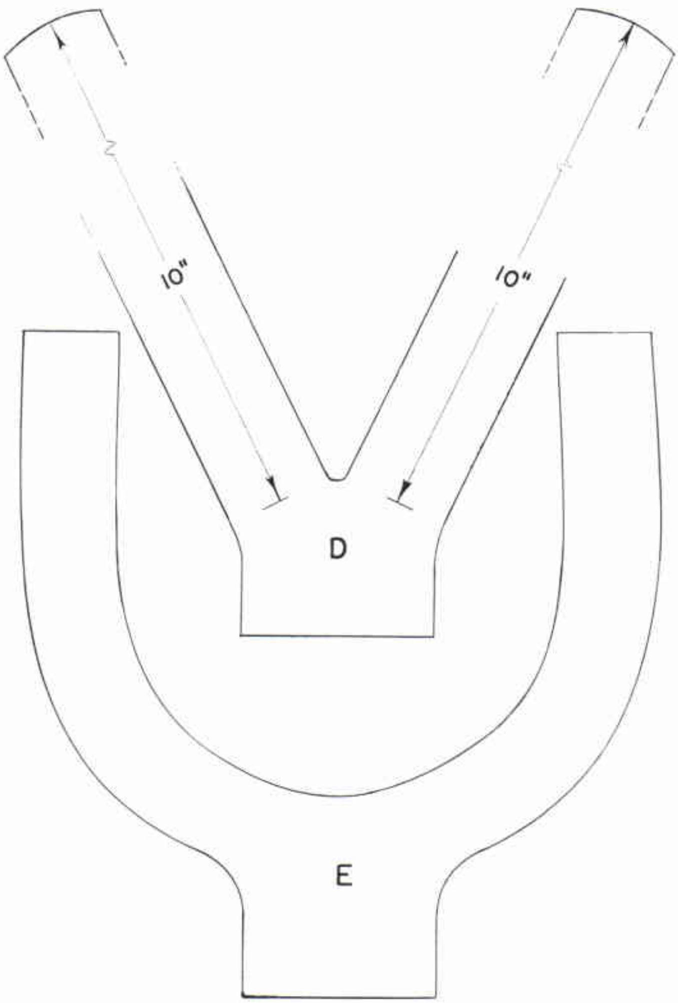


Fig. 72. Patterns (one half actual size) for suspension straps when (*D*) thigh corset and sidebars are used and (*E*) when thigh corset and sidebars are not used.

(Fig. 71), two pieces according to pattern *B* (Fig. 71), and two pieces according to pattern *C* (Fig. 71). These form respectively the boomerang-shaped portion of the waistband (section *A* in Fig. 73*A*), the buckle billets (⅝-in. buckles) to be installed on the belt (*B* in Fig. 73*B*) and at the proximal end of the elastic suspensor (*B* in Fig. 74), and the two elements labeled "sections *C*" in Figure 73*C*.

When, in addition to the thigh corset and sidebars, the pelvic belt is required, suspension is by virtue of the inverted Y-strap shown in Figure 74, the forked section being fashioned according to pattern *D* of Figure 72 and the ends of the fork being attached to the prosthesis above the mechanical axes of the artificial knee joints, as already pointed out (page 61). When pelvic suspension is required in the absence of thigh corset and sidebars, section *D* (Fig. 72) is replaced by section *E* (Fig. 72), or the elastic vertical suspensor (Figs. 74 and 75) may be attached directly to the anterior aspect of the supracondylar cuff (Fig. 75) without the necessity for sections *D* or *E* (Fig. 72). Details of fabrication technique for these several variations in auxiliary suspension are readily to be had from Figures 71 through 75.

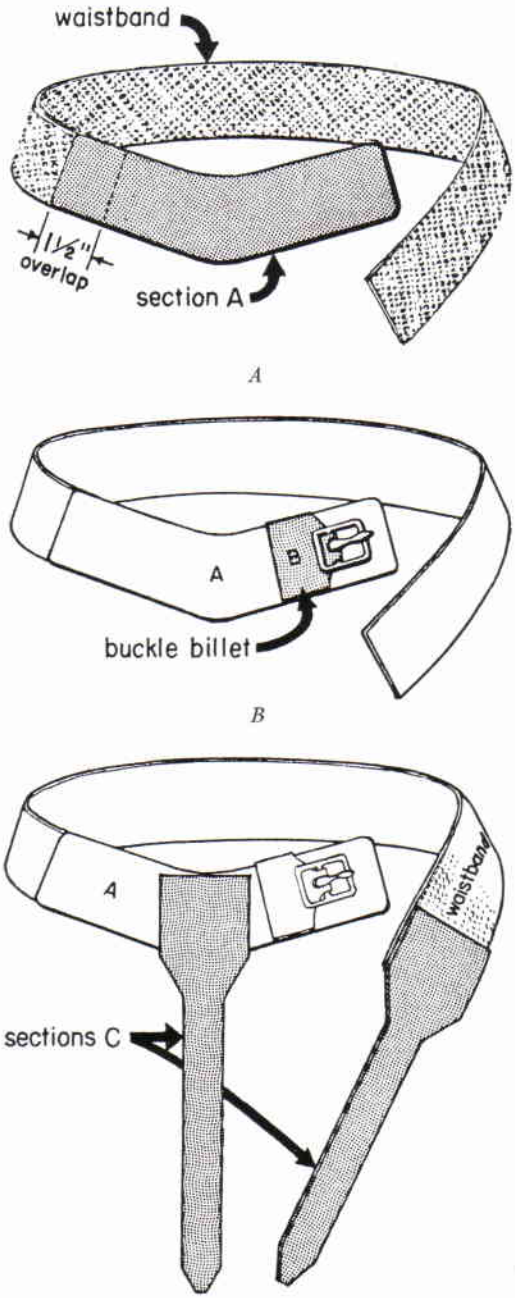


Fig. 73. Details of assembly of the pelvic belt.

As for details of actual construction, section *A* (Fig. 73) is first bonded to the waistband with rubber cement with an overlap of 1-½ in., the bonded side being on the side of the amputation (Fig. 73*C*). The skived ends of the leather sections *B* (Fig. 71) are lapped back on each other, each piece is threaded with a ⅝-in. buckle, and the billets so formed are applied, one to section *A* (Fig. 73) and one to the proximal end of the elastic vertical suspensor (Fig. 74). The billets (*B*) having been fixed in place with rubber cement, the forked section *D* (or the U-shaped section *E*) is cemented to the distal end of the elastic webbing, as shown in Figure 74, and the ends of the fork (or of the inverted U) are attached to the socket just below its brim on the medial and lateral sides. When belt suspension is intended simply to supplement the cuff-suspension system, less corset and sidebars, the vertical section shown in Figure 74 is attached directly to the anterior portion of the supracondylar cuff (Fig. 75). In every case all leather parts are backed with a lining of horsehide, and all segments are sewed around, excess horsehide being trimmed off close to the stitching.

Conclusion

In the construction or manufacture of any piece of apparatus or equipment, for whatever purpose, there may occur to the experienced craftsman any number of variations in technique to effect the same result—some in the interest of economy perhaps, some possibly with the intent of making the task easier, conceivably some with the idea of improving reliability in a stepwise procedure and hence of reducing the possibility for error, some perhaps for other reasons. Just so with the patellar-tendon-bearing, total-contact, below-knee socket. The particular method herein described for construction of the PTB socket, and of associated equipment for use in special cases, is not, therefore, the only possible method. It is simply the one which, in U. S. experience covering more than four years, has proved to be successful and the one most widely used. It is entirely possible that desirable changes in the recommended technique of construction, or with respect to the materials used, will be apparent at once to prosthetists and others. There is, indeed, nothing particularly sacred about the actual stepwise procedure described for fabrication, or about the

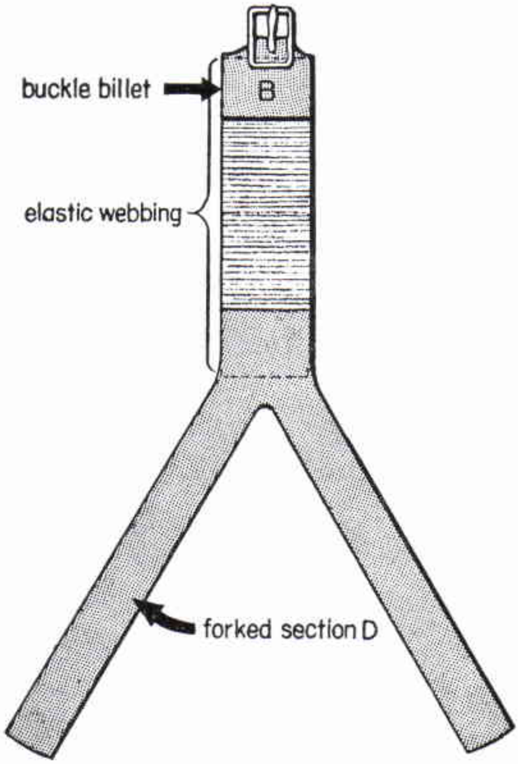


Fig. 74. Details of suspensor strap when pelvic belt is used in addition to thigh corset and sidebars. When thigh corset and sidebars are not required, section *D* (Fig. 72) is replaced by section *E* (Fig. 72).

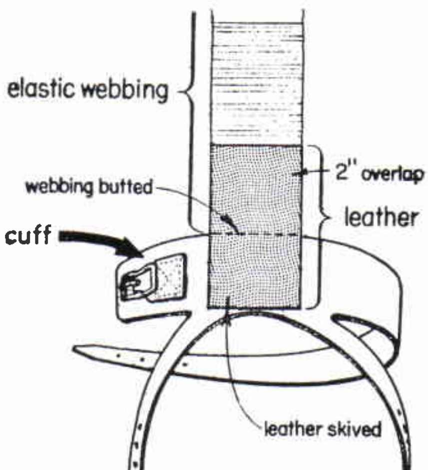


Fig. 75. Arrangement of suspensor strap when auxiliary support from pelvic belt is used in conjunction with the supracondylar cuff but without thigh corset and sidebars.

actual materials suggested, so that it is reasonable to expect changes here and there as the application of the PTB prosthesis comes more and more into widespread use.

Whatever changes in materials or fabrication technique may in the future be found to be useful, however, it is essential that the principles utilized in the PTB socket—in its design and in its application with respect to the wearer and to the rest of the prosthesis—be held inviolate if success is to be attained in the majority of cases. Features such as the ledge for weight-bearing on the patellar tendon, the high sidewalls for increased mediolateral stability in standing and walking, the relief for the hamstring tendons during knee flexion in sitting and in the swing phase of walking, the firm but gentle contact of stump with socket throughout its length as well as at the terminal end, the soft liner and end pad for shock absorption, and the subtle aspects of alignment in slight adduction and slight initial knee flexion are all based on systematic analysis of physical and anatomical fact and are therefore indispensable to the usefulness of the true patellar-tendon-bearing below-knee prosthesis. If, in the otherwise average below-knee case, any one of these details is lacking, difficulty in one form or another will ensue, in which case other and undesirable expedients have to be devised and the inherent advantages of the PTB prosthesis—freedom from the restrictions imposed by additional equipment—are at best seriously discounted and may in fact be lost entirely.

Although precision and meticulous workmanship are generally acknowledged to be essential requirements in the successful construction and fitting of any limb prosthesis, they are in the PTB limb especially in need of emphasis. Since the self-stabilizing, total-contact, patellar-tendon-bearing, below-knee socket is intended to be manageable by the wearer with little or no external assistance, all features of measurement, of fit, and of orientation are particularly critical, so that even a minor fault may result in gross deviation from proper performance. The eventual outcome of any PTB fitting is thus not only a matter of formal instructions but also of the

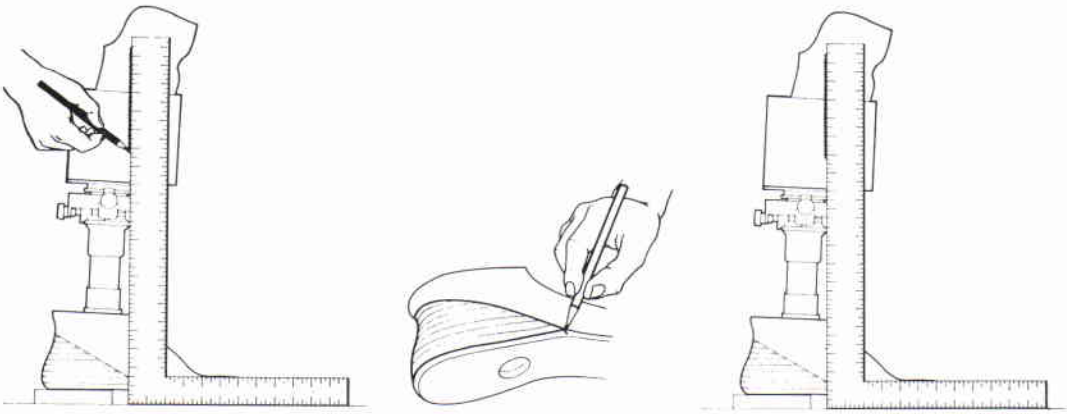


Fig. 1. Method of changing heel cushion in SACH foot whenever cushion is found to be too soft or too stiff. *A*, Recording existing alignment (to be preserved); *B*, marking about sole of heel to establish anterior point of heel wedge (also to be maintained); *C*, checking alignment after new cushion has been inserted.

exercise of sound judgment on the part of the clinic team in each and every individual case. General experience to date has indicated that the added investment in time and precaution almost always results in a satisfied and successful wearer. Failure to attend details almost always gives rise to failure and disappointment.

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APPENDIX A

Formulation of Polyester Laminating Resin
(For Each 100 Grams)

Into 100 gms. of polyester resin mix thoroughly 2 gms. of ATC catalyst. Then mix in color paste according to manufacturer's recommendation. Add 10 drops of Naugatuck Promoter No. 3. Mix thoroughly.

Resin thus prepared will gel in about 30 minutes.

APPENDIX B

Procedure for Changing Heel-Cushion Stiffness in SACH Foot

In the event the amputee, standing on the socket-shank-foot-shoe combination, demonstrates proper heel elevation (11/16 in.) but too hard or too soft a heel cushion during walking, the heel wedge must be replaced with another, either softer or harder as the case may be. The amputee first steps out of the socket, the shoe is removed from the foot, and the remaining unit is placed on a level bench with a block of wood 11/16 in. deep under the heel (Fig. 1*A*). By means of an ordinary carpenter's square, a vertical reference line is marked on one side of the socket block in the vicinity of the anteroposterior midline so that, after the wedge has been replaced, the prosthetist can be certain that the same orientation of the socket has been re-established.

The edge of the sole around the heel is now marked in such a way as to locate the anterior point of the existing heel cushion (Fig. 1*B*), the shank is clamped in a wood vise heel up, and the entire heel cushion is cut out with a sharp knife, the sole being peeled back first, the wedge itself later. Any irregularities in the cut surfaces are smoothed with a fine file, and the new wedge is inserted, longest lamination next to the sole, and to such an extent that the point falls as nearly as possible into the position previously occupied by the point of the old wedge.

Thereafter the whole unit is removed from the vise and placed upon the bench with the 11/16-in. heel block under the heel as before. Movement of the new wedge forward or backward, as required, re-establishes the original alignment, as indicated again by the square (Fig. 1*C*). When all is in order, the new wedge is cemented into place with Stabond T-161, and the heel is again shaped in the way previously recommended (page 39).

Some Experience with Patellar-Tendon-Bearing Below-Knee Prostheses[1]

FRANK A. WITTECK, B.M.E.[2]

In the latter part of 1958, prothetists of the Limb and Brace Section of the U. S. Veterans Administration Prosthetics Center, New York City, were indoctrinated in the technique of fabricating the patellar-tendon-bearing (PTB) cuff-suspension below-knee prosthesis. Preliminary experience encouraged VAPC to institute in the spring of 1959 a form of clinical study. Selection of the patients fitted with the PTB prosthesis was not rigorous, potential wearers being recruited from among veteran beneficiaries having an approved request for a new or a spare below-knee prosthesis. Availability for follow-up examinations was an important consideration, and many patients otherwise acceptable were excluded because, as it turned out, they were unable, for one reason or another, to make themselves available for the several necessary one-hour follow-up visits to the VAPC clinic. Several patients sent to VAPC from other VA Regional Offices were included in the study even though the distance from residence to fitting facility posed problems.

Although from the standpoint of fitting the study was concluded in November 1960, follow-ups continued through September 1961. During the 21-month period, 53 adult, male, below-knee amputees were selected for participation. With a few exceptions, all had been wearing conventional below-knee prostheses—carved wood socket, side joints, and leather thigh corset, or lacer. Two had only recently undergone amputation, and their initial fittings were with the PTB prosthesis. Fifteen cases out of the 53 were selected for discussion in some detail in this summary. They represent the types of adult male amputees seen in Veterans Administration clinics throughout the country. In addition to those amputees who present no problems and who are therefore fitted successfully with a minimum of difficulty, there are included those who had been wearing a prosthesis with a thigh corset that furnished either partial or full ischial weight-bearing, those whose previous prostheses had sockets of varying types (*i.e.*, soft, slip, suction, etc.), those who had worn a number of different types of prostheses over the years, and those who had worn the same prosthesis for 15 years. Included also are recent amputees who were to be fitted for the first time, as well as one typical bilateral below-knee amputee who benefited by use of PTB fitting concepts.

Fifteen Case Histories

CASE 5 (J. D.)

Case 5, a 43-year-old dock checker 5 ft. 11½ in. tall and weighing 178 lb., lost his left leg below the knee as a result of a mortar-shell explosion. Simultaneously, he lost some muscle power in his left hand. While the patient was hospitalized from March 1945 to March 1947, a revision was performed on the stump, and first fitting was with a prosthesis having a wood socket large enough for two stump socks to be worn. A long thigh corset had a strap-and-buckle arrangement to facilitate harnessing with the right hand. Succeeding prostheses were of the same type. Gait was fair.

When the patient was first seen at VAPC, his stump was 4 in. long and conical. There was evidence of chronic infection in the vicinity of the patellar tendon, the skin over the patella

[1] This study was conducted by the Veterans Administration Prosthetics Center Clinic under the direction of Herman Gladstone, M.D., Orthopedic Consultant, VAPC.

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and over the medial tibial condyle was tender, and there was some scarring over the head of the fibula. In February 1960, a PTB prosthesis with side joints and thigh corset was delivered, but the patient did not report for follow-up examination until the following August. At that time he returned the prosthesis and requested fitting with the conventional type. Although he had worn the prosthesis only occasionally on weekends for a few hours at a time, he complained of excessive piston action and irritation of the skin in the popliteal area and claimed that he could not take time off from his job for the necessary socket modifications.

The clinic recommended that a conventional type of below-knee prosthesis be fabricated for this patient because of his inability to cooperate through no fault of his own.

CASE 9 (A. E.)

Owing to complications of diabetes, Case 9, a 44-year-old postal worker and part-time stevedore weighing 190 lb. and standing 5 ft. 10 in., underwent a left below-knee amputation in 1944. The prostheses issued over the years were always of the conventional type with carved wood socket, side joints, and thigh corset.

When, in October 1959, the patient was first seen by the VAPC clinic, the 6-in. stump was in excellent condition, quadriceps and hamstring muscle groups were adequate. Gait was poor, and training was recommended. A PTB prosthesis was delivered in late October 1959, but the patient failed to report for any follow-up examinations until June 1960, whereupon it was discovered that the prosthesis had been worn during the first three months only. The patient claimed that during the following five-month period he had never been able to come in for socket modifications. Gait was still poor. A new PTB prosthesis was prescribed and finally delivered in October 1960, and the patient was cautioned to use it gradually until he could wear it for eight-hour periods without difficulty. When seen again in March 1961, the patient claimed that he could wear the prosthesis after work and on weekends with little or no difficulty but that he found the conventional prosthesis with sidebars and thigh corset better for the heavy labor in both his regular and his after-hours jobs. The clinic team felt that the use of the two different prostheses was a reasonable approach in this case.

It was recommended that this procedure be followed until the PTB prosthesis could be worn full time without difficulty. A follow-up made several months later showed that the patient was able to put aside the conventional prosthesis and wear the PTB type comfortably.

CASE 15 (D. H.)

Case 15, a 54-year-old information officer weighing 220 lb. and standing 6 ft. 3 in., had his right leg amputated in September 1944 as a result of wounds from shellfire. A final surgical revision was performed in December 1944 leaving a stump 7½ in. long. The prostheses worn had all been of the conventional type—carved wood socket, side joints, and thigh lacer.

The patient was fitted with a PTB prosthesis in November 1958 prior to the institution of the study. He received a second, or spare, prosthesis in the summer of 1959 and at that time accepted a job assignment in the Midwest. Thereafter his prosthetic needs were accommodated by a shop in his new location.

The patient is extremely active and does not spare his prosthesis. The SACH foot, for example, required replacement after several months of use. Because of wear, at least four socket inserts were made within a six-month period. Although the horsehide linings were worn through in the areas of weight-bearing, there was no stump discomfort. According to a letter report, both the SACH foot and the socket insert had to be replaced again because of wear. Despite these difficulties, the patient was extremely pleased with the PTB prosthesis and continued to use it.

CASE 17 (F. H.)

In June 1947, Case 17, a 42-year-old salesman weighing 185 lb. and standing 6 ft. 3½ in., had his right leg amputated below the knee owing to gunshot wounds. Because of pain in the stump, he later underwent surgery twice for removal of neuroma, and a sympathectomy also was performed. Referred to the VAPC clinic in March 1959 by another VA Regional Office, he complained of stump pain which could be relieved only by not wearing the prosthesis, a slip-socket type worn over three stump socks. Examination of the 6½-in. stump revealed a reddened scar in the popliteal area and discoloration and sensitivity in the vicinity of the fibular head such that slight tapping with the fingers produced shooting pains in the stump.

The initial prescription for this patient was a soft-socket prosthesis with a thigh corset designed for ischial weight-bearing. The prescription was filled in April 1959, but having worn the prosthesis only four hours the patient complained of pain and numbness in the stump. He felt that the thigh corset was cutting off circulation and "choking" the stump. Because the patient claimed that he could take weight-bearing on the stump, the thigh corset was loosened, whereupon he walked painlessly. Upon re-evaluation of the case, the prescription was modified to PTB fitting. But before the PTB prosthesis could be delivered the patient was hospitalized for pancreatitis, and delivery could not be made until June 1959. In the three months thereafter, several socket modifications were required—in the area of the tibial crest, about the medial tibial condyle, and in the region of the patellar tendon. Discharged from the hospital and back at work, the patient reported that he was comfortable and free of stump pain with the PTB prosthesis. But later, in February 1960, the patient was reported to have died, cause not given.

CASE 19 (W. H.)

Case 19, a 41-year-old VA prosthetics specialist weighing 190 lb. and standing 5 ft. 8 in. tall, suffered irreparable damage to both legs in March 1944 as a result of gunshot wounds. Amputation of both legs below the knee was necessitated. Revision of the stumps was carried out in July 1944.

This patient was able to tolerate almost full end-bearing on both stumps (3½ in.), and accordingly conventional prostheses were made with closed-end sockets to take advantage of the ability to carry weight on the stump ends. Some years later, when SACH feet were used on his prostheses, the patient complained of insecurity and a poor gait pattern. Hence, the feet and ankles used subsequently were of the conventional type.

A pair of PTB prostheses was provided in November 1959, the initial fittings being attempted without side joints and thigh corsets. But it was quickly determined that there was mediolateral instability and a tendency for the knee to hyperextend. Inasmuch as the patient obviously did not have to rely upon full thigh corsets for weight-bearing, whereas side joints were indicated, a combination of side joints with reverse thigh bands (Fig. 1) was tried. This arrangement was found to be effective both in providing mediolateral stability and in preventing hyperextension of the knee. When, on one of his infrequent visits to the Center, the patient returned to the shop for modification of the sockets, the distal ends of both were modified to permit insertion of additional pads for increased weight-bearing, the new inserts being prepared from a rubber of durometer higher than that used formerly.

The modified prostheses are now worn for periods of five to six hours per day, but major use is still made of the older prostheses. The "weaning process" is a slow one.

CASE 21 (J. M.)

Case 21, a 36-year-old, 140-lb. telephone coordinator 5 ft. 11 in. tall, suffered irreparable injuries to his right leg when he stepped on a landmine. Amputation of the leg below the knee was performed early in 1944. There was no further surgery. For eight years the patient had been wearing, with little or no difficulty, a conventional below-knee prosthesis with a modified thigh corset giving ischial weight-bearing.

The stump, 6-¾ in. long, was conical in shape. Pressure on a sensitive area over the posterodistal aspect of the stump just above the end radiated pain up the thigh, apparently along the course of the sciatic nerve. There was the usual atrophy of the thigh on the side of the amputation, but knee motion was good.

Upon delivery of a PTB prosthesis in August 1959, the patient's initial comments referred to a change in gait pattern—to the inability to take a full step as he could with his old prosthesis. During the first 90 days of use, several socket modifications were made, relief

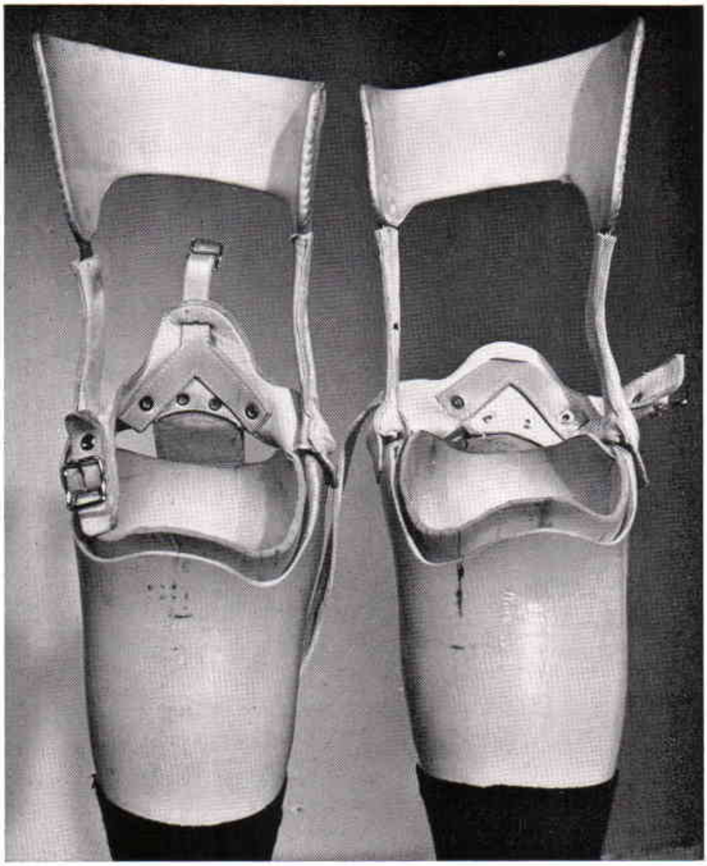

Fig. 1. Case 19. Posterior view of bilateral PTB prostheses with side joints and anterior thigh bands.

being given about the medial tibial condyle, the crest of the tibia, and the distal end of the stump. To accommodate stump shrinkage, the patellar-tendon area was built up to restore proper weight-bearing. A spare socket insert, to permit change of liner every day, was provided in an attempt to alleviate a perspiration problem.

The patient continued to wear his prosthesis without incident until June 1960, at which time a spare PTB prosthesis was prescribed. The major complaint after 30 days of wear of this limb had to do with excessive perspiration. The horsehide liner showed signs of cracking, and a vinyl plastic ("Doe-Lon") was substituted for the horsehide. Washing and drying this insert at the end of each day minimized the adverse effects of perspiration on the liner.

At last report the patient was still wearing his new prosthesis and had no wish to return to the older conventional one. He was pleased with the coincident weight reduction of the prosthesis—from 7½ to 4½ lb.

CASE 25 (S. M.)

Case 25, a 42-year-old retailer weighing 195 lb. and standing 6 ft., suffered irreparable damage to his right leg in October 1944 when he stepped on a landmine. Amputation below the knee followed. Numerous metallic foreign bodies remain in the left leg and in both hands.

The first prosthesis worn by this patient was of the conventional type—carved wood socket, side joints, and thigh corset. Subsequent prostheses had soft sockets instead of the carved-wood type. Patient was always fitted with, and wore, two wool stump socks, and he was a frequent visitor to the shop for socket modifications and limb repairs. The stump was in excellent condition, conical, and 6-¾ in. long.

In March 1960, when a PTB prosthesis was made, it was noted that, as usual, the patient wished to wear two stump socks. The patient was insistent that the socket be made accordingly. With the new PTB prosthesis, he was able to sit more comfortably because he could now flex his knee to 145 deg. as compared with 80 deg. with his old prosthesis. The PTB prosthesis also felt lighter than any of those previously worn.

In a follow-up examination three months later, the patient claimed that the fit was still good even though he had lost some weight. Some stump irritation was evidently due to excessive perspiration.

The patient was seen again in September 1960, at which time a new cuff suspension strap was provided and socket modification was required to relieve pressure in the anterodistal area. The perspiration problem was alleviated by a change during the day of one of the two stump socks he was wearing. The fresh, dry sock was worn next to the stump. There had been no stump breakdown since application of the PTB prosthesis, and at last report the patient was still wearing his appliance comfortably.

CASE 26 (W. O.)

Case 26, a 30-year-old claims adjuster and part-time professional golfer weighing 150 lb. and standing 6 ft., had his right leg amputated below the knee in November 1952 as the result of a landmine explosion. A surgical revision of the stump was done later the same year. The stump was cylindrical and 6½ in. long, skin type was classified as tough, there was minimum distal padding, the quadriceps muscle group was strong, and there was only slight atrophy of the thigh on the side of the amputation.

The first prosthesis had a soft socket fitted in a laminated fiber shank with side joints and thigh corset, the foot and ankle being of the Navy type (*i.e.*, with a two-durometer rubber ankle block). The second and third prostheses were similar except that the shanks were made of wood. The Navy ankle assisted in providing the pivoting action necessary in playing golf. Gait was excellent.

In April 1960, a PTB prosthesis with SACH foot was delivered to the patient, but he returned after a week and asked to have the SACH foot replaced with a Navy-type foot and ankle. The SACH foot, he claimed, did not give him the function he desired—primarily the pivoting action or rotation at the ankle. Replacement was made to the patient's satisfaction.

After the prosthesis had been worn five months, the socket was modified to provide additional relief for the medial hamstring area. Perspiration was not a problem. The patient was well satisfied and more comfortable. At last report the prosthesis had been in use for nine months with an average wearing time of 12 to 16 hours per day. A spare PTB prosthesis was fabricated.

CASE 27 (C. Q.)

Case 27, a 43-year-old sheetmetal worker weighing 175 lb. and standing 6 ft. 2 in., had his right leg amputated below the knee in June 1945. In November 1947, a right lumbar sympathectomy was performed in an attempt to relieve intractable pain. Several weeks later a revision of the stump was carried out. But the patient continued to complain of pain in the stump and was again admitted to the hospital in June 1948, when the sciatic and saphenous nerves were sectioned. Stump pain persisted, and in January 1956 further surgery was performed. The remnant of the fibula was removed; the distal portion of the right deep peroneal nerve was identified, resected out, and divided high; and the stump was injected with 50-percent alcohol. Final diagnosis on discharge in January 1956 was "abnormal amputation stump characterized by pain, right lower extremity below the knee."

From 1946 to 1957, the patient had received six conventional carved-wood-socket below-knee prostheses, six new carved-wood sockets, and two major repair jobs, including the addition of ischial-bearing thigh corsets. In February 1957, a soft-socket plastic-laminate below-knee prosthesis was prescribed and delivered by VAPC. Numerous complaints of pain and irritation made it necessary to deliver another prosthesis in October 1957. In September 1958, the patient was hospitalized for removal of a foreign-body granuloma from the right knee.

In January 1959, the patient was again hospitalized for possible revision of the 6½-in. stump to a Gritti-Stokes type of amputation, but it was decided that conservative management should be continued before institution of any further surgical procedures.

In February 1959, the patient reported to the VA Prosthetics Center for delivery of a PTB prosthesis. At the time, he was wearing a prosthesis with a slip socket and long thigh corset. The patient spent ten days at the Center to assure a satisfactory fitting and returned in March 1959 for socket modifications. Contrary to advice given him he had tried to walk with the prosthesis without using the cuff supension strap. The results were predictable: prosthesis slipped off, patient fell and damaged his stump. A modification of the socket corresponding to the area of the tibial tubercle was made, and a spare insert was fabricated.

In December 1959, the patient again reported to the Center with complaints of an ill-fitting prosthesis. Arrangements were made to fit and fabricate a new PTB prosthesis. As a stopgap measure, an insert using thicker rubber was provided, and the new prosthesis was delivered later in the month. When the patient was seen again after 30 days (mid-January 1960), he was experiencing pressure on the distal end of the stump. Suitable relief was provided by building up the socket in the patellar-tendon area. Because of excessive perspiration, a spare insert was furnished at this time.

The patient has not been seen at the Center since January 1960. Reports indicate that the litany of complaints is again being recited. Patient's stump seems to be in good condition and is as well fitted as possible, but the case remains a problem. The consensus is that past objective difficulties, perhaps complicated by emotional overtones, have resulted in an unusually strict standard for comfort.

CASE 42 (E. B.)

Because of a landmine explosion in 1945, Case 42, a 37-year-old accountant weighing 170 lb. and standing 5 ft. 10½ in., was subjected to amputation of the left leg below the knee. A revision performed later that year left deep folds and scars on the end of the stump. The right ankle had been fractured, and with increased activity it became swollen and painful.

The first, second, and third prostheses worn by this patient were of the conventional type—carved wood socket, side joints, and thigh corset. The fourth prosthesis substituted a "muley" type of suspension for the side joints and thigh lacer. The fifth and sixth prostheses were suction-socket prostheses (*1, 3*), a type worn by the patient for almost two years. The patient claimed to be comfortable in the suction socket but was concerned about the increasing edema at the stump end.

The 9-in. stump had an hourglass shape, and the distal end was edematous and discolored (Fig. 2). There was evidence of many old ulcerations on the distal end, and during weight-bearing the tissue overlapped the socket brim (Fig. 3).

A course of whirlpool therapy was instituted to reduce the edema as quickly as possible, and a PTB prosthesis with a functional ankle was prescribed and delivered in July 1960. When, after 30 days, the patient was seen again, the edema had been reduced and the skin color was lighter. Three months later, in November 1960, the patient again reported to the clinic. The prosthesis had been worn routinely since delivery, and the hourglass shape of the stump was not as prominent. Discoloration was still evident but greatly reduced. The patient claimed that perspiration had increased so that the liner had to be dried each evening. Accordingly, a spare insert was furnished.

CASE 44 (T. MCA.)

In February 1960, Case 44, a 38-year-old sheetmetal worker weighing 185 lb. and standing 5 ft. 10 in., had his right leg amputated below the knee because of chronic osteomyelitis. At the distal end the stump was slightly edematous, a condition not unexpected at eight weeks postamputation. The 7½-in. stump was slightly bulbous. There were no sensitive areas.

The prescription for the PTB prosthesis, this patient's first artificial limb, contained

Fig. 2. Case 42. Anterior (left) and posterior (right) views of stump showing discoloration and hourglass shape.

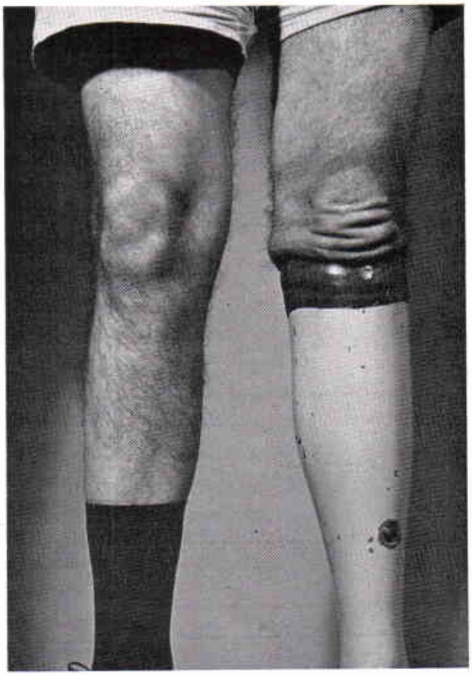

Fig. 3. Case 42 wearing suction-socket prosthesis. Note overlap of tissue above socket brim.

instructions that the socket was to be mounted on an adjustable pylon as a shank (Fig. 4). Because the amputation was so recent, considerable stump shrinkage was anticipated, and it was felt that the use of the adjustable pylon would facilitate socket replacement and the necessary alignment changes as anticipated. A PTB prosthesis was delivered in April 1960, the pylon shank being concealed by a plastic-laminate cosmetic cover. After 30 days of wear, the socket needed modification in the areas of the patellar tendon, the flare of the medial tibial condyle, and the crest of the tibia. Several alignment changes were required, and the patient complained of excessive perspiration of the stump.

The pylon-type prosthesis, with modified socket and alignment, was worn until June 1960, at which time a new "permanent type" PTB prosthesis was delivered. A spare socket insert was furnished to help alleviate the perspiration problem. The new limb, lighter by 1½ lb. than the pylon-shank prosthesis, added to the patient's satisfaction. Subsequent follow-ups revealed no new problems.

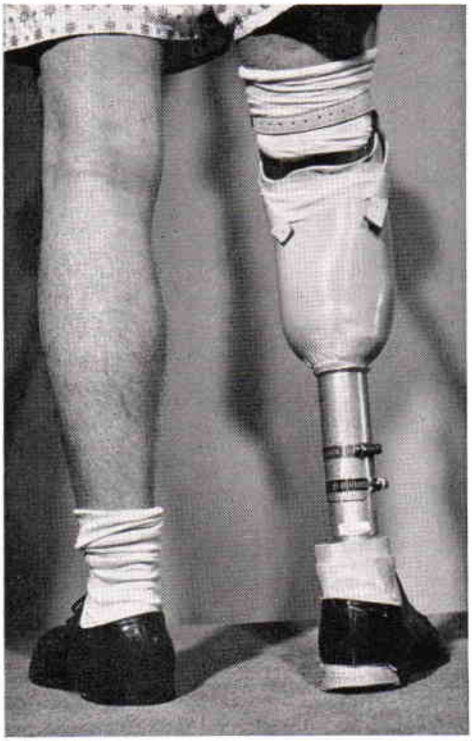

Fig. 4. Case 44. PTB socket mounted on an adjustable pylon.

CASE 46 (R. R.)

Case 46, a 58-year-old assistant director of athletics weighing 192 lb. and standing 5 ft. 10½ in., had his left leg amputated in 1945 as a result of severe leg wounds suffered in 1944. No further surgery was necessary. Prostheses had all been of the conventional type—carved wood socket, side joints, and thigh lacer.

The stump was 9 in. long and bulbous. A nonadherent, longitudinal scar, 7¾ in. long, extended up the back of the stump from the anterodistal aspect to the mid-posterior aspect. There was some sensitivity of the stump end to palm pressure. Skin type was classified as delicate.

A PTB prosthesis was delivered in June 1960, and the patient returned two months later for socket modifications. During this period, the patient had done some mountain climbing and stream fishing, activities which probably expedited stump shrinkage. The weight-bearing areas were restored by building up in the areas of the medial and lateral tibial condyles and of the patellar tendon. After another 30 days, the patient returned with the complaint that the posterior scar had been irritated and opened up. Playing baseball did little to help the situation. Whirlpool treatment expedited healing. The socket was relieved to prevent a recurrence of this irritation, and a spare socket insert was provided.

As of last report, the patient continues to wear the PTB prosthesis satisfactorily and without discomfort. He has requested a spare prosthesis of the same type.

CASE 47 (H. H.)

Case 47, a 44-year-old sales representative weighing 160 lb. and standing 5 ft. 10 in., had his right leg amputated below the knee in 1944 as the result of severe wounds. Two surgical revisions were performed in 1947. The stump was 6½ in. long, cylindrical in shape, and classified as redundant. Because of discomfort, all of his prostheses, though otherwise conventional, had been made with a modified ischial-weight-bearing thigh lacer.

A PTB prosthesis was delivered in August 1960. At follow-up examinations it was learned that no difficulty had been experienced as a result of going from one type of weight-bearing to a radically different type. The patient preferred the intimate fit, and he expressed the opinion that the prosthesis seemed more a part of him rather than an appendage.

CASE 49 (V. M.)

Case 49, a 43-year-old, 185-lb. VA contact representative 5 ft. 10 in. tall, suffered severe injuries to his left leg from a shell explosion. Amputation of the leg below the knee was performed in July 1944. Two surgical revisions were done in 1950.

This amputee had worn the conventional type of below-knee prosthesis with carved wood socket, side joints, and thigh lacer. When seen at the VAPC clinic early in 1960, he was wearing a Blevens-type prosthesis (*2*) that had been issued him in 1956. He was satisfied with the prosthesis, but it was badly in need of repair. The stump, cylindrical and 7¼ in. long, showed evidence of multiple skin ulcerations and numerous areas of infection.

A PTB prosthesis was prescribed and delivered in July 1960.

Follow-up examinations showed great improvement in the condition of the stump. The prosthesis was worn routinely for 14 to 16 hours a day.

CASE 51 (J. W.)

Case 51, a 43-year-old editor weighing 165 lb. and standing 5 ft. 11½ in. tall, lost his right leg below the knee as the result of a landmine explosion. Amputation was performed in October 1944, and a revision was effected early in 1945. The patient's stump was in excellent condition, conical, and 7½ in. long. Musculature was active.

The prosthesis that the patient was wearing was the first one issued to him, some 15 years earlier. It had a leather socket in a fiber shank, side joints, and thigh lacer (Fig. 5). A second prosthesis had been made in 1950, but it had never been worn because the original prosthesis had been so comfortable and generally satisfactory. As a result of the clinic team's examination and recommendation, the patient was willing to try the PTB prosthesis.

In July 1960 a PTB prosthesis was delivered. At a follow-up examination made after 30 days, the patient reported great satisfaction with the prosthesis. He wore it 14 to 16 hours a day and felt it was lighter, more comfortable, and "easier walking" than his old prosthesis. He also appreciated the freedom from sidebars and thigh corset. Subsequent follow-ups merely confirmed earlier impressions.

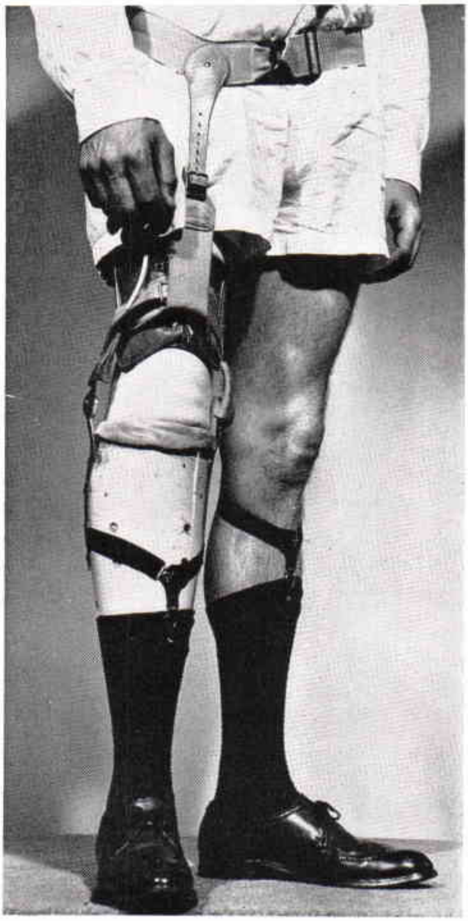

Fig. 5. Case 51 wearing 15-year-old conventional prosthesis.

Summary

Details covering these 15 cases, and also some information on the 38 others, are summarized in Table 1. Although the study was concluded in November 1960, wear-experience data were carried to September 1961. Experience has shown that as stump changes occur certain modifications are more prevalent than others. In 27 cases, modifications (build-ups) were required in the area of the patellar tendon and in the popliteal region. The necessity for this type of modification was evidenced by pressure at or on the distal end of the stump, and the discomfort could be alleviated by restoring the stump to its proper position in the socket by building up on the socket shell.

In 24 cases it was necessary to modify the socket in the area of the flare of the medial tibial condyle, a modification also of the build-up type. Since the medial flare has excellent weight-bearing ability, a good fit in this area is essential.

The medial hamstring area of the socket had to be relieved or lowered in 15 instances. In general, the socket brim was made lower for proper accommodation of the medial hamstring than for the lateral hamstring.

Seven cases experienced pressure on the crest of the tibia, a condition that was relieved by building up the socket shell on both sides of the tibial crest.

Table 1

SUMMARY OF 53 CASES FITTED IN VA PROSTHETICS CENTER WITH PATELLAR-TENDON-BEARING BELOW-KNEE PROSTHESES

Case No. and Initials	Age (yr.)	Wt. (lb.)	Hgt. (in.)	Stump Length (in.)	Occupation	Months Worn to Sept. 1961	Results as of Sept. 1961
1. H. B.	42	170	70	6	Plumber	4½	Developed dermatitis, refitted with "soft" socket, sidebars, and thigh lacer.
2. W. B.	55	162	65	8	Clerk	17	Uses spare insert because of perspiration.
3. G. C.	36	180	68	7	Clerk	15	Successful wearer.
4. V. D.	36	210	67	9	Printer	4	Taken off PTB (socket modifications done by untrained prosthetist resulted in stump damage).
5. J. D.	43	178	71½	4	Dock checker	5	Taken off PTB owing to inability of patient to co-operate.
6. B. D.	42	150	64	7½	Restaurateur	21	Added side joints and thigh lacer.
7. A. D.	37	180	69	6½	Technician	18	Satisfied wearer.
8. W. D.	43	214	71	7	Teacher	19	Uses spare insert because of perspiration.
9. A. E.	44	190	70	6	Postal worker, part-time stevedore	13	Alternates use of PTB and conventional prosthesis.
10. A. E.	49	160	68	4½	Retailer	33	Satisfied wearer.
11. I. F.	51	135	65	5½	Physician	17	Satisfied wearer.
12. R. F.	41	176	71	7½	Prosthetics specialist (VA)	18	Satisfied wearer.
13. E. G.	38	180	72	7½	Lawyer	21	Satisfied wearer.
14. J. G.	22	220	73	14	Student	2	Taken off PTB (lack of co-operation).
15. D. H.	54	220	75	7½	Information officer	22	See case study.
16. J. H.	49	165	68	6	Prosthetist	19	Satisfied wearer.
17. F. H.	42	185	75½	6½	Salesman	8	Patient died prior to February 1960.
18. J. H.	39	180	74	5½	Prosthetics specialist (VA)	13	Satisfied wearer.
19a. W. H. (Rt.)	41	190	68	3½	Prosthetics specialist (VA)	22	See case study.
19b. W. H. (Lt.)				3½		22	See case study.
20. W. L.	38	200	66	7	None	14	Satisfied wearer.
21. J. M.	36	140	71	6¾	Coordinator (telephone service)	25	See case study.
22. J. M.	36	180	66	8	Shipping clerk	3	Taken off PTB (lack of co-operation).
23. A. M.	52	178	71	5½	None	19	Satisfied wearer.
24. W. McD.	36	135	68	8	Accountant	18	Satisfied wearer.
25. S. M.	42	195	72	6¾	Retailer	19	See case study.
26. W. O.	30	150	72	6½	Claims adjuster, professional golfer	18	See case study.
27. C. Q.	43	175	74	6½	Sheetmetal worker	21	See case study.

Table 1—*Continued*

Case No. and Initials	Age (yr.)	Wt. (lb.)	Hgt. (in.)	Stump Length (in.)	Occupation	Months Worn to Sept. 1961	Results as of Sept. 1961
28. K. R.	41	228	73	6½	Manager (limb facility)	18	Furnished with spare unit.
29. B. R.	44	260	72	9½	Real-estate broker	3	Taken off PTB (lack of co-operation).
30. L. S.	39	175	68	7½	Burglar-alarm installer	26	Satisfied wearer.
31. A. S.	21	178	71	11	Student	27	Added side joints and thigh lacer.
32. L. S.	44	185	71	6	Supervisor	5	Satisfied wearer.
33a. D. S. (Rt.)	50	148	70	8½	Racehorse groom	18	Satisfied wearer.
33b. D. S. (Lt.)				8½		18	Satisfied wearer.
34a. W. T. (Rt.)	43	184	69	4	Prosthetics administrator (VA)	1	Could not be fitted satisfactorily (excessive scar tissue in popliteal region).
34b. W. T. (Lt).				6½		28	Given spare insert.
35. J. T.	48	190	71	7	None	26	Given new prosthesis and spare insert.
36. G. T.	45	180	68	6½	Foreman	13	Deceased.
37. M. T.	54	180	71½	6	Physician	22	Satisfied wearer.
38. A. T.	35	190	74	5	Prosthetist	19	Satisfied wearer.
39. D. T.	30	150	71	7	Draftsman	14	Had "choking" at stump end, relieved same, satisfied.
40. W. W.	48	150	73	4	Designer	20	Highly satisfied wearer, went skiing for first time since amputation.
41a. F. W. (Rt.)	44	150	69	3½	Engineer	12	Needed several new sockets.
41b. F. W. (Lt.)				6		26	Satisfied wearer.
42. E. B.	37	170	70½	9	Accountant	15	See case study.
43. V. B.	48	180	66	7	Technician	14	Satisfied wearer.
44. T. McA.	38	185	70	7½	Sheetmetal worker	14	See case study.
45. L. McC.	44	210	73	4	Prosthetics specialist (VA)	23	Satisfied wearer.
46. R. R.	58	192	70½	9	Athletic director	16	See case study.
47. H. H.	44	160	70	6½	Salesman	15	See case study.
48. C. K.	38	160	70	5	Real-estate salesman	15	Satisfied wearer.
49. V. M.	43	185	70	7¼	Contact representative (VA)	15	See case study.
50. J. F.	47	150	71	7	Clerk	16	"New" amputee, satisfied wearer.
51. J. W.	43	165	71½	7½	Editor	15	See case study.
52. J. Z.	46	215	71	7	Clerk	14	Satisfied wearer.
53. T. K.	39	175	70	7½	Inspector	12	Satisfied wearer.

In 14 cases, stump shrinkage after one to three months of wear made it necessary to fabricate new PTB sockets. These amputees all had either fleshy or bulbous stumps and in some cases both conditions prevailed.

Perspiration had been anticipated as a major problem with the PTB socket, but only 16 cases complained of excessive perspiration. For these cases spare inserts were provided. The facility with which inserts can be changed makes such a measure practical.

Conclusions

Experience in the fitting of PTB prostheses has led to some general prescription criteria. The amputee should have a sound, stable knee. Instability of the knee that cannot be corrected by physical therapy is a contraindication to the use of a PTB prosthesis without thigh lacer.

Caution should be exercised in prescribing a PTB prosthesis for heavy individuals. They often cannot tolerate, for long, full weight-bearing on the stump and will often require the additional support of a thigh lacer.

The amputee with a long stump (*i.e.*, with an amputation in the lower third of the leg) can, and does, present many problems. Often there are circulatory complications. Achievement of the required intimate fit is much more difficult. Proper fit and alignment can be arrived at initially but are difficult to maintain over long periods of time.

Similar comments can be made regarding sensitive stumps and those that are badly scarred. These should be treated with particular care.

The bilateral below-knee amputee presents another special situation. It is often feasible to limit the use of the PTB prosthesis to one side only. After a period of successful, problem-free wear, a fitting can be attempted on the other side. In general, one may say that prescription for bilateral fitting should be limited to young, slender amputees of average weight.

Another factor of prime importance is the skill and ability of the prosthetist. His talents must be brought into full play to achieve a good socket fit. Use of an adjustable alignment device is mandatory. The old cut-and-try methods have no place in the fitting and alignment of the PTB prosthesis.

Finally, the amputee should be oriented, or indoctrinated, by the clinic team even before fitting of a PTB prosthesis is attempted. In general, initial PTB fittings are much less troublesome to the patient than are initial fittings with a conventional carved below-knee socket. In the PTB case, therefore, the amputee may be lulled into an overly optimistic belief that the initial level of comfort will always continue. To avoid any disappointment on the part of the wearer, the clinic team should make clear the substantial possibility that stump changes and other factors may later necessitate socket modifications. Because, indeed, the usual indications for a change in socket fit are not as sharply defined in the PTB socket as they are in the conventional wood socket, it is essential that the clinic team plan for periodic follow-up examinations over a relatively long period until the stump reaches a comparatively stable condition. Similarly, the patient himself should be prepared to give adequate time for the examinations (and, if need be, for socket modifications), and he should be encouraged to be constantly on the alert for subtle but progressive changes that might signal impending difficulties. Persistence on the part of the team, together with investment of the amputee's time and interest, leads eventually to a significant return in the form of a comfortable, well-fitting, and functional prosthesis without the restrictions of sidebars and thigh corset.

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Below-Knee Amputation Surgery[1]

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THROUGHOUT the history of lower-extremity amputation surgery, the relative emphasis placed on various parts of the procedure has undergone many changes as new techniques have become available and as new goals have been appreciated. At present, the amount and direction of available knowledge demand the surgeon's concern with fundamental principles. Since some of these problems must be considered whatever level is chosen for amputation, they will be discussed before those that are peculiar to below-knee amputation.

As seen in the earliest reports on amputation, from the times of Hippocrates and Galen, this drastic measure was taken for the sole purpose of saving life but, as it usually turned out, it was instead a lethal procedure owing to shock and to loss of blood. Therefore, all emphasis was placed on the speed with which the operation could be completed. Patients who survived the operation frequently died of septicemia. After hemostasis, antisepsis and asepsis, and anesthesia all came into use in the mid-nineteenth century, however, speed became less important, less painful and extreme surgical procedures could be developed, and surgeons began to give more attention to conservation of tissues. Another change in emphasis was prompted by technical advances in articulated prostheses (first invented in the sixteenth century). Functional aspects of the stump then became the main consideration, and together with the prosthesis they came more and more to dictate the level and type of amputation.

This development is most fully illustrated by the popularity—which persists even now (*9*)—of the zur Verth scheme, or "site-of-election" concept. A "functional" means of determining the optimum amputation level, this arbitrary plan was obviously never intended for use in any and all situations, such as trauma, and certainly not under conditions of mass casualties, where conservation of tissue and open drainage are essential. But it has been used in such situations and has led to unnecessary loss of valuable segments of limbs. Dederich (*8*) points out that a military order of the German Army Medical Corps during the last part of World War II was necessary to prohibit use of zur Verth's scheme for primary and usually septic amputations, the order directing that tissue-sparing open amputations be used.

Since that time it has become increasingly clear that distinctions must be made in regard to the conditions under which the amputation is done and that the technique must be related to these distinctions. Under emergency conditions, the primary consideration of the surgeon is to treat for shock to save the life of the patient. His thought and his actions are directed toward preservation of the limb rather than toward amputation. Conservation of blood supply, restoration of nerve connections, and débridement of crushed tissue are his main concern. Large operative procedures should not be undertaken, because surgical shock cannot be added to the already existing shock. If amputation becomes a matter of life or death, the level is then not the choice of the surgeon. It is forced on him. He will try to preserve as much useful tissue as possible, but the general condition of the patient dictates the measures. It is because of these factors that even revised stumps are often not of a length that the limbfitter might consider ideal.

In a recent publication (*7*) of the Committee on Trauma of the American College of Sur-

[1] A contribution from the Biomechanics Laboratory, University of California, San Francisco and Berkeley, aided by National Institutes of Health Research Grant 4856.

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geons, it was stated:

> For the lower extremity, the desideratum is weight-bearing, and for this reason adequate soft tissue coverage over the end of the stump is more important than extra length. If it appears likely, however, that revision of the stump will be necessary, it is best to leave as much length as possible at the primary amputation.

Also emphasized was the point that the preferences of the limbmaker should not be considered in emergency amputations, but approval was given for reamputations "in accordance with accepted concepts concerning elective levels for a prosthesis."

The implications of this persistent concept need to be examined, particularly since the surgeon, in fashioning a stump, is often faced with difficulties that are not related to principles of prosthetics at all. His decision as to the level of amputation has to be based on the reaction of individual tissues. Thus present-day practice should not have as much influence as present knowledge of anatomic and physiological changes that occur as the result of amputation of an extremity or of any part of it.

Unfortunately, few publications evaluate these changes completely and relate them to the functional losses. The techniques they recommend often seem inadequate and, in many instances, contradictory. Even techniques valuable in themselves are given limited application, and advances in amputation procedures have come about very slowly. Over the past 75 years a number of surgeons have published new techniques, successful in their hands, which were not widely accepted because definite and fundamental biological principles were lacking. Also implicated in this situation is the frequently found—and understandable—attitude of the physician who has attempted to save an extremity with all the skill at his command and makes the decision to amputate only as a last resort and reluctantly, then performing the operation as expediently as possible.

For the patient, however, amputation initiates a new life with a whole set of new problems. In addition to the functional loss, psychological trauma is inevitable. Preamputation psychological preparation is, if time permits, always advised, but while it can do much to alleviate some of the problems it is not enough if persistent physiological disorders prevent the patient from using a prosthesis adequately. The goal of rehabilitation, which may in this way begin before amputation, is return of the amputee to as near a normal life as possible, and this calls for coordinated efforts by various workers—efforts that should begin with the surgeon's understanding of the many biological and biomechanical principles involved.

It was postulated at the Biomechanics Laboratory, University of California, that these principles could be derived from a cooperative, interdisciplinary approach to the various aspects of lower-extremity amputation and then applied back to specific procedures and treatments (*13*). It is from this point of view that the following sections review the known principles and how they have been and can be brought to bear in surgical practice in regard to pain, bone, muscles and fascia, and skin. First to be described are the special problems of below-knee amputation and how other workers have sought to solve them.

Special Problems in Below-Knee Amputation

It has long been accepted, but for varying reasons over the years, that the middle third of the leg is the best site for a below-knee amputation. This gives a stump of 5½ to 7 in. below the knee joint. Current opinion (*1,2,11,19*) is based mainly on reasons of circulation, which is often reported to cause problems when amputation is done in the lower third where the circulation is relatively poor, and on prosthetics practice, which is conventionally most able to make use of a bone lever at least 2 in. long. It must be remembered, however, that satisfactory results can be achieved with both longer and shorter stumps. As Watermann (*21*) has indicated, very short below-knee stumps are preferable to reamputation at an above-knee level, providing that the insertion of the patellar ligament is retained or re-established, and long below-knee stumps may be kept if soft-tissue and circulatory conditions are adequate.

Peculiar to below-knee amputation is the presence of two bones. The tibial crest, lying close to the surface of the skin, is always beveled slightly. But the fibula, normally a non-weight-bearing bone, has received various treatments. Its complete excision is frequently recommended (*1,11,14,21*), at least in very short stumps, first because of its tendency to lateral deviation and rotation caused by pull of the tendon of the biceps and, secondly, because of the protuberance of the head, which is subjected to pressure by the prosthetic socket. For stumps of average length, the advice usually is to section the fibula 1 to 1½ in. above the end of the tibia in order to facilitate fit in the socket (*1,14,19*). This treatment does not, however, take account of certain surgical provisions, which are discussed more fully in the next section.

Treatment of Tissues

The whole problem of pain in the amputee, both in the stump and in the phantom, is known to be extremely complex. It is clear that removal of so large a mass of tissue must cause a gross disturbance in the balanced input of peripheral sensory nerve impulses. For one thing, a neuroma forms at the cut end of nerves. Its regenerating nerve fibers intertwine, and it may be considered a grossly abnormal "receptor organ" (*17*) which is painful on mechanical stimulation. The mobilization of skin in forming flaps is inevitably accompanied by partial denervation and often by regeneration that is faulty and incomplete. Transection of muscles naturally deprives them of their insertions so that they then lack normal antagonistic action, and impulses from the muscle spindles and Golgi organs in the tendons are altered or absent. Other scars and inflammatory lesions of the soft tissues and bone may contribute to the generation of impulses that are interpreted as pain. Furthermore, it is known that painful stimuli elsewhere in the body tend to produce pain in the stump or phantom.

In the knowledge of these unavoidable, devastating changes, the surgeon has the obligation to try to prevent any tissue destruction that is unnecessary or that can be circumvented in any way. He must try to fashion a stump that will function in as nearly "normal" a way as possible. This will eliminate at least some kinds of pain and help to normalize sensory return.

BONE

Bone is a living tissue composed of ossein (a protein) intimately combined with inorganic substances, chief among which is calcium phosphate. The inorganic substances give hardness and rigidity to the bone, while the ossein determines its toughness. Bone function is affected by alterations in nutrition and in the metabolism of both organic and inorganic substances, as well as in conditions of loading.

Of the various functions of normal bone, the principal one with which we are here concerned is to transmit load. The long bones of the thigh and leg transmit loads that, at moments, amount to many hundreds of kilograms. These forces, together with muscle forces, determine the final detailed form and internal structure of the bone (*18*). When the bone is severed and no longer bears weight in its long axis, changes in the mineral metabolism occur rapidly, and osteoporosis, which can be a cause of exquisite tenderness and spontaneous pain, sets in. Severing the diaphysis of a long bone leaves an open-end medullary cavity, thus altering normal conditions of pressure and circulation within the bone. In addition, joints proximal to the amputation show such degenerative changes as sclerosis and narrowing of the joint spaces. These changes are the usual lot of most lower-extremity amputees today. If, however, direct loading along the long axis of the bones can be provided after amputation, many of these undesirable changes can be prevented. In this case, the socket of the prosthesis transfers the floor reaction to the skeletal system via the distal end of the stump. This theoretically desirable goal is, however, not easy to attain, which explains why it is not even attempted by most surgeons or planned for by most prosthetists. The great majority of amputees cannot stand pressure on the distal end of the stump for any length of time, even when the tissues are confined in a cuplike socket end to provide hydrostatic cushioning by the soft tissues. Deep palpation of the tissues over the transected end of the bone usually causes pain in the hypersensitive bone.

Many methods have been proposed for making the distal end of the stump less sensitive and more capable of bearing weight. In 1893 Bier (*3*) described the pain felt over the cut end of the bone and ascribed it to the "Knochennarbe," or bone scar. He recommended an osteoplastic procedure in which the cut end of the bone was covered with a flap of cortical bone attached by a periosteal hinge. This method was later largely abandoned, perhaps because of difficulties similar to those we often encountered when we attempted to use it: sometimes bony union did not take place; some plates became sclerotic, others required an excessively long healing time.

The next attempt to desensitize the end of the bone was that of Bunge (*5*), who attempted to achieve an "ebonized" end by stripping the periosteum to a few millimeters from the distal end of the bone and scraping out the endosteum to the same level. This technique became much more popular and is still recommended by some textbooks (*11,19,20*). Since, however, this procedure destroys the periosteal and endosteal blood supply to the end of the bone, it usually results in a ring sequestrum that may cause foreign-body reactions and that may even be eliminated by the body. Even without this drastic procedure, avascular necrosis develops at the end of the transected bone, and this greatly inferior bone tissue is a constant source of irritation and pain.

How might this zone of avascular necrosis be eliminated? Even if Bier's osteoplastic procedure (*3*) was not entirely satisfactory, it still seemed logical to cover the cut end of the bone with osteogenic material. Ertl (*10*) developed a special adaptation—the pliable osteoperiosteal flap for below-knee amputees. As he described this procedure, three periosteal flaps, with small flakes of cortical bone attached to them, are cut, two from the tibia and one from the fibula. The three flaps are fashioned into a tube, which is attached to the two bones in such a way as to bridge them and cover both distal surfaces (Fig. 1). The method has several advantages: (*a*) elimination of the exposed cut surfaces of the bones and thus of the possibility of avascular necrosis; (*b*) provision of an insensitive surface capable of partial end-bearing; (*c*) prevention of lateral deviation and rotation of the residual fibula; (*d*) occlusion of the medullary cavities of both tibia and fibula, thus restoring normal intramedullary pressure and normal deep venous return; and (*e*) provision of a protective wall for the cut ends of nerves and vessels in the interosseous space. For this procedure, the fibula should be sectioned at the same level as the tibia, and the anterior tibial crest should be beveled in the usual manner.

MUSCLE

The principal function of normal skeletal muscle is to provide motion, stabilization, or restriction of bony structures. In the conventional amputation, the muscles are severed, usually through the muscle bellies, and are thus deprived of their distal attachments and consequently of the length-tension relationships under which they normally act to best advantage. In the typical conventionally amputated stump, the muscle tissue atrophies rapidly; circulation becomes poorer, especially since venous return is no longer aided by the muscle pump, so that stasis and edema may result. Mondry (*16*) developed a satisfactory method of dealing with this problem. The flexors, tapered if necessary, and the extensors, including the musculature of the fibula, are sutured together over the osteoperiosteal bridge and to the periosteum of the tibia (Fig. 2). Thus the muscles have new attachments and are able to become more functional. The stump is stronger and, with improved circulation, much healthier. When a total-contact prosthesis is used, the well-developed muscles are able to hold the prosthesis on by their contraction alone.

BLOOD VESSELS AND NERVES

Blood vessels should be dissected out carefully, with the veins separated from the arteries, ligated, and cut at different levels. The main nerve trunks are cut high under moderate traction. Trunks of both nerves and blood vessels are buried in the interosseous space proximal to the osteoperiosteal bridge.

Such techniques for the treatment of nerves as alcohol injection, cauterization of the cut end of the nerve, and suturing of the sheath over the cut end have not seemed to influence the formation of neuromas or the presence of phantom sensation or pain, as has been claimed for them, but not enough evidence has been obtained to allow any conclusions. Further study must also be undertaken before state-

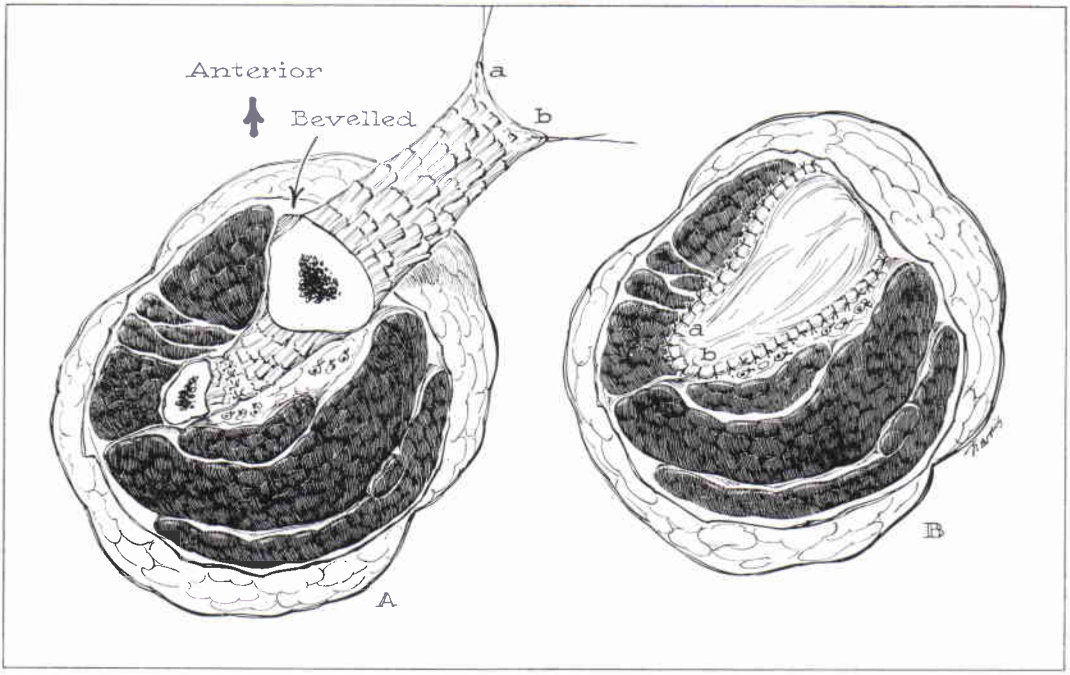

Fig. 1. Ertl's osteoplastic procedure. Before the bones are sectioned, two small periosteal flaps, the fibular one being the shorter, with flakes of cortical bone attached, are chiseled from the opposing surfaces of the tibia and fibula and sutured together, and a third flap, similar but larger, is cut from the anteromedial surface of the tibia (*A*). The anterior crest of the tibia is beveled, as in other amputation procedures, but the two bones are sectioned at the same level after the flaps have been cut free. *B*, The third flap (points labeled *a* and *b* are holding sutures) is brought across the two bones to cover their distal surfaces and is sutured to the other flaps and to the periosteum of the bones, forming a tubelike connection, or bridge, between the two bones.

ments can be made about Lenggenhager's technique (*12*), in which three progressively weaker compression points are applied at successive distances of about 1 cm. from the transected area of the nerve for elimination of phantom pain. In another method of altering conditions with which pain occurs, as studied by Boldrey (*4*), the nerve end is removed from mechanical irritation by being implanted and thus protectively enclosed in the medullary cavity of the residual bone. The neuroma that might then develop is also said to be reduced in size, but, again, results have not been conclusive.

FASCIA

The fascia should be kept in place as much as possible during the amputation procedure, and any part that has been separated from the underlying muscle should be entirely removed since otherwise this mobilized fascia reattaches itself to the musculature in the form of a hard fibrous cover that forms a barrier to the penetration of the blood vessels serving the skin. It may even become necrotic and be extruded shortly after operation.

SKIN

One reason for skin breakdown is poor circulation in the stump, with resulting stasis, edema, and anoxia. Attempting to provide, at the time of surgery, for as good circulatory conditions as possible is, therefore, requisite to the subsequent health of the skin (*13*). Impairment of the blood vessels and nerves serving the skin cannot be avoided in amputation, but it can be minimized by the following procedures: (*a*) placement of the skin flaps directly over well-functioning muscles; (*b*) moderate reduction of subcutaneous fat; and (*c*) careful suturing of the skin, with avoidance of excessive tension on the flaps and place-

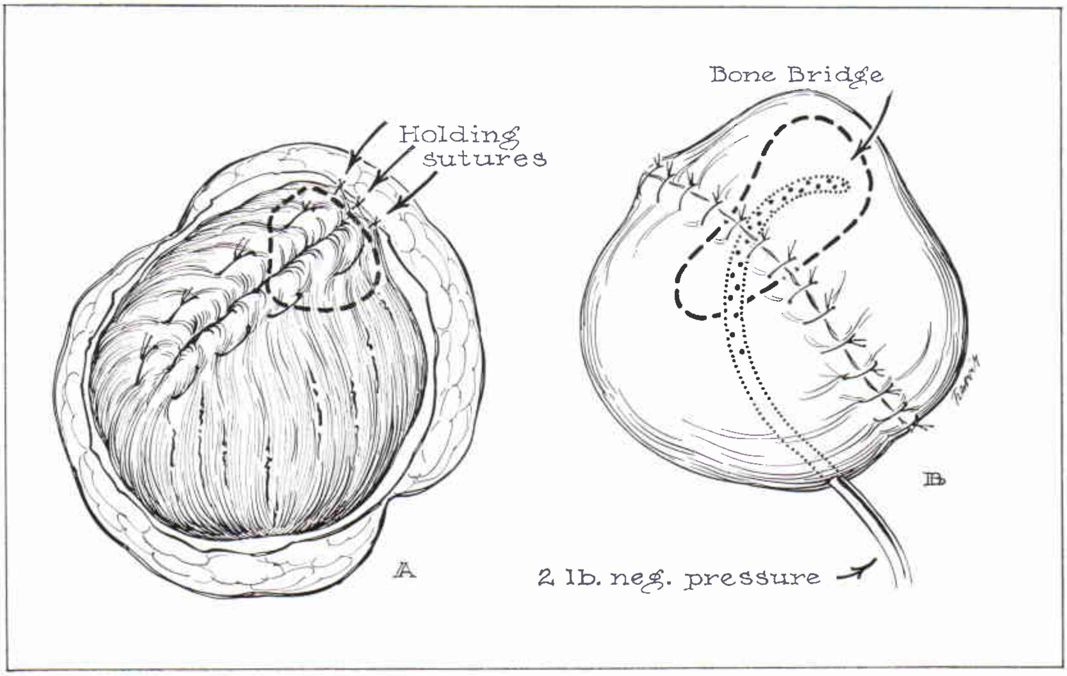

Fig. 2. Mondry's myoplastic procedure. *A*, The anterior tibial and fibular muscle groups, which, depending on their bulk, should be tapered, are joined under moderate tension to the gastrocnemius-soleus muscle group over the osteoperiosteal bridge, with sutures as well to the periosteum of the tibia (*dashed* line). As much of the fascia is kept in place as possible, and what is mobilized should be resected. *B*, The terminal suture line of the oblique skin flaps is at right angles to the osteoperiosteal bridge (*dashed* line) and muscle sutures. The suction tube is shown in place.

ment of the scar so that it does not lie directly over the end of the bone and is not subject to irritation by the prosthesis. Other than this consideration, the position of the scar is immaterial if healing is *per primam*. A good choice is an anterolateral-to-posteromedial suture line, the resulting scar lying at right angles to the suture line of the muscles (Fig. 2*B*). The skin flaps should then be of equal length. This approach is in agreement with Marquardt (*15*).

Preoperative and Postoperative Treatment

Prolonged and intensive preoperative care is essential for the success of an osteoplastic-myoplastic amputation or revision. The patient should be hospitalized preoperatively for a minimum of three weeks, preferably for six. During this time everything possible should be done to improve the condition of the limb. If localized infections are present, they should be treated topically. The skin should be given the best of care. Hydrotherapy for stimulation of circulation and drugs (intra-arterial procaine to the femoral artery of the affected side) to increase peripheral circulation may be administered. The limb should be exercised within the limits of tolerance of the patient.

Equally important is proper postoperative treatment. Postoperative hematoma should be prevented by use of suction-drainage (negative-pressure bottle), which will help avoid tissue destruction because of pressure, painful distention, and the presence of a medium for growth of bacteria.

A splint should be used for two to three weeks with the knee in slight flexion; no exercises are prescribed for this period. Then an Ace bandage should be applied and exercises gradually increased over a period of time, the aim being especially to strengthen the anterior

Fig. 3. Case 1. Roentgenogram showing evidence of development of synostosis between tibia and fibula of patient whose amputation was done 32 years earlier at the age of 9.

Fig. 4. Case 2. Roentgenogram showing solid, well-formed bone bridge 8-½ years after osteoplastic-myoplastic revision.

tibial and calf muscle groups. A shrinker should be used only if distention is present. The distal surface of the stump should be toughened by pounding and by vibration treatments.

After eight to ten weeks, well before solidification of the bone bridge, the prosthesis can be fitted. A pad should be put in the bottom of the socket and the pressure on the distal end gradually increased. This procedure will accelerate the solidification of the bone bridge and further decrease postoperative edema and the sensitivity of the distal end of the stump.

Brief Reports of Cases

Of the cases illustrated here, 2 through 6 are of amputees seen in Herborn, Marburg, and Bonn, Germany, in 1958, and 1, 7, and 8 are taken from recent experience with osteoplastic-myoplastic procedures at the Biomechanics Laboratory.

CASE 1

Figure 3 shows evidence of partial synostosis between the tibia and fibula of a man whose primary amputation was done 32 years ago, when he was 9 years of age. This roentgenogram substantiates the statement made by Ertl (*10*) that Nature itself tries to connect the transected surfaces of the fibula and tibia, thus showing the way for surgical action.

CASE 2

Reamputation of both legs of a 52-year-old man was done by Mondry in 1950. The left stump, which is 7 in. long, is shown in Figure 4. Excellent results were obtained in this case by the osteoplastic-myoplastic procedures used at reamputation. At the time of examination, 8 years postoperatively, the patient reported that he could walk well, with good control of his prostheses, and that he had proprioception in both stumps and no phantom pain. Examination showed good temperature and no discoloration of the skin or hypersensitivity at the distal end of the stumps; the bone bridge was palpable through the soft-tissue pad; and there was full range of motion of the knee joint. Some atrophy of the gastrocnemius-soleus muscle group had occurred. It is unfortunate that the prostheses did not provide for at least some end-bearing, since the patient

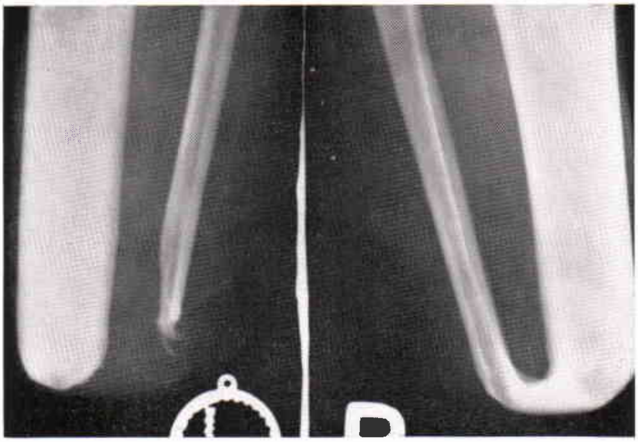

Fig. 5. Case 3. Roentgenograms of bilateral amputee with osteoplastic revision of right stump only (taken 11 years after revision). Relative increase in thickness of cortex of fibula and tibia of right stump, with normal appearance of bone tissue, is remarkable.

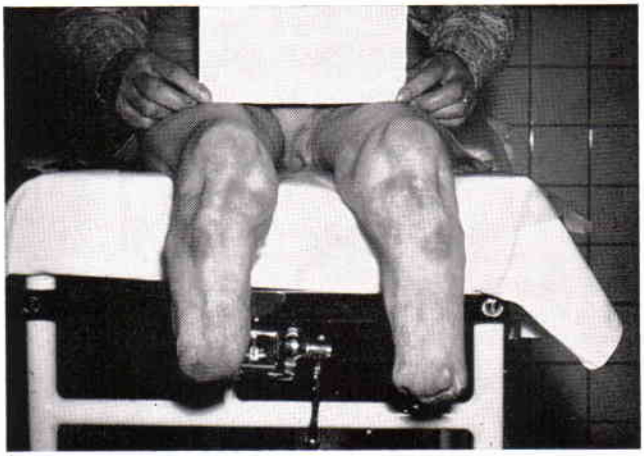

Fig. 6. Case 3. Unrevised left stump (viewer's right) and osteoplastically revised right stump (viewer's left), same as in Figure 5. Muscle atrophy is evident in both stumps, since myoplasty was not done at time of revision of right stump. Skin changes resulting from inadequate prosthesis are less severe on the right stump.

could support weight on both stump ends. The roentgenogram shows a well-rounded bone bridge, with good bone tissue extending to the distal ends of both bones except for slight osteoporosis resulting from use of a prosthesis that did not provide for any axial loading.

CASE 3

A 58-year-old man, also a bilateral amputee, had revision of his right stump only. The operation was performed by Ertl in 1947 with use of the osteoplastic technique because of pain, increased sensitivity of the bone, inability to wear a prosthesis, and, finally, penetration of the bone through its inadequate skin cover. The two sides may be compared in Figure 5 and from the following observations. With respect to the right stump, no complaints of the sort heard before revision were heard afterward. Shortened to 7¼ in., the bone was soon insensitive and capable of bearing weight, although no postoperative physical therapy for toughening of the stump had been given. At the time of examination the left stump (8 in. long) was, however, reported by the amputee to be subject at times to inflammation, neuritis, and radiation of pain into the adductor region of the thigh. Both stumps had only skin over the bone at the distal end, and the bone bridge of the right stump was palpable. Myoplasty had not been done at the time of revision of the right stump, and resulting atrophy of the anterior tibial group was noticeable. On the left (unrevised) side, an exostosis was present on the medial aspect of the distal end of the fibula. While the left stump was sensitive to palpation, the right stump was completely insensitive, even to heavy punishment. Skin changes resulting from use of open-end prostheses with thigh corsets were present but less severe on the right side (Fig. 6).

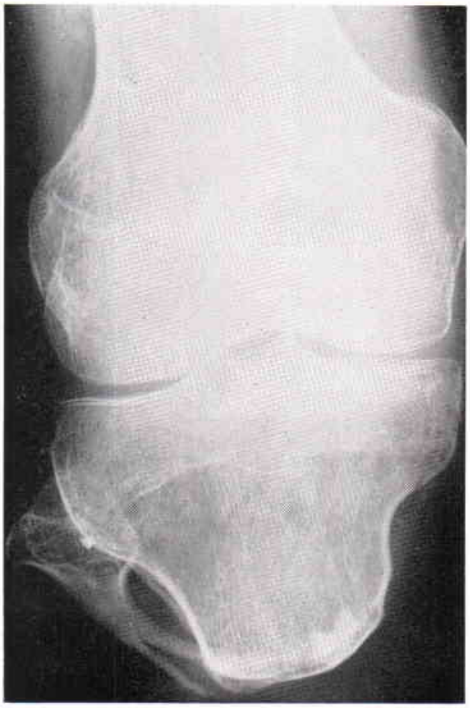

Fig. 7. Case 4. Roentgenogram taken shortly after osteoplastic revision to anchor head of fibula in short stump.

CASE 4

Figure 7 shows a bone bridge in formation soon after revision was done for the purpose of anchoring the fibula in a very short stump. The resulting short but well-shaped and functional stump is shown in Figure 8.

CASE 5

A variation of the osteoplastic technique was successfully done in another case. In order not to reduce length, a homogeneous graft from the anterior tibial crest was applied in bridging the two bones (Fig. 9). The operation, including a myoplastic procedure, was performed by Ertl in 1947. When the amputee, a 34-year-old man, was examined in 1958, he stated that since revision he had never had any discomfort in his stump and could walk considerable distances. His socket provided for weight-bearing over the medial tibial flare

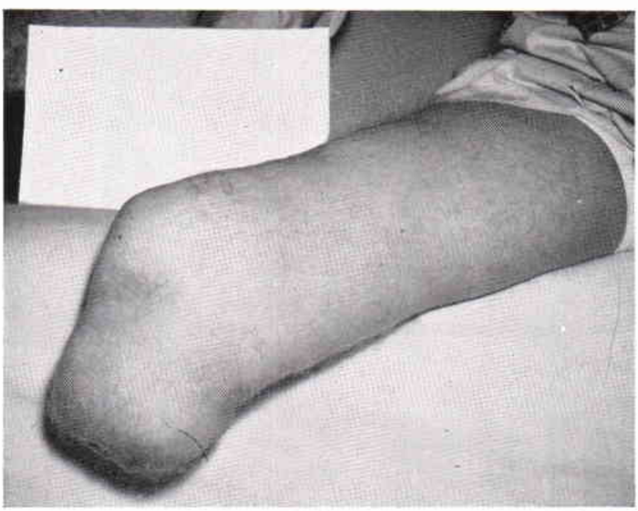

Fig. 8. Case 4. View of short, well-shaped stump, same as in Figure 7.

Fig. 9. Case 5. Roentgenogram taken 11 years after revision with homogeneous bone graft to form bone bridge.

none over the stump end. The stump (Fig. 10) was pointed and its musculature somewhat atrophied; there was hyperkeratosis anteriorly over the distal end of the tibia, as well as abrasions and signs of constriction in the area of weight-bearing. These conditions, along with discoloration from the supporting thigh corset, were evidence that the patient's prosthesis did not exploit the potentialities of his stump. He had full range of motion at the knee joint, and the muscle power was good.

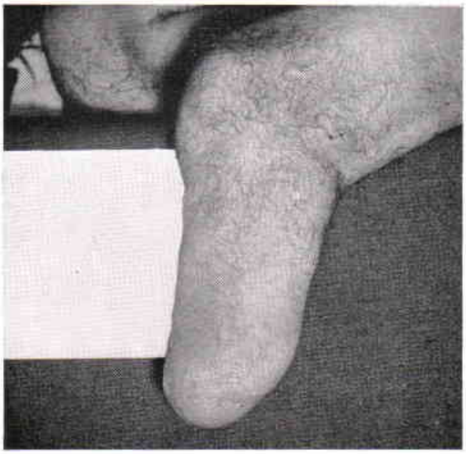

Fig. 10. Case 5. Lateral view of stump, same as in Figure 9.

Fig. 11. Case 6. Roentgenogram showing fracture in sagittally slanted bone bridge.

CASE 6

Figure 11 shows a fracture that occurred in the bone bridge of an unusually athletic amputee. The shortness of the fibula in relation to the tibia, with resulting curved and slanting bone bridge, should be noted. At the time of examination the stump was, however, completely insensitive over the distal end, and the patient had no complaints.

CASE 7

Primary amputation of the left leg of a 31-year-old man was done in 1951 because of a war injury. After recurrent breakdown of the redundant soft tissue along the surgical scar, persistent severe stump and phantom pain which had led to drug addiction and prevented rehabilitation, and prevailing coldness of the

Fig. 12. Case 7. Roentgenogram taken 4 months after osteoplastic-myoplastic revision, showing satisfactory progress of ossification of bone bridge.

Fig. 13. Case 8. Roentgenogram taken 7 months after osteoplastic-myoplastic revision, with slow development of bone bridge in presence of osteoporotic tissue.

stump skin, osteoplastic-myoplastic revision was carried out on March 24, 1961. The roentgenogram shown in Figure 12 was taken on July 31, 1961. At the time of writing, the shape and condition of the stump are most satisfactory—warm and insensitive to pressure, with normal skin color. The patient is wearing a well-fitting prosthesis with a total-contact socket that provides for patellar-tendon-bearing and partial end-bearing. He has no localized or phantom pain and has resumed a normal life with steady employment.

CASE 8

In 1955, when the patient was 48 years old, his left foot was crushed in a railway accident. After a variety of efforts to save the foot had failed on account of prolonged osteomyelitic suppuration, a below-knee amputation was done in December 1956. Because the patient had continuous, severe stump and phantom pain, which was established to be of peripheral origin, an osteoplastic-myoplastic procedure according to Ertl and Mondry was done in January 1961. At this time the bone tissue was found to be of a deep yellow color, with rarefication of the trabeculae and almost no points of bleeding from the bone. Although healing was slow (see Fig. 13, photo taken 7 months after revision), the patient's condition appears to be considerably improved. He no longer has the acute phantom pain that used to torture him; phantom pain now occurs only during occasional stump pain. The latter, considerably less than before, is probably due to the poor bone material with its protracted healing time. The patient's stump is being toughened by percussion and by use of a total-contact prosthesis which provides vertical loading of the bone.

Conclusions

The osteoplastic-myoplastic procedure, occasionally used as a primary procedure under special conditions, is indicated for revision of below-knee stumps (*a*) when there is intractable stump pain with clearly established peripheral cause; (*b*) when the stump is severely hypersensitive, either superficially or in the deeper tissues; (*c*) when the stump has gross circulatory deficiencies, is easily distended and edematous, or is subject to skin breakdown, ulceration, or types of hyperplastic growths that may become malignant; (*d*) when the stump has redundant tissue and excessive scar tissue, adherent or nonadherent to deeper tissues, preventing tolerance of the prosthesis; (*e*) when the stump is long and has atrophic retracted musculature; and (*f*) when there is at the distal end of the stump a localized, deep infection which after nonoperative treatment has proved inadequate, must be resected *in toto* with reamputation at a slightly higher level. For unequivocal success, however, it is important to amputate through viable, well-vascularized bone. In the presence of advanced atrophy and osteoporosis, the solidification of the bone bridge takes much longer, and complete elimination of spontaneous, deep-seated pain becomes questionable (Case 8).

Much has been written about the optimum level of amputation below the knee, and usually from the point of view of how well the conventional prosthesis could be applied. Thus, the main reason for the 2-in. minimum given by various authors has been the problem of maintaining the stump in the socket. With certain prosthetic advances that are now coming into use, however, a shorter stump can be fitted successfully, provided some weight-bearing potential exists at the distal end. Most very short stumps are completely insensitive over the cut surface of the tibia because the cancellous bone at this high level heals well with formation of a solid bony cover. The main problem, then, is the presence of the head of the fibula, which, when it is deprived of much of its interosseous membrane, is subjected to the full force of the pull of the biceps tendon, with resulting abduction of the distal end of the residual fibula and rotation of the head. The solution many surgeons recommend is resection of the head of the fibula, but doing so gives a conical stump even more difficult to fit because of excessive stump rotation inside the socket.

What might be done in these cases is demonstrated in Case 4, in which a modification of Ertl's technique was done. Not only was anchorage of the head of the fibula achieved in this case, but allowance was made for full use of the knee joint in an adequate prosthesis. Because of the high level of amputation in this type of case, the anterior tibial group is dissected at or close to its tendinous origin, so that a muscle plasty is not only technically difficult to perform but also not essential.

A shortening of the stump occurs as a result of fashioning the osteoperiosteal flaps from the surfaces of the tibia and fibula, but the surgeon should not hesitate to make this sacrifice in length when an increase in function can thereby be obtained. Because of sensitivity of bone or excoriated skin, most conventional stumps can be fitted snugly in the proximal half only. The distal half is subjected to excursion and resulting mechanical irritation in a loose socket because it has to be relieved of pressure. When the hypersensitivity of the tissues is eliminated by the osteoplastic and myoplastic procedures herein described, the stump can be fitted closely over its full length, thereby reducing excursions in the socket and actually increasing functional length. If, however, the surgeon is reluctant to shorten the bones in the presence of adequate viable soft tissue at the distal end, an equally satisfactory bridge can be formed with use of a homogeneous bone graft, as is illustrated by Case 5.

Contrary to the recommendations, given with other surgical techniques, to shorten the fibula in relation to the tibia, with the osteoplastic technique best results are obtained when the two bones are transected at the same level. The bridge is then approximately horizontal to the ground. When the fibula is shorter, the bone bridge must be formed on a sagittally directed slant. While the presence of the bridge is, in any case, desirable to prevent biological difficulties, any slant will subject it during weight-bearing to vertical shearing forces it may not be able to withstand. The fracture reported in Case 6 is one of two seen in 1958—both being diagnosed only through roentgenograms since they were asymptomatic and did not prevent the patients from participating in competitive sports.

Of relatively less importance is the placement of the scar. Even if it falls across the distal surface of the bone, the well-vascularized, relatively insensitive skin is able to withstand socket rub and shear effectively.

Good circulation to the deep as well as to the superficial tissues is one of the most advantageous results of the osteoplastic-myoplastic operation (*13*). The muscles, able to contract by virtue of distal attachments, are used continuously. The bones, protected by the bone bridge and used for weight-bearing throughout their length, are preserved from the avascular necrosis to which the distal ends of conventionally amputated bones are ordinarily subject. Participation of the fibula in weight-bearing leads to hypertrophy of the cortex and increase of the over-all diameter. Finally, support of weight on the distal end leads to much greater proprioception, with resulting greater security in walking and improved ability to use the prosthesis easily even in poor light.

In 1923, Burrows (*6*) had conceived of stumps that were functional in much the same way and for the same reasons as have been described in this paper, but he felt forced to abandon his idea of an osteoplastic operation to create conditions for end-bearing because, as he said, "it seems to be impossible to get a limb-maker to get out of his groove and make a suitable limb for such a stump," and he had to conclude that, until more imaginative prosthetists were found, "osteoplastic flaps must be classed as surgical mistakes." Now we are no longer faced with this dilemma. The patellar-tendon-bearing cuff-suspension prosthesis is easily adapted for total contact and partial end-bearing, so that now there is no excuse for inadequate amputation surgery. Results of clinical experience in Germany and at the Biomechanics Laboratory of the University of California have shown definitely the advantages to be had from the osteoplastic-myoplastic procedure.

Acknowledgments

Figures 1 and 2 were drawn by Mr. Thomas Harris. I wish also to express my thanks to the director of Gehschule Hessen, Oberregierungs-Medizinalrat Dr. Rost, Marburg an der Lahn; the director of the Orthopedic Clinic in Herborn, Dr. Hanns Lerch; and Oberarzt Dr. R. Dederich, St. Petrus Krankenhaus, Bonn, Germany, for their assistance in obtaining some of the case material.

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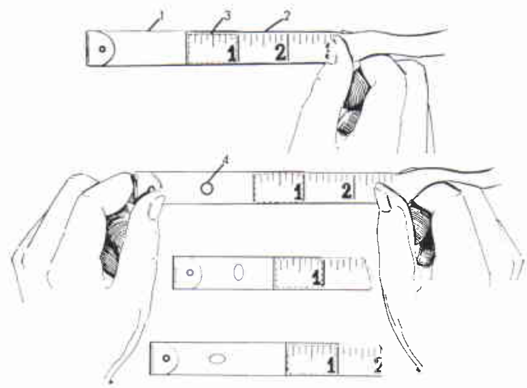
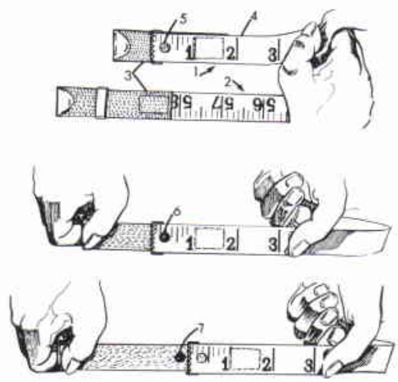
Technical Notes from the Artificial Limb Program

This section of Artificial Limbs *is intended as an outlet for new developments in limb prosthetics which, though not deserving of a long feature article, nevertheless ought to be brought to the attention of the readers of this journal. Notes may vary in length from a single paragraph to several pages of manuscript, as appropriate. Illustrations also are acceptable.*



THE ROSENKRANZ "CIRCOMETER," ONE VERSION—A simple and practical means of obtaining consistent circumferential measurements of soft tissue by more than one operator or by the same operator in successive tries.



THE ROSENKRANZ "CIRCOMETER," A VARIATION—An alternative design giving the same result as in the preceding illustration.

Improved Anatomical Measurements

Because the soft tissues of a living organism distort so readily even under the slightest pressure, the amount of tension placed on a tape measure in the course of taking circumferential measurements of parts of the anatomy has a critical influence upon the consistency with which such measurements can be made. The lack of a suitable means of assuring consistent circumferential measurements of a single subject by different workers, or by the same worker on successive tries with the same subject, has therefore long presented a serious problem for anthropologists and physicians and particularly for prosthetists, who need to be able to obtain reliable measurements of amputation stumps and of the neighboring structures involved in limbfitting. Although in the past various schemes for controlling tension in a measuring tape have been proposed from time to time, until recently none has proved to be of practical value in routine use.

Now, it has been announced, Dr. Gabriel Rosenkranz, Prosthetics Consultant to the U. S. Veterans Administration Prosthetics Center, New York City, has developed a simple and economical device, known as the "Circometer" (pronounced *sûr·kŏm'ē·tẽr*), which solves many of the problems in circumferential measurement of soft tissues. As can be seen in the first of the two accompanying illustrations, a short length (enough to extend about 2 in.) of rubber band (1) sewed to a tape measure (2) at the "zero" end (3) is punched with a circular hole (4) while the rubber is under the degree of tension commonly used in body measurements. To the loose end of the rubber band is attached a simple metal tab to facilitate handling. Whenever subsequently the rubber band (and the tape itself) is under more, or less, tension than that selected originally, the outline of the hole becomes elliptical. Re-establishment of the original tension is evidenced whenever the hole becomes circular again. Thus, if measurements are read only when the hole has the shape of a circle, consistent results can be obtained.

Another version, based on the same principle, is shown in the second illustration. A suitable length of rubber band is sewed to the end of a tape measure an inch or so back from the end (1) so that it overlaps the side of higher dimensions (2) and extends beyond the "zero" end (3). The tape (4) is punched with a circular hole (5), and, while the rubber band is held under suitable tension, the hole is marked through to the rubber with pen and ink (6). Again a metal tab is attached to the end of the rubber as a matter of convenience, and a metal guide for the loose end of the rubber is crimped over the tape near the end. Whenever tension on the rubber band and tape is greater (7), or less, than the tension selected originally, the mark on the band is out of alignment with the hole in the tape. Matching mark to hole re-establishes original tension.

Comments on the utility of these simple expedients will be welcomed from prosthetists and others concerned. Communications may be addressed directly to Doctor Rosenkranz at the U. S. Veterans Administration, 252 Seventh Ave., New York 1, N. Y.

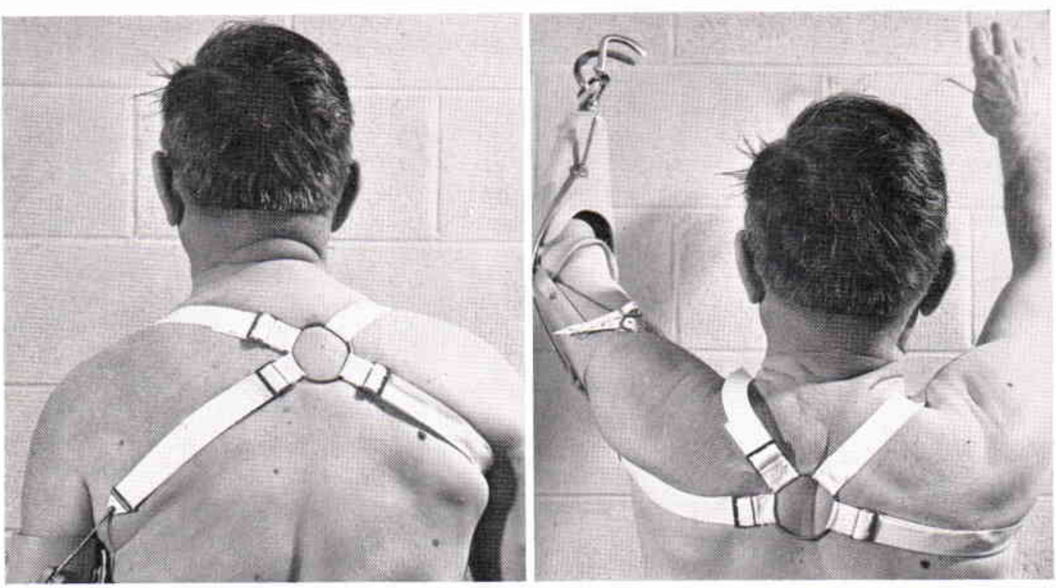
Improved Figure-Eight Harness

It has been customary to fabricate each figure-eight harness to what is judged to be the requirements of the individual patient, and the various parts are sewn together to form an assembly with little or no provision for adjustment. To provide for adjustability and at the same time to provide a more comfortable and functional harness, the Prosthetics Research Center, Northwestern University, has devised for the below-elbow case a method employing for the crossover of the backstraps a ring rather than the customary stitched overlap. The ring is of sufficient diameter and the straps are connected loose enough that they slide around the periphery of the ring as the direction of forces change and thus lie flat across the back at all times.

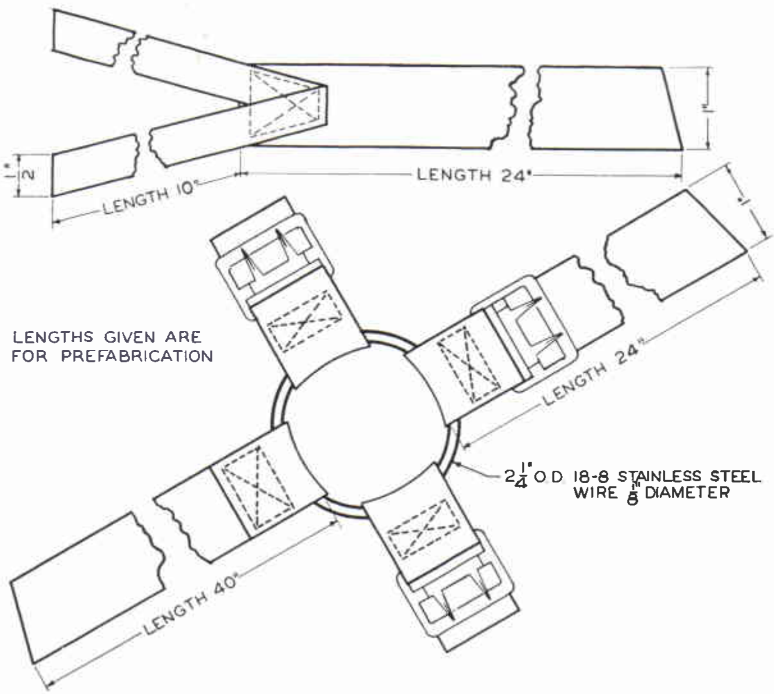
Buckles used to connect the axilla loop, the Y-suspensor strap, and the control strap to the ring provide for adjustability. Tang-type buckles may be used but a recently introduced four-bar buckle results in a neater arrangement.

Another advantage of the Northwestern ring-type harness is that it can be prefabricated to be stocked and used when required. Dimensions of straps and ring that have been found satisfactory for most adults are given in the accompanying illustration.

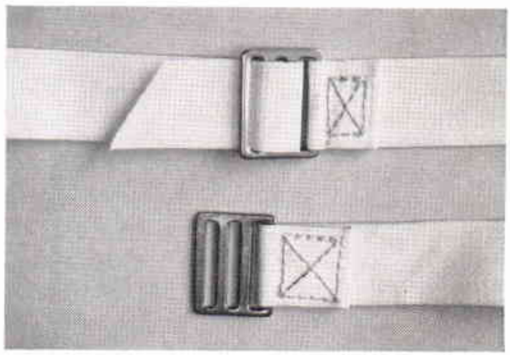
Experiments are being carried out to determine the feasibility of employing the ring in a harness for above-elbow cases.



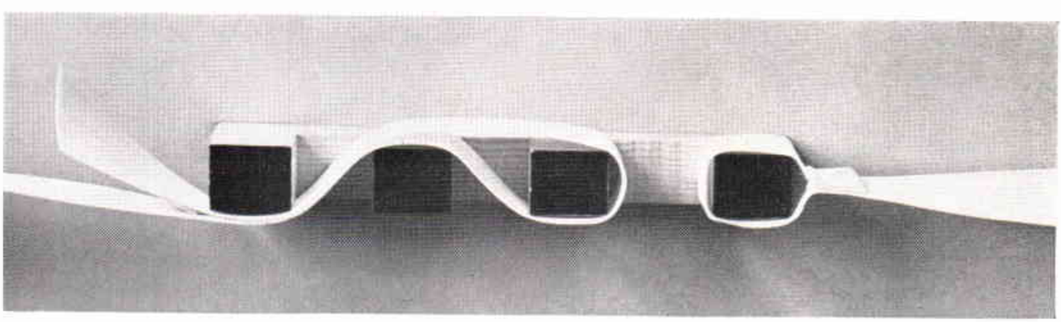
NORTHWESTERN RING-TYPE HARNESS—For below-elbow application.



NU HARNESS—Suggested pattern for prefabricated ring-type harness for adults.



NU HARNESS—Four-bar buckle recommended.



NU HARNESS—Mock-up of a four-bar buckle to illustrate proper method of attaching and threading tape.

NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL

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

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

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

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