Anatomical and Physiological Considerations in Below-Knee Prosthetics

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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.

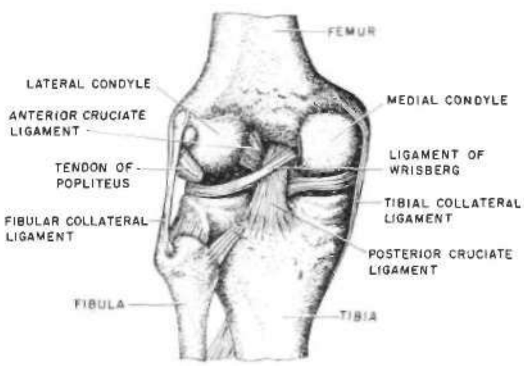


Fig. 1. Posterior view of left knee joint, showing anterior ligaments. Redrawn from Gray's *Anatomy.*

THE KNEE JOINT

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

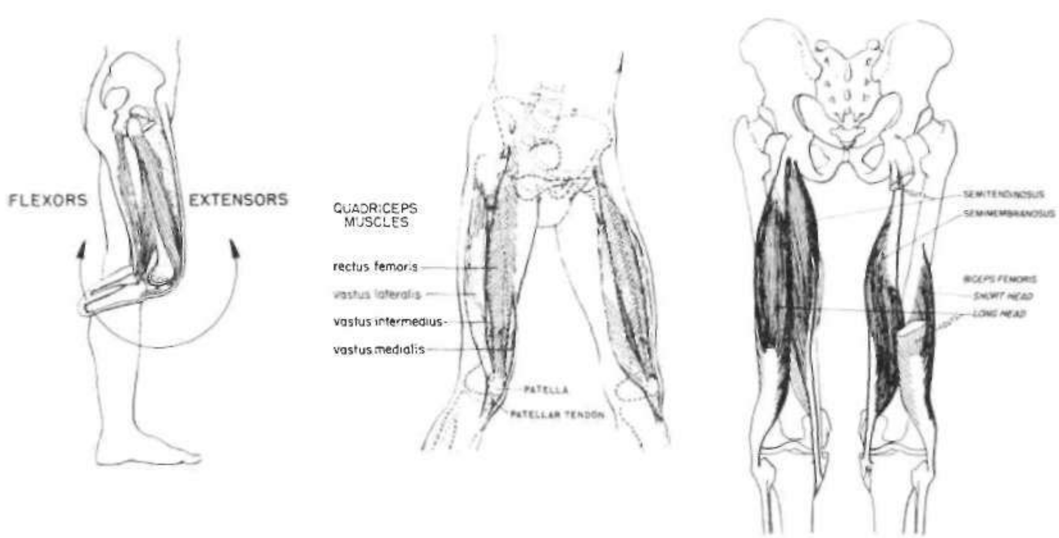


Fig. 2. The major muscles that flex and extend the knee joint. From *The Patellar-Tendon-Bearing Below-Knee Prosthesis* (4).

Fig, 3« X-rays of a typical below-knee Slump. J, Anterior view; *B.* medial view ("ouitesy *Veterans Ad»iin-istration* ***Prosthetics Center,***

Fig 4. Lateral and anterior \ieus of a typicaJj well formed, rijiht below knee slump ('ourtes\ 1 *eleran^ id))i'nn\h alion P) osihe/ics Cenfcr.*

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.*

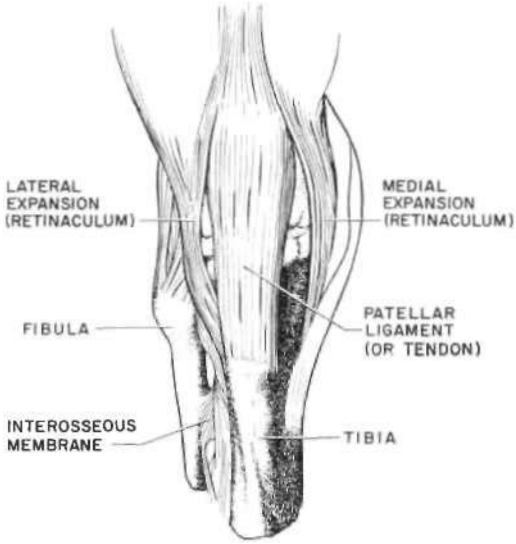


Fig. 6. Anterior ligamentous structure of the right knee.

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

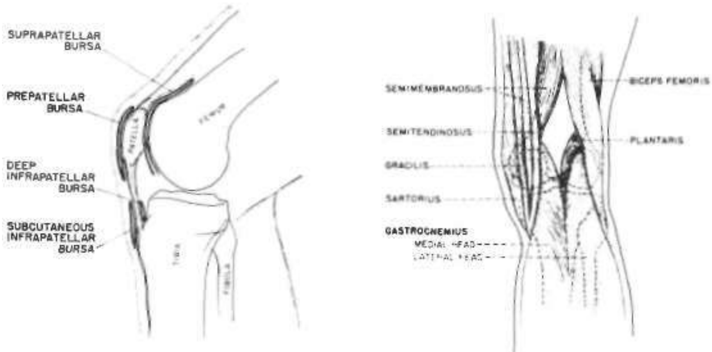


Fig. 7. Major structures that form the knee joint. From *The Patellar-Tendon-Bearing Below-Knee Prosthesis (4).*

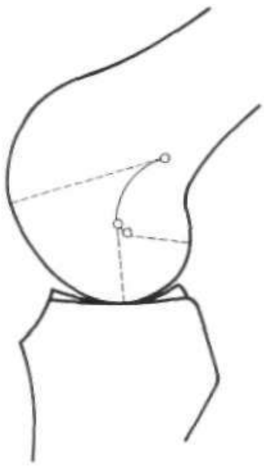


Fig. 8. Section through the medial condyle of the femur and through the tibia. The center of curvature is shown for three parts of the articular surface. As gliding occurs in the joint, the instantaneous center moves along the curve connecting these centers of curvature. From Elftman (2).

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.

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 counter-pressure 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. 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.

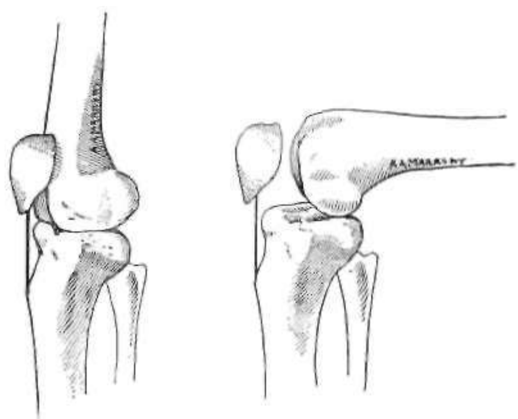


Fig. 10. Schematic drawing showing the nearly complete lack of relative motion between patella and tibia during flexion of the knee. The inextensibility of the patellar ligament prevents the patella from moving proximally with respect to the tibia. From Marks *(3).*

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.

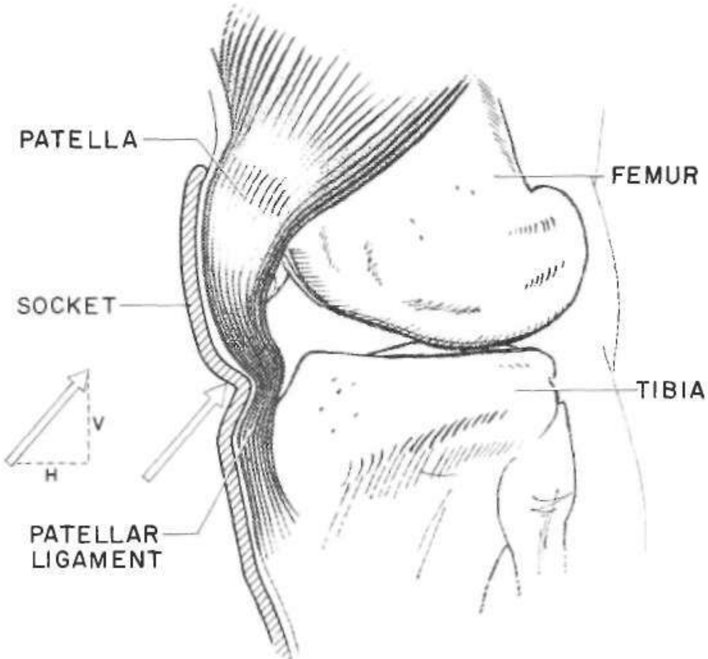


Fig. 11. Vertical cross-section of anterior portion of socket designed to take maximum advantage of patellar ligament for transmission of weight-bearing loads. Compare with Figure 12.

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. Similarlv, 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).

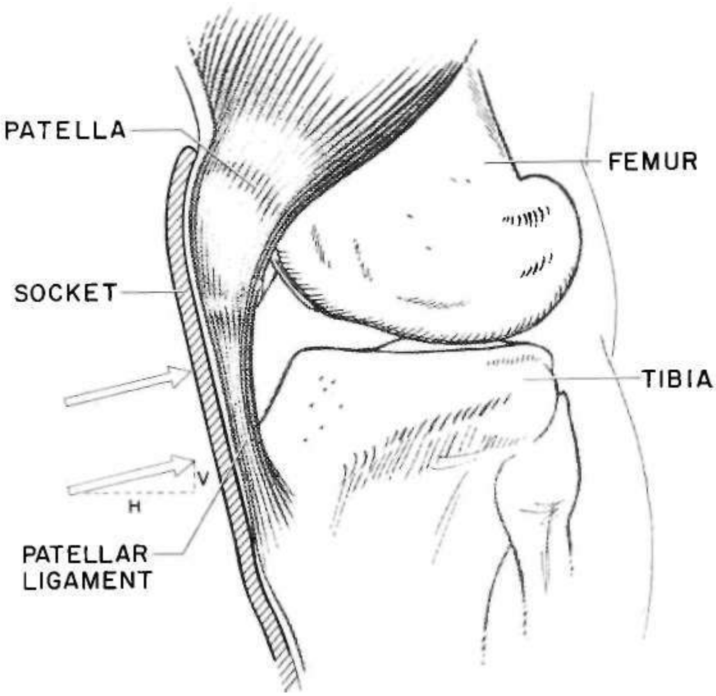


Fig. 12. Vertical cross-section of anterior portion of socket with little provision for use of the patellar ligament for transmission of weight-bearing loads. Note the small vertical component of the force between socket and stump in this area as compared to the condition shown in Figure 11.

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 poster or 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

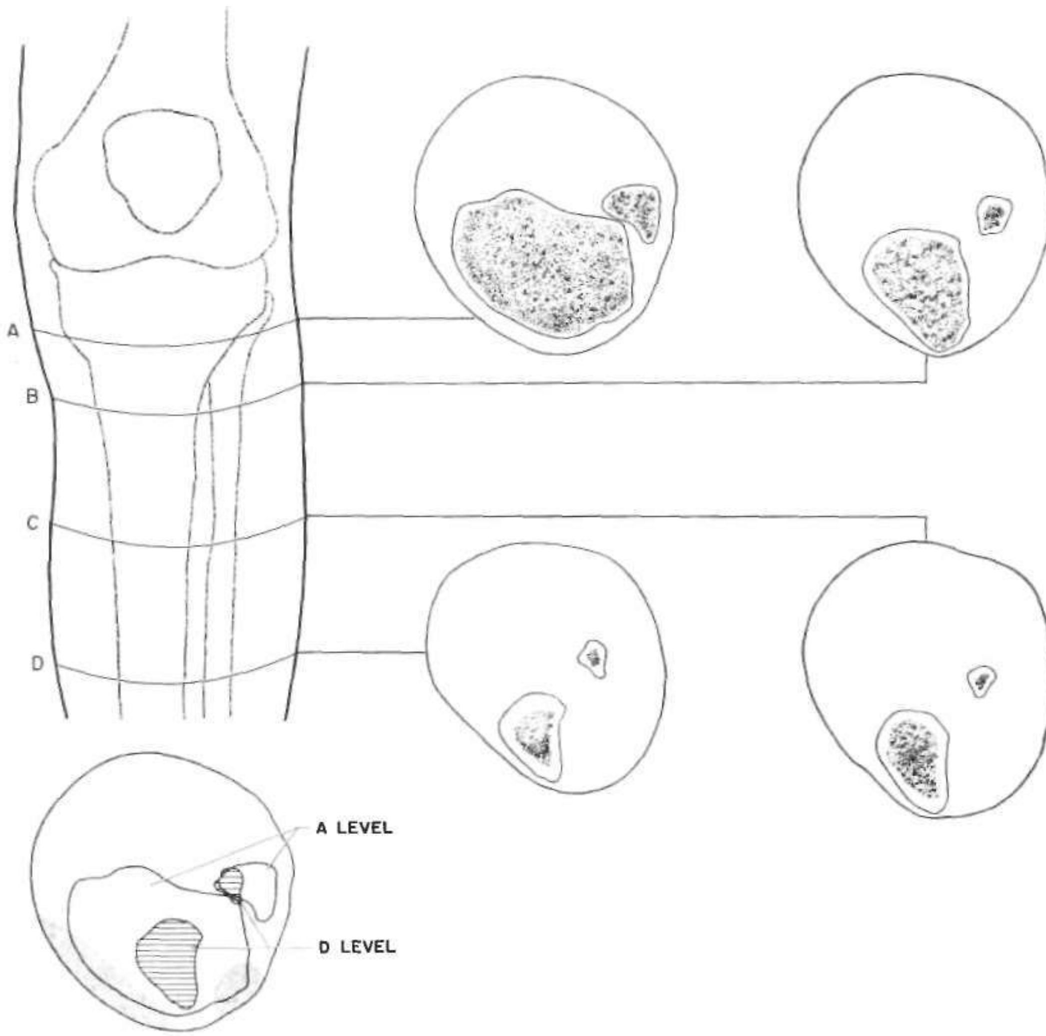


Fig. 13. Horizontal cross-sections of leg at four different levels. View below leg shows level *A* superimposed on level *D* to illustrate the horizontal area potentially available for vertical support along the sloping areas of the tibia.

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

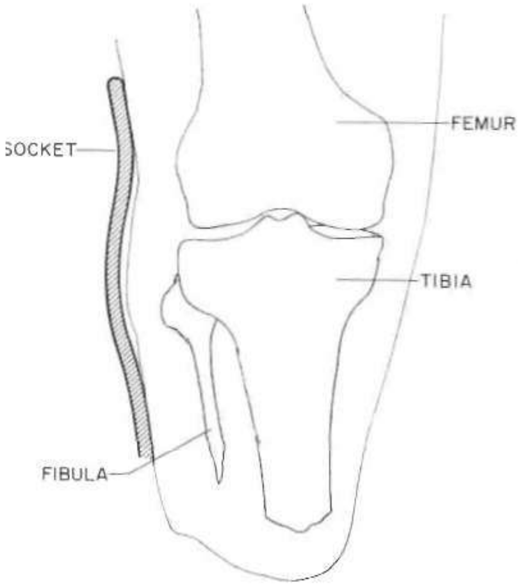


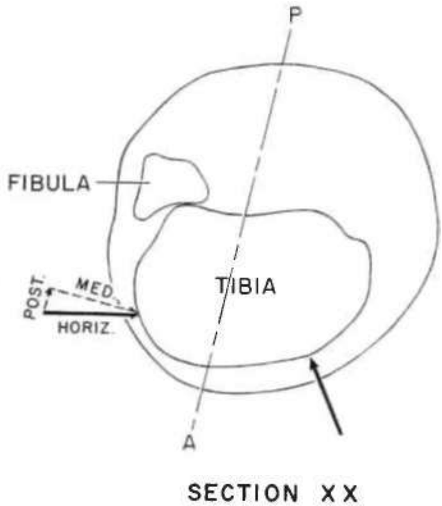
Fig. 14. Cross-section showing typical method of avoiding pressure between socket and tender areas on stump, in this case the area about the head of the fibula.

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



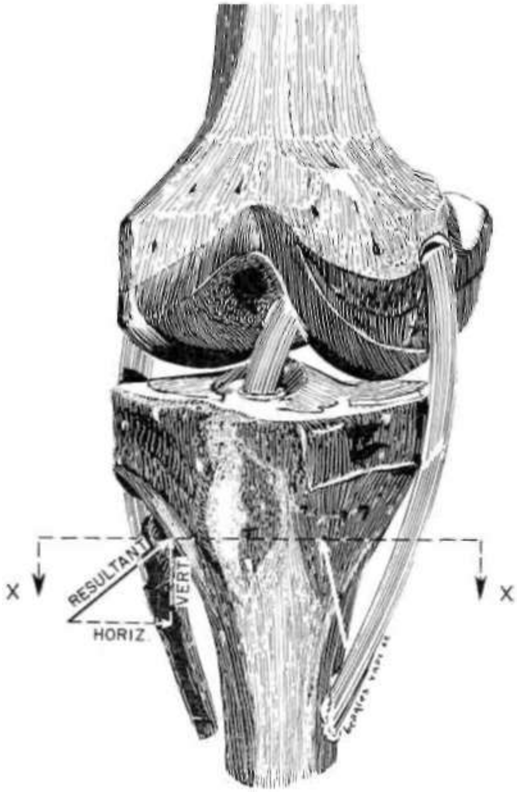


Fig. 15. Schematic drawing showing the approximate direction of forces acting on the flares of the tibial condyles. The vector representing the force on the lateral side is shown in true view in the lower sketch. Note the components developed in the horizontal plane. The components shown must of course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

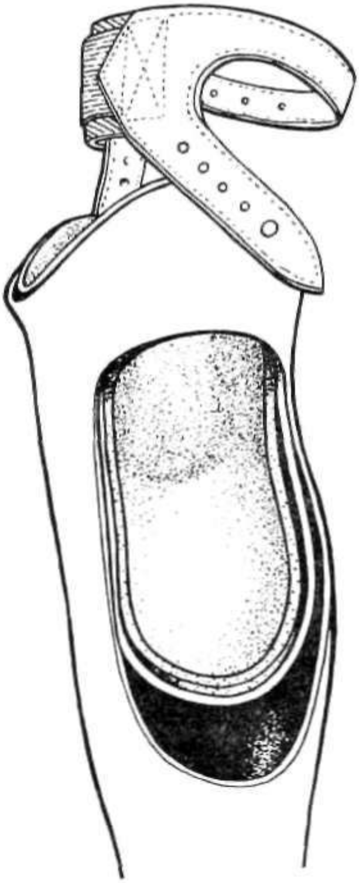


Fig. 16. Cutaway view of the patellar-tendon-bearing socket incorporated in a thin-walled plastic shank. Note especially cuff-suspension strap, high lateral and medial walls, and the total-contact feature.

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 1/8 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

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