# Construction of the Patellar-Tendon-Bearing Below-Knee Prosthesis

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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,

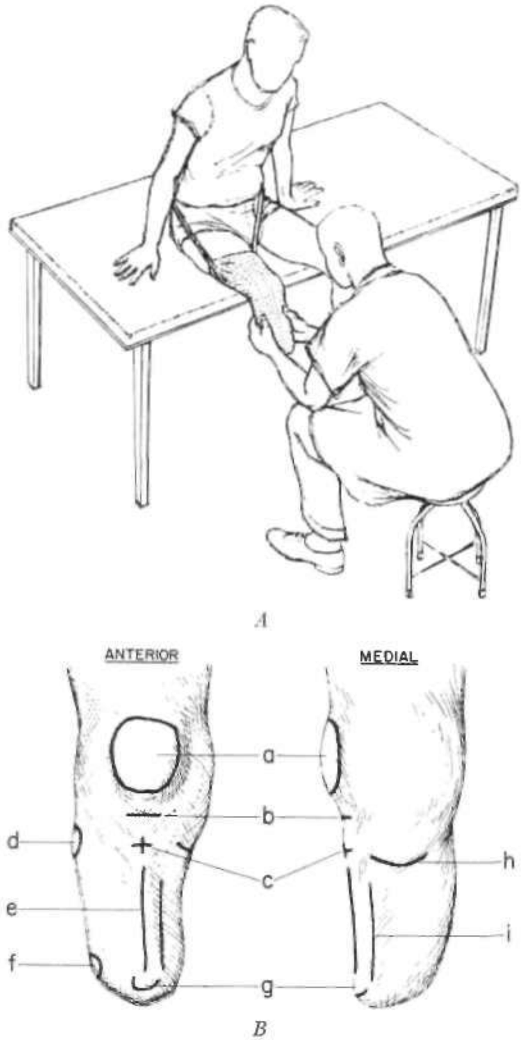



Fig. 1. Preparations for taking the negative cast. *A*, Patient seated with stump relaxed and knee flexed easily (about 30 deg.), cast sock applied and retained well above knee, prosthetist identifying (by palpation) bony landmarks and other pertinent features to be outlined by indelible pencil; *B*, 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

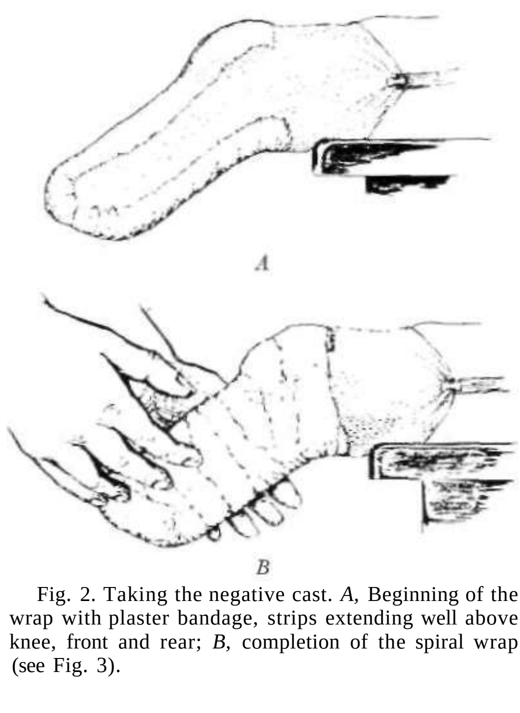
Unlike numerous other below-knee sockets heretofore recommended, the socket for the patellar-tendon-bearing (PTB) prosthesis is intended to remain at all times in intimate contact with the entire surface of the below-knee stump. The stump is therefore contained firmly in the socket throughout its length, 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 \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. 15, *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 anterodistal 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. *2A),* 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).

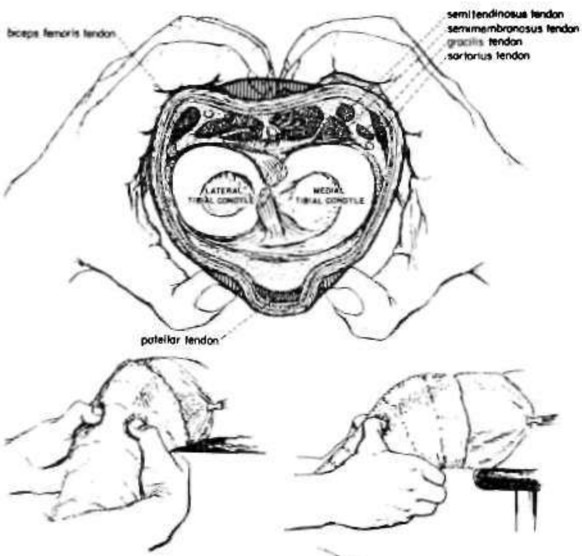



Fig. 3. Use of the hands to shape cast while plaster is hardening. Thumbs compress bandage in and around patella, fingers force cast into popliteal area.

tinued until the shell thus formed has a thickness of about 1/8 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 1/2-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 1/2 in. deep, on a radius of about 1 in., and extending horizontally across the front about 1/2 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 1/8 in.

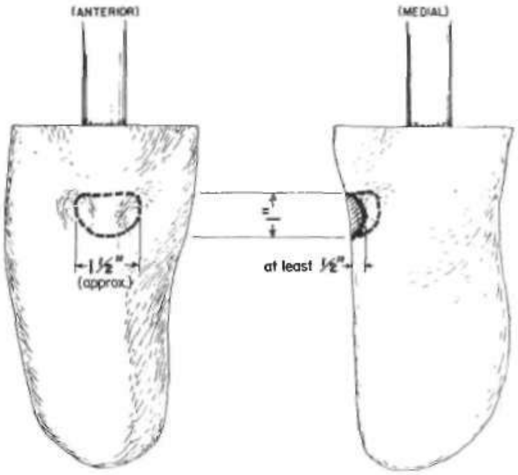



Fig. 5. Initial step in modification of the positive mode]—undercutting to enhance support on patellar ligament.

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 *6B*. Depending upon the individual characteristics of the particular stump concerned, 1/8 in. to 3/8 in. of plaster is removed, beginning about 3/4 in. below the border of the head of the fibula and continuing to within 1/2 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. 6C). The result is a wedgelike support along both sides

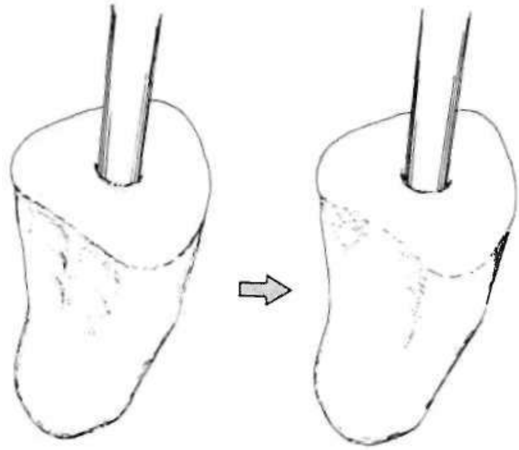


Fig. 7. Further modification of the model. Popliteal area is shaved away to provide countersupport against forces from the front, thus improving anteroposterior stability of socket.

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 1/4 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

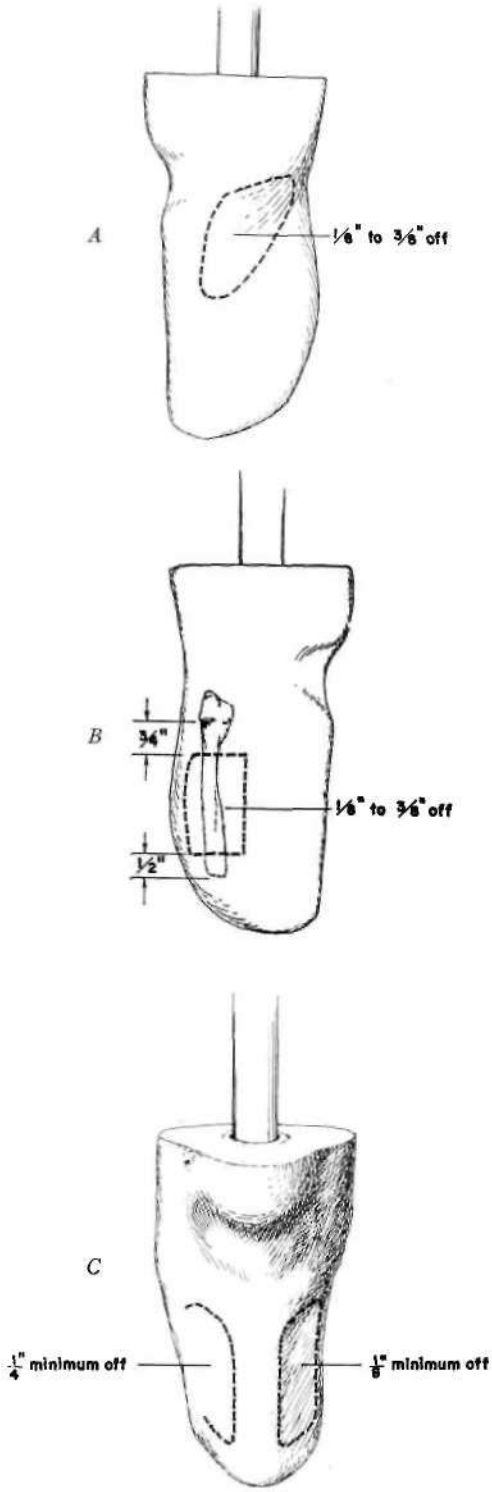



Fig. 6. Successive steps in modification of the positive model. *A,* Reduction for enhanced support on medial tibial condyle; *B,* the same to provide lateral support against fibula; C, the same to avoid pressure on anterior crest of tibia.

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 1/8-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 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 1/8 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.

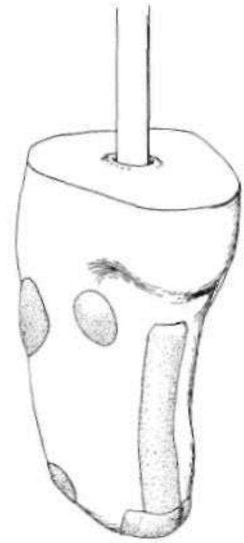


Fig. 8. Build-up of positive model to furnish relief in pressure-sensitive locations. Skiving of the leather patches provides a smooth transition from plaster to build-up.

To form an end pad for the socket, there is now cut from a 1/8-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,

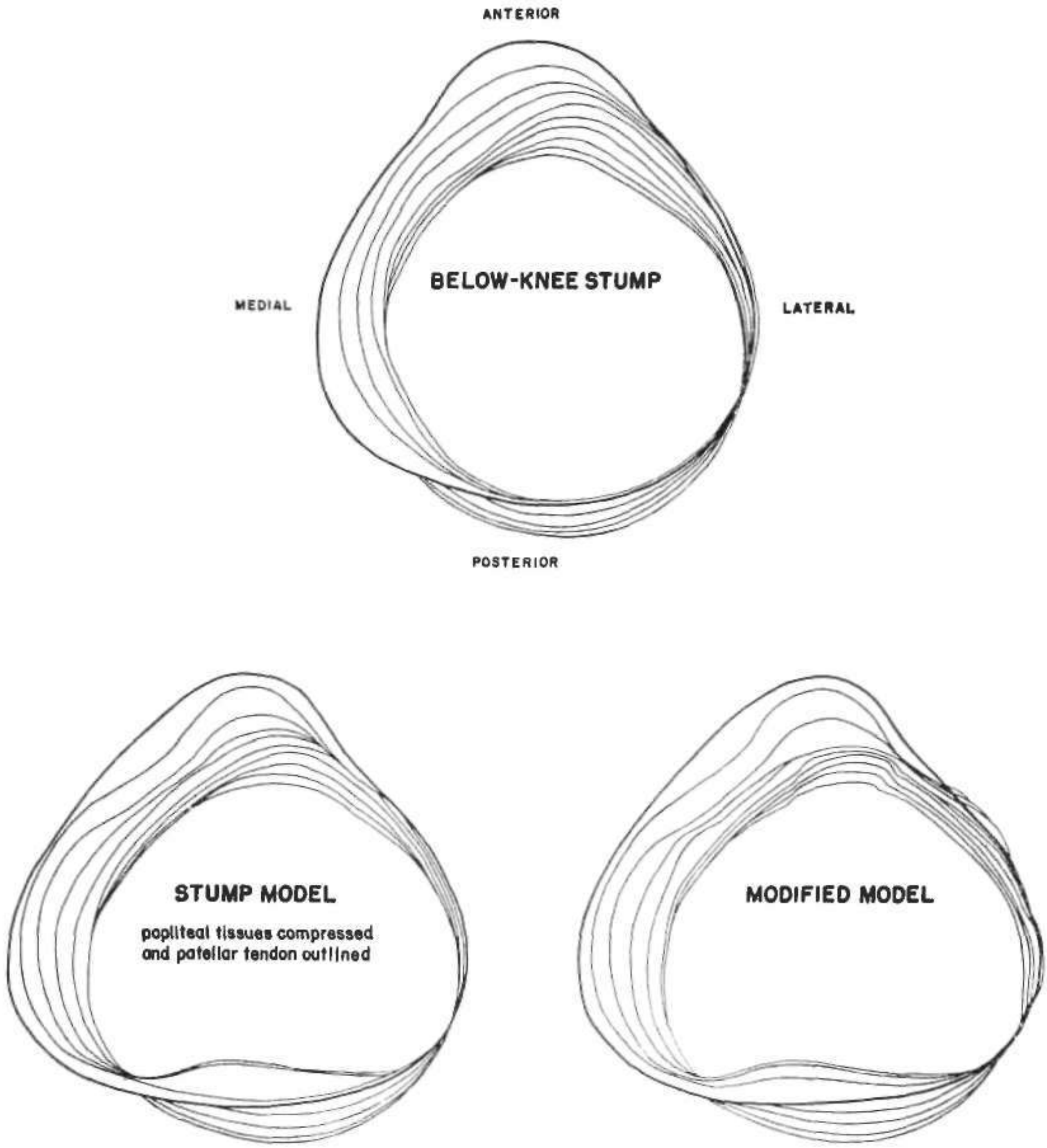



Fig. 9. Contours at successive levels overlaid to show comparative shapes of stump, of stump model as made from the cast, and of stump model after suitable rectification (modification). The specific shapes vary from patient to patient, of course, depending upon individual differences.

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 1/2 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

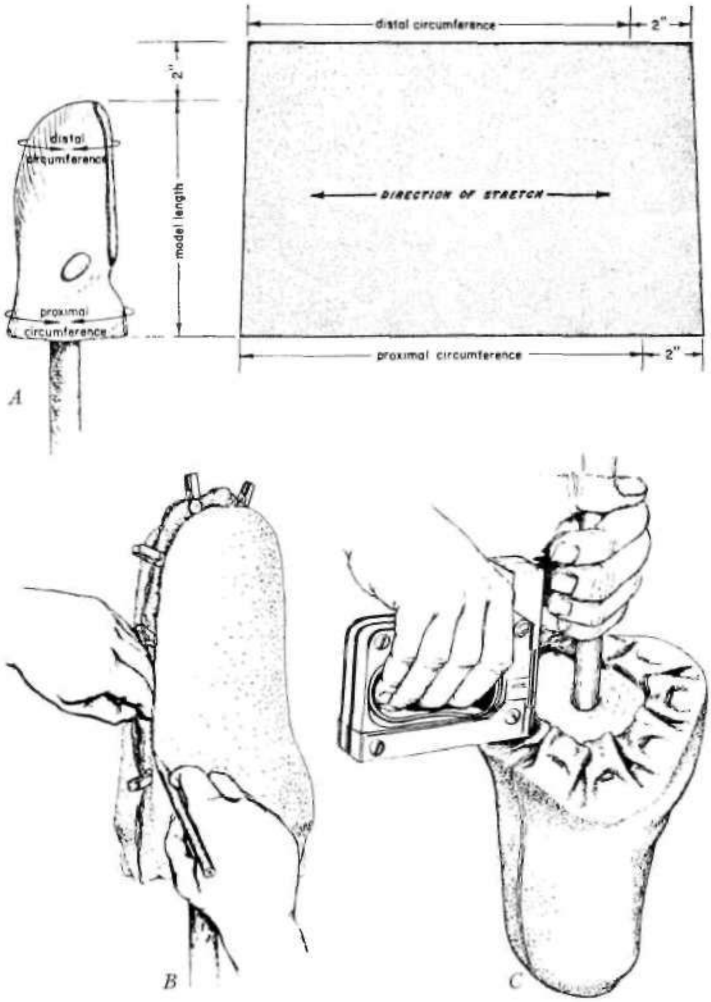



Fig. 10. Preparation and layup of the feather insert, or socket liner,

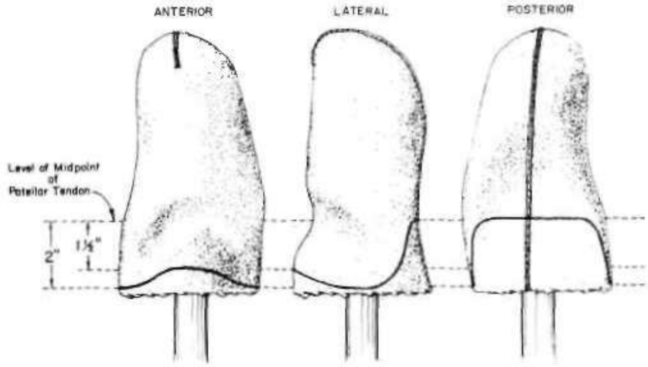



Fig. 11. Proximal trim line of the leather liner,

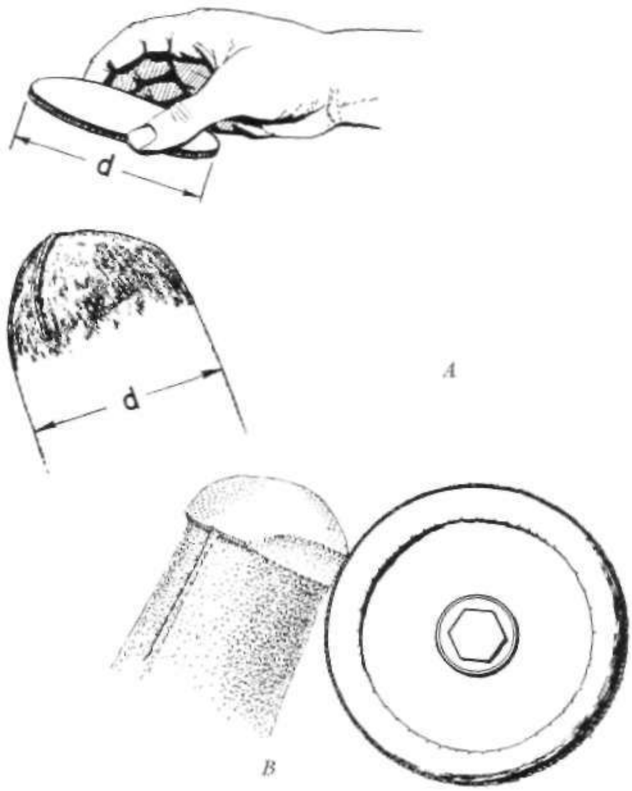



Fig. 12. Construction of the socket end pad.

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. 13C). 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

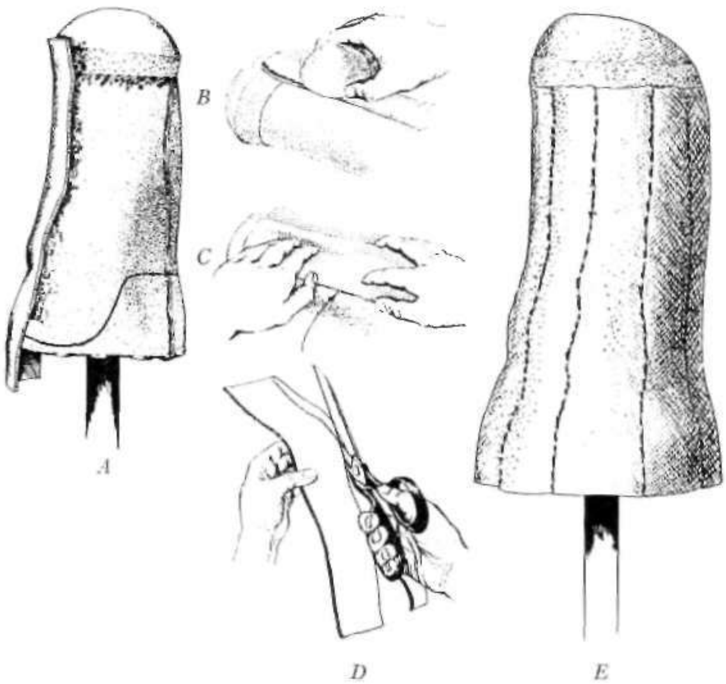



Fig. 13; Layup of the soft liner of sponge rubber (Kemblo). One edge of the first strip (*A*) becomes the pattern {*B, C, D)* for the second, and so on, until the entire model is overlaid with a smooth and neatly fitted covering (*E*).

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. 15C). 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 1/2-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.

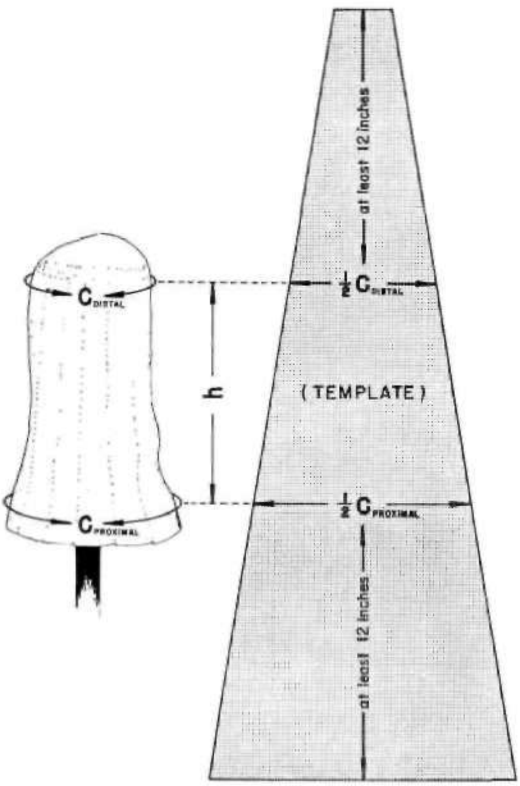


Fig. 14. Pattern for preparation of the PVA sleeves.

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. 175) 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 17C.

## 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

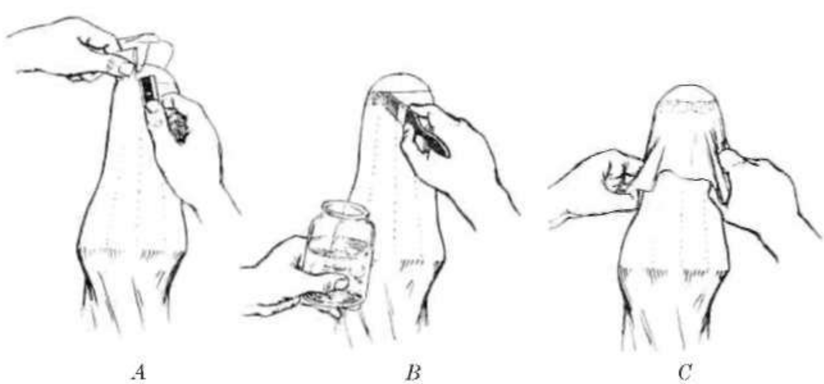
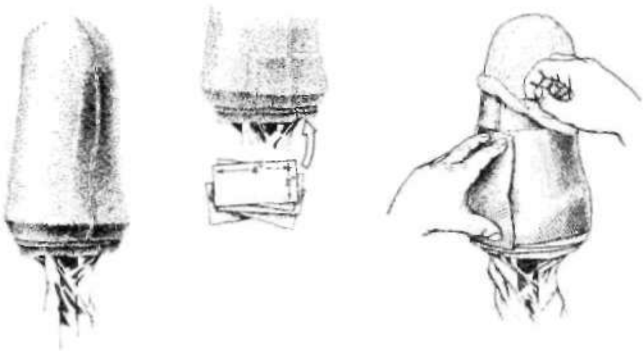
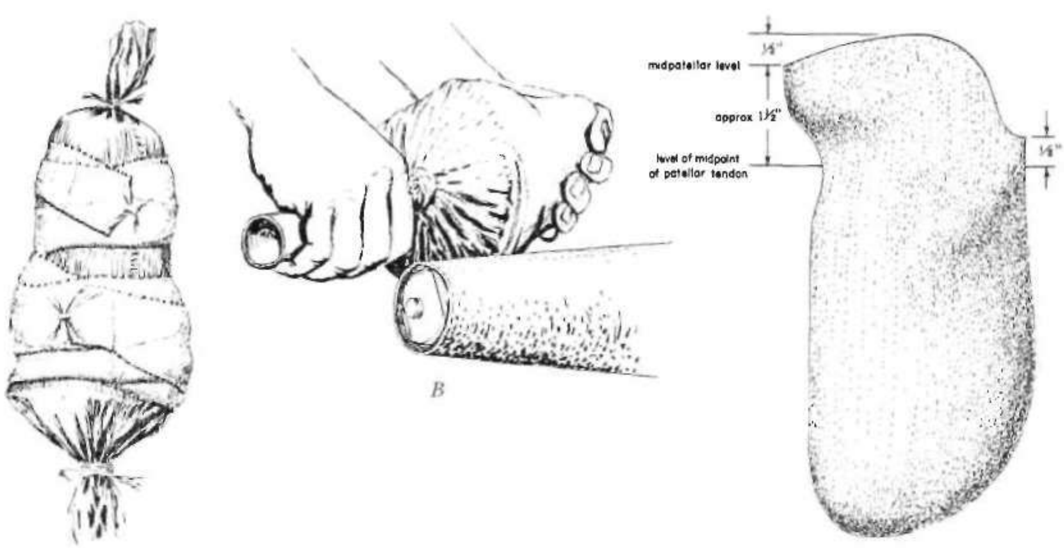


Fig. 15. Application of PVA separator over socket liner and model



A B C

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.




A C

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

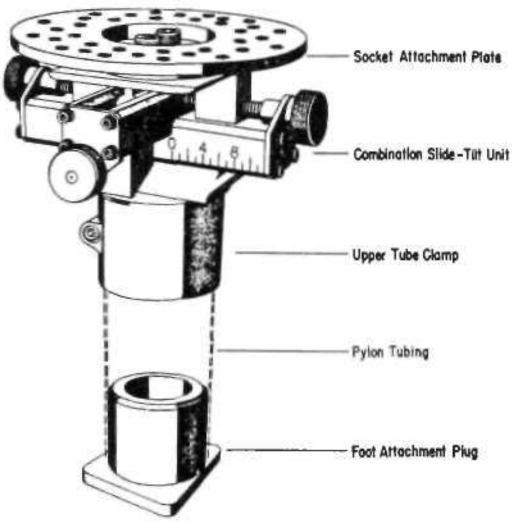



Fig. 18. The University of California below-knee adjustable shank.

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

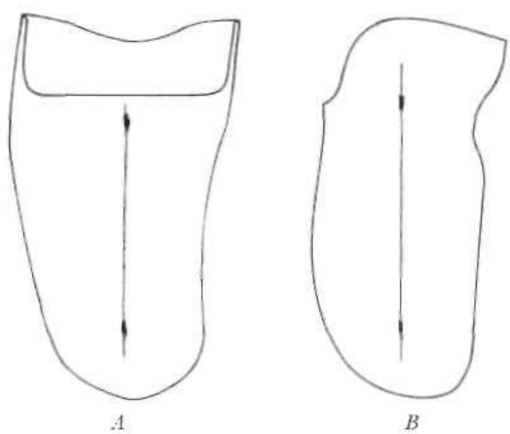



Fig. 19. Anteroposterior and mediolateral centerlines of the socket, intended for reference in alignment. In each of the two views, the approximate "center" of the brim and the estimated "center" of the bottom of the socket are connected by straight lines, except that in the lateral view the proximal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

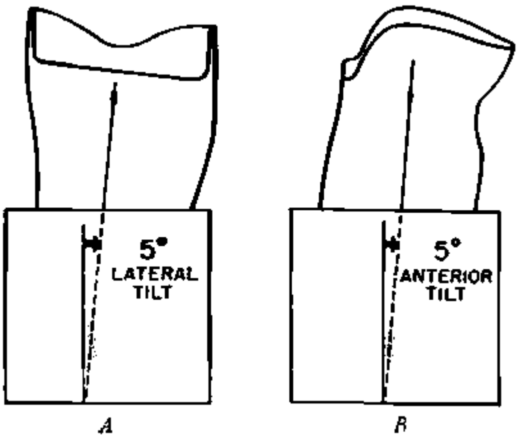



Fig. 20. Positioning of the socket in the socket block to give 5 deg. of adduction and 5 deg. of initial flexion.

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 1 1/2 in. in front of the centerline of the upper tube clamp (Fig. *2\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 1/2 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.

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 3/4-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.

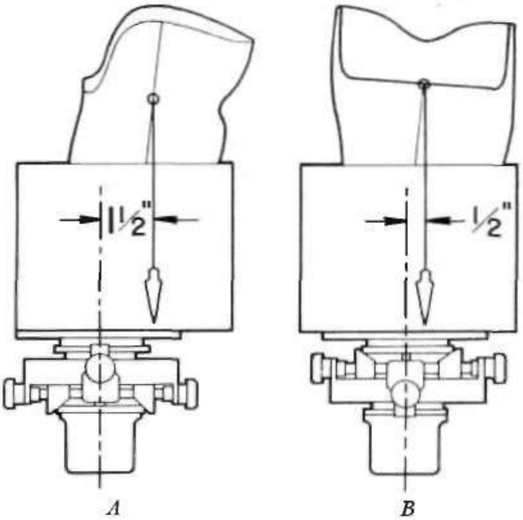



Fig. 21. Orientation of socket and socket block upon adjustable shank using socket centerlines for reference.

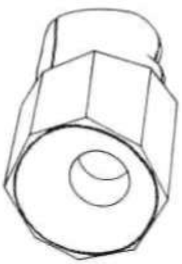


Fig. 22. Socket and socket block after removal of excess wood from the latter. Circle on base marks position of socket-attachment plate for reattachment of adjustable shank.

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

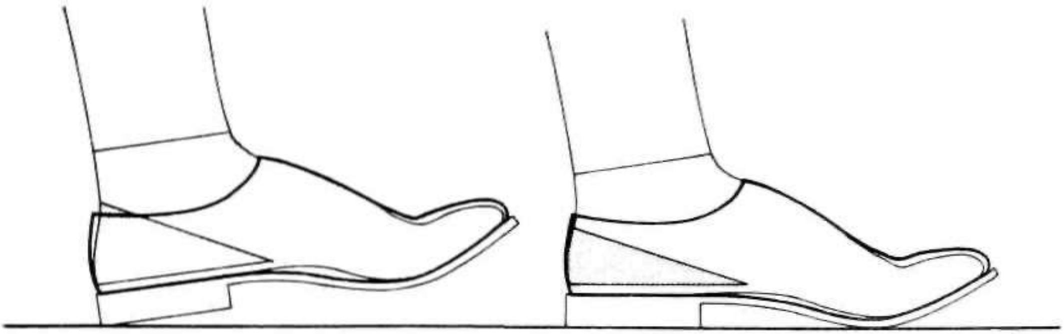



Fig. 23. The SACH foot, in transparent shoe, schematic. *A*, Heel contact; *B*, plantar flexion immediately after heel contact, heel wedge compressed. Rocker shape of keel at the ball of the foot gives support during roll-over and furnishes needed assistance at toe-off. Flexible toe piece permits normal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

foot-ankle units commercially available, the most satisfactory results are usually obtained with the nonarticulated SACH foot (Solid Ankle, Cushion Heel), 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 |

Table 1. 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

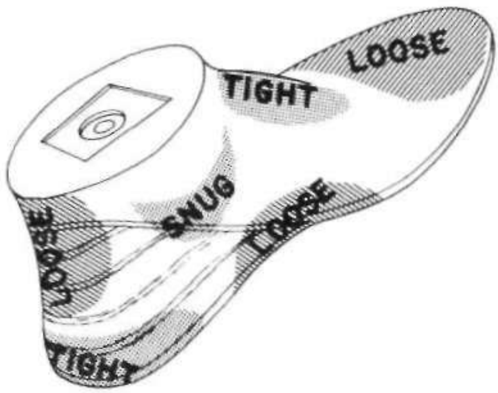



Fig. 24. Shaping of the SACH foot blank to the requirements of the shoe. Failure to maintain tightness in the areas indicated, or to provide relief in the others, leads to abnormal gait regardless of the care taken in construction of the rest of the prosthesis.

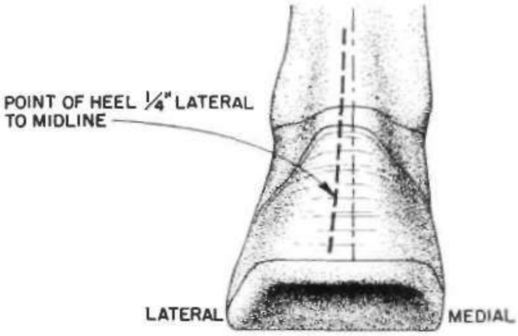



Fig. 25. Shaping of the heel of the SACH foot to accommodate proper toe-out in the finished prosthesis.

(Fig. 23). Required here is a minimum clearance of 1/8 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 1/8 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 1/4 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-

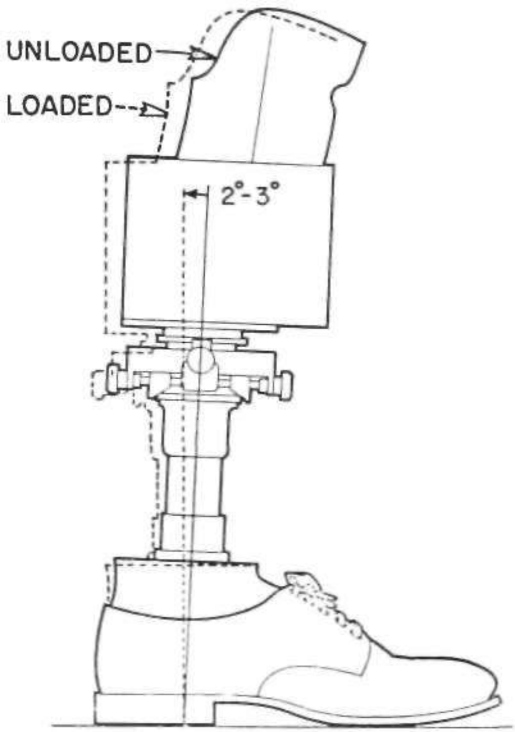



Fig. 26. Trial below-knee leg showing proper anterior tilt of shank (2 to 3 deg.) in the unloaded condition (without weight of wearer). Dotted outline shows return of the long axis of the shank to the vertical when amputee stands upon the prosthesis (initial compression of heel wedge). Should these relationships 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. *23B).* 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

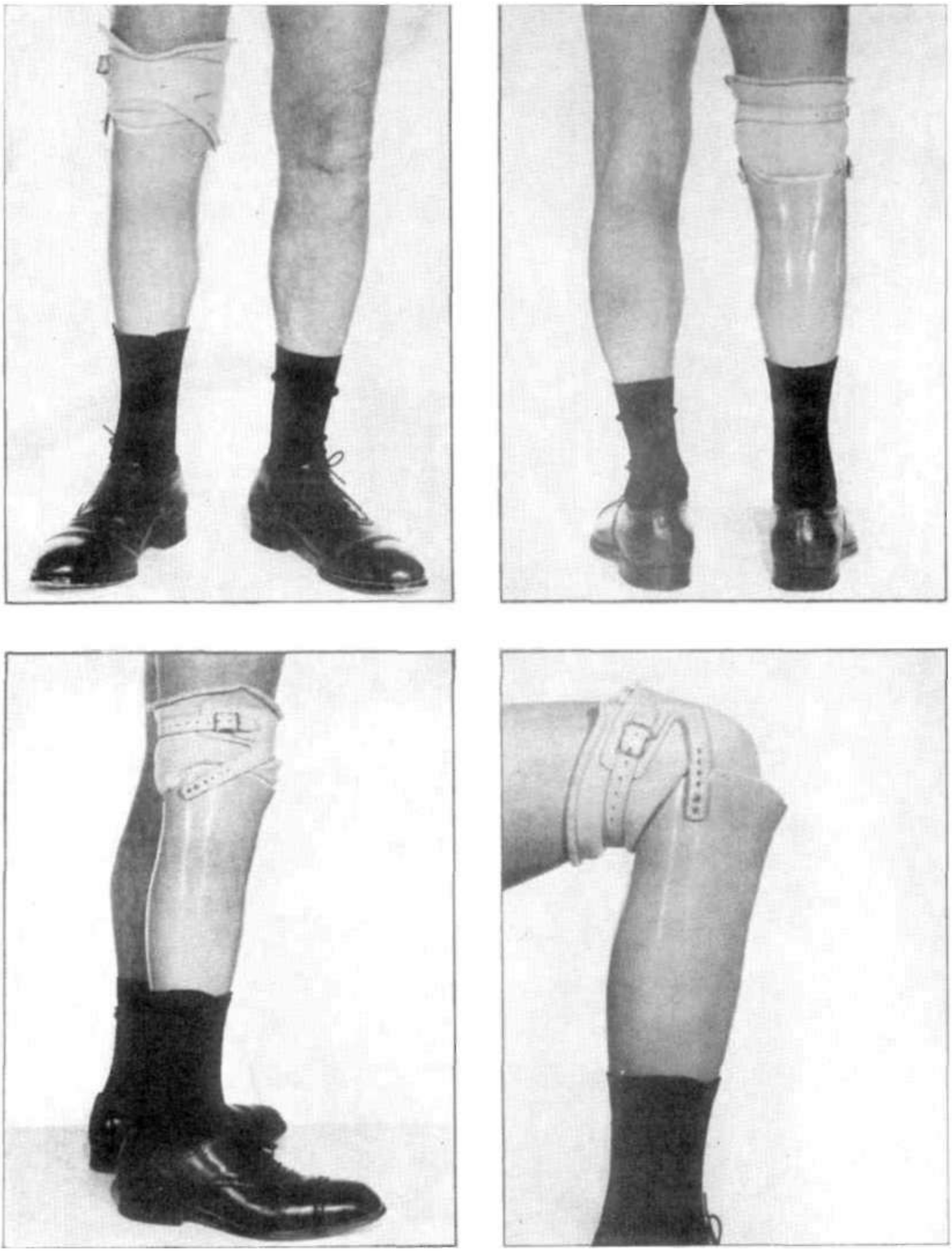


Fig. 27. Finished PTB prosthesis using supracondylar cuff as only means of suspension.

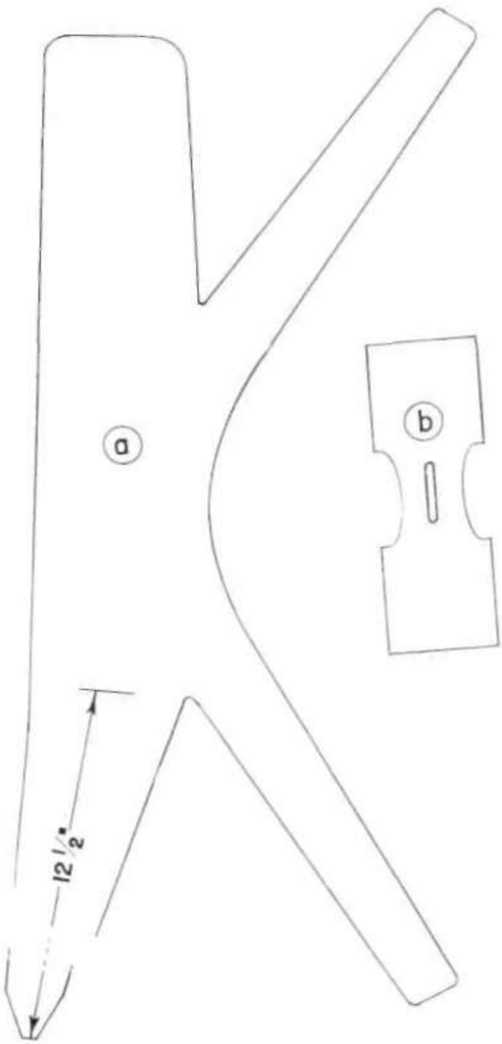



Fig. 28. Patterns (one half actual size) for preparing supra condylar cuff, a, Pattern for the cuff itself; *b*, pattern for the buckle billet.

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.

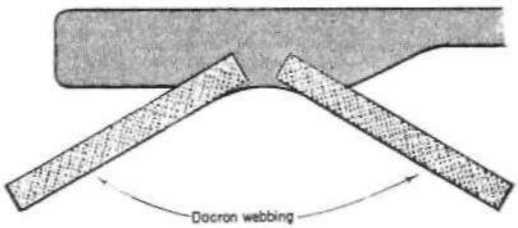



Fig. 29. Application of Dacron webbing to cuff side tabs to prevent undue stretching of the leather.

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).

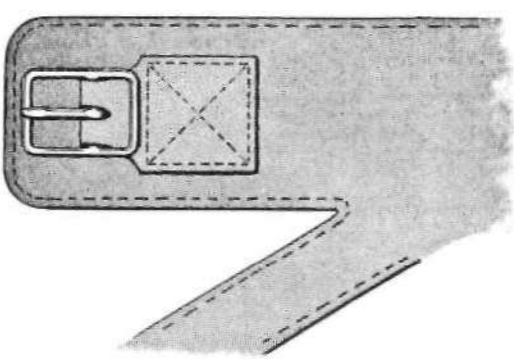


Fig. 30. Installation of buckle and buckle billet on condylar cuff.

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

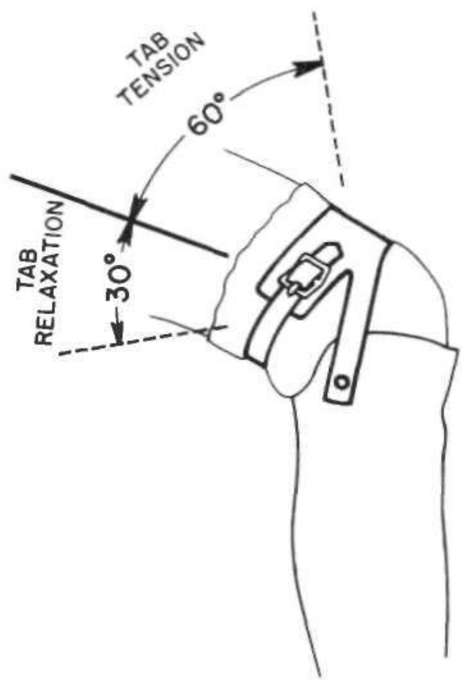



Fig. 31. Positioning of cuff side-tab attachments such as to provide tab tension throughout 60 deg. of knee flexion in the swing phase of walking and tab relaxation throughout an additional 30 deg. to accommodate comfortable sitting with knee flexed a full 90 deg.

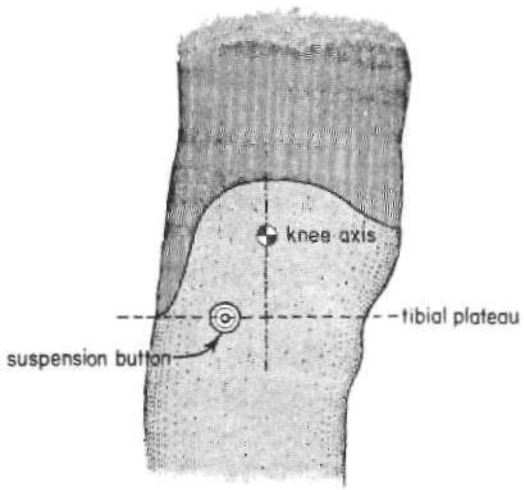



Fig. 32. Attachment of side-tab buttons at position determined in Figure 31. The usual position, arrived at by trial and error, is behind the average anatomical knee axis at the level of the tibial plateau.

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.

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

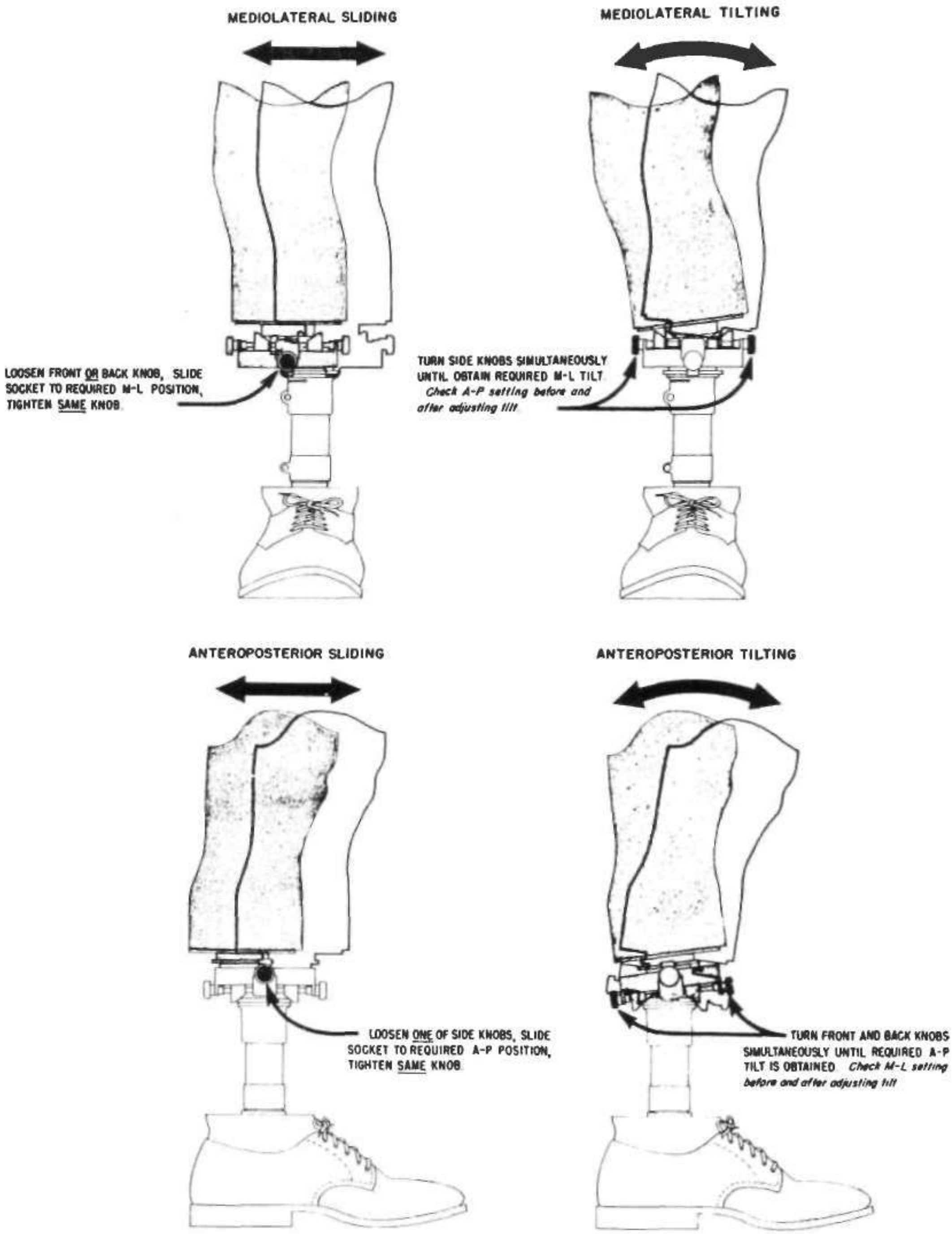
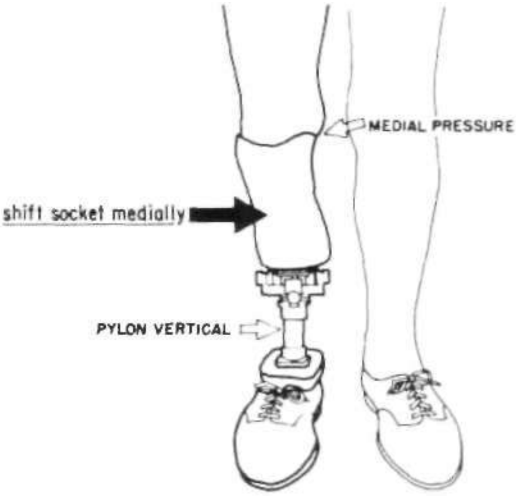



Fig. 33. Preliminary alignment of trial leg in four successive steps using the adjustment facilities of the UC below-knee adjustable shank.

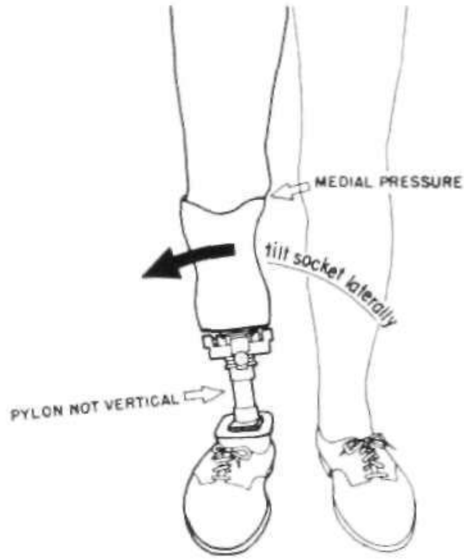
made to correct a fault at a given point without considering the possibility of thus upsetting position relationships at another. The whole process of alignment is in fact a series of checks and rechecks, and it is the responsibility of the prosthetist to determine the site of faults, if any, and to 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 encountered 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

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.

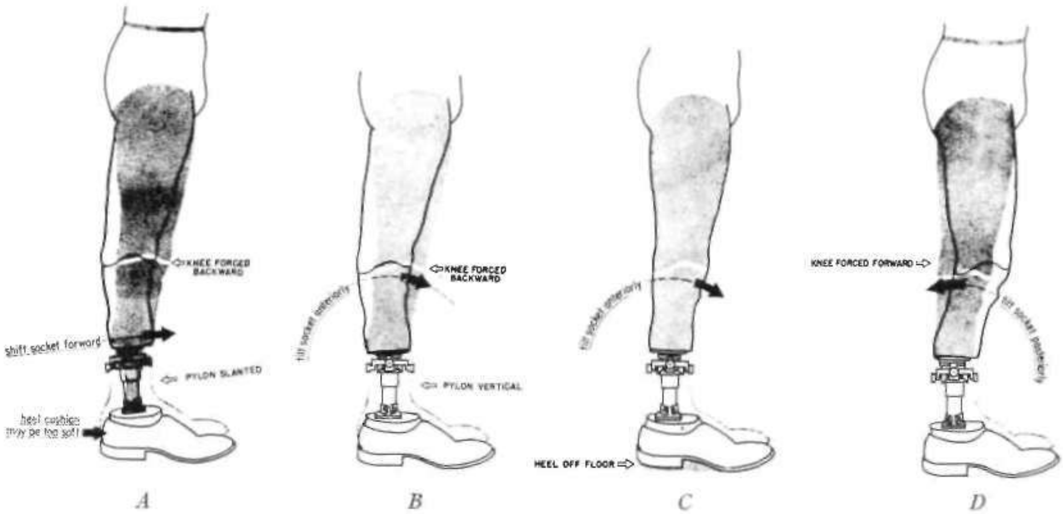



Fig. 35. Faults in anteroposterior alignment sometimes found during initial trials of prosthesis on amputee. *A*, Knee forced backward, shank pylon tilted posteriorly so that too much weight is borne on heel; *B*, knee forced backward but with shank pylon vertical (foot flat); *C*, heel off floor, all 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. 345, 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. 345). When, in Figure 345, 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. *35A)*, standing vertical in another (Fig. 355). 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. 355), 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. *35D).* 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. 35C), 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

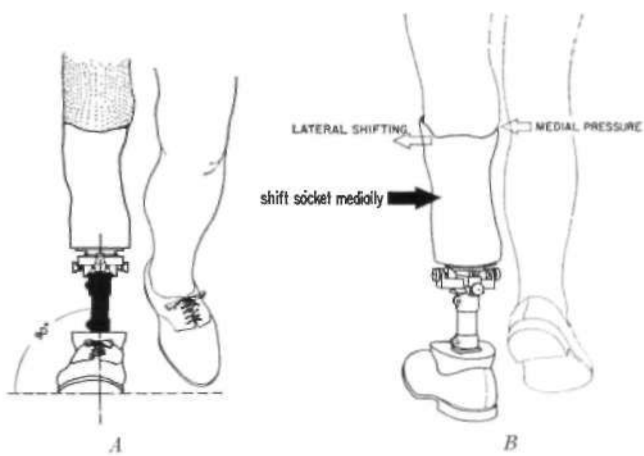



Fig. 36. Check of foot and socket in mediolateral plane during walking. *A,* Proper alignment in front view; *B,* correction for undue pressure at medial brim of socket, rear view. Compare with Figure 34*A.*

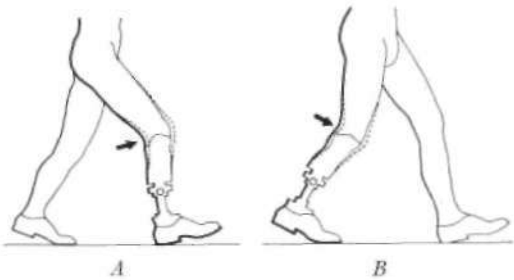



Fig. 37. Check of anterior tilt of socket (and hence of initial knee flexion). Too much initial flexion, as here, may cause loss of knee stability at heel contact *(A)* or lack of support (drop-off) at the end of the stance phase (B), or both.

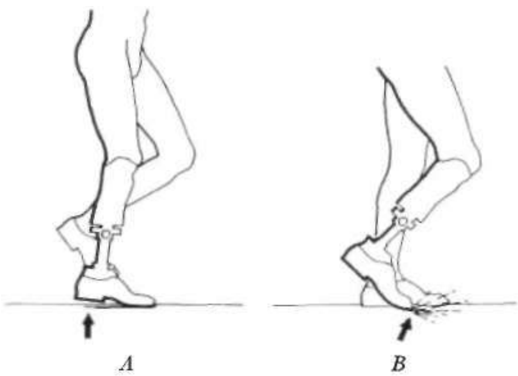



Fig. 38. Check of posterior tilt of socket. Too little initial knee flexion (excessive posterior tilt of the socket) may cause early arrest of knee flexion after heel contact, or a prolonged period of unstable weight-bearing on the heel, or an excessive shift of the body weight to the ball of the foot 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-

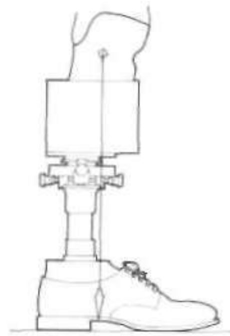


Fig. 39. Ultimate anteroposterior position of socket with respect to shoe. A plumb line dropped from the anteroposterior centerline of the socket at the level of the midpatellar tendon should pass just ahead of the breast of the heel of the shoe.

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-

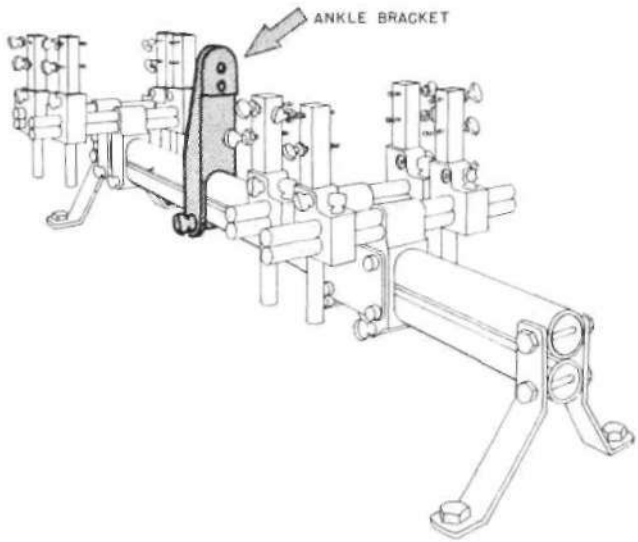



Fig. 40. University of California alignment-duplication jig for above-knee prostheses, as adapted for below-knee alignment duplication through substitution of the ankle bracket (cross-hatched) for one of the adjustable clamps.

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 of the way temporarily (Fig. 40). Drilled through the top of the ankle bracket is a 3/8-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

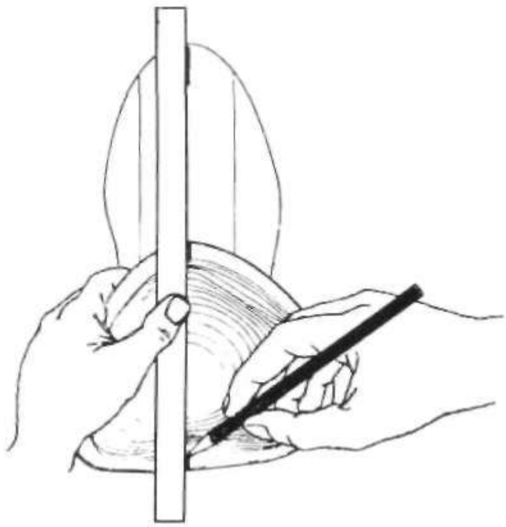


Fig. 42. Recording toe-out of foot before removing foot from adjustable shank. Same toe-out must be re-established later. See Figure 50.

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-

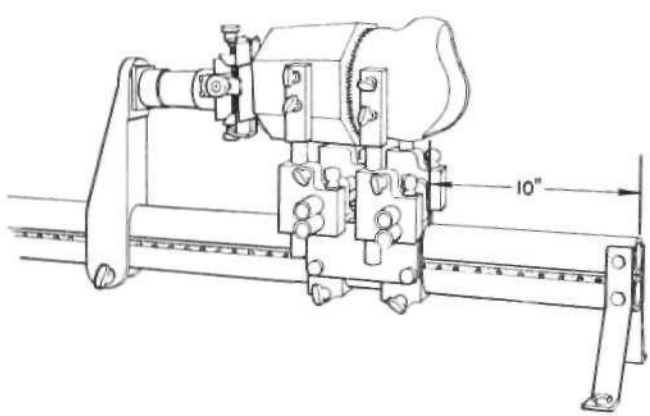



**Fig.** 43. Setting of socket clamp to the orientation previously established by the ankle bracket. At least 10 in. should be allowed at socket end so that socket clamp and socket may later be moved out of the wav. See **Figure** 45.

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 1/4 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

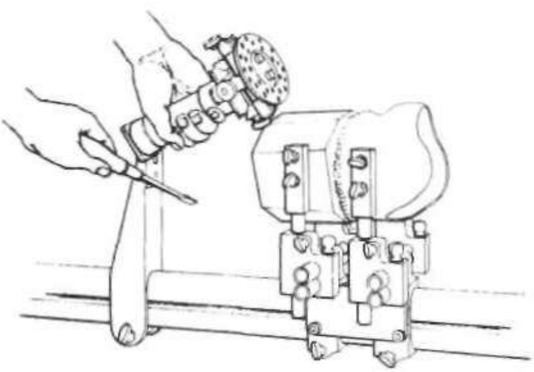


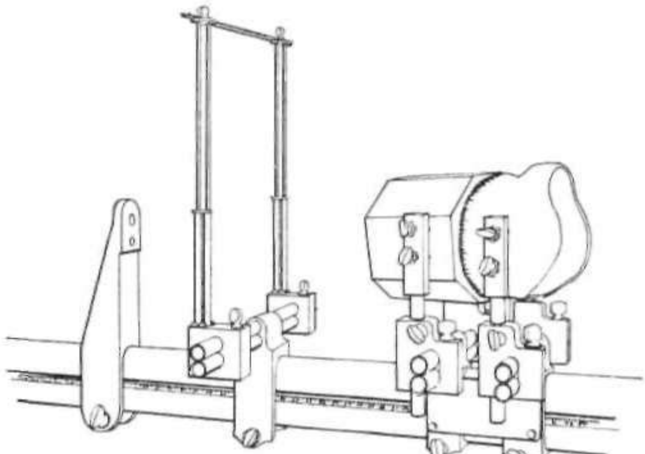
Fig. 44. Removal of the adjustable shank.

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.

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



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

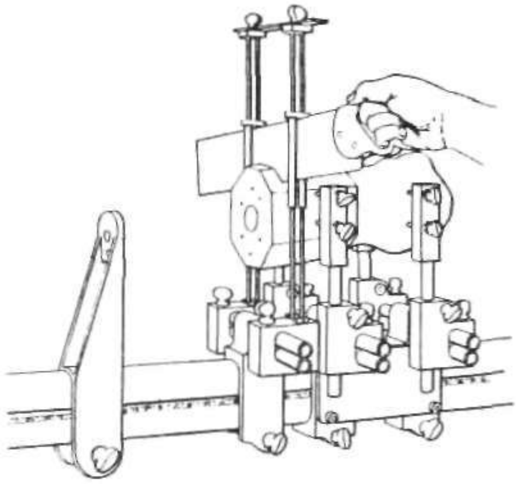


Fig. 46. Making saw cut on bottom of socket block. Remove not more than 1/4 in. at thinnest point about periphery.

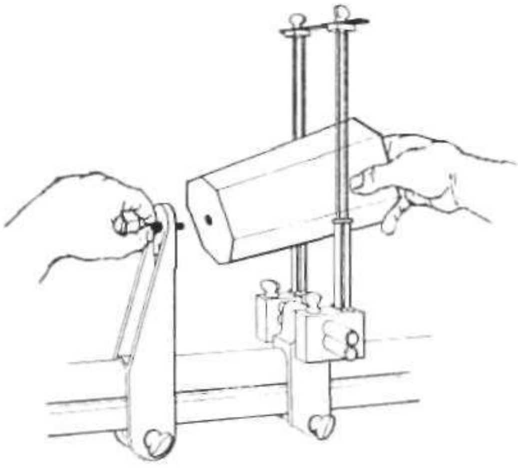


Fig. 47. Attachment of shank block to ankle bracket.

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

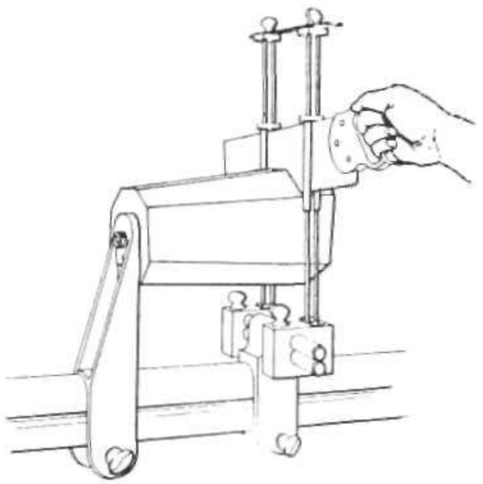


Fig. 48. Making saw cut on top of shank block. Length of block after cutting shall be such that it may be substituted for the adjustable shank and pylon without significant change in over-all length of the prosthesis.

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. *52B).* 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 1/16 in. from the edge (Fig. 52C), 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

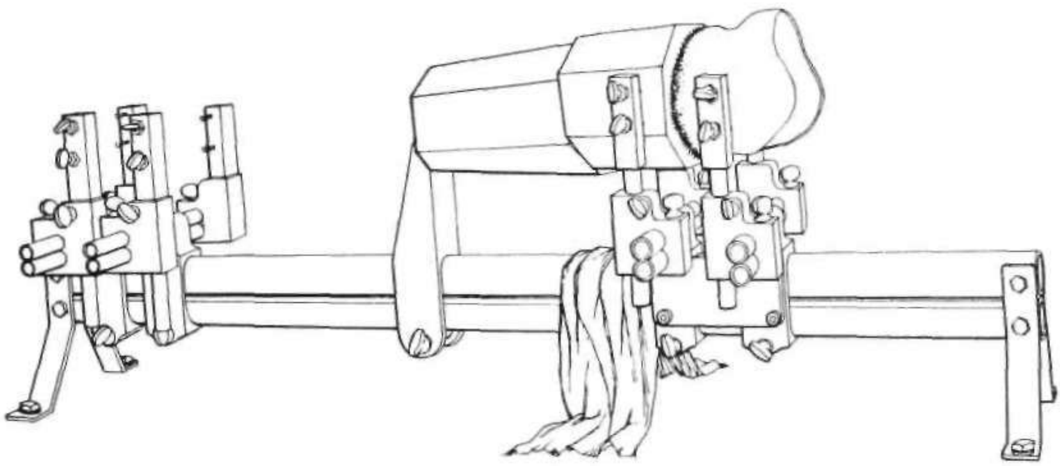


Fig. 49. Shank and socket block glued together in relationship established by jig fixtures. Dripping glue is caught by waste thrown over jig base.

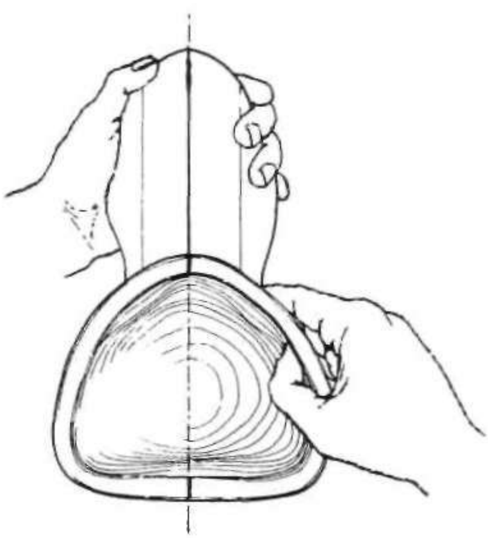


Fig. 50. Attachment of foot to shank with same relative toe-out as existed in trial leg using adjustable shank. Compare with Figure 42.

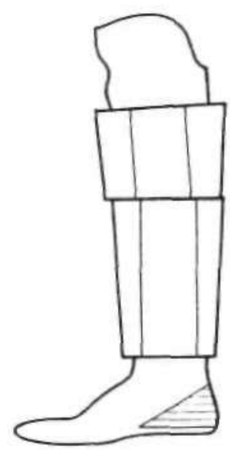


Fig. 51. Assembled prosthesis ready for external finishing. Orientation of parts is that established in trials of static and dynamic alignment.

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 1/4 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.

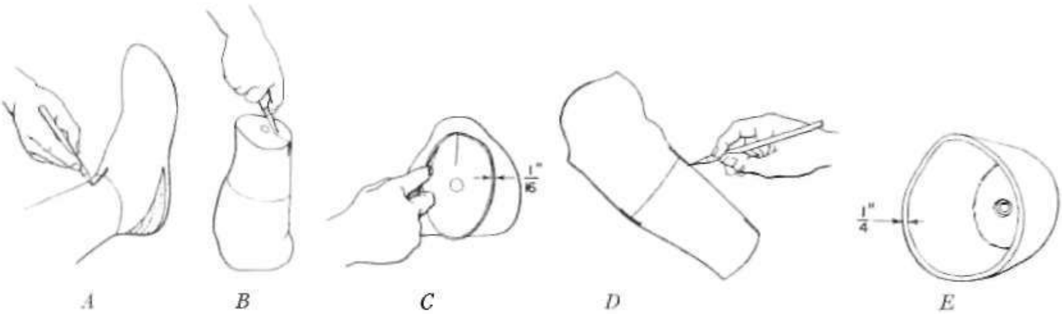



Fig. 52. Preliminary steps in the finishing of the PTB prosthesis. *A*, Marking the established toe-out of foot with respect to shank; *B*, foot removed, reference mark transcribed to bottom surface of shank to avoid obliteration in next step; C, 1/16 -in. annular ring marked about bottom surface of 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.

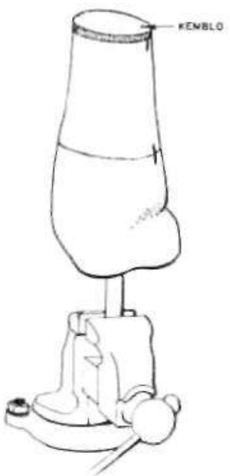



Fig. 53. Application of disc of Kemblo to end of shank prior to layup and lamination.

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. When the resin has cured, the excess (including the ends of the PVA sleeve) is trimmed off at top and bottom

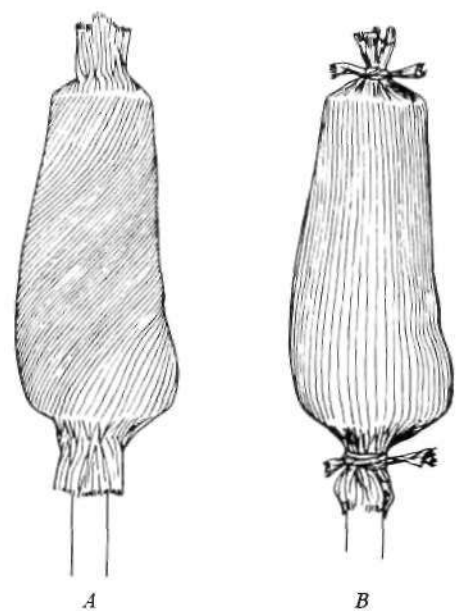



Fig. 54. Layup for lamination of socket-shank combination. *A*, First of two layers of nylon stockinet twisted over layer of Fiberglas cloth; *B*, second layer of nylon stockinet applied and tied off at both ends.

(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.

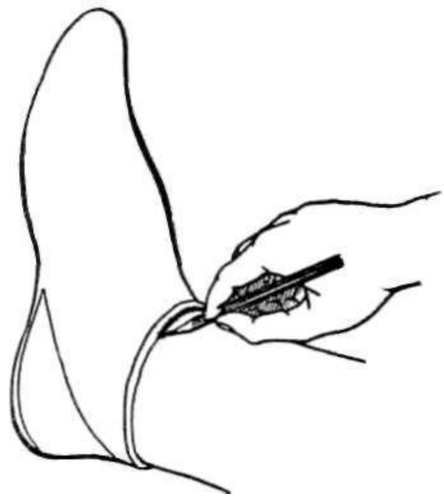


Fig. 55. Scribing foot at ankle line for sanding to provide smooth transition between foot and shank.

## 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

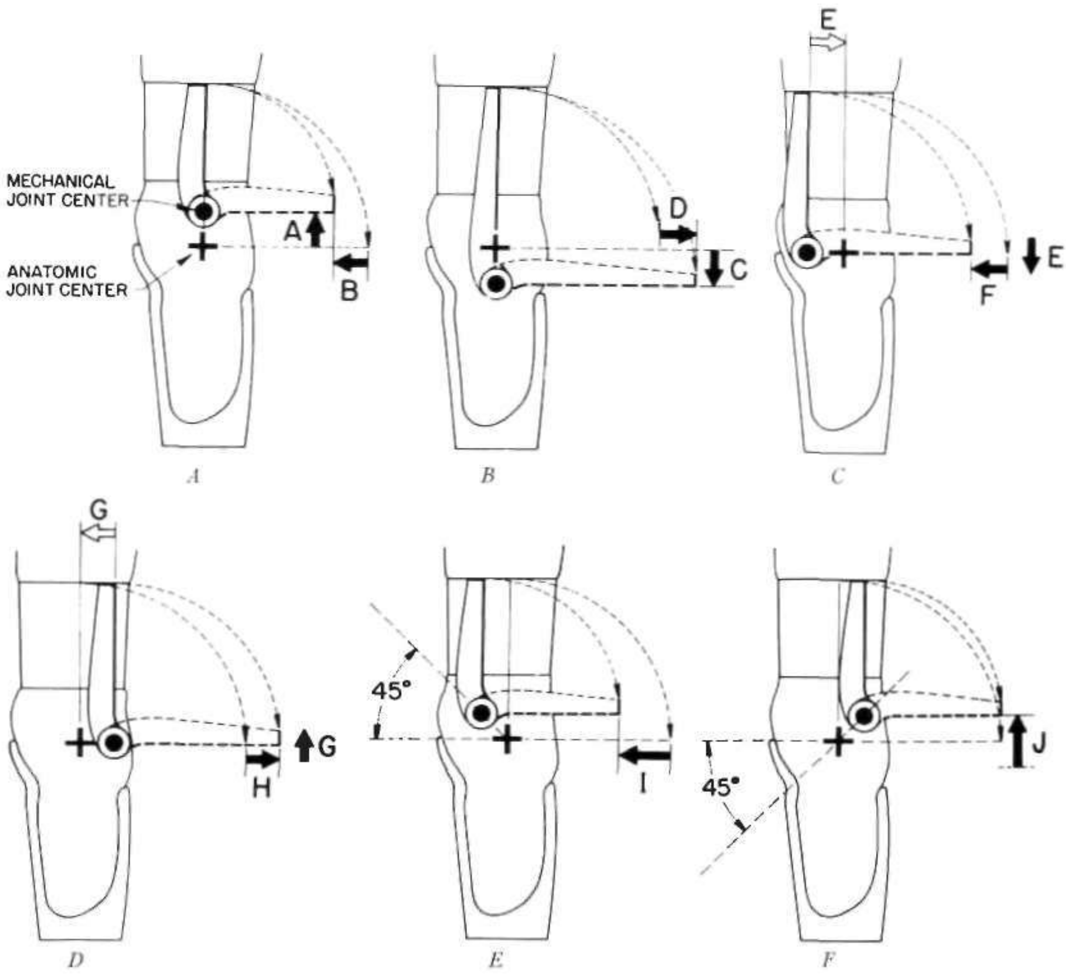



Fig. 56. Relative motion to be expected between thigh and thigh corset (stump fixed in socket) during 90 deg. of knee flexion when single-axis mechanical joints are placed in any of six positions relative to a hypothetical average anatomic joint center.

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[6] 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 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 *56B* 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 56C 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 *56D* 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 / (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 moLions 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 56.4, *D,* and *F).* To move the slump 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 *56A, 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,

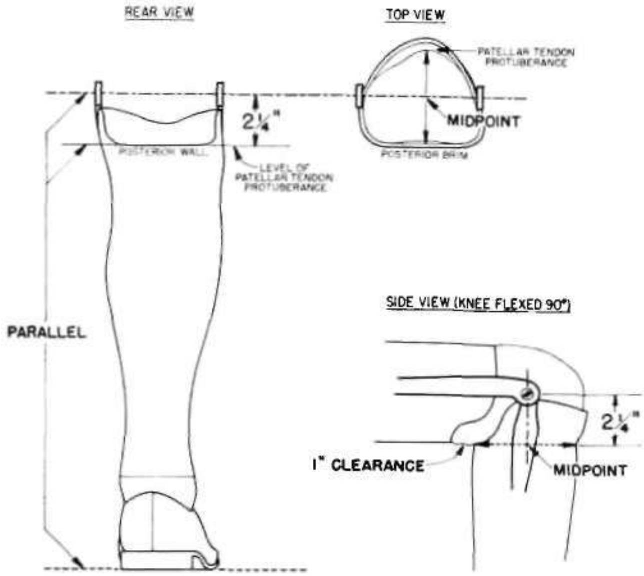



Fig. 57. Typical relationship between socket, joints, and thigh corset in a below-knee prosthesis.

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 2-1/4 in. above the level of the mid-patellar 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 2-1/4 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.

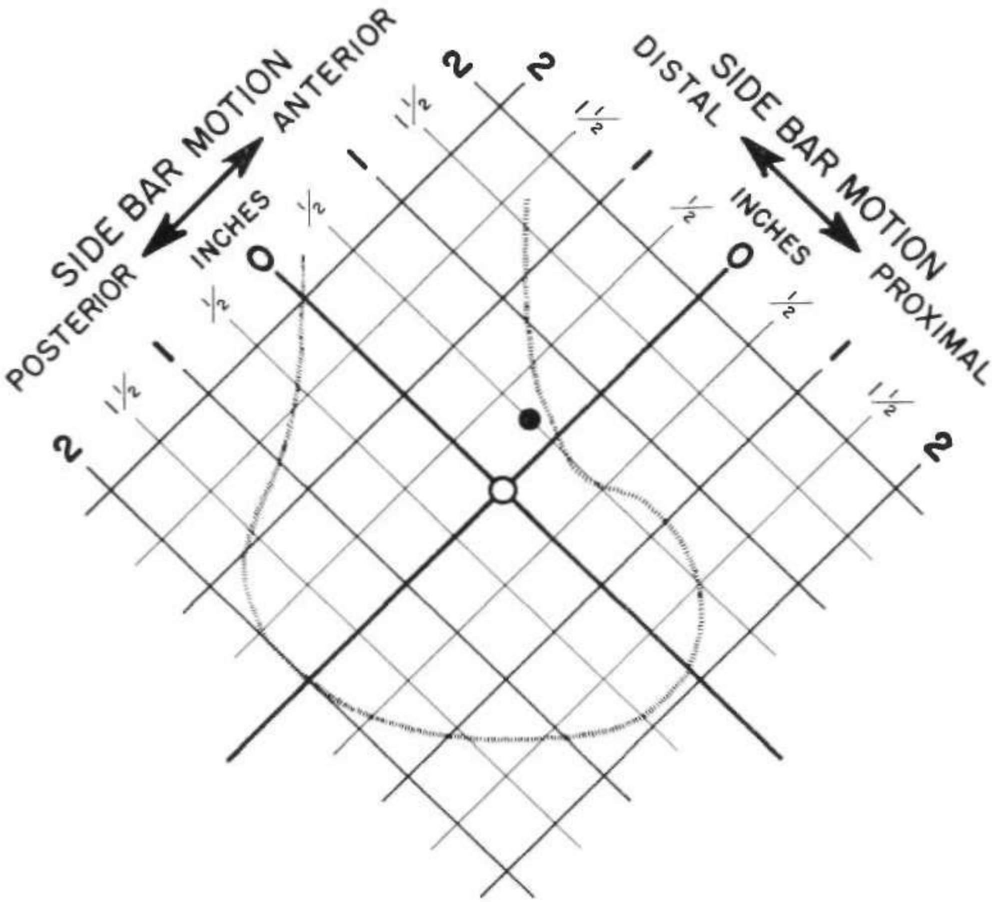
2. The amputee stands and extends the mechanical joint. The position of the front and top edges of the sidebar on the thigh is marked with a skin pencil.

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, O, represents the average anatomic knee center; the black circle 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 1/4 in. with 90 deg. of knee flexion. A motion between 1/4 and 1/2 in. is allowable. Motion greater than 1/2 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 1/2 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.

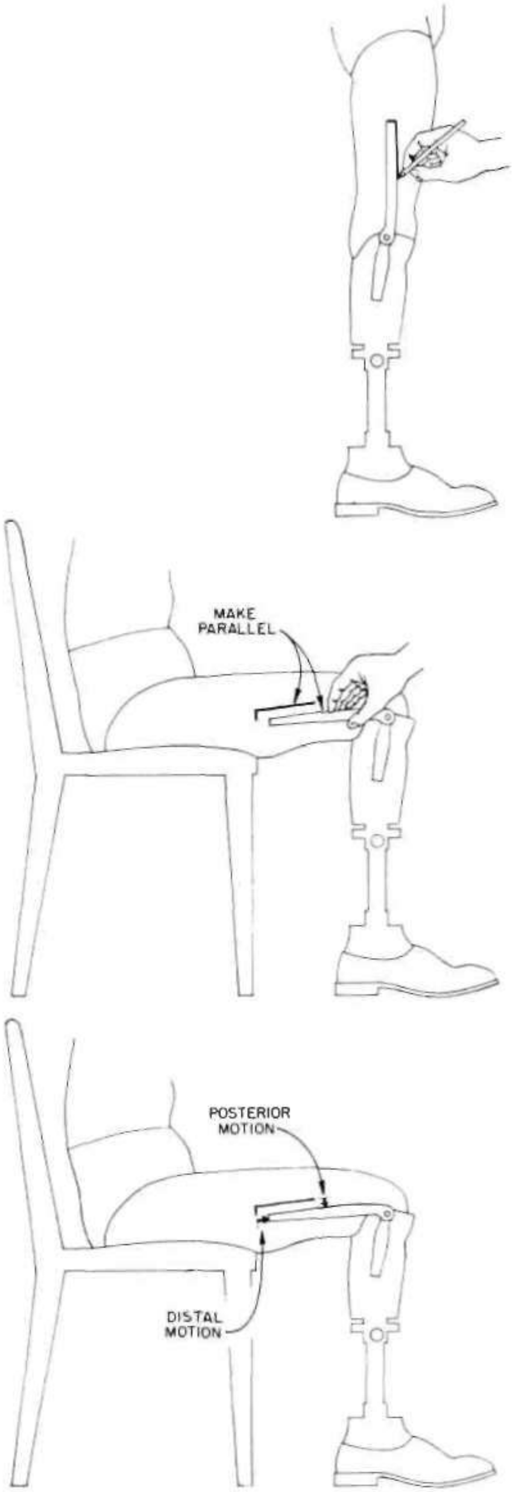



Fig. 59. Compromise location of upper sidebar straps in optimum position for comfortable walking as well as for comfortable sitting.

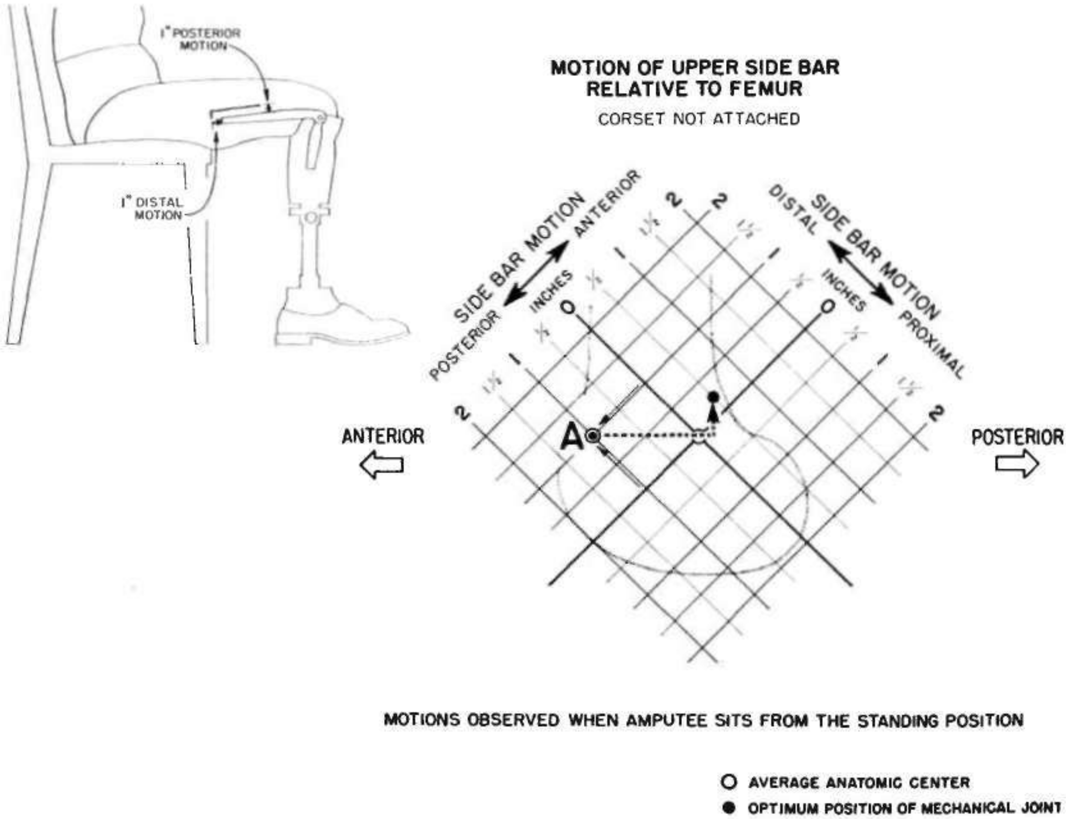



Fig. 60. Example of use of chart shown in Figure 58, chart reduced from actual size.

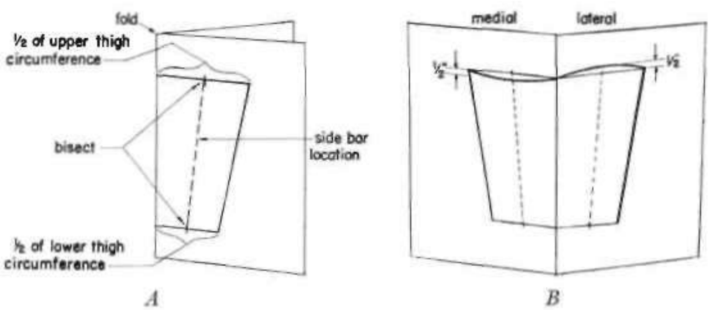



Fig. 61. Preparation of corset pattern. *A*, Paper folded in half, top and bottom margins of corset marked, lines parallel to edge projected to the extent of half the circumference of thigh at upper margin and half the circumference of thigh at lower margin respectively, ends of lines connected by straightedge, 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 1/2 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 61.4) 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 615, and the proximal margin is cut roughly in the shape of a sine curve of 1/2 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

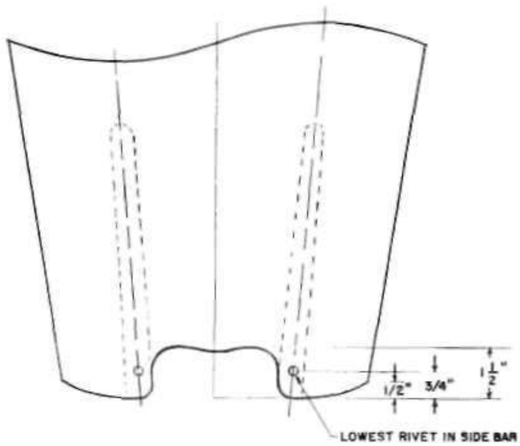



Fig. 62. Distal margin of corset pattern outlined to match requirements of popliteal space, location of upper straps of single-axis sidebars marked for future reference.

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 3/4 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 1/8 in. in diameter and so spaced along the length of each strap that the first is 1/2 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, 1/8-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.

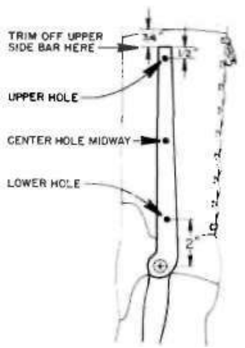



Fig. 63. Preparation of upper sidebar straps for later attachment to leather thigh corset.

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. 645), 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. *(AC)*. 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 1-1/4 in. apart (Fig. 65). The corset is removed from the patient, the edges trimmed as marked, and 1/4-in. holes for the lacing are punched along each edge on 1-in. centers along lines 3/8 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-

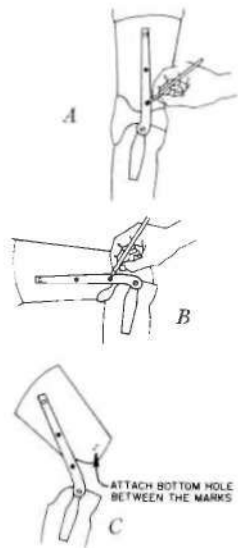



Fig. 64. Tentative attachment of upper sidebar straps to corset.

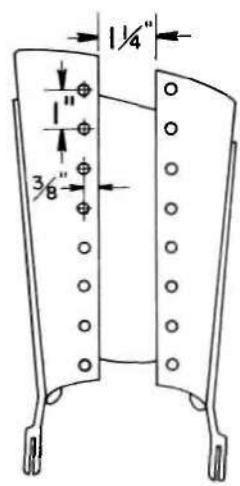



Fig. 65. Trimming of front edges of corset, placement of lacing holes in proper position.

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 2-1/2 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

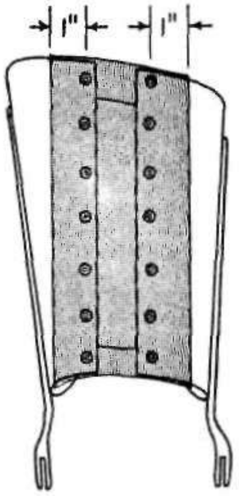



Fig. 66. Relative size and shape of corset tongue.

in and skived edge lying 2-1/4 in from the edge (which leaves about 1/4 in. of surplus horsehide for later trimming).

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 2-1/4 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

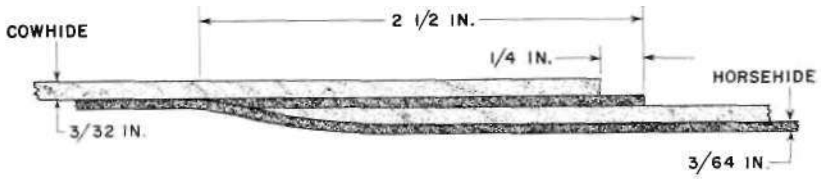



Fig. 67. Lining of corset tongue area on fixed side of tongue.

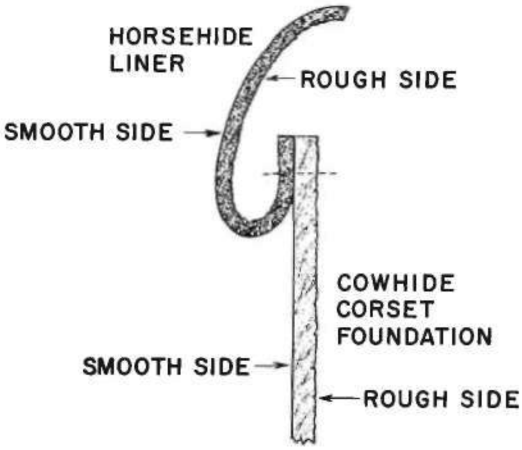



Fig. 68. Lining of entire internal surface of corset and tongue.

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

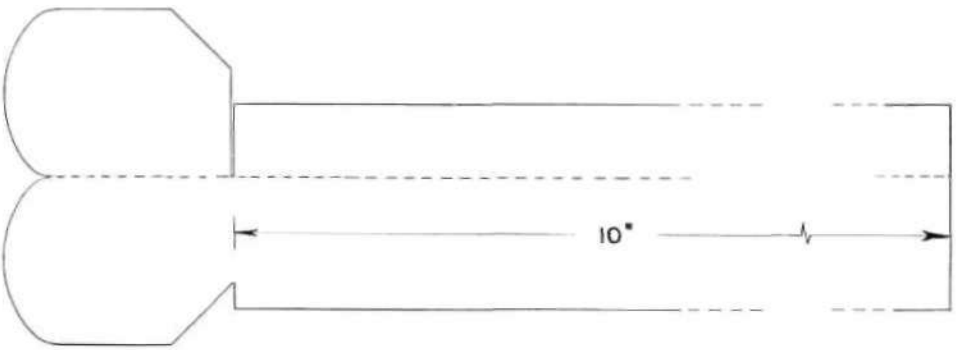



Fig. 69. Pattern for side-joint covers, half actual size.

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 1/8-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

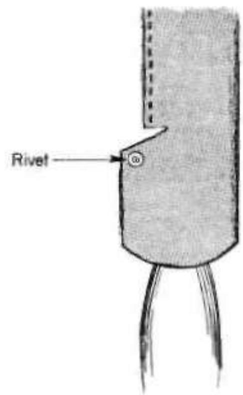



Fig. 70. Installation of side-joint covers for protection of clothing.

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*

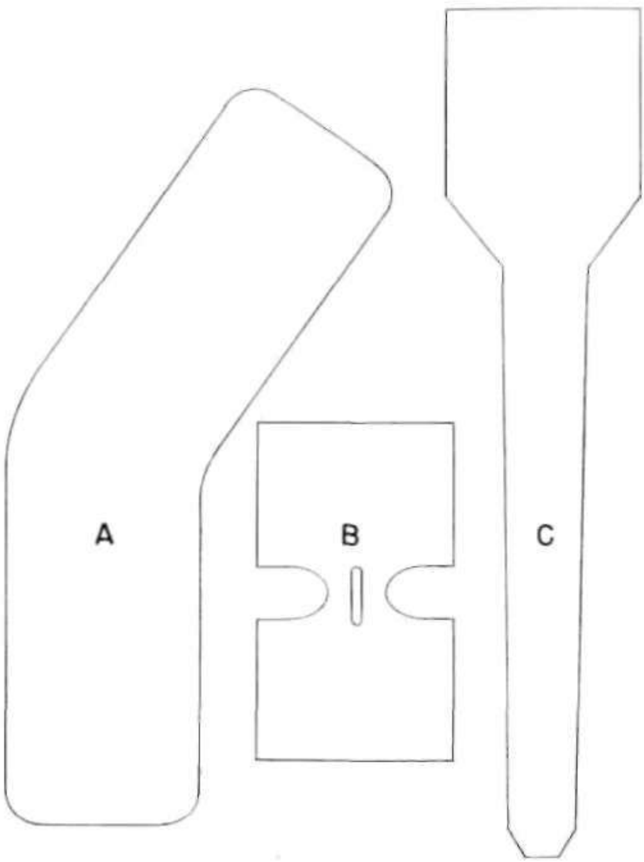



Fig. 71. Patterns for construction of the pelvic belt shown in Figure 73, half actual size.

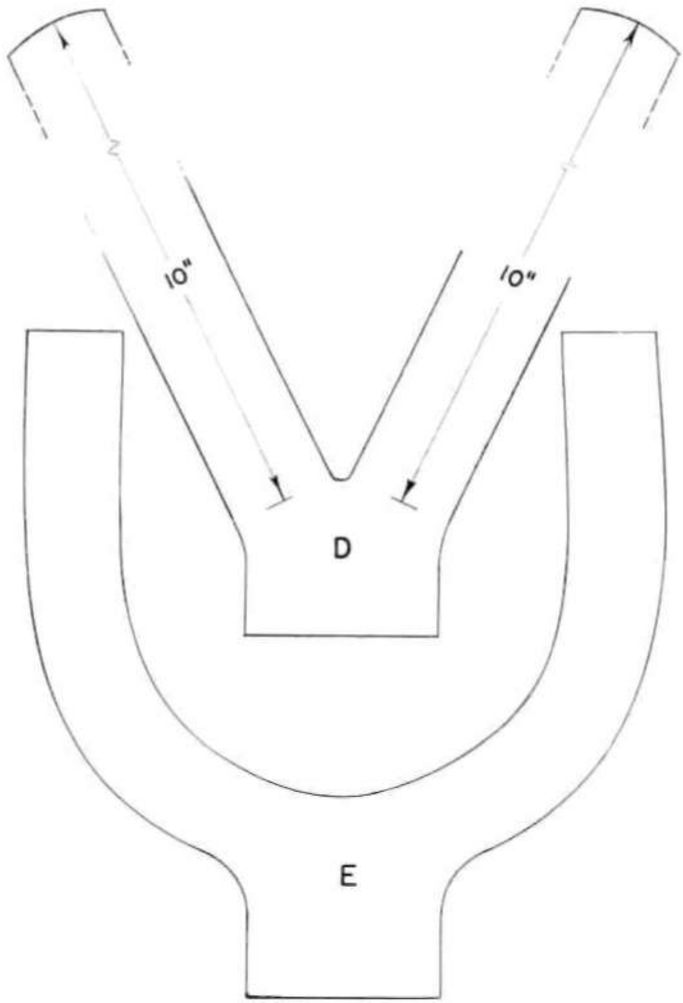



Fig. 72. Patterns (one half actual size) for suspension straps when (*D*) thigh corset and sidebars are used and *(E)* when thigh corset and sidebars are not used.

(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 (5/8-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.

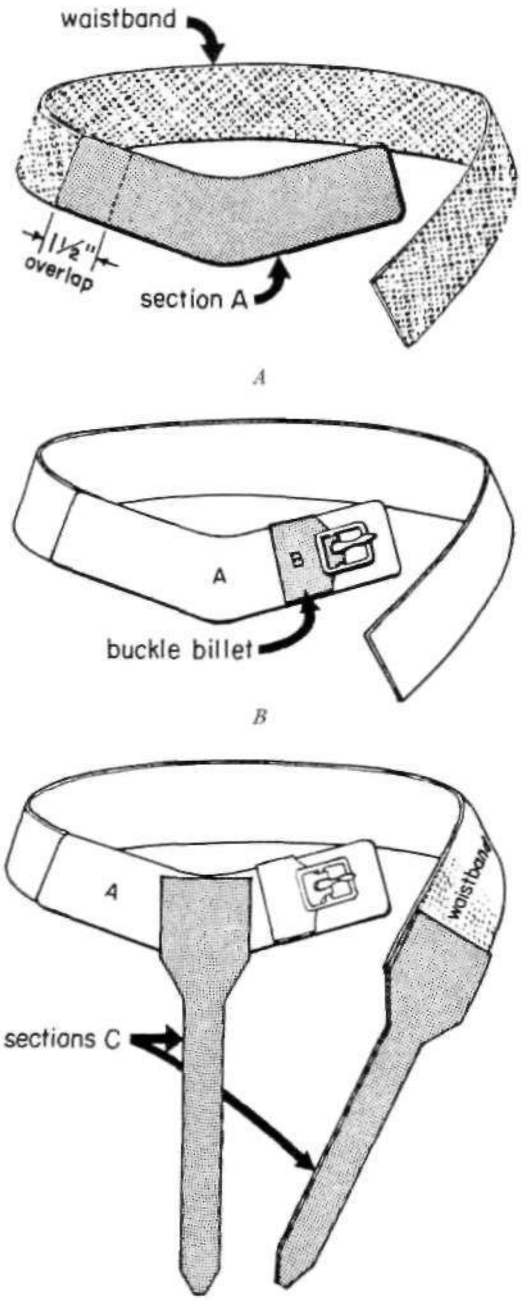



Fig. 73. Details of assembly of the pelvic belt.

As for details of actual construction, section *A* (Fig. 73) is first bonded to the waistband with rubber cement with an overlap of 1-1/2 in. the bonded side being on the side of the amputation (Fig. 73C). The skived ends of the leather sections *B* (Fig. 71) are lapped back on each other, each piece is threaded with a 5/8-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

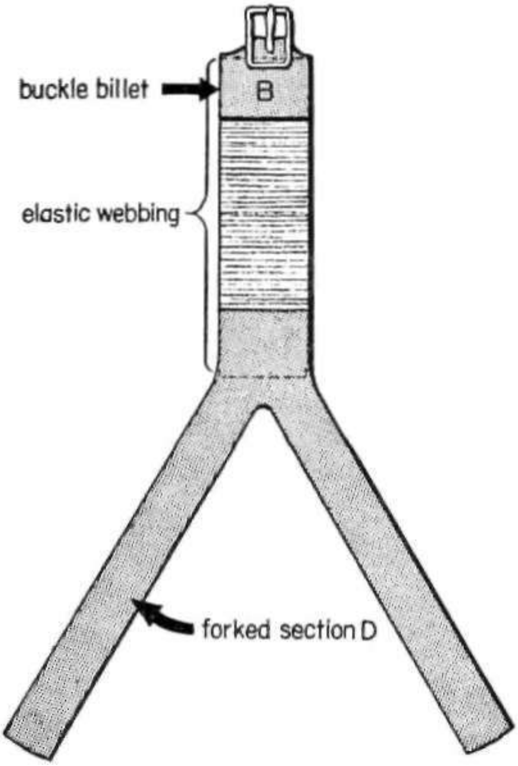



Fig. 74. Details of suspensor strap when pelvic belt is used in addition to thigh corset and sidebars. When thigh corset and sidebars are not required, section *D* (Fig. 72) is replaced by section *E* (Fig. 72).

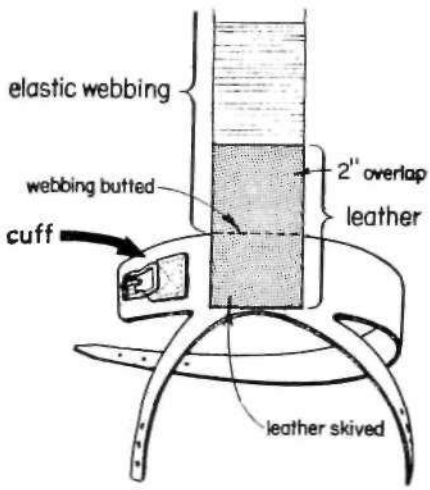



Fig. 75. Arrangement of suspensor strap when auxiliary support from pelvic belt is used in conjunction with the supracondylar cuff but without thigh corset and sidebars.

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

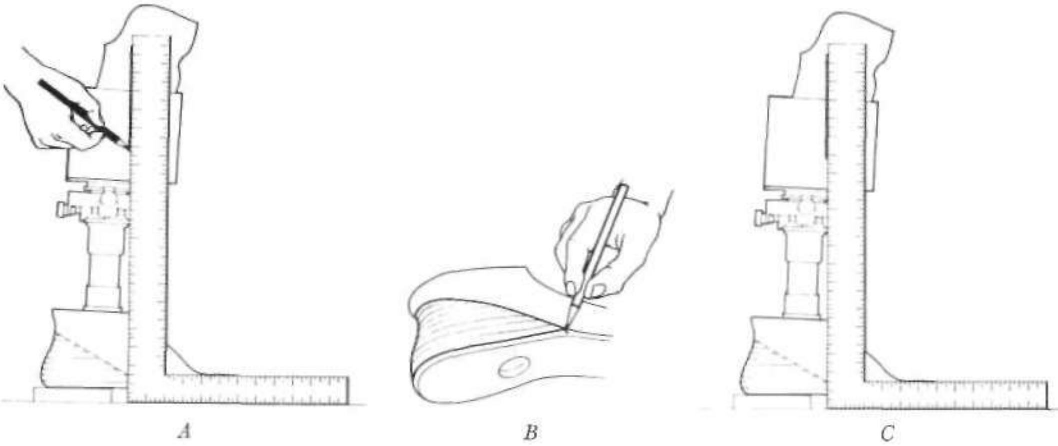



Fig. 1. Method of changing heel cushion in SACH foot whenever cushion is found to be too soft or too stiff. *A*, Recording existing alignment (to be preserved); *B*, marking about sole of heel to establish anterior point of heel wedge (also to be maintained); *C*, checking alignment after new cushion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