Evaluation for a Prosthesis

When a candidate is being evaluated for a transtibial prosthesis, a comprehensive physical examination including a detailed history or interview is essential to determine his or her needs and limitations. The interview assesses the individual’s cognitive level, age, health history, vocation, avocation, support system, and home living status. A typical physical examination includes inspection, palpation, sensory testing, and skin integrity assessment. The examination should also include manual muscle testing, an evaluation of muscle performance using both active and passive range-of-motion (ROM) testing. This is also an ideal time to discuss rehabilitation goals with the person with amputation and the rest of his or her clinical team. Setting challenging yet realistic goals offers opportunities for incremental victories, which can go a long way toward reaching a successful outcome. Each member of the clinical team—the person with amputation, the therapist, the physician, and the prosthetist—has information and input that can be useful in the rehabilitation process. The best outcome will be achieved through a collaborative endeavor involving all team members. There are no hard-and-fast rules to determine an individual’s rehabilitation potential. The decision to move ahead with fitting a prosthesis is made on an individual basis.

When the candidate for a prosthesis is being interviewed, the individual’s motivation and belief in his or her ability to walk with such an aid will be the deciding factors. The rehabilitation process will require both physical and mental effort; sometimes it will involve working through pain, discomfort, and weakness. When persons with amputation have the desire and drive to walk again, it is rare that they will not succeed in attaining that goal. Alternatively, if a person does not believe that walking will be possible, all efforts to enhance that person’s recovery may be in vain. Involving the person with recent amputation in an amputee support group or asking a local prosthetist to arrange for a peer visit by another person with amputation can provide inspiration. Encouragement from therapists, family members, or prosthetists who have not experienced amputation may not have the same impact. Peer visitors are individuals of similar age, gender, and amputation level who have been through the rehabilitation process and have successfully reintegrated into their communities (work, leisure, and/or social). Peer visitors are often available to spend time with those with recent amputations and to share their experiences. The internet hosts a variety of organizations that provide support and information for persons new to amputation and the use of prostheses; it can serve as a way of finding local groups that may be helpful to the patient.

Because amputation is often the result of trauma or disease, there may be comorbidities that can complicate the overall management of the person with amputation. A variety of options are available to the prosthetist to provide a functional prosthesis even when the condition of a residual limb is not ideal. Mild to moderate knee flexion contractures and weakness, for example, may be accommodated by altering the alignment of the prosthesis. Skin issues, such as adherent scarring and eczema, can be addressed by selecting the appropriate interface material. Pressure on skin and soft tissue over prominent bones can be relieved by altering the socket shape. There are also options for those with severe upper-limb dysfunction that will enable the individual to don and doff a prosthesis independently. It is only with careful consideration of the persons complete profile that the clinical team can recommend the components and design that will lead to an optimal outcome.

This clinical analysis includes choosing the features that are most appropriate for the individual’s current status and the anticipated level of function. The most appropriate prosthesis is the prosthesis that suits the person’s individual requirements. One size does not fit all: the ideal prosthesis for one person may be completely unsuitable for another.
Prosthesis design is often a compromise of weight versus function. Adding features that may seldom be used will increase the weight and maintenance requirements of the device. Increased weight leads to increased energy expenditure and premature fatigue. On the other hand, exclusion of features that the patient will need on a regular basis may lead to excessive stresses on the limb, premature component wear or breakdown, and inefficient gait, resulting in the inability to attain optimal function. The clinical team should agree on the individual’s goals so that the prosthesis can be designed to meet these goals. With the advanced materials and fabrication techniques available to prosthetists, individuals using a prosthesis are able to walk farther and with greater energy efficiency than ever before.

Generally speaking, individuals who undergo transtibial amputations are likely to return to their previous level of function. Those with dysvascular disease or those who have additional comorbidities because of injury or disease need special consideration as they develop their rehabilitation goals and anticipated level of function. The Center for Medicare Services created a hierarchical system to classify the functional potential of those with lower limb amputations. This system, comprising “K-levels,” is summarized in Table 23.1. Note that each functional level uses the phrase “has the ability or potential” in the description. This highlights the fact that individuals cannot reach their full potential until their prostheses are provided and rehabilitation has been successful. For certain benefits to be covered under Medicare, the individual must be certified by his or her prosthetist and physician with the appropriate K-level. This is to prevent the prescription of prostheses with costly components that the user will not be able to manage or use effectively. The selection of the proper K-level is greatly facilitated by the use of a validated, objective measurement instrument such as the Amputee Mobility Predictor. These measurement instruments can be used to assess the functional level of a person with an amputation even if they have not yet received a prosthesis.

### Early Management of a Prosthesis

Goals for the postoperative management of a transtibial amputee include (1) maintaining full ROM of the hip and knee, (2) facilitating rapid healing of the suture line, (3) maintaining or improving cardiovascular and pulmonary conditioning, (4) enhancing static and dynamic balance, and (5) maintaining functional strength in the remaining musculature. Table 23.2 breaks the lifelong rehabilitation of the amputee down into nine distinct stages and summarizes the goals of each stage.

One common complication of transtibial amputation surgery is a loss of full knee extension. Failure to promote full extension of the tibiofemoral joint can lead to delays in prosthetic fitting while ROM is restored. If the lack of knee extension remains, a permanent joint contracture can alter the prosthetic fitting process and lead to a decreased functional level for the person with an amputation. The clinical team generally encourages rigid dressings that extend well above the knee and hold the knee in full extension. Rigid removable dressings (RRDs) provide more favorable outcomes than elastic bandages when used to control postoperative edema and provide protection to the surgical site.

#### Table 23.1 Classification of the Functional Potential of Patients with Lower-Limb Amputations

<table>
<thead>
<tr>
<th>K-Level</th>
<th>Medicare Functional Classification Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>K0</td>
<td>The patient does not have the ability or potential to ambulate or transfer safely with or without assistance, and a prosthesis does not enhance quality of life or mobility.</td>
</tr>
<tr>
<td>K1</td>
<td>The patient has the ability or potential to use a prosthesis for transfers or ambulation on level surfaces at fixed cadence. This level is typical of the limited and unlimited household ambulator.</td>
</tr>
<tr>
<td>K2</td>
<td>The patient has the ability or potential for ambulation with the ability to traverse low-level environmental barriers such as curbs, stairs, or uneven surfaces. This level is typical of the limited community ambulator.</td>
</tr>
<tr>
<td>K3</td>
<td>The patient has the ability or potential for ambulation with variable cadence. This level is typical of the community ambulator who has the ability to traverse most environmental barriers and may engage in vocational, therapeutic, or exercise activities that demand utilization of a prosthesis beyond simple locomotion.</td>
</tr>
<tr>
<td>K4</td>
<td>The patient has the ability or potential for prosthetic ambulation that exceeds basic ambulation skills, exhibiting high-impact, stress, or energy levels. This level is typical of the demands of the child, active adult, or athlete.</td>
</tr>
</tbody>
</table>


#### Table 23.2 Phases of Rehabilitation for Persons with Amputation

<table>
<thead>
<tr>
<th>Phases</th>
<th>Hallmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Preoperative</td>
<td>Medical and body condition assessment, patient education, surgical-level discussion, functional expectations, phantom limb discussion</td>
</tr>
<tr>
<td>2. Amputation surgery and wound dressing</td>
<td>Residual limb-length determination, myoplastic closure, soft tissue coverage, nerve handling, rigid dressing application, limb reconstruction</td>
</tr>
<tr>
<td>3. Acute postsurgical</td>
<td>Residual limb shaping, shrinking, increasing muscle strength, restoring patient’s sense of control</td>
</tr>
<tr>
<td>4. Preprosthetic</td>
<td>Wound healing, pain control, proximal body motion, emotional support, phantom limb discussion</td>
</tr>
<tr>
<td>5. Prosthesis prescription and fabrication</td>
<td>Team consensus on prosthetic prescription</td>
</tr>
<tr>
<td>6. Prosthesis training</td>
<td>Prosthetic management and training to increase wearing time and functional use</td>
</tr>
<tr>
<td>7. Community integration</td>
<td>Resumption of family and community roles, regaining emotional equilibrium, developing healthy coping strategies, resuming recreational activities</td>
</tr>
<tr>
<td>8. Vocational rehabilitation</td>
<td>Assessment and training for vocational activities, assessment of further educational needs or job modification</td>
</tr>
<tr>
<td>9. Follow-up</td>
<td>Lifelong prosthetic, functional, and medical assessment; emotional support</td>
</tr>
</tbody>
</table>

have also been shown to significantly reduce the time between amputation and commencement of prosthetic management. In some regions, persons with new amputations are fitted with immediate postoperative prostheses (IPOP) in the operating room or soon after surgery. The IPOP is intended to serve the same purpose as the RRD while also additionally allowing supported weight bearing for early mobility. IPOP sockets are designed to allow some weight-bearing forces direct to the medial tibial flare and patellar tendon because these structures are far from the surgical site and are not likely to be affected by postoperative edema. It is important to note that weight bearing while in an IPOP should be at the level of toe-touch partial weight bearing. Full weight bearing is discouraged, as there is generally not enough area to distribute the full body weight in a manner that the skin will tolerate for extended periods of time. Full weight bearing through an IPOP can damage the healing surgical construct, thus delaying healing and the fitting of a prosthesis. Assistive devices should be used to encourage toe-touch weight bearing while allowing functional use of the remaining muscles.

The limb will change rapidly throughout the early rehabilitation process, therefore the prosthetist and therapist must closely monitor the fit and alignment of the IPOP. Adding extra layers of socks to the residual limb will accommodate early changes in limb volume. Eventually this will become counterproductive, and a replacement socket will have to be ordered. IPOPs are fabricated with modular components that allow changes to be made easily.

The surgeon may decide that an IPOP is not an option for the individual due to excessive soft tissue damage or delayed wound healing. In these circumstances, an RRD should be utilized. One variant of the RRD is a custom-molded plaster socket with a prefabricated plastic collar encapsulating the individual’s limb from the distal end to approximately two-thirds of the thigh. There are also other variations, including an adjustable prefabricated plastic socket or a custom-molded plastic socket made from a digital scan of the limb. Regardless of the style of RRD chosen, the goals are the same. The RRD keeps the knee in full extension to prevent contracture, protects the limb from exterior trauma, and controls swelling through total contact. This removable device is worn over at least one layer of cotton sock and is held in place with Velcro straps (Fig. 23.1). It is also fenestrated to allow airflow and release moisture. The device can be worn 23 hours a day and can be removed easily for dressing changes and bathing. Chapter 20 offers a more detailed discussion of postoperative care.

**Prescription of a Prosthesis**

Such a prescription details all the features of the completed prosthesis and should include socket design, skin-socket interface, suspension strategy, and additional modular components. For transtibial prostheses, the modular components are limited to feet, ankles, shock absorbers, torque absorbers, and dynamic pylons.

The socket is the structural component of the prosthesis in which the residual limb is contained. All the forces from the ground during gait are transferred to the limb through the socket. The forces from the limb needed to control the motion of the prosthesis are transferred to the prosthesis through the socket. Much care and time should be spent on socket design and fitting, as a less than ideal fit can quickly lead to pain, injury, and lack of function. The socket design, interface, and suspension must be considered together, as their functions are often interrelated and interdependent. A soft liner, for example, can function both as an interface and as the suspension for the prosthesis. In the same way, a socket that is designed with a different interface may contraindicate certain suspension options. Forethought regarding how those three design elements intermingle will increase the probability of producing a comfortable and functional prosthesis.

**Socket Designs**

Early transtibial prostheses were fashioned by hollowing out a block of wood and attaching metal single-axis knee joints and a leather thigh corset. The sockets were referred to as “plug-fit” sockets because they were open-ended and the limb fit into the socket like a plug fits in a drain. The attached thigh corsets took advantage of the conical shape of the thigh to transfer weight proximally and transmit mediolateral forces to and from the limb. Although many persons with amputation were able to function with this system, the lack of contact on the distal end of the residual limb often led to painful edema in that area. Such lack of contact can also lead to verrucous hyperplasia, a painful skin condition with a warty appearance. Additionally, the joints and corset added bulk and weight to the prosthesis, which restricted knee motion.
PATELLAR TENDON–BEARING SOCKET

By the end of World War II, the large number of veterans who suffered limb loss during combat inspired prosthetists to experiment with new materials and techniques to improve the comfort and function of prostheses. In 1959, a symposium was held at the University of California Biomechanics Laboratory to promote the development of transtibial socket fitting. The result was the patellar tendon–bearing (PTB) socket design. This design has been used successfully over the past six decades to strategically load the limb in areas that are more tolerant of pressure. The patellar tendon, calf musculature, and medial tibial flare are used for weight loading, while reliefs are made over bony prominences like the tibial crest and head of the fibula. In most cases this eliminated the need for proximal weight bearing.12

The main goal of the PTB socket design was to increase the surface area on the residuum available for weight bearing so as to eliminate the need for the knee joints and thigh corset. The PTB socket was described as “total contact,” meaning that there were supposed to be no voids or air pockets between the limb and the socket. This design allowed weight bearing to occur in any area capable of supporting a load. The term patellar tendon–bearing originates from the use of a patellar “bar” built into the socket at the level of the center of the patellar ligament, midway between the patella and the tibial tubercle (Fig. 23.2). The socket is aligned in approximately 5 degrees of knee flexion, allowing the bar to act as a weight-bearing surface within the socket and enabling 5 degrees of adduction. The proximal trim line of the posterior wall should be located just proximal to the patellar bar to stabilize the limb in the anteroposterior direction and prevent the limb from sliding too far down into the socket. The posterior trim line should be lower on the medial side to accommodate insertion of the medial hamstring tendon during knee flexion. Anteriorly directed compression of the calf musculature maintains the patella tendon firmly against the bar and stabilizes anteroposterior motion of the residual limb within the socket.

The other major weight-bearing surface in the PTB socket is the medial flare of the tibia. The proximal end of the tibia broadens out medially and, when stabilized by pressure from the lateral wall of the socket, can effectively accept loading. It is necessary also to create a relief for the fibular head, which is at the same level, to avoid any pressure on that bony structure. Filling the distal end of the socket with a compliant foam material provides slight pressure during full weight bearing, which is necessary to control distal edema. The medial and lateral walls of the PTB socket extend up to the level of the adductor tubercle to provide lever arms for mediolateral stability of the prosthesis. The PTB technique is still used successfully today, and many modern fitting techniques incorporate at least some of the attributes of the original PTB design.

TOTAL SURFACE–BEARING SOCKET

The total surface–bearing (TSB) socket serves to further distribute the weight-bearing load over the entire surface of the limb, even in areas that had been traditionally considered to be pressure-intolerant. Strategic compression of soft tissue and relief for bony prominences are the tools used to direct more force into areas of the limb that can tolerate it and less force into areas prone to skin breakdown. The intent in designing a TSB socket is to distribute uniform pressure over the entire surface of the limb.13 It is expected, however, that during a typical step, the pressure in any given location would change from a negative pressure during swing phase to high pressure in stance; if sustained, this would cause tissue damage. Because the forces on the limb change dramatically throughout the gait cycle, this dynamic pattern must be anticipated so that those forces can be used to protect the pressure-intolerant areas. Larger forces mean more tissue compression, requiring greater relief. The density and structure of the tissues comprised by the limb must also be taken into consideration. These properties vary widely between skin, muscle, adipose tissue, and bone. They can even vary within the same tissue type; muscle tissue, for example, behaves one way when it is relaxed and very differently when it is contracting. Once tissues are accommodated, the relative locations of these tissues within the socket must be preserved. This not only provides for optimum positioning of the tissues, but also allows accurate control of the prosthesis.

To fully accommodate the dynamic tissue loading that occurs in a prosthetic socket, the prosthetist must consider both the shear and the normal forces on the limb. Shear forces run parallel to the limb surface and are best mitigated through the use a socket interface. Interface materials—such as socks, sheaths, flexible liners, and gel liners—offer a continuum of shear reduction on the skin surface. The best materials to minimize shear are those found in gel liners. Normal forces are those that are applied perpendicular to the surface of the limb. The socket walls should be contoured according to the type of tissue in the area and the anticipated loading patterns. There is no way to reduce...
the force on the limb without restricting the individual’s activities; therefore the best way to reduce pressure is to distribute the forces over as broad a surface as possible. The actual forces on the limb are a combination of shear and normal forces that occur together in various proportions.

Ambulation is a dynamic event in which the forces on the limb are continually changing. For this reason the prosthetic socket must be designed to function under a variety of loading patterns. The socket must be designed and fitted under physiologic conditions that match those of the intended use. Soft tissue compression will vary with load; the socket contours must reflect the anticipated load so as to prevent excessive loading on bony prominences. Throughout the gait cycle, the forces and moments on the socket and limb change continuously. There is a flexion moment during loading response, a varus moment throughout mid stance, and a flexion moment again in preswing (Fig. 23.3). The forces on the limb range from a compressive force 1.2 times body weight in stance to a distractive force slightly higher than the weight of the prosthesis in swing phase.14 A well-fitting prosthesis must provide tolerable pressure distribution in all of these loading conditions. Soft tissue, muscle tissue, and bone contours must each be accounted for in a specific way to achieve a good fit. Soft tissue can tolerate moderate compression, so the prosthetist will precompress that tissue in the socket. Muscles can tolerate mild compression but should be able to contract with each step; therefore less precompression should be applied. The shape of muscle tissue changes when contracted. Flexible materials can be used over muscle bellies to allow for this geometric variability. Finally, bony prominences must be given extra volume within the socket so that when the tissue around them compresses during loading, the pressure will not exceed the tolerable limit.

The load-bearing capabilities of the limb can also be affected by the surgical technique used for the amputation. The Ertl procedure, named after Dr. Janos Ertl Sr., involves the creation of a bone bridge between the distal end of the tibia and fibula, as shown in Fig. 23.4 (see Chapter 19 for more detail). The goal of this procedure is to create a tougher, more force-tolerant limb. One problem this technique aims to solve is nerve impingement. Transstibial amputees are prone to nerve compression between the long bones of the lower leg.15 Forces within the socket push the tibia and fibula together and compress anything in between. If the tibial nerve is trapped between the bones, pain can result. By fusing the bones together at the distal end, the relative motion is minimized, thereby protecting the soft tissue located between them. Many individuals who have had this type of surgical procedure can bear weight directly on the distal end of their limb. This end-bearing capability allows the prosthesis to distribute the person’s weight differently and potentially to provide a prosthesis that does not extend as far proximally. This can increase comfort over standard weight-bearing areas and increase the range of knee flexion available to the individual. However, the increased surgical time and subsequent increase in infection risk are often cited as reasons to forgo the Ertl procedure.16

Interface Materials

The material that separates the limb from the socket is referred to as an interface. Interfaces play an important role in lower-limb prosthetics. They can offer shock absorption, mimic soft tissue to provide an extra layer of cushioning for individuals who are bony, and help to mitigate shear forces on the limb. Interfaces influence the hygiene, ease of donning, and maintenance requirements of the prosthesis.
they are often an integral part of prosthetic suspension. With new materials being developed continuously, there are many interface options for the prosthetist; a discussion of commonly used interface materials is presented here.

**HARD SOCKET**

Early prostheses were made from hard materials like wood, which did not offer much cushioning. Persons with amputation used layers of cotton or wool socks to provide a soft interface between their limbs and the hard sockets. There are several advantages to this system. The socket is relatively thin, so it is easily concealed under clothing; a clean sock can be used each day or changed throughout the day as needed; the number and ply of socks can be adjusted to accommodate fluctuations in limb volume during the day, and the socket itself is very durable. Because there are no compressible surfaces, the fit is reliable; it will not become “packed down” in high-pressure areas. It is nonporous, easy to clean, and relatively maintenance-free. It also does a fair job of eliminating shear, as the coefficient of friction between the socks and socket is relatively low compared with that between the socks and the skin. This type of socket is most challenging to fit and is not recommended for mature limbs that have lost much of their soft tissue protection over bony prominences. It is also more difficult to adjust than other socket styles.

**SOCKS AND SHEATHS**

Prosthetic socks can be made from various combinations of cotton, nylon, wool, Lycra, polyester, and spandex. Some manufacturers use silver fibers in their fabrics to enhance the antimicrobial properties of their socks and sheaths (Fig. 23.5). The prosthetic sock provides shock absorption, decreases the shear forces on the limb, wicks away moisture, and is used to accommodate fluctuations in limb volume. To further decrease friction, a nylon sheath is often recommended as the initial layer, with the thicker socks donned over the sheath. The sock also serves as a method of controlling socket fit; as the residual limb matures and shrinks, additional sock plies may be required to restore the fit and comfort of the socket. For convenience, prosthetic socks come in various ply thicknesses. For example, a person can wear one five-ply sock rather than having to don five single-ply socks. This is particularly important since it has been shown that even within the same manufacturer, three one-ply socks are not the same thickness as one three-ply sock. It is important to teach the person wearing the prosthesis to use the fewest number of socks to achieve the proper number of plies. New users of a prosthesis are typically provided with an assortment of one-, three-, and five-ply socks from which to select. The socks can be layered one on top of the other to achieve the appropriate number of plies.

**SOFT INSERTS**

Closed cell foam, used because it does not absorb moisture, can be molded over a model of the limb to create a soft insert.
in the case of a Syme example, an insert for a limb with a bulbous distal end, as would not be able to slide directly into a rigid socket. For can be used to accommodate anatomic irregularities that Soft inserts that can deform during the donning process plastic deformation and extend the useful life of the insert. used alone. Mating that material with one that has low good shock absorption but would wear out very quickly if a material that has high plastic deformation might offer the force-altering characteristics of each layer. For example, whereas multidurometer inserts, made from layers of differ- such inserts can be worn over a nylon sheath, which is a very thin nylon stocking similar to women’s stockings, or over any number of sock plies. Wearing the insert directly over the skin without a sock can lead to excessive shear and skin breakdown due to the relative motion between the limb and insert. Single durometer inserts provide a uniform compression profile, whereas multidurometer inserts, made from layers of different materials with varied properties, can take advantage of the force-altering characteristics of each layer. For example, a material that has high plastic deformation might offer good shock absorption but would wear out very quickly if used alone. Mating that material with one that has low compression resistance would prevent some of the plastic deformation and extend the useful life of the insert. Soft inserts that can deform during the donning process can be used to accommodate anatomic irregularities that would not be able to slide directly into a rigid socket. For example, an insert for a limb with a bulbous distal end, as in the case of a Syme’s amputation, can be made thicker in the narrow area above the bulge so that the diameter of the finished socket would not impede donning. Another example is the wedge needed for supracondylar suspension: this wedge can be integrated as part of the soft insert to facilitate ease of donning.

Such an insert lines the entire socket and terminates just proximal to the socket’s trim lines (Fig. 23.6). For increased protection, a distal end pad, which is an extra layer of soft material at the bottom of the insert, can be used to cushion the distal end of the tibia. Soft inserts provide an extra layer of cushioning, which is needed for more mature limbs that lack adequate soft tissue thickness. Soft inserts also give the prosthetist a way of adjusting socket volume and shape for a limb that is prone to change. Such an insert can be worn over a nylon sheath, which is a very thin nylon stocking similar to women’s stockings, or over any number of sock plies. Wearing the insert directly over the skin without a sock can lead to excessive shear and skin breakdown due to the relative motion between the limb and insert. Single durometer inserts provide a uniform compression profile, whereas multidurometer inserts, made from layers of different materials with varied properties, can take advantage of the force-altering characteristics of each layer. For example, a material that has high plastic deformation might offer good shock absorption but would wear out very quickly if used alone. Mating that material with one that has low compression resistance would prevent some of the plastic deformation and extend the useful life of the insert. Soft inserts that can deform during the donning process can be used to accommodate anatomic irregularities that would not be able to slide directly into a rigid socket. For example, an insert for a limb with a bulbous distal end, as in the case of a Syme’s amputation, can be made thicker in the narrow area above the bulge so that the diameter of the finished socket would not impede donning. Another example is the wedge needed for supracondylar suspension: this wedge can be integrated as part of the soft insert to facilitate ease of donning.

**FLEXIBLE INNER SOCKET**

If P'TB theory is to direct weight bearing into specific areas of the limb and away from others, then the flexible inner socket is the incarnation of that idea. With this system, an inner socket is made over a model of the limb from a flexible material that will stretch upon the application of force. Then a rigid frame is built around the inner socket, corresponding to areas of the residual limb where weight bearing is desirable. The result is a socket that flexes away from forces in areas that are not pressure-tolerant but remains rigid in the force-tolerant areas. Because flexible sockets in rigid frames can eliminate compressive forces in any specific area, this system is useful for persons with particularly bony residual limbs and those with severe localized sensitivity. However, they are not recommended for residual limbs with adherent scarring because pressure differentials created by the frame tend to amplify the shear forces on the limb.

**EXPANDABLE WALL SOCKET**

When a limb is amputated at or below the ankle, the resulting long residual limb present an interesting challenge to the prosthetist. The proximal trim lines of the prosthesis can be lowered to a more distal position on the limb because there is a long lever arm for prosthetic control during ambulation. However, the distal end of the residual limb is larger in diameter than it is more proximally because of the presence of malleoli. The prosthetist can accommodate for a larger distal size by creating a removable wall in the socket that is replaced after the prosthesis is donned by using a specially designed soft liner or by creating an expandable wall socket. The expandable wall socket is made from an elastici-

ized material that stretches enough for the individual to push his or her limb through in weight bearing and tightens up over the malleoli to provide suspension. This socket is too flexible for the attachment of a foot, so a rigid frame is made over the flexible socket, leaving a small space in which the expansion can occur. This is a self-suspending socket that can be very comfortable for the wearer. It is difficult to fab-ricate this kind of socket and even more difficult to make adjustments to the fit once it has been fabricated. More information on these designs can be found in Chapter 22.

In addition to traditional expandable wall sockets, other technologies have been applied in this area of socket design to create nontraditional sockets. These designs have significant open areas and apply the majority of their support between the muscle bellies, so the amount of soft tissue between the socket and the bone is minimized. This allows space for the muscles of the residual limb to expand during muscle contraction and provides maximum stability to the bone of the residual limb. Examples include the Socket-Less Socket from Martin Bionics and the HI-FI Socket from Biodesigns.

**GEL LINER**

The term gel liner is loosely used in the field to describe a liner that is made from a material that exhibits gel-like properties. There are three basic varieties of these liners: (1) silicone elastomers, which are highly cross-linked at the molecular level; (2) silicone gels that have a relatively low amount of cross-
So that only a small percentage reaches the skin (Fig. 23.7). A tighter fit creates higher frictional forces, and if the pressure distribution is not equal, the frictional forces on the skin will be uneven, leading to blisters and skin problems. Excessive pistoning can also lead to decreased function for the user, due to fear of the prosthesis coming off. Great care should be taken to minimize motion within the socket. There are several strategies for suspension, which can be used individually as the primary mode of suspension, or more than one technique can be used simultaneously to provide auxiliary suspension. In addition to the methods detailed here, several other methods can be employed. They include such concepts as texturizing the inside of the socket to increase the surface contact area or the use of a unidirectional fabric to allow the residual limb to easily slide into the socket (stance phase). But these increase friction when trying to remove the residual limb (swing phase). These types of supplemental suspensions are not detailed due to the lack of published data to support their efficacy.

**WAIST BELT**

A waist belt connected by an elastic strap to the thigh corset was used to suspend early transtibial sockets. These belts are

**Suspension**

Another important consideration when a prosthesis is being designed is “suspension,” the method by which the prosthesis is held to the limb. When a prosthesis is suspended perfectly, there is no relative motion between the socket and the limb. When motion occurs because of a faulty or inadequate suspension system, the limb is subjected to an entirely different loading pattern. This motion is referred to as “pistoning,” as it bears some resemblance to the motion of a piston in the cylinder of an internal combustion engine. Pistoning can lead to pain, skin breakdown, and reduced control of the prosthesis. Excessive pistoning can also lead to decreased function for the user, due to fear of the prosthesis coming off. Great care should be taken to minimize motion within the socket. There are several strategies for suspension, which can be used individually as the primary mode of suspension, or more than one technique can be used simultaneously to provide auxiliary suspension. In addition to the methods detailed here, several other methods can be employed. They include such concepts as texturizing the inside of the socket to increase the surface contact area or the use of a unidirectional fabric to allow the residual limb to easily slide into the socket (stance phase). But these increase friction when trying to remove the residual limb (swing phase). These types of supplemental suspensions are not detailed due to the lack of published data to support their efficacy.
rarely used today and are discussed here primarily as a historical reference. The belt encircles the pelvis between the iliac crests and the greater trochanters. These adjustable belts have buckles on the anterior aspect that mate with an inverted Y-strap attached to the socket, allowing them to be donned separately and then joined together. Because this system crosses the hip and knee joints, flexion and extension of these joints must be accommodated by an elastic component. Further accommodation of knee flexion is accomplished by the inverted Y-strap (Fig. 23.8). The Y-strap is fitted over the patella so that the two arms of the Y move posteriorly during knee flexion to reduce elongation of the elastic strap. The person with amputation can adjust tension in the strap based on individual comfort. Pistonning in the socket is controllable with enough tension in the elastic. Tension in the strap decreases with hip flexion so that the strap has slack while the person is seated. Hip extension produces tension in the strap and aids in limb advancement as it assists hip flexion in preswing.

JOINTS AND CORSET

The joints and corset feature (first discussed in the section on “Socket Designs”) provides suspension as well as a weight-bearing element if the thigh corset is properly fitted over the femoral condyles. A skillfully molded corset can gain purchase over the smaller circumference of the thigh just proximal to the knee joint. The stiff leather corset is fabricated with either straps or laces that can be tightened as the wearer dons the prosthesis. This permits the limb to pass through the corset and be held securely in position once the corset is tightened. The knee joints, which are typically made of steel, provide a secure connection to the socket. When the condyles are prominent, this can serve as the primary means of suspension, and a waist belt is not needed. As the prosthetic knee joints are positioned slightly posterior to the anatomic knee joint center, tension in the cuff decreases over the condyles as the knee flexes, thereby enhancing sitting comfort (Fig. 23.9). The joints and corset system can also include a posterior check strap that limits full knee extension. This can be used to eliminate the terminal impact at the end of swing phase, which can be audible, and to prevent excessive wear on the prosthetic knee joints. The thigh cuff allows for full functional range of knee flexion but will cause binding in the popliteal fossa when the knee is flexed beyond approximately 110 degrees. Joints and corset may be the suspension of choice for persons with ligamentous instability of the knee or for those who have a very short residual limb. The joint and corset system can also be used to reduce rotation of the prosthesis in certain activity-specific applications.

CUFF STRAP

A cuff strap is a flexible leather cuff that attaches to the medial and lateral walls of the socket at the same point at which orthotic knee joints would be positioned—that is, just posterior and proximal to the anatomic knee center (Fig. 23.10). The cuff has an adjustable strap that
completely encircles the thigh just proximal to the patella. After the person dons the socket, the cuff is secured in place so the prosthesis will hang from the cuff during standing and walking. Excessive circumferential tension should not be necessary to maintain the prosthesis in place. The anatomic structures that provide the suspension are the patella and the femoral condyles. To create a strong hold, the medial and lateral walls of the socket must be lower than the standard height. Because this reduces mediolateral stability, cuff strap suspension is not a good choice for short residual limbs. An elastic component may be added to the strap over the patella to increase sitting comfort. This system is simple, quick to fabricate, and provides a secure suspension for the prosthesis while accommodating an unencumbered angle of knee flexion. The cuff does not provide any weight-bearing or mediolateral stability. Cuff strap suspension may also be contraindicated for persons with extra muscle or adipose tissue around the lower thigh.

SUPRACONDYLAR SUSPENSION

Suspension can be achieved by incorporating the femoral condyles completely within the rigid transtibial socket. By extending the medial and lateral trim lines of the socket approximately 2 cm proximal to the adductor tubercle, the mediolateral dimension of the top of the socket can be made narrower than the knee joint. This prevents the knee joint from moving upward out of the socket by capturing the femoral condyles. Supracondylar suspension also adds significant mediolateral stability to the prosthesis by increasing the length of the lever arm proximal to knee center and also by increasing the surface contact area, which can be helpful for short residual limbs. This technique combined with a PTB-style socket is referred to as a PTB-SC.

This type of socket can be difficult to don because the width of the proximal opening is smaller than the width of the condyles. This problem can be addressed in two ways: either by including the supracondylar wedge in a soft insert or by using a detachable medial wall. The first method uses a flexible liner that has a wedge built into it proximal to medial condyle. The rigid socket is fabricated over the liner such that the mediolateral dimension of the proximal end of the socket is equal to the widest dimension of the knee. This makes it possible to don the flexible liner first. Then, with slight compression of the liner, the limb and liner together slide into the socket and are locked in place through pressure and friction (Fig. 23.11). The second method uses a steel bar that is formed into the prosthesis. The entire medial wall of the prosthesis, along with the steel bar, can be removed for donning. Once the limb is in the socket, the bar slides back into a channel in the distal portion of the socket and locks into position with a ball detent (Fig. 23.12).

It is necessary to have at least a 1-cm difference between the mediolateral dimension of the knee joint and that of the thigh just proximal to the adductor tubercle so as to provide a secure supracondylar suspension. Widening the socket in the region just posterior to the condyles serves to loosen the grip over the condyles while the wearer is seated in 90 degrees of knee flexion. It is worth mentioning that the high medial and lateral walls of this type of socket are apparent, even through long pants when the knee is flexed. Some people might find this unsightly and unacceptable.
SUPRACONDYLAR/SUPRAPATELLAR

By extending the trim line of the anterior aspect of the PTB-SC socket up to the level of the medial and lateral walls, the proximal surface of the patella can also be used to assist suspension (Fig. 23.13). The patellar tendon–bearing supracondylar/suprapatellar (PTB-SCSP) socket allows the formation of a quadriceps “bar” above the patella, which provides suspension and resists hyperextension. The continuous trim line at the proximal brim also increases the rigidity of the medial and lateral walls, further enhancing suspension. The advantages and disadvantages of this variation match those of the PTB-SC except that it is even more visible under clothing when the knee is flexed.

SLEEVE

One of the most versatile means of suspending a prosthesis is with a suspension sleeve. A suspension sleeve provides suspension through two biomechanical principles: friction and vacuum. The sleeve extends approximately 20 cm proximal and distal to knee center and is fitted over the proximal end of the prosthetic socket (Fig. 23.14). The sleeve should fit snugly but not hinder circulation. Sleeves can be made of a variety of materials depending on the goals of the design. Neoprene and elastic fabric are common materials used for sleeves because they contour nicely to the anatomy and provide a high coefficient of friction with the skin. These sleeves use friction only to suspend the prosthesis because they allow for air to flow through them, in and out of the socket. This is useful for dissipating perspiration and keeping the skin dry. Sleeves can be used either as primary or secondary suspension. (Photo courtesy Todd DeWees, CPO, Shriners Hospital, Portland, OR.)
limb cooler, but it also allows undesirable motion to occur between the socket and the limb. Over time, this can lead to pain and skin breakdown. The sleeve can be worn over a sock, which can be good for hygiene; however, this will affect the coefficient of friction between the sleeve and the limb, which could lead to suspension failure. Sleeves permit functional ROM for the knee, but because they bunch up in the popliteal fossa, they can restrict knee flexion beyond approximately 100 degrees.

SUCTION

Modern sleeves are referred to as “sealing sleeves” because they are made of nonporous materials that seal the proximal end of the socket against the skin so that no air can flow into or out of the socket. This creates a suction suspension. One-way air valves are commonly used in conjunction with sealing sleeves to allow air trapped during donning to escape from the socket. Sealing sleeves provide excellent suspension when they are combined with TSB sockets. Once the socket is sealed, very little pistoning can occur, as there are no voids between the limb and the socket. For the sleeve to seal, the sleeve must touch the skin directly for at least the top 5 cm. The skin must be free of deep scars or invaginations in that area, as they would provide a path for air to enter under the sleeve. Because the sealing sleeves rely on an airtight seal to function, they are highly susceptible to failure as a consequence of leaks. Even a small hole in the sleeve can allow air to flow into the socket, defeating the vacuum and impairing suspension. Although sleeves are not very durable, they can be replaced without any special tools or equipment.

The soft tissue of the residual limb behaves like an incompressible fluid. For the limb to move within the sealed volume of the socket, the volume of the limb itself would have to change. This can happen only if fluid moves into or out of the limb through the bloodstream, a process that is too slow to be accomplished within the short interval of swing phase. Therefore the cyclic alteration between compression in stance and tension in swing slows fluid into the limb and pushes it back out, assisting normal circulation. Suction suspension may provide a means for improving healthy circulation in the residual limb and controlling limb volume.

LOCKING LINERS

The first references to locking liners involved the use of a roll-on silicon liner, referred to as an “Icelandic roll-on suction socket.” However, the use of the term suction for this type of suspension is incorrect. The liner is primarily held on by friction because it is not possible to maintain a vacuum within a flexible structure. If friction is eliminated through the use of a lubricant, the liner can be pulled off the limb. It is more accurate to describe this type of suspension as a locking mechanism. These roll-on gel liners are compliant enough to contour nicely to the shape of the residual limb and include a threaded hole at the distal end. This hole serves as a point of attachment for the suspension hardware.

There are four basic options for the hardware:

1. Early sockets used a ring screwed into the distal end of the liner. When the ring came through a special opening on the distal end of the socket, the wearer could pass a thin bar through the ring so that it could be retracted back into the socket. This system is still good for individuals who have difficulty doffing their prosthesis, as it allows them to remove the bar and then use both hands to push the socket off. This system requires additional clearance under the limb to accommodate the diameter of the ring and the associated attachment fixture. The bar is also a separate component, so it can easily get lost. The wearer should be instructed to store the bar in the prosthesis and take it out only during the donning process.

2. Difficulties with the ring gave rise to using a strap that is manually fed through a hole in the distal end of the socket and then secured to the outside of the socket (Fig. 23.15). The strap must be of sufficient length to be put through the hole before the limb enters the socket. This eliminates the need to carefully align the sleeve during donning as the limb will be drawn down into the socket by tension in the strap. It also eases the donning force required to get into the socket because the limb elongates and decreases in girth under tension as it is pulled into the socket. As no locking mechanism is mounted on the distal end, no additional clearance is needed, leaving precious space for other components. One variant of this system uses a lanyard and a special lock mechanism to secure the lanyard in the distal end of the socket. The lanyard is permanently attached to the locking mechanism; therefore it must be disconnected from the liner each time the liner is taken off.

3. Most modern sockets use a pin-and-lock mechanism. The pin can range from approximately 3 to 10 cm in length. It works in conjunction with a locking mechanism built into the distal end of the socket, which engages when the individual dons the prosthesis. Some wearers experience frustration with this as it can be difficult to align the pin so that it engages with the locking mechanism. To remove the prosthesis, the wearer must disengage the pin manually while pushing the socket off with the other hand. There are several variants of locking mechanisms. Some produce an audible “click” to indicate that the pin has engaged, but it will lock in only a limited number of positions. Others use a clutch mechanism or a smooth pin that allows for an infinite number
of locking positions. Ideally only one position should be needed—that is, when the limb is positioned correctly in the socket. However, as the limb volume varies throughout the day, it is not uncommon for there to be an additional click or two as the wearer spends more time bearing weight in the prosthesis (Fig. 23.16).

4. Proximal suspension through the use of a ladder strap and ratchet buckle is a fourth option. Those who find the “milking” sensation of a distal suspension unbearable or wearers who do not have clearance for a distal suspension can use this method. In this system, a ladder strap is attached to the anterolateral side of a cushion liner between the fibular head and the tibial tubercle and just low enough to be contained within the socket. An opening is made in the socket wall just large enough for the ladder strap to pass through. As the ladder strap passes through the socket, it is inserted into a ratchet buckle that has been incorporated into the socket or attached to its side. The ladder strap makes an audible click as it is locked into the buckle to help the user know that the suspension is engaged. Care should be taken not to overtension the strap, as this can damage the cushion liner. One drawback to this method is that there is slightly more motion of the residual limb in the socket as compared with distal suspension.

Locking liners allow some pistoning to occur.23 The amount of motion can be dramatic when loose tissue is present at the distal end of the residual limb. As the limb is lifted off the ground in swing phase, the weight of the prosthesis pulls on the pin, causing the liner and limb to become longer and contract in girth. This effect is most apparent at the distal end. This milking motion creates unnecessary stress on the distal end of the limb and can lead to pain, edema, and skin breakdown.24 This is especially problematic for limbs with adherent scar tissue, as the liner will attempt to pull the tissue away from the bone. This type of suspension is not ideal for a newly amputated limb, as the distal end will not be fully healed. This problem can be averted if suction rather than the pin is used to hold the liner to the socket wall.

**SEMI-RIGID LOCKING LINER**

A semi-rigid locking liner is used to combine the convenience of a locking liner with the benefits of a full-suction suspension. The individual first dons an interface—which can be a sheath, sock, or cushion gel liner—that was designed to go under the prosthesis. Then the wearer dons a thin, flexible, custom-molded socket that has a locking liner rolled over it. Finally, the wearer steps into the rigid frame to engage the locking mechanism. Because the locking liner is under the rigid frame rather than stretched over it, the life of the locking liner is greatly extended. Having the socket under the liner prevents the locking liner from becoming deformed, so that pistoning is virtually eliminated and the distal tissue is protected. To further enhance the suction of this system, an expulsion valve can be incorporated into the flexible socket. This allows any air trapped in the socket during donning to be removed. This one-way valve provides a path for air to move from inside the socket to the outer side of the locking liner. Wearing a sock or a liner with a fabric exterior helps any remaining air to migrate toward the valve and out of the socket.

**ELEVATED VACUUM**

As the advantages of suction suspension are clearly documented in the literature,23,26 there has been considerable interest in using external vacuum pumps to increase the level of suction (decrease the pressure) within the socket. Such a system is referred to as providing an *elevated vacuum*. Pumps can be either electrical (battery-operated) or mechanical. Mechanical pumps use the natural cycle of compression during stance and distraction during swing to pull air from the socket during gait. Electrical pumps have the added benefit of being able to accurately control the level of vacuum within the socket by turning on and off at preset thresholds (Fig. 23.17). Both systems have advantages and disadvantages. Mechanical pumps tend to be lighter in weight, lower in profile, and easier to maintain. Electrical pumps allow more precise control of the negative pressure, and some models allow for situational control of the negative pressure. The downsides are similar except that...
motion and therefore to fewer skin problems, improved pro-

vacuum environment within the socket leads to decreased

limb as compared with the passive suction suspension.30

shown to reduce axial motion of the socket relative to the

phase of gait, the elevated vacuum suspension has been

Another way to precompress the tissue is to use a pressuriz-

PRESSURE CASTING

features. The insertion of the hamstrings, for example, can

tions have set up. This allows the prosthetist to position the

casting procedures involve molding specific regions of the

limb individually and joining them once the individual sec-

tions have set up. This allows the prosthetist to position the

limb in multiple postures during casting to capture unique

features. The insertion of the hamstrings, for example, can

be molded during active knee flexion, when they are most

prominent. Chapter 6 gives more details about casting.

HAWD CASTING

During hand casting, the limb is gently wrapped with either

plaster or fiberglass bandage and the prosthetist pushes in key

weight-bearing areas while the casting material is setting up.

How much compression is needed and which areas to com-

press is determined based on bony anatomy and the prosthet-

ist’s individual knowledge, skill, and experience. Multistage

casting procedures involve molding specific regions of the

limb individually and joining them once the individual sec-

tions have set up. This allows the prosthetist to position the

limb in multiple postures during casting to capture unique

features. The insertion of the hamstrings, for example, can

be molded during active knee flexion, when they are most

prominent. Chapter 6 gives more details about casting.

PRESSURE CASTING

Another way to precompress the tissue is to use a pressuriz-

ing technique.31 This involves placing the limb into a vac-

uum or pressure chamber while the plaster is setting up

(Fig. 23.18). A vacuum chamber is typically a latex bladder

pulled over the wet cast and sealed on the thigh. A vacuum

pump attached to the distal end removes all air between the

cast and bladder, allowing the atmospheric pressure to com-

press the limb up to approximately 14 psi. A pressure cham-

ber with a latex bladder attached inside it is another option.

The limb, wrapped with wet plaster, is placed in the bladder

and air is pumped into the space between the cylinder and

the bladder. The pressure in the cylinder can be increased

to 30 to 40 psi, providing additional compression. Alterna-

tively, pressure casting can be done with the PCAST method,

where pressure is provided by water in a closed cylinder. The

full length of the residual limb is wrapped in casting material.

The limb is then placed on a flexible bladder inside a metal

cylinder. The cylinder is then filled with water, creating a

supportive environment in which the prosthetic user can

bear weight. He or she then places equal body weight on

each limb until the casting has set. This method makes it pos-

sible to produce a weight-bearing mold of the residual limb.32

In all three methods, once the casting material has hard-

ened, the pressure is released and the limb is removed from

the chamber. Regardless of the casting method, differential

pressure between the limb and the environment serves to

apply uniform pressure over the entire surface of the limb.

This leads to the most tissue compression in the softest areas

and the least amount of tissue compression in the bony

areas. The amount of differential pressure required will vary

with the individual’s weight, and the prosthetist will use the

least amount of pressure required to achieve the optimal fit.

OPTICAL SCANNING

Optical scanners can be used to capture the three-

dimensional external shape of the limb to within 1 mm

of accuracy (Fig. 23.19).13 They are quite useful

in situations when hand casting is impossible or impractical,

as immediately following surgery or with bulbous limbs that

cannot be removed from a plaster cast without cutting or

distorting the cast. Digital markers and alignment lines

can be attached to the virtual model to reference the loca-

tion of bony landmarks and pressure-sensitive areas.

Although it is not possible to compress the skin by hand

while scanning because the hand would block the view of
the surface, compression of tissues and reliefs for bony landmarks can be accomplished using modification software.

Scanners used in applications involving the construction of prostheses typically fall into one of two categories: (1) laser scanners and (2) structured light scanners (white or blue light). Laser scanners use triangulation of the beam reflecting off the surface of an object to determine its position in space. Since this process happens millions of times per second, the software is able to produce a map of the three-dimensional surface by connecting these points. Structured light scanners project a light pattern onto the surface of an object and, by measuring the distortion of that pattern, the software can calculate the three dimensionality of the object being scanned. Both systems provide great accuracy and fast scan times, which makes them useful tools in the clinical setting.

The use of an optical scanning system to create a digital model of the residual limb, or a computer-aided design (CAD) (Fig. 23.20), also requires a method of transferring that digital model to the real world, referred to as computer-aided manufacturing (CAM). CAD/CAM is a process used extensively in the manufacturing world, but in the Orthotics and Prosthetics world, it is often closely associated with three-dimensional printing (additive manufacturing) and foam carvings of molds (subtractive manufacturing). Although three-dimensional printing of prosthetic devices is done in some limited circumstances, it has not yet become a standard tool employed by the prosthetist. This is expected to change as advances in print materials, print methods, and print speeds are made. Currently three-dimensional printing in transtibial prosthetics is most prevalent in the production of check sockets and custom artistic fairings to provide shape to the prosthesis. More commonly, transtibial models are fabricated using a carver that is computer-guided and carves a foam block into the desired shape. The model produced in this way is then used to produce the prosthetic socket using traditional methods. Prosthetic sockets produced using a CAD/CAM carver have been shown to improve quality-of-life parameters and reduce the wearer’s socket adaptation. This system has the additional advantages of reducing fabrication time and maintaining objective data on socket shape and volume over the life of the prosthetic user.

**Alignment**

Alignment refers to the spatial orientation of the prosthetic socket relative to the foot. Alignment will influence the magnitude and direction of the ground reaction force throughout the gait cycle. There are four goals in prosthetic alignment: (1) facilitating heel strike at initial contact, (2) providing adequate single-limb stability during the stance phase, (3) creating smooth forward progression (rollover) during the transition from early to late stance phase, and (4) ensuring adequate swing-phase toe clearance. These goals are reached through dynamic alignment of the prosthesis, during which the person walks on a prosthesis that is fitted with an adjustable device that allows for alignment changes in all three planes. Although “normal” gait is not a goal, modern components do allow many persons with transtibial amputations to evade detection of gait abnormalities or deviations by all but the most skillful gait observers. Prosthetic alignment can also be used in conjunction with socket fit to address pressure issues within the socket. Because of this, socket fitting and dynamic alignment must occur simultaneously. Effective fitting and alignment...
requires an iterative process, as changing one aspect can affect many others. The end result is often a compromise. For example, the foot may require excessive dorsiflexion in order for the person to achieve sufficient swing clearance, even though this may contribute to a higher than optimal knee flexion moment during the loading response. The prosthetist must understand the biomechanics of the limb and gait cycle to weigh the factors appropriately and make the best decisions.

The modular components that connect the socket, pylon, and foot allow the prosthetist to make angular changes to the alignment. In the sagittal plane, socket flexion or socket extension refers to the tilting of the proximal end of the socket forward or backward in the anteroposterior direction, respectively. In the frontal plane, socket abduction moves the proximal end of the socket medially while socket adduction moves it laterally. Adjustments around the ankle can be described with standard anatomic terminology: inversion, eversion, plantarflexion, and dorsiflexion. Changes to the alignment can refer to the motion of the socket relative to the foot, or vice versa. Dorsiflexing the foot for example, causes socket flexion; while everting the foot leads to the same motion as adducting the socket.

The socket can also be shifted medially or laterally in the frontal plane and anteriorly or posteriorly in the sagittal plane. These shifts are referred to as linear changes or slides. These, too, are relative changes. A lateral slide of the socket for example, is equal to a medial slide of the foot. This type of adjustment is useful during static alignment to ensure the foot is directly under the individual’s knee. Linear adjustments can be made by either using a special component that permits this type of slide (Fig. 23.21), or by using a pair of standard pyramid connectors and making equal but opposite angular adjustments.

**Bench Alignment**

The first step in the alignment of a transtibial prosthesis is to position the socket in what is known as “bench alignment.” This alignment serves as the starting point for the dynamic alignment process. In a standard bench alignment, the socket is set at 5 degrees of flexion and 5 degrees of adduction while the top of the prosthetic foot is level in both the frontal and sagittal planes and the medial border of the foot is parallel to the line of progression. When viewed in the sagittal plane, a plumb line should fall from anatomic knee center and pass through the foot at a point one-third of the foot length from the back of the heel. In the frontal plane, the line should go from mid-patella through the center of the heel. The reason for the 5 degrees of socket flexion is to elongate quadriceps muscles slightly so that they are better prepared to accept the full weight of the body and to aid in shock absorption during loading response. The 5 degrees of adduction ensures that the foot is sufficiently inset to create the appropriate varus moment during stance. This properly loads the proximomedial and distolateral aspects of the limb that are best able to carry those forces. Standard bench alignment is not used when joint contracture or deformity is present; instead, the actual limb alignment is marked during the casting procedure and that alignment is used as the starting point in the dynamic analysis.

**Height**

Once the prosthesis has been bench-aligned, the person dons the prosthesis and stands while bearing equal weight on both lower extremities. The first measurement examines the length of the prosthesis. The goal is to achieve relatively equal leg length by comparing the intact and prosthetic limbs. There are two accepted ways to assess the height: statically and dynamically. In a static assessment, the individual is asked to stand with feet shoulder-width apart, knees fully extended, and bearing equal weight on both limbs. The distances from each iliac crest to the floor can be measured and compared. An alternative is to evaluate whether left and right iliac crests appear to be level. The measurement should not be taken in the supine position because the length of the prosthesis changes during weight bearing as a consequence of flexion of the dynamic components and compression of the interface material. In a dynamic assessment, the person is asked to walk and the entire body is observed, especially the head and torso. Many factors will affect the motion of the head and torso, so it is best to focus only on gross asymmetries that can be corrected by changing the length of the prosthesis. When the static and dynamic height measurements are different, a clinical decision is made to determine the optimal length for the prosthesis to provide the best function for the individual. It is not uncommon for the prosthesis to be up to 1 cm shorter than the sound limb under static conditions.

**Dynamic Alignment**

Alignment changes can be made with the standard modular connectors that are used to fasten the components of the prosthesis together. A standard pyramid connector (Fig. 23.22) can be set anywhere within an approximately 20-degree arc of adjustability. This means, for example, that
the socket can be flexed up to 10 degrees or extended up to 10 degrees from the neutral starting position. This is accomplished by loosening one screw and then tightening the opposite screw equally. Each pyramid permits adjustment in two orthogonal planes. For simplicity, the prosthetist will typically rotate the pyramid so that the adjustable planes are aligned with the frontal and sagittal planes. Transverse plane rotation is almost always infinitely adjustable; the standard connectors can accommodate any foot position. When the dynamic alignment differs greatly from bench alignment, it may be necessary to add a special alignable component to the prosthesis. This component will accommodate a larger window of adjustment and allows for linear changes in addition to angular changes. For example, the foot can be inset relative to the socket simply by sliding the foot medially and retightening the connector. This device is to be used during the dynamic alignment only and then removed during the final fabrication procedure. Small linear adjustments can also be made without the special component by performing equal but opposite angular adjustments on two adjacent pyramid connectors. This method will, however, simultaneously affect the height of the prosthesis.

During the dynamic analysis, the prosthetist will ask the individual to walk in a safe environment, typically within the parallel bars, and observe the motion of the prosthesis throughout the gait cycle. Adjustments are made to minimize gait deviations and create a smooth, stable gait pattern. The prosthetist will attempt to create an energy-efficient stride by minimizing the horizontal and vertical displacement of the center of mass. Goals for the optimal alignment are stance stability, swing clearance, equal step length, and energy efficiency. Socket fit and suspension play an important role in providing stability, so final adjustments to both aspects are included as part of the dynamic analysis. Although dynamic alignment is typically done on a flat, level surface, many prosthetists will also attempt to simulate other terrains that an individual will encounter in the course of daily life. Ramps, stairs, and uneven surfaces all require slightly different alignments for optimal performance. It is very important to optimize prosthetic alignment as it has been shown to have significant clinical impact on gait kinetics and spatiotemporal parameters, including cadence and mediolateral displacement of the socket.  

Final alignment is often a compromise of function on the varied terrain that an amputee will encounter.

As the question of whether the alignment of the prosthesis is “good” is ultimately answered by the function and satisfaction of the person wearing the prosthesis. A fairly broad range of alignments can be considered acceptable. In an effort to standardize what is ultimately a subjective estimate of proper alignment, the concept of vertical alignment axis and alignment reference center has been proposed. The vertical alignment axis is a vertical line that passes through the geometric center of the socket at the level of the midpatellar tendon. The alignment reference center is the point along the line from the center of the foot through the tip of the shoe, one-third of the way forward from the back of the heel.

To align the prosthesis, the individual is asked to bear full weight on the socket while the socket is supported on a padded stand. He or she then determines the socket axis based on the most comfortable weight-bearing position. When the socket is aligned with the socket axis in the most comfortable position and the vertical alignment axis goes directly through the alignment reference center (Fig. 23.23), the prosthesis is generally felt to be well aligned.

**ELECTRONIC ALIGNMENT**

Technology has been developed to help the prosthetist to make the alignment process more objective, thereby making prosthetic alignments more repeatable and predictable. Electronic sensors imbedded in the prosthetic components are capable of transmitting real-time gait data to a nearby computer (Fig. 23.24). The computer processes socket load information during the stance phase of gait, which is superimposed over the patient’s baseline data to create a graph (Fig. 23.25). Displaying the otherwise invisible forces and moments on the prosthesis cues the prosthetist to focus in on specific variances and consider their possible causes. This can prevent undetected problems with alignment from causing long-term damage to the individual’s limb. For example, an excessive varus moment at the knee can lead to premature medial compartmental osteoarthritis over a long period. This objective data can be captured and kept in the person’s medical record to be referenced if problems arise or changes are necessary in the future.

**Additional Features**

There are many modular components that can be added to a prosthesis between the socket and the foot to enhance certain features and functions. These include shock absorbers, torque absorbers, and dynamic pylons. The downside of such...
components is the greater overall weight of the prosthesis and the requirement of sufficient clearance between the socket and foot. When clearance is an issue, the foot choices may be limited. Typically these components are used in cases where excessive shock is expected or when an acceptable gait pattern is not attainable with the existing feet alone. Care should be taken to mount these components on the prosthesis as proximally as possible to minimize the inertial effects of the additional weight on the swing phase of gait.

TORQUE ABSORBER

When rotational motion in the socket causes discomfort or excessive stress on the skin, a torque absorber can be used to decrease the rotational torque from the ground reaction force. A torque absorber is a component that uses a viscoelastic bumper to allow a limited amount of rotation to occur at the foot without displacing the socket. The amount of rotation is proportional to the torque and can range up to 30 degrees in either direction. This is especially useful in sports applications, such as golf and tennis, which require a wide range of rotation during the activity. Torque absorbers have been shown to increase participation in low- and medium-intensity activities while reducing the interference of associated pain. Torque absorbers may also be beneficial for turns encountered in normal daily ambulation, especially for individuals with fragile skin.

SHOCK ABSORBER

Although much of the functional shock absorption needed for gait is attainable with controlled knee flexion in loading response, some individuals benefit from the additional vertical excursion afforded by the addition of a shock absorber.
This component uses a viscoelastic spring to dampen the ground reaction forces by slowing their transmission to the limb. As weight is transferred to the prosthesis, the shock absorber compresses relative to the magnitude of the ground reaction force. This reduces impact by spreading the force out over a longer time interval, leading to a lower overall prosthesis height during early stance. Additionally, both features can be combined into a single unit (Fig. 23.26).

**DYNAMIC PYLON**

Typical prosthetic pylons are rigid and function only as attachments between the socket and foot to establish the correct overall height. Dynamic pylons allow for energy to be stored as spring tension as they flex through midstance and into terminal stance. This energy is released in preswing to assist with hip and knee flexion, promote toe clearance, and assist limb advancement. The energy return allows the individual to walk with less energy consumption and increased efficiency, meaning that he or she can walk farther and longer. The angle of flexion in a dynamic pylon is small and is difficult to observe during casual ambulation. The effects are more readily apparent during jogging or running (Fig. 23.27), although even in walking the use of a dynamic pylon has been shown to increase step length and decrease dependency on mobility aids such as crutches.41
Microprocessor-Controlled Foot/Ankle Systems

Microprocessor controlled foot/ankle systems (MPAs) use computer controlled hydraulic cylinders to preposition the foot to accommodate for variations in terrain (Fig. 23.28). This is accomplished through one of two methods. The first is for the ankle to adapt to the slope or variation in terrain during the swing phase of gait while keeping the ankle fixed during stance. The second approach is to adapt to surface changes during the stance phase of gait. Regardless of the approach, all MPA systems have advantages and disadvantages. Advantages include better adaptation to slopes and stairs, increased stability on uneven ground, and decreased fall risk. Disadvantages include cost, weight, greater maintenance requirements, and the need for greater clearance under the prosthetic socket.

Prosthetic Feet

Improvements in prosthetic foot design have led to the availability of foot systems that incorporate one, two, or all three of these features in one device. This has reduced the obstacles of increased weight and the need for extra clearance under the socket. The advancements are attributable to improvements in composite materials, manufacturing processes, and engineering design. An example of such a foot type is a crossover foot in which the design elements of a running-specific foot and those of a daily-use foot are combined. In healthy active prosthesis users, these feet have been shown to reduce oxygen consumption. A much more detailed discussion of prosthetic feet can be found in Chapter 21.

Case Example 23.1  A Traumatic Transtibial Amputation

PRESCRIPTION OF A PROSTHESIS

Let us consider the case of J.W., a 37-year-old male whose left leg was amputated below the knee following a motorcycle accident. He has since recovered from all injuries and is now medically stable. He was recently approved for weight bearing on his left limb as tolerated. He is 5 ft 8 inches tall, weighs 175 lb (79.5 kg), and his residual limb measures approximately 20 cm from knee center to distal end. J.W. has significant amounts of scar tissue on the surface of the residual limb, including a skin graft from his thigh. The skin on the distal end of the limb is adherent to the distal end of the tibia. He was very active prior to his injury and would like to return to that lifestyle as soon as possible. He arrived at the clinic on crutches.

QUESTIONS TO CONSIDER
- Is J.W. a good candidate for a prosthesis?
- What type of interface, suspension, and socket design would be appropriate?
- What other components could be recommended?

RECOMMENDATIONS

The first decision is to determine whether J.W. is a good candidate for a prosthesis. His entry into the clinic on crutches indicates that his balance, upper extremity strength, and contralateral limb are all sufficient condition for gait. The only factor jeopardizing J.W.’s candidacy is the condition of the soft tissue of his residual limb. In the past, poor soft tissue condition could have prevented successful use of a prosthesis, but with the help of modern techniques and materials, a successful fitting may well be possible.

The interface with the skin should be determined next. Two conditions must be considered: the adherent tissue on the distal end and the fragile skin graft. Gel liners are most efficient at eliminating shear forces on the limb. This will be a major factor in preventing skin breakdown of the adherent skin. The skin graft would benefit from a soft durometer gel rather than a silicone elastomer or urethane liner. Selection of the right interface will be critical to J.W.’s outcome. The decision to use an off-the-shelf size or a custom-made liner will depend on the shape of the limb and how well he could be fitted with a standard-size liner.

The suspension for J.W. should be the system that will lead to the least amount of pistoning. Elevated vacuum will maintain the limb volume by drawing fluid back into the tissues between weight-bearing cycles. This is important for J.W., as the tissues of his limb will be subjected to a large amount of strain once he reaches his goal of readopting an active lifestyle.

FITTING AND ALIGNMENT OF THE PROSTHESIS: VISIT 1

J.W. is seen today for the initial fitting of his first prosthesis. The gel liner is donned directly on the skin and a single- ply sock is worn over the liner. The limb is then placed into the socket and a sealing sleeve is rolled up to mid-thigh to seal off the proximal edge of the socket. J.W. is then asked to stand up between the parallel bars, keeping all his weight on the sound limb. J.W. will...
Case Example 23.1  
**A Traumatic Transtibial Amputation (Continued)**

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then slowly transfer his weight over to the prosthesis as tolerated. Once he is comfortable bearing his full weight on the prosthesis, he can begin to take his first steps.

As he begins to walk and feel more confident, J.W. begins to let go of the bars and walk hands-free. Once he does this, his knee begins to flex rapidly during the loading response and the foot starts slipping the floor.

**QUESTIONS TO CONSIDER**

- Is the alignment of the prosthesis adjusted properly? Is the foot making an appropriate heel strike? Has the heel height of the shoe been properly accommodated?
- Is the socket stable on his limb? Are there signs of pistoning?
- Is there excessive medial shift of the prosthesis during stance?
- Are his knee extensors strong enough to eccentrically control knee flexion during full weight bearing?

**RECOMMENDATIONS**

A plumb bob through the midline of the socket falls between the posterior one third and anterior two thirds of the foot when the shoe is donned, and the top of the foot shell is level with the ground. This indicates that the alignment is appropriate. Muscle strength testing reveals that the quadriceps of the residual limb are 2/5 (two out of five). Due to the lack of strength in the quadriceps muscle group, J.W. is unable to regulate knee flexion during the loading response. A rehabilitation protocol for quadriceps strengthening that includes ambulation with the prosthesis should be implemented. At the same time, the prosthesis can be altered to improve J.W.’s gait pattern as he regains his strength. The foot should be moved anteriorly, relative to the socket. This will decrease the mechanical advantage of ground reaction force to flex the knee by shortening the heel lever. It will simultaneously increase the length of the toe lever, which will provide more stability in midstance. The potential downside is that the knee extension moment in terminal stance will also be increased, so there is potential for the knee to hyperextend. J.W. should be asked to monitor his posterior knee pain and report any as soon as it is recognized.

Because his muscle weakness is expected to resolve relatively quickly, alignment of the prosthesis should be monitored on a regular basis so that the foot can gradually be shifted back to the appropriate position and normal gait can be restored.

**FITTING AND ALIGNMENT OF THE PROSTHESIS: VISIT 2**

J.W. has done well with rehabilitation and use of his lower-extremity prosthesis. His limb has healed well and his strength is generally good. He has good balance and endurance for walking with the prosthesis. He has gradually increased his wear time and activity level. He works a 5-hour day in agriculture.

Today he returns to therapy for a scheduled follow-up appointment. He complains of discomfort at the distal end of his residual limb and loss of stability in the socket. While observing his gait, the prosthetist finds that it appears to be a bit short. Assessment of the residual limb reveals erythema on the distal end and on the distal aspect of the patella.

**QUESTIONS TO CONSIDER**

- What changes have occurred since J.W.’s last visit? Has he made changes in the number of sock plies or in his footwear? Has he gained or lost weight?
- Is this an alignment- or fit-related issue? When does the pain occur in the gait cycle? Does the pain increase throughout the day?
- Is the interface worn out? How old is the interface now? How long should it be expected to last? Are there thin areas in the interface that might indicate excessive pressure and premature wear?

**RECOMMENDATIONS**

J.W. reports that his weight and footwear have not changed. He is wearing the same single- ply sock with which he began. His gel liner is still in excellent condition and should be expected to last for about a year of constant wear. Consideration of all the information indicates that the limb has changed since the initial fitting. As his pain is worst at midstance and increases proportionally with the time spent bearing weight, the prosthetist concludes that the limb is too far distal in the socket. J.W. should increase the number of socks he is wearing, one ply at a time, until the limb is seated correctly in the socket. This will also address the length of the prosthesis, which had appeared to be too short.

In experimenting with sock plies, J.W. went from initially wearing a single sock to six plies, but he found that this number of socks created a new set of problems. He is feeling excessive pressure on the tibial tubercle and proximal aspect of the fibular head. During loading response, he is unable to regulate his knee flexion because of pain on the anterodistal aspect of the tibia. Despite good suspension, he is also starting to scuff his toe during swing phase. All these symptoms indicate that he is now too far out of the socket. This position decreases control of the tibia and allows the socket to flex and extend beyond the position of the limb, leading to excessive pressure on the ends of the bones. It also positions the bony prominences of the limb in areas that do not have adequate reliefs. Removal of several sock plies is the correct intervention, as this will allow J.W. to seat his limb further into the socket and thus increase comfort and stability. When he wore four-ply socks, his comfort and control were restored.

Case Example 23.2  
**An Amputation Related to Vascular Disease**

**PROSTHETIC PRESCRIPTION**

G.R. is a 76-year-old woman with type 2 diabetes and peripheral vascular disease. She sustained an abrasion at the lateral malleolus of the right leg that failed to heal and developed into a stage 4 nonhealing wound. Circulation at the lower leg was markedly impaired. After several months of multiple failed therapies to improve circulation and promote wound healing, the right leg was amputated below the knee. G.R. is 5 ft 4 inches tall and weighs 204 lb (92.5 kg). Prior to the problems with her leg, she was living independently and caring for her husband, who is significantly disabled. Two months after her surgery, the transtibial amputation wound site was fully healed. Her physician is recommending that she begin bearing weight on the limb as tolerated. She has been using a wheelchair for mobility in the house, but she is able to stand on her left leg with the support of a standard walker. She is concerned that she will not be able to do her chores around the house and go shopping even after she receives her prosthesis.

**Continued on following page**
Case Example 23.2 An Amputation Related to Vascular Disease (Continued)

QUESTIONS TO CONSIDER

- What are G.R.’s goals for the prosthesis? Will she be a functional ambulator? Will the prosthesis be used only for standing and transfers?
- Will she require assistance with activities of daily living and care for her husband?
- What are the main design goals for her prosthesis? What system will allow her to don the prosthesis independently? Which type of prosthesis will require the least maintenance and have most reliable function?

RECOMMENDATIONS

Evaluating G.R.’s candidacy for a prosthesis will involve assessing her risk-to-benefit ratio as a bipedal ambulator against the negative health effects of prolonged sitting. Her motivation to ambulate is clear in her expressed desire to continue to care for her husband. Her ability to stand on one leg is a fortuitous sign, even if her balance is impaired at this point. Her knee ROM is within normal limits. If her skin integrity is good and her right knee extensors are four of five, she will likely be a good candidate for a prosthesis.

Her prosthesis should be easy to put on, as she will not have assistance available. Her limb has ample soft tissue based on her weight and etiology, although her diabetes puts her at risk for fragile skin and delayed healing. The most appropriate interface for her will be one that most effectively reduces shear. A silicone elastomer cushion liner in a TSB socket will work well for her. A sealing sleeve and expulsion valve will utilize suction as a means of suspension, thus minimizing pistoning. This prosthesis should allow her to wear a cotton sock that is easily laundered as she loses limb volume. The trim lines should be set higher proximally to gain as much control as possible for her prosthesis.

FITTING AND ALIGNMENT OF THE PROSTHESIS: VISIT 1

G.R. is seen for delivery of her preparatory prosthesis. She is instructed on donning the device and is able to roll on the gel liner and place her limb into the socket with moderate effort. Her limb is seated correctly all the way in the socket. After she rolls the sealing sleeve into position, she stands at her walker and slowly begins to load the prosthesis. She is comfortable in the socket and a small amount of air is heard as it is expelled from the socket through the valve. The sleeve is rolled down so that a corset stay can be inserted between the gel liner and the socket. As no areas of excessive pressure are found, the corset stay is removed and the sleeve is rolled back up. Her first steps are tentative and she is bearing the majority of her weight through her arms during stance on the prosthetic side. After some guidance from her therapist, she begins to bear more weight through the prosthesis. Her strides are asymmetric, with a very large step on the contralateral side. As no areas of excessive pressure are found, the corset stay can be inserted between the gel liner and the socket. A small amount of air is heard as it is expelled from the socket through the valve. The sleeve is rolled down so that a corset stay can be inserted between the gel liner and the socket. As no areas of excessive pressure are found, the corset stay is removed and the sleeve is rolled back up. Her first steps are tentative and she is bearing the majority of her weight through her arms during stance on the prosthetic side. After some guidance from her therapist, she begins to bear more weight through the prosthesis. Her strides are asymmetric, with a very large step on the contralateral side.

QUESTIONS TO CONSIDER

- Why is G.R.’s step length shorter on the sound side? Is the prosthesis aligned properly? Is her range of hip flexion and extension within functional limits? Is she stable in stance?
- What are her goals for ambulation? Does she have sufficient stance stability? Does she have adequate clearance in swing? Is her gait pattern energy-efficient?

RECOMMENDATIONS

The gait pattern G.R. uses is typical of the individual with recent amputation who is uncertain about weight bearing through a mechanical device. The feeling of instability on the prosthesis causes G.R. to limit stance time on that side, thereby shortening swing phase on the sound side. Alternately, the individual may be accustomed to bearing weight unilaterally on the sound side so that the stance time is increased, allowing the prosthesis to move ahead excessively. Weakness of the quadriceps and gluteus minimus and medius will also impair stance stability. G. R. should be encouraged to take smaller steps with the prosthesis and larger steps with her sound limb. She may need further conditioning of her knee extensors and hip abductors to completely eliminate this asymmetry.

Excessive socket flexion can increase prosthetic step length, but it also tends to increase the step length on the sound side as well. Extending the socket makes it more difficult to advance over the foot during stance and will tend to shorten step length on the contralateral side.

FITTING AND ALIGNMENT OF THE PROSTHESIS: VISIT 2

G.R. returns for therapy and complains about discomfort in her socket. Inspection of her skin reveals excessive pressure, as evidenced by erythema, on her femoral condyles and fibular head. She has been doing a good job managing her sock plies and is now seated correctly in the socket wearing eight plies. She explains that the tightness she feels does not get worse during weight bearing.

QUESTIONS TO CONSIDER

- What changes may have taken place since her last visit? As her activity level increases, what is the effect on limb volume? Which areas of the limb are most susceptible to volume loss?
- What is the source of the erythema? Is there swelling of the knee? Does the redness appear anywhere else on the limb? Does it appear to be an allergic reaction, such as contact dermatitis? Is her liner clean and in good condition?

RECOMMENDATIONS

After discussing good hygiene and prosthesis care with G.R., it is clear that she is washing her gel liner daily with a mild soap and then rinsing it thoroughly; she is also washing her limb every day and patting it dry. She is not using any lotions that could create buildup in the liner or cause an allergic reaction within the warm, moist environment of the liner. The fit of the socket is assessed next by probing between the liner and socket with a thin metal corset stay. This is done in the non-weight-bearing state, as that is when she feels the pressure. The corset stay encounters great resistance when it passes over the fibular head and is completely stuck when trying to pass over the femoral condyles. This indicates excessive pressure over those bony structures. Although G.R. is wearing the appropriate number of socks, they are creating extra bulk, which makes the socket too tight in those areas. A referral should be made to her prosthettist so that the socket can be modified. It is likely that pads can be added in strategic areas that are more prone to volume loss, such as the area over the calf muscle and on either side of the tibia. This will take up volume in the socket and require G.R. to reduce the number of sock plies she is wearing. Following that adjustment, she is feeling more comfortable in the socket and her skin is free of irritation.
which is used during the fitting process and then discarded and often destroyed during the fabrication process. The diagnostic socket or “check socket” is made of a transparent thermoplastic so that the prosthetist can inspect the limb during loading and see the blanching of the skin as the person goes through various activities of weight bearing. The plastic is also very amenable to changes in shape and volume simply by heating a given area and reforming the plastic. Extended fittings, during which the individual takes the diagnostic socket home for a day or more, must be conducted carefully, as some of the materials used for diagnostic sockets are brittle and can fracture under normal loading conditions. Extended fittings can be quite useful, however, the prosthesis will be used under more realistic conditions and some problems will become apparent only after the wearer has spent several hours wearing the prosthesis.

### Finishing Techniques

After the prosthetist and the wearer are both satisfied with the fit and alignment, the final prosthesis can be fabricated. The exact finishing technique varies based on the components selected, but the main goal is to preserve the alignment and create a lightweight prosthesis with a cosmetically satisfactory appearance. The foot is removed and the remainder of the prosthesis is secured in a vertical alignment jig (Fig. 23.29). The socket is filled with plaster and a pipe, held in place by the alignment jig, and set into the wet plaster. After the plaster hardens, the alignment has been captured and the prosthesis can be removed from the jig. The jig preserves the alignment until the final prosthesis is reassembled. The prosthetist will determine the best method of fabrication to create the lightest-weight prosthesis without sacrificing structural integrity. Extra alignment devices are removed during this process. The final limb is assembled with either endoskeletal or exoskeletal components based on the user’s individual needs.

### ENDOSKELETAL CONSIDERATIONS

As the term endoskeletal implies, the structure of this type of prosthesis is located deep inside the device. The exterior of the prosthesis may consist of passive foam rubber or latex that gives the prosthesis a more anatomic appearance and protects the structural and functional parts hidden underneath (Fig. 23.30). This type of prosthesis has two distinct advantages: adjustability and a realistic appearance. Endoskeletal design allows for the use of modular components that can be adjusted or replaced quickly and easily as needed. If a single component were to fail, repair would involve simple removal and replacement of that component, just as a tire on a car can be changed. These modular components can easily be obtained from the prosthetist, as they are not custom-made. The appearance of the endoskeletal limb can be quite realistic. Virtually any size and shape can be created by shaping soft, lightweight foam over the components. The foam can be coated with a variety of finishes that provide color and texture and may include life-like details such as moles, freckles, pores, and even hair.

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**Fig. 23.29** A prosthetist uses this device to preserve the relative positions of the foot and socket during fabrication. This allows the exact alignment of the diagnostic prosthesis to be transferred to the definitive prosthesis. (Image provided by Fillauer.)

**Fig. 23.30** A diagram of an endoskeletal prosthesis in which the socket and pylon are concealed within a cosmetic cover. (From Knee Prosthetics, Prosthetics-Orthotics Program, University of Texas Southwestern Medical Center, TX, 1998).
Premium restorations are nearly indistinguishable from a sound limb.

**EXOSKELETAL CONSIDERATIONS**

When a more durable and easily cleanable prosthesis is desired, an exoskeletal prosthesis can be fabricated. The socket of an exoskeletal prosthesis is attached to the foot through an external composite lamination custom-shaped for the individual (Fig. 23.31). To create this shape, a prosthetic ankle block is first bonded to the socket with rigid foam in the vertical alignment jig. The foam is rigid enough to maintain the alignment between the socket and foot that was preserved in the jig. The foam and ankle block are then shaped by hand to match the contralateral side, only a little bit smaller to accommodate the thickness of the final lamination. The final step is to seal the foam and laminate the exterior. This final composite covering provides the structure of the prosthesis as well as the anatomic shape. Exoskeletal prostheses are often heavier than their endoskeletal counterparts and are always less adjustable. The advantage of the exoskeletal system is durability. The hard surface covering the prosthesis is nonporous, chemically inert, and waterproof, making it easy to clean and less susceptible to damage.

**Deviations in Gait**

Gait deviations can be caused by improper socket fit, by misalignment of the prosthesis, or by weakness or other musculoskeletal pathologic conditions of the individual. They can be quite common in persons with transtibial amputations; one study has shown deviations in nearly 20% of the 60 kinetic, kinematic, and temporospatial parameters of gait.44 Such deviations are known to increase metabolic cost due to excessive displacement of the center of mass.45

Careful evaluation is essential to determine the cause of deviations and what can be done to correct them (Chapter 5 presents a review of the biomechanics of normal gait). Variations in limb volume or shoe type can introduce deviations in a wearer’s gait that had not been noted before. It can be very productive to ask wearers whether they have recently made any changes in their routines. Changes in diet, medications, shrinker wear, or activity level can all affect limb volume. If a shoe with a higher or lower heel is placed on the prosthesis, it will change the socket’s orientation to the ground. Unless there is a component that will accommodate the new heel height, the wearer’s gait will be affected adversely. Common gait deviations are reviewed in the following paragraphs as they occur in the gait cycle in each individual plane.

**INITIAL CONTACT**

**Sagittal**

Initial contact should be made with the heel (Fig. 23.32). If the user makes contact at the midfoot/forefoot first, there may be either excessive plantarflexion of the prosthetic foot or limitation of the person’s knee extension ROM (i.e., knee flexion contracture). Both of these circumstances contribute to a high knee extension moment during loading response that causes the knee to move posteriorly. This motion negatively impacts efficiency and can damage the knee joint over time. Every effort should be made to create a heel strike at initial contact. Interventions include therapeutic
exercises to increase knee ROM and knee extensor strength, prosthetic alignment changes to accommodate knee flexion contractures, and proper height and suspension of the prosthesis. If the prosthesis is too long or does not suspend well, the prosthesis may hit the ground early, shortening swing phase.

**Frontal**

Excessive inversion or eversion of the foot at initial contact indicates misalignment of the prosthesis. The heel of the prosthetic foot should be level when it meets the ground. The lateral border of the heel should contact the surface first; this is related to the transverse plane alignment of the foot to accommodate a normal toe-out angle of 5 to 10 degrees. This lateral heel contact sets up the standard progression of the ground reaction force up the lateral border of the foot and then crossing to the medial aspect of the forefoot during stance phase.

**Transverse**

The rotation of the prosthesis is fairly consistent throughout stance phase. The medial border of the foot should be parallel to the line of progression. Transverse plane rotation at initial contact is an indicator that the limb is fitting too loosely in the socket or that the foot is not directly under the limb. External rotation of the prosthesis may be seen with an inset foot, whereas internal rotation could be a result of an outset foot (Fig. 23.33).

**Loading Response**

**Sagittal.** Excessive knee flexion moment during loading response is caused by a foot that is set too far posteriorly, is too dorsiflexed, or has a heel that is too rigid. The transition during loading response should be smooth and controlled. The knee should bend to approximately 20 degrees of flexion as the forefoot meets the ground. This advances the limb and aids in shock absorption. Insufficient knee flexion moment can be caused by a heel that is too soft or a foot that is positioned too far anteriorly. This can cause the knee to hyperextend, leading to pain and inefficiency. Adjustment of the heel lever length, stiffness, and orientation should be made to provide the appropriate degree of knee flexion. When accommodation for the heel stiffness is made, the soling material of the shoe should also be taken into account, because an excessively stiff or soft heel material can exaggerate this tendency.

**Frontal**

Rapid loading of the foot during this phase would produce significant moments at the knee if the foot is not parallel to the ground at initial contact. The plantar surface of the foot should be level during this phase as viewed in the frontal plane. Some modern prosthetic feet have rearfoot inversion and eversion capabilities and can adapt to the surface on weight bearing, making them useful for uneven surfaces. The prosthetist must make sure to observe the motion as the loading occurs. When there is motion while ambulating on a flat surface, the alignment of the foot should be changed to eliminate that motion.

**Transverse**

Any rotation of the foot during loading may indicate an excessively loose socket or faulty torsion adapter. Rotary moments can be generated by excessive toe-in or toe-out, and the torsion adapters allow that motion to occur uncontrolled.

**MIDSTANCE**

**Sagittal**

A choppy or segmented midstance is caused by differences in the dynamic characteristics between the prosthetic heel and the prosthetic toe, indicating a lack of stability. The heel and toe lever arms are adjustable by shifting the socket anteriorly to shorten the toe or posteriorly to shorten the heel. The optimal foot position is one where the forward velocity of the knee is consistent between loading response and midstance. The prosthetic foot must accommodate smooth transition of the ground reaction force from the heel to the forefoot during midstance. Over this period, the moment at the knee changes from a flexion moment to an extension moment. A steady increase in dorsiflexion should be observed as the knee moves over the foot.

![Diagram](Fig. 23.33 The progression of the transtibial prosthesis during stance phase. Initial contact is made at the heel, and compression of the prosthetic heel simulates controlled lowering of the foot during loading response. At midstance, weight-bearing forces move anteriorly to the ball of the foot. In terminal stance, the anterior portion of the prosthetic foot simulates toe extension and the heel rises. In preswing, the individual rolls over the toe and moves into knee flexion for effective shortening of the limb for swing limb clearance. (Diagram courtesy David A. Knapp, CPO, Hanger Prosthetics & Orthotics, North Haven, CT.)
Frontal
There is a normal and desirable varus moment during midSTANCE. In order to maximize energy efficiency during gait, the body’s center of mass does not shift all the way over the stance foot. The knee should move laterally approximately 1 cm during midstance. Shift of the knee greater than 2 cm indicates an excessive varus moment and will lead to stress on the medial compartment and lateral ligaments of the wearer’s knee. This stress can be reduced by adducting the socket or shifting it medially. If the socket does not move or shifts medially during midstance, the socket is too far inset (or the foot is too far outset), or the socket is excessively adducted. Lateral gapping is a condition in which a large gap occurs during loading between the limb and the lateral wing of the socket. If a gap larger than 2 cm is observed, the socket may be too loose and an additional ply of sock should be added.

Transverse
Rotation that occurs during midstance is typically seen between the limb and socket and is almost always attributable to poor socket fit. If motion occurs, the wearer may complain of patellar impingement on either the medial or lateral aspects of the patella. Often, the remedy is to tighten the socket by adding a ply or two of socks. In cases where socks are insufficient to stabilize the rotation, the socket should be adjusted by the prosthetist. Pretibial pads that provide pressure on either side of the tibial crest are an effective solution to stop rotation.

Terminal Stance
Sagittal
Drop off is the excessive descent of the center of mass during terminal stance caused by a toe lever that is either too short or too soft. It is often characterized by diminished heel rise. This compromises the energy efficiency of walking. It occurs at a point when the body’s center of mass is already near the bottom of its sinusoidal path. The toe lever of the prosthetic foot must have sufficient stiffness to resist dorsiflexion when the wearer’s entire weight is placed on the ball of the foot. In terms of energy efficiency, this is a critical phase of gait. Proper loading of the forefoot promotes knee stability, maintains altitude (i.e., level pelvis), and stores energy in the ligaments that can be released during swing phase to assist with limb advancement (Fig. 23.34).

Early heel-off is an indication that the foot is too plantarflexed or the toe lever is too stiff. The heel should come off the ground at the point when the swing foot has already passed anterior to the stance limb. Forward momentum of the body is impeded by early toe-off and may force the individual into an anterior lean with the trunk to maintain forward progression. The ankle should be set to dorsiflex until the swing limb reaches terminal swing so that the heel remains on the ground until the center of mass has progressed sufficiently forward. This will preserve step length and enhance stability.

Fig. 23.34 The socket angle will affect the magnitude and timing of the ground reaction force through the knee during stance phase. Optimal alignment (center) varies with specific foot design but will be approximated by the centerline of the socket falling through the posterior one third and anterior two thirds of the foot. (Diagram courtesy David A. Knapp, CPO, Hanger Prosthetics & Orthotics, North Haven, CT.)
Frontal
The heel should rise off the ground with the knee breaking over the point on the foot between the first and second toes. Any large variance from this position will create instability and consequently shorten step length. The knee should travel in a straight line as it flexes; any lateral motion during this phase will lead to a whip in swing.

Transverse
The toe load is highest during this phase of gait; therefore there is potential for rotation of the prosthesis due to suboptimal alignment. External rotation can be caused by a foot that is too far outset or having excessive toe-out. Internal rotation is caused by an excessively inset or internally rotated foot.

PRESWING
Sagittal
As the body weight transfers rapidly to the contralateral limb, the prosthesis should roll forward over the toe and lift off the ground. Toe-drag may result from a foot that is excessively plantarflexed or from a faulty suspension system.

Frontal
The knee should not move medially or laterally during preswing. An externally rotated foot can cause a valgus moment that pushes the knee medially as weight is transferred off the prosthesis. A valgus moment can also be caused by an outset foot or an excessively adducted socket. Lateral motion during preswing can be caused by an internally rotated foot, an excessively inset foot, or an excessively abducted socket.

Transverse
Many of the same factors that lead to instability in the frontal plane can lead to instability in the transverse plane. Appropriate attention to transverse plane alignment throughout stance phase should help to avoid issues in preswing as well.

SWING PHASE
Sagittal
The transtibial prosthesis swings passively forward during swing phase. If sufficient ground clearance is not obtained, the amount of knee flexion should be noted. In cases where appropriate knee flexion is observed, the suspension of the prosthesis should be evaluated. A faulty suspension or a plantarflexed foot will reduce swing clearance. The amount of pistoning varies with the type of suspension used. Motion exceeding 1 cm should be considered excessive. If knee flexion is observed during swing phase, active and passive motion should be assessed. Weakness or contracture of the knee can limit knee motion, as can a tight suspension sleeve or an aggressive supracondylar wedge. Although suspension and knee flexion are often adversarial, a balance should be attainable that permits enough foot clearance for safe ambulation; otherwise the prosthesis may require shortening.

Frontal
Socket instability during swing is typically caused by either a faulty suspension or a loose-fitting socket. The weight of the socket pulls the prosthesis into varus during swing if the limb is not well seated in the socket. Adding more sock plies and implementing an improved suspension should remedy any swing-phase instability.

Transverse
Rotation during swing phase is often caused by a prosthetic “whip.” A medial whip occurs when the heel of the prosthetic foot moves medially in initial swing and then laterally during midswing. A lateral whip follows the opposite pattern. Whips can be caused by misalignment of the knee axis at the onset of swing or by irregular loading of the limb in terminal stance. Alignment of the knee axis in a person using a transtibial prosthesis is determined by the function of the hip and should be addressed by strengthening and ROM exercises. Remedies involve examining the loading of the prosthesis. Medial whips can be caused by a foot that is too far inset or externally rotated. Both medial and lateral whips can be caused by a foot that is too plantarflexed or a toe lever that is too stiff.

Troubleshooting
A common problem encountered by individuals with recent transtibial amputation is the application of too few or too many sock plies. Sock-ply management is a skill that develops as the individual wears the prosthesis more and is conscientious about examining the limb after doffing the prosthesis. The number of socks will eventually become consistent, but variability is common early in the process of limb maturation. The correct number of socks may vary from day to day or even from hour to hour. There are a few basic cues that those new to the use of a prosthesis must consider to ensure that the limb is in the correct position within the socket.

The first cue arises during donning—the limb should slide into the socket with some resistance. This is a subjective determination, and the wearer should be trained to recognize the amount of force needed to fully don the prosthesis with the correct number of socks. Too few socks allows the limb to “bottom out” in the socket, where most of the weight bearing occurs on the distal end, leading to pain, instability, and increased pistoning. Conversely, too many socks prevent the limb from fully entering the socket; leading to loss of control and pressure on bony prominences. Too many plies of socks can also lead to hammocking, which is stress on the distal end soft tissues as they are pulled tight over the distal tibia during weight bearing. For the person who has recently started using a prosthesis, this sensation may feel very much like the bottoming out sensation they feel with too few sock plies. It is important to educate the wearer on differentiating between the two conditions.

The second cue indicating the limb is not in the correct position within the socket is increased pistoning, anteroposterior, or mediolateral motion within the socket while walking. This can be caused by an insufficient number of socks.

The final cue to incorrect position are signs of erythema found while doffing the prosthesis. Erythema on the distal
aspect of the fibular head or patella indicates that the limb is too far in the socket and that more socks are needed. If too many socks are being used, the erythema will appear on the tibial tubercle or the proximal aspect of the fibular head because the limb is not far enough into the socket. In this case, there may also be signs of verrucous hyperplasia on the distal end of the limb due to the lack of distal contact.

Another common problem that arises is caused by inappropriate shoe wear. Although some prosthetic feet accommodate for the heel height of the shoe, most do not. Wearing a heel that is too high positions the limb, such that there is a relative excessive flexion of the socket and actual excess flexion of the knee joint during stance. A heel that is too low or is used without a shoe tends to hyperextend the knee. Proper footwear is important for safe ambulation. The prosthesis can be checked by evaluating the top surface of the foot shell while the prosthesis is stands on a level surface. If the top of the foot shell tilts posteriorly, the heel is too low (Fig. 23.35). Similar sagittal-plane gait problems can occur by changing between footwear of similar heel height but differing stiffness on soling material. A stiff-soled (leather-soled) shoe will have similar effects to an increased heel height and a softer sole will be similar to bare foot. These changes will be most noticeable in the initial contact and loading response phases of gait.

In a well-fitting socket, the skin should appear uniform in color after the prosthesis has been worn. Areas of erythema that fade after 20 minutes are not likely to be problematic. The skin should be soft and supple, especially on the distal end. Firm tissue associated with edema is a sign of poor contact, and an effort should be made to create some contact in the area of the firm tissue. The wearer may not tolerate much pressure, but only a small amount of pressure is needed to push the extra fluid back into circulation. If erythema is observed over bony prominences and the person’s residual limb is properly seated in the socket, pressure in those areas must be relieved. Prosthetists can adjust the fit of thermoplastic sockets by heating and reshaping the areas needing adjustment. Thermoset sockets, like composites, can be adjusted only by cutting out fenestrations or adding padding to the area around the prominent bone to shift it away from the socket wall. It is important to note that the addition of padding requires the removal of some sock plies to maintain the same volume within the socket.

If skin irritation is present, especially over a bony prominence, placing a small mark on the affected areas with lipstick before donning the prosthesis will allow the lipstick to transfer to the socket during ambulation. Once the wearer removes the prosthesis, the lipstick will mark the areas of excessive contact. Alternatively, a thin flexible steel probe (a corset stay works exceptionally well) can be inserted between the socket and the interface to act as a feeler gauge to find areas of high pressure. The wearer should be putting some weight through the socket during this evaluation. To assess distal contact in a finished socket, a ball of soft clay about the size of a pea can be placed into the bottom of the socket prior to donning. After the person dons the prosthesis and walks a few steps, the prosthesis should be removed and the clay examined. The clay should appear compressed. A postcompression clay thickness of 3 to 5 mm is considered ideal. Total contact in the socket can be assessed by lightly powdering the interior surface of the socket with a fine powder like cornstarch and having the individual carefully don the prosthesis and walk a few steps. Any powder that remains on the socket’s surface after walking indicates that those areas are not in contact with the residual limb.

The amount of pistoning that is present in a socket depends on the socket design and the type of suspension.
The swimming prosthesis can also be fitted with an adjustable path to get back out once the person finishes swimming. Any water that gets inside the prosthesis should have a quick ability to keep his or her head above the water surface, and a buoyancy of the device. Neutral buoyancy is preferred just the ability to get wet. Attention must be given to the flexed foot, or an excessively extended socket.

When a shoe that has a socket flexion, or a heel that is too firm. This pattern can also be observed when an individual wears a shoe that has a higher heel than the prosthesis can accommodate. Conversely, if the person goes barefoot, the opposite pattern of pressure will be observed — erythema on the posterior distal aspect of the limb may be a result of an excessively long heel lever arm, excessive dorsiflexion, excessive socket flexion, or a heel that is too firm. This pattern can also be observed when an individual wears a shoe that has a higher heel than the prosthesis can accommodate. Conversely, if the person goes barefoot, the opposite pattern of pressure will be observed — erythema on the posterior distal end and the anteroproximal end. The same pattern can be caused by a toe lever arm that is too long, an overly plantarflexed foot, or an excessively extended socket.

There are several patterns of erythema that indicate poor alignment of the prosthesis. Excessive varus moment on the limb is suspected when signs of pressure are observed on both the distolateral and the proximomedial aspects of the limb. This pattern can be caused by excessive foot inset or too much socket adduction. When the erythema is observed on the distomedial and proximolateral aspects of the limb, an excessive valgus moment is likely. The foot may be too far outset or the socket may be excessively abducted. Anterior distal pressure accompanied by pressure in the posterior proximal aspect of the socket may be a result of an excessively long heel lever arm, excessive dorsiflexion, excessive socket flexion, or a heel that is too firm. This pattern can also be observed when an individual wears a shoe that has a higher heel than the prosthesis can accommodate. Conversely, if the person goes barefoot, the opposite pattern of pressure will be observed — erythema on the posterior distal end and the anteroproximal end. The same pattern can be caused by a toe lever arm that is too long, an overly plantarflexed foot, or an excessively extended socket.

**Specialty Prostheses**

There are novel prosthetic designs that are intended for use in specialized activities such as water sports, running, and bicycling. The biomechanical goals of these prosthetic devices are different from those designed for everyday ambulation. The designs must take into account the unique loading and various environmental exposures. Running feet, for example, lack a heel spring because sprinting takes place on the toes only; a heel would interfere with limb motion and add unnecessary weight. As knee flexion during a sprint may reach beyond 110 degrees, the posterior proximal trim line must be lower. There is significantly more impact force at initial contact; therefore more care should be taken to make sure the person and prosthesis are capable of absorbing the impact slowly in a manner that will prevent damage to the skin and limb. Running also subjects the prosthesis to greater tension in swing phase, so the suspension system will be under increased strain. Runners often use an auxiliary suspension in case their primary suspension fails at high speed.

A prosthesis designed for swimming includes more than just the ability to get wet. Attention must be given to the buoyancy of the device. Neutral buoyancy is preferred because a prosthesis that floats may inhibit the individual’s ability to keep his or her head above the water surface, and a prosthesis that sinks could drag the person down with it. Any water that gets inside the prosthesis should have a quick path to get back out once the person finishes swimming. A swimming prosthesis can also be fitted with an adjustable ankle that allows the swimmer to lock the ankle in approximately 70 degrees of plantarflexion, which accommodates the use of a swim fin. Waterproof components and materials that do not absorb water are the best choices when one is designing a swimming prosthesis so that the individual can also use the device on the way to and from the swimming area. Any time the prosthesis is used in salt water, it should be thoroughly rinsed with fresh water after swimming, even if it was designed for the marine environment.

There are specialized feet for downhill skiing that clip directly into the ski bindings, rock-climbing feet that require no shoes, cycling feet that clip directly into the pedals, and many other specialized feet for sports and recreational activities. To save money and time and to avoid having to carry several complete prostheses, active wearers can use a quick disconnect adapter to keep one socket and rapidly switch between different specialty feet. The adapter ensuring the alignment of the prosthesis is optimal for each activity for which the specific foot is intended. It also provides a secure and safe connection so that the individual can feel confident that the prosthesis will not fail. This component does add weight to the system and requires additional clearance under the socket. Most insurance companies will pay for these types of prostheses when the medical necessity is well documented.

**Summary**

Individuals with transtibial amputations have the opportunity to participate in a rehabilitation process that seeks to maximize function and minimize impairments so that they can participate as fully as possible in activities of daily living and instrumental activities of daily living. An interdisciplinary team is available to support medical, nursing, social/psychosocial, rehabilitation, and prosthetic needs of the individual. The team helps develop a plan of care that addresses the goals of the person, family, and caregivers. Current technology, along with advances in prosthetics for persons with transtibial amputations, offer a wide array of options to the user. These options range from prosthesis use for cosmetic purposes and for home-bound ambulation to community ambulation with variable cadence to intensive athletic involvement. The clinicians dedicated to enhancing the quality of life of persons with transtibial amputation must evaluate many variables when engaging in a postamputation rehabilitation program including the following: (a) the amputee’s overall health, functional status, and mobility skills; (b) the amputee’s motivational level; (c) the componentry and technology of the prosthesis to make sure that the most appropriate and best-fitting prosthesis is produced; and (d) materials and equipment tailored to the individual to optimize the outcome of the rehabilitation process. The Medicare K-level standards speak to the “potential” to achieve a level of ambulation and community engagement. Persons with transtibial amputation should be scheduled for follow-up care to ensure that the prosthetic prescription provided at one point in time meets the needs of the individual later on as changes associated with skill progression and advancement occur. Therapists, prosthetists, and other health care providers should advocate on behalf of persons with amputation for changes in prostheses as the need arises.
References


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