Lecture # 6

Artificial Limbs I

Transfemoral Prostheses

ADVANCES IN TECHNOLOGY

Advances in technology, materials, and prosthetic components have had a considerable positive impact on the quality of life of individuals with transfemoral amputation. In the past, ambulation wearing a transfemoral prosthesis was labored and often painful. Only the most physically fit individuals attempted to run with their prostheses. Now socket designs better approximate anatomy of the lower limb, suspension systems enhance and maintain intimate residual limb contact within the socket, and dynamic prosthetic feet and knee components offer improved energy-efficient function. The result has been a significant improvement in quality of gait, allowing more people with transfemoral amputation to walk comfortably and naturally with their prostheses.

PROSTHETIC MANAGEMENT AFTER KNEE DISARTICULATION OR TRANSFEMORAL AMPUTATION

An amputation proximal to the anatomical knee joint is referred to as a transfemoral (above knee) amputation. An amputation through the center of the anatomical knee joint is known as a knee disarticulation (Figure 1). Individuals with knee disarticulation present with prosthetic challenges and functional advantages when compared with those with Transfemoral amputation. The disarticulation residual limb tends to be long and distally bulbous, a result of the preservation of the femur and its condyles. Prosthetically, this creates a challenge in donning the prosthesis and cosmetically finishing a knee component. The bulbous distal end does, however, enhance prosthetic suspension. The normal adduction angle of the lower extremity is more likely to be preserved, and the long lever arm of the femur facilitates control of the prosthetic knee. Also, as the proximal component of a weight-bearing joint, the distal femur tolerates end-bearing pressures within the socket.

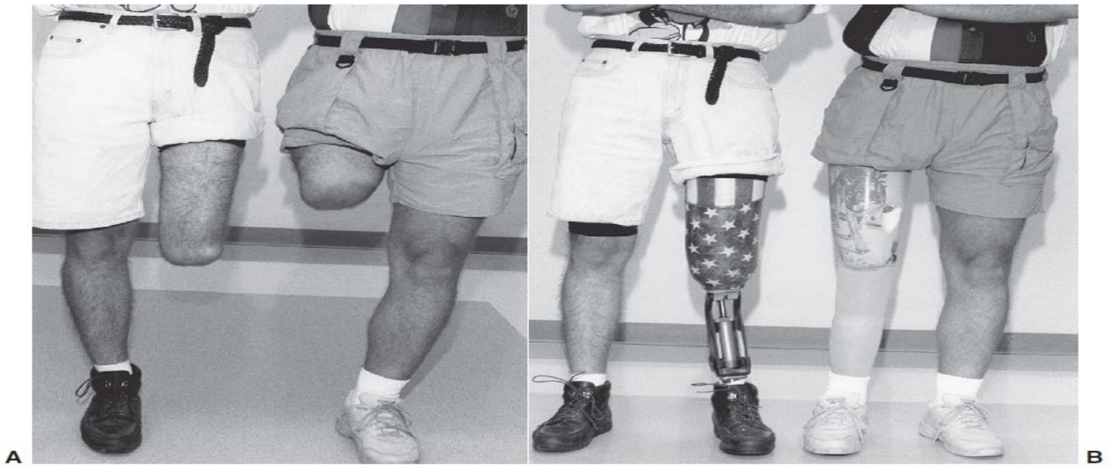

Figure 1:- The similarities and differences in prosthetic fit and function between amputations at transfemoral and knee disarticulation levels are determined, to a large degree, by the length of the preserved femur. A, The knee disarticulation residual limb is long and bulbous, whereas the Transfemoral residual limb is a tapered cylinder. B, In a knee disarticulation prosthesis, the center of the prosthetic knee is generally lower than that of the intact limb, whereas the knee center of most Transfemoral prostheses matches that of the intact limb.

In contrast, the transfemoral residual limb varies in length, depending on how much of the femur has been retained. The shape of the residual limb is likely to be a tapered cylinder so that donning a prosthesis is less difficult.

Suspension can be challenging, however, as a result of this cylindrical shape of the residual limb. The fleshiness of the transfemoral residual limb presents an opportunity for suction suspension. As the length of the residual limb decreases, socket suspension and control of the prosthetic knee (especially stance stability) become more problematic.

The successful prosthetic management of individuals who have suffered an amputation above the knee involves:

- Providing a prosthesis that is comfortable in containing the residual limb.
- Stable during the stance phase of gait.
- Smooth in transition to the swing phase of gait.
- Acceptable in appearance.

In choosing components for an individual's transfemoral or knee disarticulation prosthesis, the prosthetic team must consider:

- The interrelationships among the component's weight, function.
- Cosmesis.
- Comfort.
- Cost.

Often the most functional or technologically sophisticated components are also the heaviest, most expensive, most likely to need maintenance, and least cosmetic. Because of the great variation in physical characteristics, health, and preferred activities of individuals with Transfemoral amputation, no single material, component, or Transfemoral design is appropriate for all persons with amputation. The preferences and needs of each individual must be considered carefully, in the context of weight, function, cosmesis, comfort, and cost, for the optimal prosthetic outcome.

TRANSFEMORAL SOCKET DESIGNS

Prior to the 1950s, prosthetists typically carved a “plug fit” socket from a block of wood, which, depending on the skill of the craftsman, was often uncomfortable and cumbersome while walking and sitting. The plug socket was crafted to contain the remnant thigh muscles, support body weight at the groin level (below the ischium), and was often open ended to eliminate distal limb contact.

Quadrilateral Socket

The traditional quadrilateral (quad) socket, developed at the University of California at Berkeley in the 1950s, offered a notable improvement in fit, total contact, function, and remained the socket design of choice until the mid-1980s. The quad socket, as its name implies, has four distinct walls fashioned to contain the thigh musculature. The quad socket was designed to be a complete above-the-knee prosthetic system that interfaces with the individual who wears the prosthesis. The socket's primary functions are to provide for weight-bearing during the stance phase of gait and to allow the hip and thigh muscles to function at maximum potential during the stance phase of gait (Figure 2-A). A flat posterior shelf, the ischial seat, is the primary weight-bearing surface for the ischium and gluteal muscles. The anterior wall contours create a posterior-directed force at the anatomical Scarpa's triangle, which is intended to stabilize the ischium on its prosthetic seat. As a result, the socket is narrower in its anterior–posterior dimension than its medial–lateral dimension (Figure 3-A).

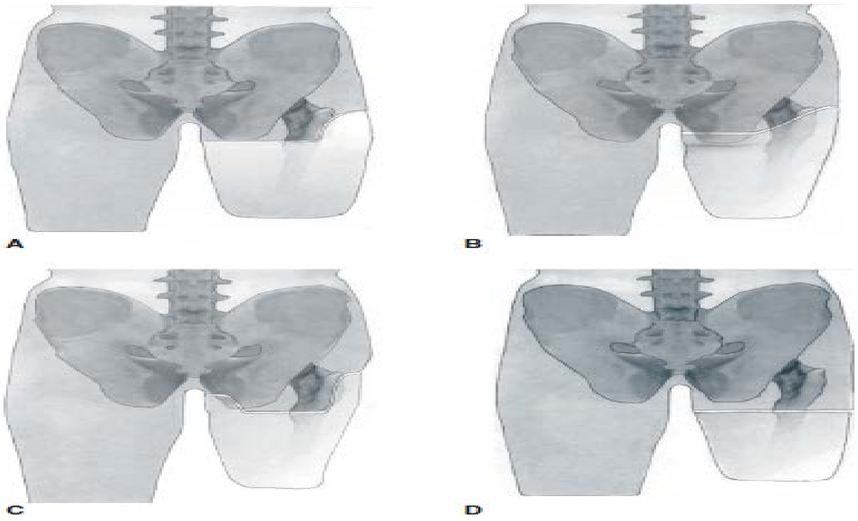

Figure 2: Comparison of the design of the quadrilateral (quad) socket (A), the ischial-ramal containment (IRC) socket (B), the Marlo Anatomical Socket (MAS) (C), and subischial socket (D) from a posterior perspective. The quad socket is designed to have the ischium sitting on the socket brim (seat). In the IRC socket and the MAS, the ischium sits inside the socket. With the subischial socket, as the name implies, the socket trim line is below the ischium.

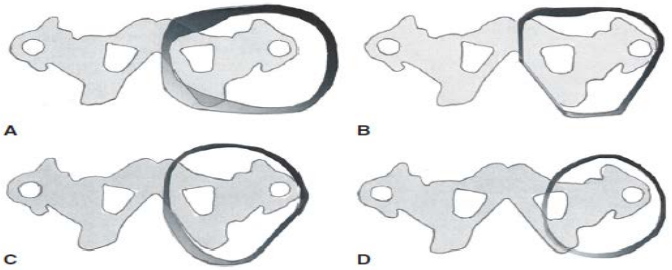

Figure 3: From a cross-section view of the four different Transfemoral sockets designs it is noted that the quad socket has a narrow anteroposterior dimension (A), the ischial-ramal containment (IRC) socket (B), and Marlo Anatomical Socket (MAS) (C) have narrow mediolateral dimensions. The subischial socket (D) has a more oval shape which is consistent with the shape of the proximal thigh.

Evolution of Ischial Containment Sockets

Long observed that many individuals who wear a quadrilateral socket walk with an extremely wide base and demonstrated a Trendelenburg or gluteus medius limp, causing the individual to lean to the amputated side. He also noted that in most cases the transected femur was aligned in abduction as opposed to the normal adduction angle of the sound side femur (Figure 4). The abnormal abduction angle of the femur was believed to be in part the result of the quad socket's unnaturally wide medial–lateral dimension and narrow anteroposterior dimension.

Long's socket design was part of a frontal plane alignment procedure that became known as “Long's Line.”, Long believed that by aligning the distal femur over the center of the knee and through the center of the foot, the wearer of the prosthesis could bring their residual limb into a normal anatomical position and walk more naturally. In the 1980s prosthetist John Sabolich expanded upon Long's concept and developed his contoured anterior trochanteric-controlled alignment method (CAT-CAM) socket (see Figure 2-B). His design attempted to both maintain the femur in an adducted position and control socket rotation by containing the ischial tuberosity within the contours of the socket.

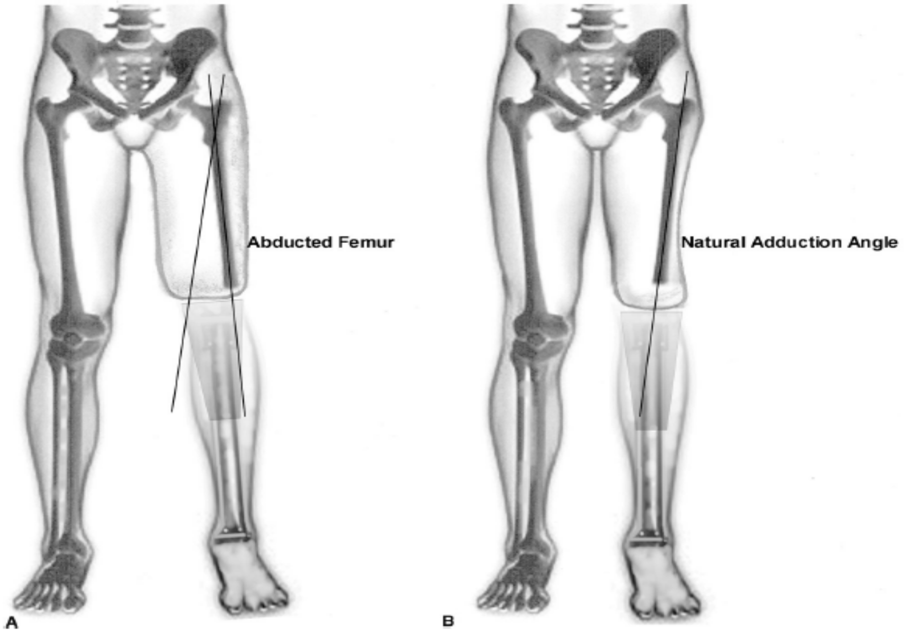

Figure 4: Long noted that for many individuals who wear a quadrilateral socket the transected femur was aligned in abduction as opposed to the normal adduction angle of the sound side femur (A). Quad socket wearers typically walk with an unnaturally wide base. Ischial-ramal containment (IRC) sockets (B) are more naturally designed and aligned to enhance an individual's gait, decrease energy expenditure, increase socket comfort, and improve function.

Socket Configuration Influence on Femur Position

The degree to which the prosthetic socket design can influence the position of the transected femur has been hotly disputed. Orthopedic surgeon Frank Gottschalk developed a myodesis surgical technique to ensure proper femoral adduction in a transfemoral residual limb. In the journal article, “Does socket configuration influence the position of the femur in above-knee amputation?” Gottschalk and colleagues concluded that the prosthetic socket cannot provide enough lateral pressure to change the position of the femur. The authors indicated that proper anatomical adduction is achieved only through specific surgical techniques. Most practitioners would agree with Gottschalk when he suggests that “successful prosthetic fitting starts at the time of surgery.” However, there is also a consensus that indicates that an intimately contoured socket in optimal alignment enhances an individual's gait, decreases energy expenditure, increases socket comfort, and improves overall function.

Marlo Anatomical Socket

In the late 1990s, Marlo Ortiz, an engineer-prosthetist from Mexico, developed a socket configuration that focuses on providing skeletal support along the medial ischial–ramal complex (IRC) (see Figure 3-C). The socket design became known as the MAS socket (Marlo Anatomical Socket). The MAS socket attempts to encapsulate the ischial tuberosity, as well as portions of the ramus, with a distinguishable containment buttress that is designed to maximize socket stabilization (see Figure 2-C).

Elevated Vacuum Sockets

The latest rendition of transfemoral socket designs has developed as a result of the ever expanding interest in elevated vacuum suspension, also referred to as subatmospheric suspension (see Figure 3-D). This socket design is characterized by lower trim lines (subischial) in comparison to other Transfemoral socket designs, resulting in substantially increased patient comfort and range of motion (see Figure 2-D).

RIGID AND FLEXIBLE SOCKET MATERIALS

Most transfemoral sockets are fabricated from various thermoplastic or thermosetting resin materials. A rigid socket consists of a resin-laminated or thermoformed plastic socket that is intended to have an intimate, total contact fit over the entire surface of the residual limb. The rigid socket is durable, easy to clean, and often less bulky and less expensive to produce than flexible sockets. The disadvantage , is that it more difficult to adjust the fit of a rigid socket, especially for individuals with “bony” or sensitive residual limbs.

The flexible socket is vacuum formed using any number of flexible thermoplastic materials. It is encased in a rigid frame, which provides support during weight bearing and helps to maintain socket shape. The flexible socket accommodates to change in muscle shape during contraction and can be easily modified after initial fabrication to provide relief for bony prominences. Flexible sockets may also be more comfortable to wear, especially in sitting, because there are no hard edges at the brim to impinge on the groin. Flexible sockets are especially useful if suction suspension is desired. They are, however, somewhat less durable, more bulky to wear (requiring a socket and a frame), and more expensive to produce than rigid sockets.

TRANSFEMORAL SUSPENSION SYSTEMS

Keeping the prosthesis on in its optimal functional position is more challenging for individuals with transfemoral amputation than with transtibial amputation. The Transfemoral residual limb is fleshy and cylindrical, lacking the bony prominences that aid in suspending the transtibial prosthesis. The weight of the transfemoral prosthesis with the addition of its knee unit creates an additional challenge for adequate suspension. Depending on the nature of the prosthetic wearer's normal activities, a single system or a combination of several systems may be chosen.

Traditional Pull-in Suction Suspension

Traditional pull-in suction suspension uses negative air pressure, skin-to-socket contact, and muscle tension to hold the socket onto the limb (Figure 5).

Figure 5: Patient donning a suction socket using a pull sock. The air expulsion valve has been removed so that the donning sock can be pulled completely out of the socket.

Suction prosthesis can be donned in several ways.

- One option uses donning sock (cotton stockinette or similar material), donning sleeve (parachute nylon or similar material), or elastic bandage to pull the residual limb down into the socket.
- A second option is to add a lubricant to the skin to facilitate the residual limb sliding into the socket.

The intimate fit required for suction suspension has several additional benefits. The wearer often reports enhanced prosthetic control and a better proprioceptive sense of the prosthesis during walking. Because an intimate fit is essential, suction suspension is inappropriate for patients with recent amputation who will continue to lose limb volume or for those with a history of fluctuating edema or unstable weight. The high shearing forces associated with donning a suction socket also may preclude its use for patients with fragile or sensitive skin, painful trigger points, significant scarring, or adhesions.

Roll-on Suspension Liners

These liners are available as an alternative to the standard suction suspension system. Roll-on liners are manufactured from various materials, including silicone, urethane, and elastomer. The roll-on suspension liner creates a negative atmospheric pressure and somewhat adhesive bond to the skin.

Shuttle Lock Systems

This liner is commonly called a locking liner. It is similar to the cushion liner except for a distal stabilizing matrix incorporated into the liner to prevent elongation. (Figure 6-A).

Lanyard System

This system uses the locking liner, but instead of a locking pin screwed into the liner's distal cap, a lanyard (strap or cord) is attached to the cap. This is routed through the distal socket to pull the residual limb into the socket (see Figure 6-B).

Cushion Liner with Air Expulsion Valve

This type of liner is generally referred to as a cushion liner. After the liner is donned on the residual limb, it is pushed into the socket, creating a negative pressure environment by expelling air through the expulsion valve (see Figure 6-C).

Elevated Vacuum

Elevated vacuum is different than suction suspension. Both methods use a difference in atmospheric pressure to suspend and secure the socket to the residual limb. Suction suspension requires a passive expulsion valve to allow air to exit from the socket, but only creates a negative pressure differential when the prosthetic limb is unweighted as when moving into swing phase. With vacuum suspension the residual limb is continuously under vacuum. A vacuum pump creates negative pressure to remove air from a sealed environment between the total surface bearing socket and a wicked-liner (see Figure 6-D).

The major advantage of roll-on suspension:

- Significant reduction in the amount of friction and shear on the residual limb.
- The donning procedure is simple, and can be accomplished while seated.
- This suspension system has been useful for individuals with short residual limbs and those who have experienced discomfort using the traditional pull-in suction method.

The disadvantages of this system include its expense and durability. Roll-on liners become worn or torn, and must be replaced two to three times a year depending on the wearer's activity level. These types of liners may also increase skin temperature and perspiration.

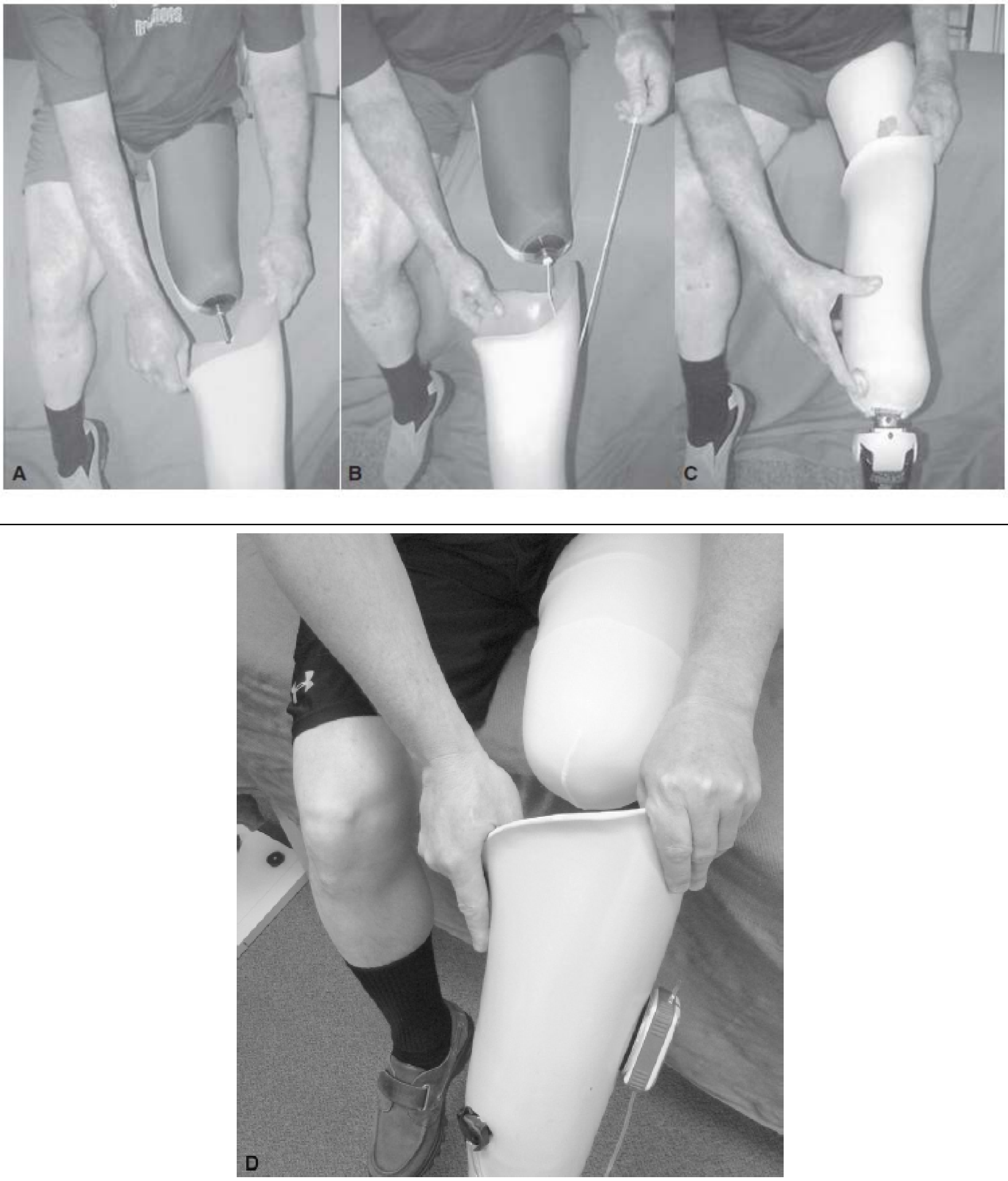

Figure 6: Roll-on liners are a popular suspension system. The liner can be used for suspension in at least four different ways. A shuttle lock system (A). The lanyard system (B). An air expulsion valve system (C). A vacuum pump (D).

Silesian Belt Suspension

A Silesian belt is usually made from leather or lightweight webbing (Figure 7). It is attached to the lateral aspect of the socket, encircles the pelvis, and then runs through a loop or buckle on the anterior of the socket. The Silesian belt is most often used as an auxiliary (backup) for traditional suction suspension systems.

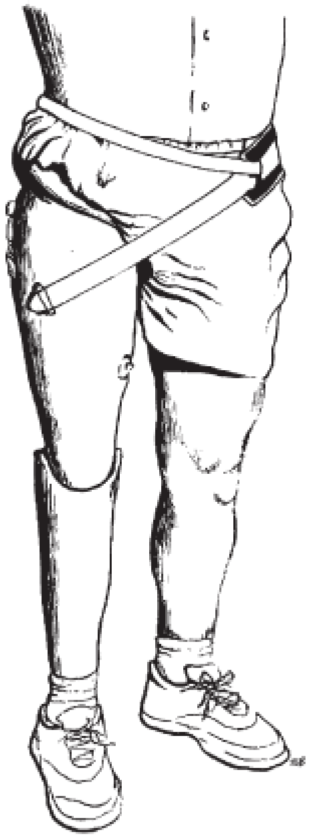

Figure 7: Example of Silesian belt suspension. Although the belt suspends the prosthesis to the pelvis, it cannot fully counteract rotary forces between limb and socket during vigorous walking.

Total Elastic Suspension Belt

The total elastic suspension (TES) belt is typically made of an elastic neoprene material. The distal sleeve of the TES belt fits snugly around the proximal half of the thigh section of the transfemoral prosthesis. The neoprene belt encircles the waist and attaches in front with Velcro (Figure 8).

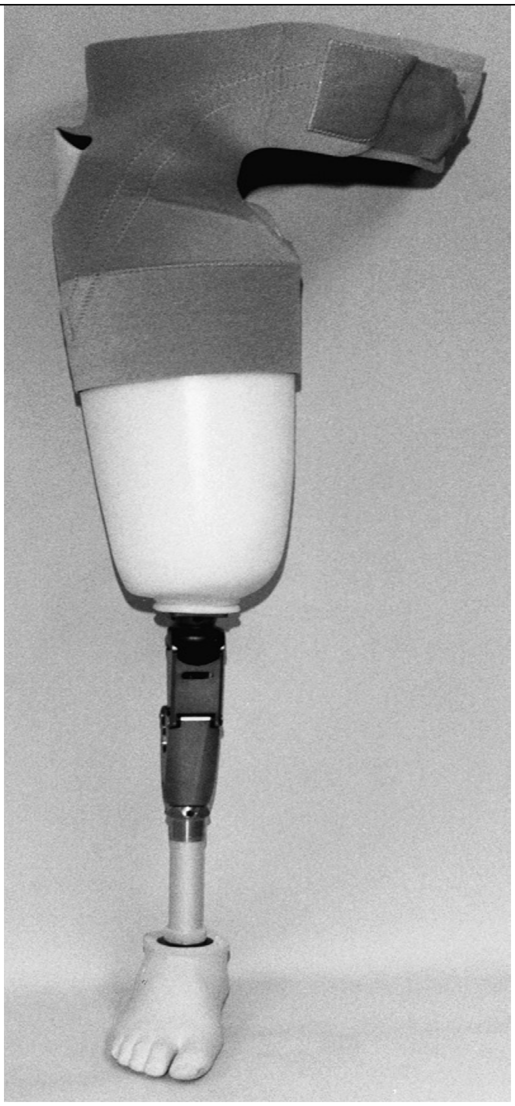

Figure 8: The total elastic suspension belt (TES) is a simple and comfortable suspension system that is often used as an auxiliary suspension.

Pelvic Belt and Hip Joint

For some patients, a pelvic belt and hip joint are used as a means of suspension (Figure 9). Generally, the pelvic belt is made of leather and attached to the prosthesis by means of a metal hip joint.

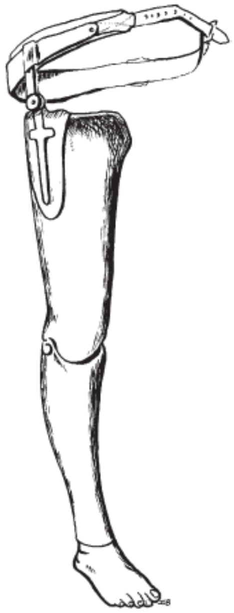

Figure 9: A pelvic belt with hip joint not only suspends the prosthesis but also helps to control rotation and increases medial lateral stability of the residual limb within the socket.

Knee Disarticulation Considerations

When femoral condyles are not prohibitively bulbous, roll on sleeves can be used in combination with air expulsion. Although a pin is not recommended because of space limitations, a lanyard system can be effective. This creates a positive lock that is engaged even if limb volume changes. When the femoral condyles are prominent, a removable door suspension design can be used to suspend the prosthesis. This suspension uses external straps, attached to a door, which can apply variable pressure proximal to the femoral condyles locking them in place (Figure 10). This suspension system is similar to the medial opening door occasionally used for Symes prosthesis.

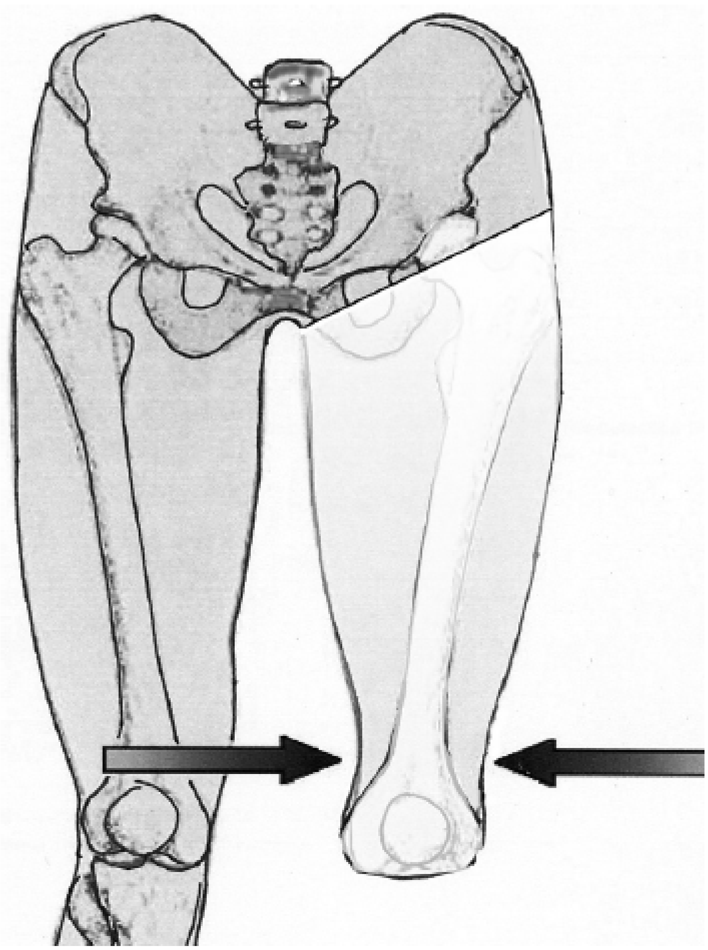

Figure 10: Generally, the residual limb of an individual with a knee disarticulation has prominent femoral condyles. When this is the case, a removable door suspension or stovepipe liner design can be used to suspend the prosthesis. This suspension applies variable pressure proximal to the femoral condyles locking the limb into the socket.

PROSTHETIC SYSTEMS

A transfemoral prosthesis can be fabricated as either an exoskeletal or endoskeletal system. The weight-bearing strength and cosmetic shape of an exoskeletal prosthesis are provided by a laminated shell that incorporates the socket, knee–shin component, and ankle block (Figure 11-A). This system is durable and requires little maintenance but cannot be easily realigned or adjusted. In the endoskeletal system, weightbearing strength comes from an internal pylon that connects the knee unit to the prosthetic foot (Figure 11-B).

Figure 11: Comparison of the rugged exoskeletal (A) and the modular endoskeletal (B) transfemoral prosthetic systems.

PROSTHETIC KNEE UNITS

The function of the human knee joint is difficult to replicate. Henschke Mauch, who developed hydraulic guidance systems for rockets during World War II, turned his considerable knowledge and creativity to designing a hydraulic prosthetic knee for veterans with amputations after the war. He commented that it was far easier to design a large rocket with a positioning of the knee unit with respect to the weight line (alignment) and muscular control (activity of hip extensors).

Single-Axis Knee Units

The single-axis knee simulates a simple hinge and allows the prosthetic shin to swing freely in flexion and extension. Stance-phase knee stability is achieved by a combination of positioning of the knee unit with respect to the weight line (alignment) and muscular control (activity of hip extensors).This knee is lightweight, durable, and low maintenance, but because of its unrestricted movement, it has no inherent mechanical stability. For this reason, it is not appropriate for individuals with relatively short residual limbs who lack the mechanical advantage of a long femoral lever for muscular control of the knee unit or for those whose stability is compromised for other reasons.

Polycentric Knee Units

The single-axis knee has a fixed center of rotation, while the polycentric knee has a moving center of rotation. Like the human knee, the polycentric knee rotates around more than one axis through a four or more bar linkage system (Figure 12).

Hydraulic Knee Units

Hydraulic knee units are cadence responsive; the forward progression of the prosthetic shin changes as gait speed changes. This is because the flow of hydraulic fluid through narrow channels within the prosthetic knee unit provides a frictional resistance, which increases with the speed of compression.

Pneumatic Knee Units

Pneumatic knee units offer the prosthetic user a varied cadence capability, using air pressure dynamics in much the same way that fluid is used in the hydraulic knee. Because air is compressible, the channels within the knee can be adjusted to affect the rate of swing. Pneumatic knees usually weigh less and are less expensive than their hydraulic counterparts; however, they provide less precise cadence control and require just as much maintenance. This is because hydraulic fluid is denser and has a higher coefficient of viscosity than air.

Microprocessor Technology

Microprocessor knees are typically equipped with sensors that monitor the knee position during swing and pressure sensors detecting and evaluating ground related forces during stance. Sensor technology is capable of measuring angles, moments, and pressures at the rate of 50 times per second.