10

Extremity Amputations: Principles, Techniques, and Recent Advances

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Abstract

It is estimated that approximately 1.7 million Americans are living with the loss of a limb, and this number is expected to nearly double by 2050. The most common reasons for amputation include vascular compromise, trauma, cancer, and congenital deformities. Orthopaedic surgeons are often called on to manage patients requiring an amputation or those with amputation-related conditions. It is helpful to review the principles and techniques for performing lower and upper limb amputations, with a focus on common complications and how to avoid them and to be familiar with recent advances in prosthetic design and management of a residual limb.

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It is estimated that approximately 1.7 million Americans are living with the loss of a limb, and this number is expected to nearly double by 2050. Vascular compromise, trauma, cancer, and congenital deformities are among the most common reasons for amputation. Traumatic and neoplastic etiologies have decreased over time, but complications from vascular disease leading to amputation have increased. The number of amputations performed for congenital deformities has remained steady.

Although amputation is typically considered a nonchallenging surgical procedure, good functional results require considerable preoperative planning, knowledge of prosthetic design, and consideration of postoperative expectations. This chapter reviews the principles and techniques for performing lower and upper limb amputations, with a focus on common complications and how to avoid them, and discusses recent advances in prosthetic design and management of the residual limb.

Upper Limb Amputations

Amputation Levels

Fingertip amputations are commonly seen in the emergency department. Treatment methods vary and are largely based on the level of amputation, the angle of injury, and soft-tissue status. Transverse injuries may be allowed to heal by secondary intention in most cases because skin match and sensation are often superior to grafting. At times, bone shortening may be required. V-Y Atasoy and Cutler flaps may be used on occasion.[1] Severe oblique injuries may require full-thickness skin grafting,

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volar advancement flaps, or coverage from adjacent digits (for example, cross-finger flaps, reverse cross-finger flaps, and dorsal metacarpal artery flaps).

More proximal-level traumatic digit amputations are most commonly closed directly with some shortening or conversion to a ray amputation. Indications for ray amputation must take into account individual patient considerations. Preoperative consultation should include discussion of cosmetic change, neuroma formation, and grip strength reduction.[2] Replantation may be considered for amputations in single digits distal to the flexor digitorum superficialis insertion on the middle phalanx, multiple digits, and thumbs and in children.

Figure 1 Clinical photograph of a double ray (index and middle finger) amputation for sarcoma.

Figure 2 Clinical photograph of a ring and small finger amputation for sarcoma.

Elective Digit and Ray Amputation

Elective digit amputation may be indicated in patients with vascular deficiency, infection, or tumors. In the elective setting, the level of amputation and flap design can be carefully planned. Fish-mouth incisions often have the optimal appearance. Volar flaps are particularly useful in the setting of distal interphalangeal joint disarticulation or interphalangeal disarticulation in the thumb. The volar skin provides excellent sensation and durable skin and may maximize tactile sensation. The level of amputation required may influence the decision for ray amputation. When amputation at the proximal phalanx level is indicated in the digits, ray amputation should be considered. The cosmetic appearance and function are often superior in the setting of ray amputation. If breadth of the palm is important for function, ray amputation may not be elected. Only rarely will metacarpophalangeal disarticulation be favored by patients.

Ray amputation without transposition is an excellent treatment option for severe ring avulsion injuries or malignant tumors of the digits.[2] Transposition may be considered for the treatment of middle finger lesions; however, it is often not needed. During this procedure, the base of the index metacarpal is osteotomized, and the entire digit is transposed to the position of the middle ray. The index metacarpal is then fixed to the base of the transected middle finger metacarpal. Attention to digit rotation is critical. This procedure can improve the appearance of the hand but at the risk of malrotation, nonunion, and (in the presence of tumors) contamination of the index ray.

Metacarpal ligament reconstruction allows narrowing of the defect and improves cosmetic appearance. Grip strength is often reduced by approximately 30%.[3] Neuroma formation is common, and the index ray has the highest rate of painful neuromas.[4,5] Phantom sensation is common, but phantom pain is infrequent. Rarely, painful neuromas may require reexcision or cryoablation.

Multiple ray amputation may be required in the presence of tumor or severe trauma. The defect produced by multiple ray amputation is much more apparent (**Figures 1** and **2**). Grip strength is often dramatically decreased. In the tumor setting, it may be reduced by 75%.[5] Function is markedly diminished.

Thumb ray amputation is not frequently indicated. Whenever possible, thumb salvage procedures should be considered.[6] Tumors distal to the interphalangeal joint often can be treated safely with interphalangeal disarticulation. Tumors at the proximal phalanx level often can be widely excised with reconstruction of the defect using bone, tendon, and vascular and nerve grafts with microsurgical soft-tissue reconstruction. Ray amputation of the thumb produces a substantial functional deficit. Toe-to-thumb transfer or index pollicization may be reconstruction options in this setting.

Wrist disarticulation is rarely required in the tumor setting. Large tumors in the region of the wrist usually require forearm-level amputation. Smaller tumors may be amenable to wide excision and reconstruction using vascularized and nonvascularized bone grafts with wrist arthrodesis. At times, bone transport can be used to bridge defects at the wrist. However, wrist disarticulation may be considered in the trauma setting when replantation is not possible. Equal flaps dorsally and palmarly are ideal, but the extent of soft-tissue injury may determine which flaps are appropriate.

Forearm-level amputation may be required for large wrist-level or carpal tunnel–based tumors. This level of amputation is functionally devastating. Because patients may have difficulty coping with the loss, preoperative psychological counseling should be routinely considered. Most commonly, when major nerves can be spared, wide excision and reconstruction are preferred. Fish-mouth incisions with volar and dorsal flaps are ideal. Myoplasty will ensure durable soft-tissue coverage for the amputated bone ends (**Figure 3**). Myodesis may improve residual forearm rotation and may facilitate prosthetic function. Nerve ends should be resected proximally to allow adequate soft-tissue coverage for the neuromas, which routinely form after amputation. Prosthetic fitting should be encouraged, but many patients commonly use prostheses only for specific activities or tasks. Most patients will adapt with the use of nonprosthetic assistive devices and greater use of the contralateral limb. Transhumeral-level amputation may be required for severe forearm trauma, traumatic amputation, or tumors of the proximal forearm or elbow with involvement of multiple major nerves. Wide excision of the entire elbow with reconstruction may be an alternative if major nerves can be spared.

In the presence of a malignant tumor, the humerus-level amputation site is determined in large part by the level of injury or the level of amputation required for achieving a wide excision. In general, amputations that maximize length are preferred, as are anterior and posterior fish-mouth–type flaps. The triceps and brachialis are used for myoplasty closure. Nerves are transected proximally to minimize pain from neuromas. Suture ligation of vessels is preferred to control proximal level vessels.

Shoulder disarticulation may be required for very proximal-level humeral amputations or when the presence of malignancy dictates the need for amputation at the level of the joint. Most commonly, a lateral flap is used for coverage. If the deltoid can be spared, it is incorporated into the flap. More proximal level amputations are commonly associated with phantom sensation and phantom pain.

Forequarter amputation is most commonly indicated for very large shoulder girdle tumors or multiple recurrent shoulder-level tumors.[7] Amputation at this level produces a major cosmetic defect and functional deficit. Preoperative counseling should be strongly considered. Prosthetic use is usually limited to a shoulder pad that supports clothing. Anterior, posterior, or combined approaches may be used. Periscapular muscles are transected posteriorly. Vessels can be approached posteriorly or anteriorly. Vessels are suture ligated, nerves are transected proximally, and the clavicle is disarticulated at the sternum or transected medially. Skin flaps may be determined by the extent of tumor contamination and previous surgical procedures. Preoperative plastic surgery consultation may be helpful in planning closure. At times, a fillet forearm flap from the amputated limb may facilitate closure.[8]

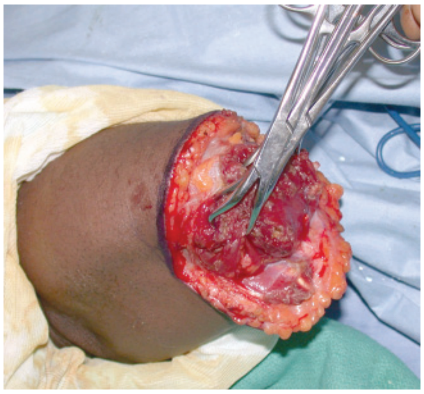

Figure 3 Intraoperative photograph of a myoplasty for a forearm-level amputation.

Lower Limb Amputations

General Principles

Between 30,000 and 40,000 lower limb amputations are performed in the United States annually, and this rate has remained fairly steady during the past 15 years.[9] The main causes of these amputations are vascular disease (54%, including diabetes and peripheral arterial disease) and trauma (45%); cancer is responsible for less than 2%.[10] In elderly patients or those with ischemic disease, amputation of one lower limb is often followed by the amputation of the contralateral limb; 15% to 28% of such amputations occur within 3 years.[11,12] Despite the advances in medicine, these statistics have not greatly improved for the dysvascular amputee. Only 50% of elderly dysvascular amputees survive the first 3 years after an amputation.[13]

However, an amputation should not be considered a failure of treatment. Frequently, an amputation is the treatment of choice for a devastating injury to the lower extremity, especially when reconstruction may be a long and costly process that results in a functionally unsatisfactory limb.

Although amputation may be perceived as a technically nonchallenging procedure, it must be well planned to be well performed. Although each amputation and amputation level has specific considerations, there are several fundamental principles common to amputation. Skin and muscle flaps should be fashioned to achieve the longest residual limb that will give the patient the best functional outcome. This length depends not only on the amount of viable tissue but on the anatomic location and the desired prosthesis that will be fashioned (for example, high-functioning knee joint or ankle joint). Skin flaps can be uniform (such as fish-mouth or posterior-anterior–based flaps) but in the dysvascular, traumatic, or oncologic setting, the flaps are often nonconventional. It is important to carefully evaluate the blood supply to the area before initiating the flap design. There are several methods that can predict at which level of the lower limb the circulation in the skin is adequate for primary wound healing; these methods include xenon-133 clearance and transcutaneous measurement of oxygen tension. These measures are particularly helpful in patients with dysvascular disorders.

As mentioned previously, the length of the residual limb can be critically important, both in terms of prosthesis wear and the type of prosthesis that can be worn. It is important to avoid extra tissue at the end of the residual limb because the extra tissue makes prosthesis wear and control quite difficult. To help avoid extra tissue, the muscle should be transected to the level where the skin has naturally retracted after the skin incision, which should be distal to the level of the bone osteotomy.

The handling of the nerves during an amputation remains controversial. There is a consensus that the nerves should be isolated and gently pulled into the wound before transection. Additional treatment of the severed nerve ending with ligation and/or injection with anesthetic is controversial because there is no definitive evidence-based consensus. Major blood vessels should be tied with a double ligature. If a tourniquet is used, it should be released, and meticulous hemostasis should be obtained before wound closure. The use of drains is encouraged to help prevent the development of hematomas.

The treatment of an amputee does not start and end in the operating room. Preoperative and postoperative planning is important. Preoperative consultation with a prosthetist can facilitate the choice of appropriate limb length and help set a patient's expectations.

There are two schools of thought regarding the postoperative dressing: soft versus rigid. When a soft dressing is used, the wound is closed, a small sterile dressing is applied to the incision, and an elastic bandage is snugly wrapped over the dressing and around the residual limb. Throughout the postoperative period, the residual limb is kept snugly wrapped in an elastic bandage until the prosthesis is fit. When a rigid dressing is used, a plaster of Paris or fiberglass cast is applied to the residual limb after surgery. The rigid dressing offers the benefit of pain reduction, edema control, protection of the suture site, contracture prevention, and possibly earlier ambulation; however, consensus on the most effective dressing is lacking.[14]

Amputation Levels

The term classic hemipelvectomy is used to describe an amputation of the pelvic ring via disarticulation of the pubic symphysis and the sacroiliac joint, division of the common iliac vessels, and closure with a posterior fasciocutaneous flap. Another current term for this procedure is hindquarter amputation. Older terms include interpelviabdominal or interinnomino-abdominal amputation. Hemipelvectomy may be indicated for patients with massive pelvic trauma, uncontrollable sepsis of the lower extremity, pervasive metastatic lesions of the extremity, or primary pelvic bone and soft-tissue tumors. The three essential components for a functional leg are the lumbosacral plexus, the femoral neurovascular bundle, and the hip joint. If two of these three structures are not functional, then amputation is usually indicated. Pelvic resections have been classified by Enneking and Dunham[15] to facilitate consistent discussions about resection and reconstruction technique. The basic pelvic resection types are as follows: type I, resection of the iliac wing; type II, resection of the periacetabular regions of the pelvic bone; and type III, resection of the obturator.

Preoperative planning for hindquarter amputations is essential. To decrease the possibility of intraoperative contamination and improve intraoperative surgical view and bowel handling, some surgeons advocate the use of preoperative bowel preparation. In theory, a bowel preparation will decrease the bacterial count and volume of bowel contents if there is spillage into the wound. However, recent gynecologic literature suggests that mechanical bowel preparation may not provide a substantial advantage in this regard.[16]

The placement of stents in the ureters can be beneficial and will help identify the ureters within the surgical field. Arterial and venous access should be established to facilitate intraoperative monitoring of the hemodynamic status and fluid resuscitation.

Discussion of the surgical procedure is not within the scope of this chapter, but it should be noted that care must be taken when performing a hindquarter amputation on the right side because the inferior vena cava lies on this side, inferior to the aorta. The surgeon must take care not to damage nor sacrifice the inferior vena cava when attempting to ligate the common iliac artery. The most common flap used in hemipelvectomies is a posterior-based flap. When the inferior gluteal vessels and cuneal vessels are preserved and the gluteus maximus muscle can be incorporated into the flap, the closure will be myocutaneous. The anterior-based flap, which is used less commonly, is a long anterior myocutaneous flap that generally includes the quadriceps muscle (**Figure 4**). Its blood supply is based on the femoral vessels. If local anterior or posterior flap-based coverage is not an option, a free fillet lower leg flap can be used. Fillet flaps are axial-pattern flaps that function as composite tissue transfers. They can be used as pedicled or free flaps and are a good option for reconstructing large defects.

Figure 4 Intraoperative photograph of an anterior-based hemipelvectomy flap.

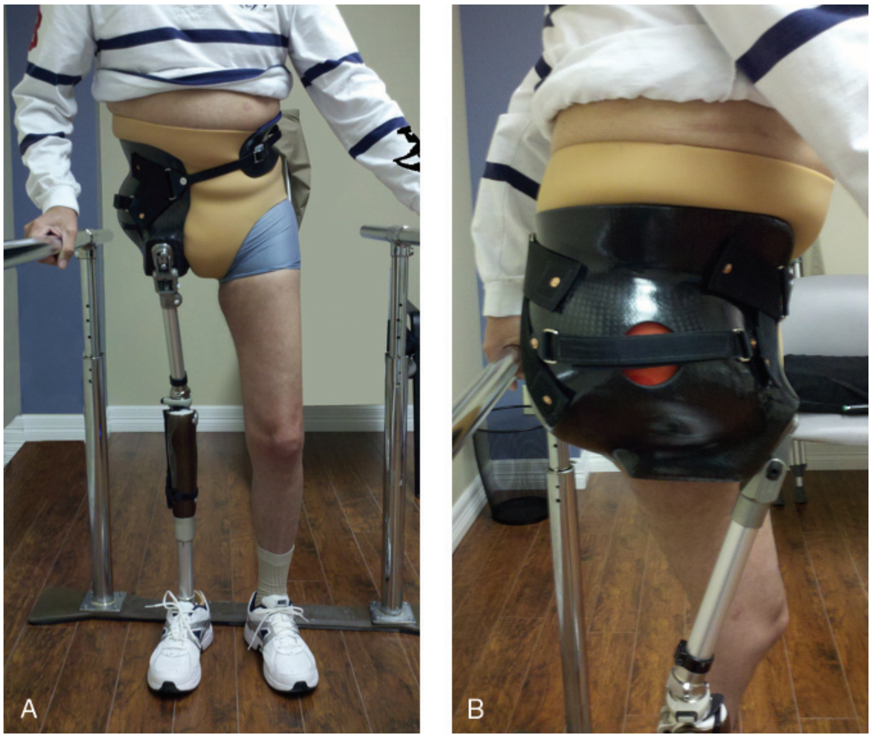

Figure 5 Clinical photographs of the anterior (**A**) and lateral (**B**) views of a hemipelvectomy prosthesis.

Patients with hindquarter amputations can regain the ability to walk (**Figure 5**). Modern advances in technology afford the patient the opportunity to regain functional and ambulatory independence. Patients who are young, motivated, and in good physical condition with a good sense of balance may ambulate without external aids. However, many patients may need some type of assistive device, such as a cane or a walker, for ambulation. In addition, many patients find that ambulating with crutches is much faster than with a prosthesis and requires no additional expenditure of energy.

Patients with this level of amputation who ambulate with a prosthesis have increased energy expenditures up to 200%.[17] The prosthesis uses the lower section of the rib cage for weight bearing and stabilization. Skin grafts and sutures in this area should be avoided, and any transected bone should be beveled and rounded to lessen the chance of skin breakdown from a sharp bony end contained within the socket. The lower back absorbs forces during ambulation. Stabilization of the hip and knee joints at heel strike places abnormally high forces along the spine. Forward propulsion of the prosthesis through the swing phase of gait requires aggressive lateral trunk shifts, increased lumbar lordosis, and transverse rotation of the lumbar spine in conjunction with contralateral vaulting.

An amputation through the hip joint is called a hip disarticulation. It is commonly used for failed vascular procedures after multiple lower-level amputations or for massive trauma with crush injuries to the lower extremity. In this procedure, the acetabulum and posterior soft tissues are spared. The incision, which transverses around the posterior thigh, distal to the gluteal crease, generally provides sufficient posterior coverage. The posterior myocutaneous flap is the most common method of coverage. An anterior myocutaneous flap also has been described, although it is not often used.[18] The prosthesis incorporates the ischium into the prosthesis, which not only allows the patient to bear weight through the ischium but also secures the prosthetic limb. It acts as a fulcrum through which the pelvis is kept level during ambulation.

Transfemoral (above-knee) amputations are performed, as the name suggests, through the femur, and the knee joint is sacrificed. Residual limbs shorter than 5 cm (measured from the lesser trochanter) function like a hip disarticulation rather than an above-knee amputation. Although it is important to preserve as much femoral length as possible during the amputation, it is equally important to provide a residual limb that has the proper amount of clearance for the prosthetic knee and to match the prosthetic knee to the center of the sound knee. The femur should be transected approximately 12 to 14 cm above the joint line.

There are two schools of thought and possibilities for muscle closure. Myoplasty is the closure of the quadriceps to the hamstrings. This method does not stabilize the femur, but it allows the femur to move freely within the soft-tissue envelope. There is less limb control with this method, and movement may result in pain. Myodesis consists of attaching the adductor magnus muscle to the lateral aspect of the femur, thus stabilizing the femur and re-creating the adductor moment arm (**Figure 6**). This is accomplished by placing drill holes in the residual femur and securing the adductor to the bone with heavy suture, such as polyester suture. Attaching the adductors to the lateral aspect of the distal femur not only pulls the femur into an adducted position but also provides good distal padding over the cut end of the femur. The attachment of the quadriceps and hamstring muscles to the opposite sides of the femur from which they originate further secures the femur. The overlying fascia and skin flaps are then closed.

After surgery, to minimize the development of hip flexion contractures, the iliac crest should be incorporated into the dressing. If it is not, it is recommended that the patient lie prone for 20 to 30 minutes, three times per day, to reduce the risk of contracture development. Patients should be mobilized the first postoperative day and begin hip range-of-motion exercises when comfort permits.

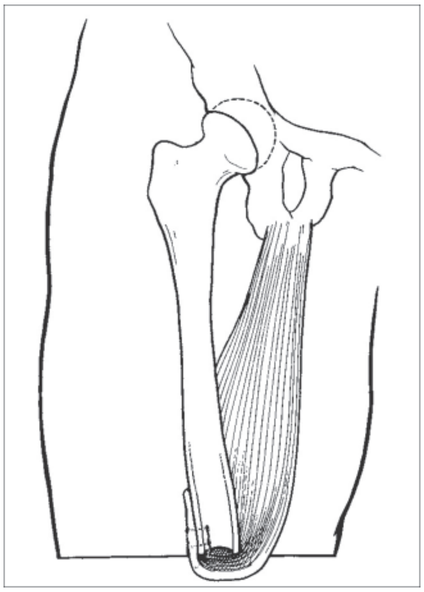

Figure 6 Illustration showing attachment of the adductor magnus to the lateral part of the femur. (Courtesy of John Bowker, MD, and reproduced from Gottschalk F: Transfemoral amputation: Surgical management, in Smith DG, Michael JW, Bowker JH, eds: *Atlas of Amputations and Limb Deficiencies*, ed 3. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2004, pp 533-540.)

Transfemoral prostheses stabilize the pelvis through ischial containment, ischial weight bearing, and hydrostatic pressures within the socket. With the fulcrum (ischial tuberosity) placed at the pelvic region, controlling the distal femur requires a strong muscle contraction from the adductor group with every step. The resulting outcome is high energy consumption and fatigue compared with normal gait. The amount of energy expenditure increase compared with baseline energy expenditure also relates to the reason the amputation occurred. Patients with traumatic transfemoral amputations have a 68%

increase in energy expenditure, whereas those with vascular amputation have a 100% increase. Strengthening and training are necessary to obtain a consistent, unnoticeable gait pattern. The most common gait deviation is that of lateral trunk lean.

If the femur is kept in an adducted position, patients expend less energy during ambulation because lateral trunk lean is reduced. If femoral adduction is not maintained, patients are forced to dramatically shift their weight over the prosthetic side during single-limb stance to allow for swing phase clearance of the sound leg and to maintain coronal stability. This procedure results in additional energy expenditure and an exaggerated Trendelenburg gait. Several variations in socket design to maintain femoral adduction and improve gait have met with varying success, especially in the absence of adductor myodesis.

A knee disarticulation is an amputation through the knee joint. By preserving the distal insertion of the adductor muscle group, the femur maintains its normal adduction angle, which allows for a more energy-efficient gait than that typically obtained in a transfemoral amputation. The fulcrum in the knee disarticulation socket is moved distally to the femoral condyles, thereby mimicking normal biomechanical loading and alignment, which also allows for a more normal and energy-efficient gait pattern.

Although the prosthesis does not require ischial weight bearing and thus does not extend as far proximally, the aesthetics of the prosthesis itself often can be disappointing. The retention of the condyles will make for a bulky prosthesis. However, this adverse cosmetic result is offset by the functional benefit. With the condyles intact, the prosthetic socket can be suspended by compression immediately proximal to the femoral condyles. Shaving the femoral condyles will improve the cosmetic appearance by reducing coronal bulk at the distal end of the prosthetic socket. Without the condyles, the prosthesis can be suspended with suction.

The addition of a prosthesis on the amputated side results in knee-center discrepancies, which are especially obvious when the patient is seated. For this reason, a patient may opt for a transfemoral amputation instead of a knee disarticulation. In patients who have not reached skeletal maturity, the option of arresting the distal growth plate on the involved limb can provide a shorter femoral length at bone maturity and thus enhance cosmetic outcome by providing symmetric knee centers. The advantages of a knee disarticulation over a transfemoral amputation include a weight-bearing stump, normal alignment of the residual limb, a more efficient gait, and less energy expenditure.[19,20]

Transtibial amputations are typically performed for patients with foot or tibial tumors or major trauma. Although experienced prosthetists can often accommodate residual limbs as short as 5 cm of tibia, to create a maximally functional limb, 2.5 cm of tibia are required for each 30 cm of adult height. This formula generally results in an amputation at the level of the musculotendinous junction of the gastrocnemius muscle. Residual limbs that are shorter than 5 cm are not functional, and it is recommended that if such a residual limb is expected, then a knee disarticulation should be performed. As with other amputations, a longer residual limb results in better prosthetic control. However, it may be beneficial to sacrifice some length to allow more room for modern prosthetic foot components. Carbon fiber foot and strut systems reduce oxygen consumption at velocities exceeding self-selected walking speeds. These feet are relatively tall and can require up to 7 inches of clearance between the residual limb and the floor. Therefore, preoperative consultation with a prosthetist is important.[21]

The surgical issues discussed for transfemoral amputation hold true for a transtibial operation. Closure of the muscle layer can be performed through a myodesis in which the muscles are sutured to the bone under physiologic tension or myoplasty in which the muscles are attached to their opposing muscle group. Myodesis provides greater control and motion of the residual limb. Typically, the fascia of the superficial posterior compartment is advanced forward and attached to the anterior periosteum of the tibia and the fascia of the anterior compartment. Additional anchorage of the muscles may be accomplished through drill holes medial and lateral to the tibial crest, although this technique also may limit excursion of the muscle advancement. Again, excessive flaps should be avoided because extra distal soft tissue will become a large loose mass of tissue at the end of the residual limb, making stabilization of the limb in the socket difficult.[22]

Transtibial amputations are extremely functional. Resumption of a preamputation lifestyle and activity level, including participation in sports and recreational activities, is possible.[23]

Rotationplasty, first described by Borggreve[24] in 1930, was popularized by Van Nes[25] for proximal femoral focal deficiency. Essentially, the rotationplasty creates a transtibial amputation

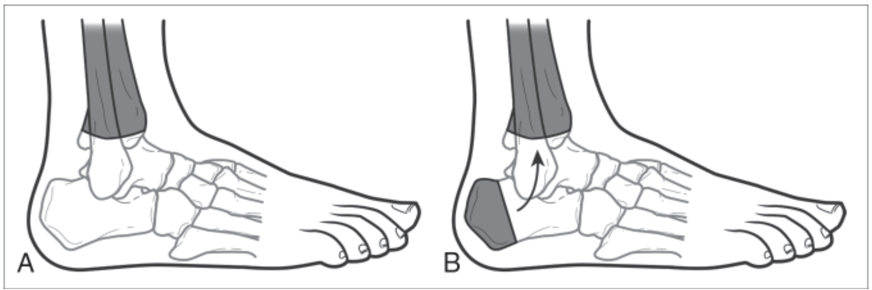

Figure 7 Illustrations of Syme (**A**) and Pirogoff (**B**) amputation of the foot. The shaded area represents the level of amputation. In a Pirogoff amputation, an osteotomy is performed through the calcaneus perpendicular to the long axis (arrow).

from a transfemoral resection. It is an excellent alternative to a transfemoral amputation and can be a salvage procedure for patients with an infected prosthesis, failed endoprosthesis, or local tumor recurrence. Rotationplasty requires an intact sciatic nerve, a functional ankle joint, and an intact foot. Initially thought to be best in children aged 8 to 10 years, rotationplasties are being performed in older patients. The main issue in older patients is the decreased flexibility of the ankle.[26]

Functionally, rotationplasty offers the advantage of a longer lever arm, a functional knee joint, and an end (foot) that tolerates socket load better than a transfemoral amputation stump. As a result, there is lower energy consumption with ambulation, patients are able to walk for longer periods of time, and they can participate in vigorous sporting activities that require knee flexion. With advancements in limb salvage, this procedure has become less popular. However, psychologically, these patients do quite well. They tend to adjust quickly to the limb appearance and often do not view themselves as amputees.[27]

The Syme and Pirogoff amputations (**Figure 7**) are both hindfoot amputations that generate a residual limb with a weight-bearing distal end, which affords the patient the ability to ambulate for short distances without the prosthesis. However, early weight bearing without a prosthesis should be avoided. The main difference between these procedures is that with the Pirogoff procedure, an osteotomy is performed through the calcaneus perpendicular to the long axis, resulting in a posterior flap that contains the calcaneal remnant and the fat pad. The benefit of this procedure is that the fat pad, which is prone to migration during the healing process after a Syme amputation, is attached to the calcaneus and, therefore, fat pad migration is rare. However, the disadvantage is that calcaneal-tibial fusion is required for the residual limb to be successful and functional. Although these amputations offer the benefit of a weight-bearing stump, cosmesis can be a problem. The bulbous appearance of the stump can be unappealing to some. In addition, not only is the choice of prosthetic foot limited, but the prosthesis, which fits over the end of the stump, often necessitates the use of a shoe lift on the side of the healthy limb to level the pelvis.

Transmetatarsal, midfoot, and ray resections may require shoe modification, a total contact insert toe filler, and/or a carbon plate to provide stability and push-off during ambulation. Amputations through the midfoot include Chopart and Lisfranc amputations. The Lisfranc amputation is performed at the tarsometatarsal joint, and the Chopart amputation is performed through the midtarsal joints. Prevention of equinus and equinovarus deformities after these procedures is critical to avoid a foot with limited functional benefit.[28]

Overall, complete ray resections produce minimal deformity, which is especially true in the lateral column of the foot where partial metacarpal resection can cause a substantial functional deficit, but ray resection will not. In addition, the gap caused by ray resection can be closed with minimal deformity and, unlike in the hand, ray transposition is rarely needed or performed. After healing, normal shoe wear is possible, and gait is unaffected. However, amputation of the first ray can cause functional gait disturbances by compromising late stance and push-off. A total contact shoe insert with filler and carbon plate may be needed to establish the third rocker of stance.

Residual Limb Considerations and Prosthetic Advancements

Initial Residual Limb Considerations

After initial wound healing has been achieved after amputation from any cause—trauma, tumor, infection, or ischemia—attention turns toward prosthetic fitting and rehabilitation. A viable and durable terminal residual limb remains an essential prerequisite to successful prosthesis fitting and use. Therefore, robust, mobile soft-tissue coverage is at least as important to ultimate amputee function as the underlying osseous platform.[29] Although length preservation is generally desirable, a shorter residual limb with a healthy soft-tissue envelope will commonly pose fewer long-term problems and fitting difficulties than a longer limb with marginal coverage. Atypical, "tweener" amputation levels (for example, very long transtibial or transfemoral amputations) should generally be avoided because, as a result of a combination of suboptimal soft-tissue coverage and novel socket requirements, such residual limbs typically offer the limitations of the proximal and distal adjacent amputations levels without achieving the full benefits of either. Stable deep muscle anchorage via myodesis should be performed to maximize residual limb control and anchor deep padding,[29-32] and the overlying myoplasty should be anchored to the fascia of the underlying myodesis whenever practicable. Mobile fasciocutaneous tissue over a terminal residual limb is desirable; mobile muscle groups are not, and they can produce painful symptoms associated with deep bursa that form beneath hypermobile, unstable myoplasties. Split-thickness skin grafts represent an occasionally necessary and viable alternative to more proximal revision[33] but should be placed only over viable, supple muscle and subcutaneous tissues (**Figure 8**). Grafts that adhere to the periosteum or the immobile tendon or fascia frequently develop ulceration or overt wound failure when subjected to prolonged direct pressure and shear forces with regular prosthesis wear. Dermal substitutes may be helpful in terms of augmenting the durability of eventual split-thickness skin grafts; they also may reconstitute an effective neodermis that facilitates improved closure and coverage in the event that revision surgery is necessary. In the experience of this chapter's authors, many split-thickness skin grafts after severe trauma serve as a length-preserving bridge to delayed soft-tissue revision, and a high reoperation rate should be anticipated.[34]

Complications

Complications and/or persistently symptomatic residual limbs frequently develop after amputation.[35-37] Deep infection or overt wound failure represent absolute indications for surgical intervention. Certain other symptoms (for example, phantom pain) cannot generally be effectively managed with surgical intervention, but aggressive treatment of focal, "fixable" problems can dramatically improve amputee comfort, satisfaction, and function.[38] Surgically correctable symptom generators include neuromata, failed myodesis, unstable myoplasty, redundant soft tissue, ulceration or poor soft-tissue coverage, and symptomatic heterotopic ossification.[39] Although revision surgery can be avoided by refusal to reoperate on the patient, this approach—beyond a reasonable period of nonsurgical management with medical management, injections, and/or socket modifications—may result in a severely disabled and dissatisfied patient with a marginal residual limb who rejects the prosthesis unnecessarily.[29,35,36]

Prosthetic Advancements

Building on the prosthetic ingenuity of past researchers (for example, suction socket suspension was patented in the United States in 1863) and the accelerating pace of available modern technology, modern prosthetic devices continue to evolve at an impressive rate.[40] Although many unilateral (particularly nondominant) upper limb amputees continue to favor simple, durable, body-powered terminal devices or abandon their prostheses altogether, myoelectric devices incorporating multiple degrees of freedom have become increasingly advanced and commonplace.[40-43] Conventional myoelectric devices have been widely available for nearly two decades and typically receive input signals from underlying muscle groups with surface electrodes within the prosthetic socket. Myoelectric hands (**Figure 9**) commonly outperform sequential, body-powered devices for precise tasks. Problems associated with weight, battery life, and limited functions have been increasingly solved by improved technologies borrowed from other industries.

Figure 8 Clinical photograph showing poor terminal coverage of the remaining femur with a split-thickness skin graft.

Since the approval and release of the initial C-leg (Ottobock; **Figure 10**), microprocessor knee joints have dramatically improved function for many patients with an amputation at or proximal to the knee joint with onboard sensors that detect limb position and accommodate activities through functions such as stance flexion and stumble recovery.[44,45] Newer-generation devices,

Figure 9 Photograph illustrating a myoelectric hand. When tying shoelaces, a myoelectric hand can be used to stabilize and hold the laces, while the opposite hand maneuvers the laces. (Reproduced from Atkin DJ: Prosthetic training, in Smith DG, Michael JW, Bowker JH, eds: *Atlas of Amputations and Limb Deficiencies*, ed 3. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2004, pp 275-284.)

Figure 10 Photograph of the C-leg by Ottobock.

including the Genium/X2 (Ottobock) have shown quick patient adaption, better use of stance flexion for a more normal and symmetric gait, and increased versatility for ambulating in different environments or over variable terrain.[40]

The first powered prosthetic knee joint is now commercially available (Power Knee; Ossur). Although in the experience of this chapter's authors many patients still prefer microprocessor knees because of weight, noise, and versatility concerns, the advent of adequate robotic power to assist ambulatory function represents a marked "step" forward for many patients and prosthetic technology. More recent commercial breakthroughs have led to microprocessor and powered ankles (BiOM Foot; iWalk), which may improve function over energy-storing, passive devices for everyday activities such as stair climbing.[46] Clearly, powered prosthetics represent the wave of the future.

Nevertheless, although improved gait patterns and energy expenditure have been objectively documented in these new devices,[44-46] patient commitment to rehabilitation and recovery remains essential. Importantly, the microprocessor knee or other devices do not "make" the amputee walk; the amputee has to learn to walk again. Furthermore, the acceleration of prosthetic technology within the past decade has outstripped investigators' ability to adequately, objectively, and critically study and assess the putative end-user benefits of each new breakthrough. Each new device will help some patients and be ignored or rejected by others; prosthetic fitting has never been and may never be a "one size fits all" methodology, regardless of future innovations. Therefore, although the objective assessment of new general technologies remains important, comparing and contrasting specific, often competing, prosthetic components has become increasingly futile because of the hastening specter of obsolescence.

Future Directions

One persistent, problematic theme, particularly for proximal transfemoral and transhumeral amputees, relates to difficulties with prosthesis suspension because of weight and comfort in conventional sockets. Within the past two decades, European investigators have developed osseointegrated, "endo-exo" devices for the direct skeletal anchorage and attachment of prostheses.[47-50] Function has been dramatically improved for many patients, but complications related to infection persist because the skin-implant interface is an imperfect and unsolved problem. Loosening and fracture also have been variably reported. Of particular concern, revision surgery to revise and replace or formally remove an osseointegrated stem typically requires substantial residual limb and/or bone shortening. No osseointegrated implants for major limb amputations are currently available in the United States, although FDA trials are in development.

Targeted muscle reinnervation (TMR), as described by Kuiken et al[51,52] and Dumanian et al,[53] via reinnervation of "unemployed" muscles and/or reassignment of residual nerves may increase signal intensity and clarity while increasing the number of potential myoelectric target sites for proximal upper limb amputees. For transhumeral amputees, TMR typically involves creating four independently controlled nerve-muscle units by transferring the distal radial/posterior interosseous nerve to the lateral head of the triceps and the median nerve motor branch to the medial (short) head of the biceps (**Figure 11**). When present, the brachioradialis also may be targeted for reinnervation with the ulnar nerve. For patients with shoulder disarticulation, the musculocutaneous nerve is typically transferred to the clavicular head of the pectoralis major; the median nerve to the sterna head of the pectoralis major; the radial nerve to the thoracodorsal nerve; and the ulnar nerve to the pectoralis minor, the long thoracic nerve, or a redundant motor branch of the split pectoralis major. Other transfer or target sites are possible depending on the residual limb anatomy and available musculature. In addition to increasing the number and signal clarity of nerve-muscle myoelectric target sites, a critical advantage of TMR is that the resultant end prosthesis actions may be intuitively programmed (for example, the median nerve closes the hand).

A related, but different, technologic advancement to TMR is that of advanced pattern recognition. In amputees who have undergone previous TMR procedures or in those who have not but experience difficulty with myoelectric control, computer-assisted interpretation of surface electrode signals is used to decode electrical signals in a more consistent and intuitive fashion. These signals are then appropriately reassigned in a customized fashion to the patient's prosthesis so that volitional intent more closely mirrors prosthesis response, and prosthesis responsiveness and signal reliability are improved.

In the near future, implanted myoelectric signal amplifiers in the residual limb may further improve signal quality and interpretation of upper limb amputees, thus improving prosthesis responsiveness and function and obviating problems related to signal noise, involuntary cocontraction of antagonist muscles, and difficult socket fit or sweating (because they decrease conventional myoelectric prosthesis function).[54,55] Intracranial signal receptors placed over the homunculus offer similar potential for proximal upper limb amputees and patients with high spinal cord or brachial plexus injuries. In addition, numerous haptic feedback technologies are in development to offer proxy sensory input from myoelectric prostheses to the amputee and facilitate improved fine motor tasks and touch feedback.

An additional treatment strategy on the horizon for upper limb amputees, particularly of the dominant limb or bilateral limbs, is that of composite tissue allotransplantation (for example, hand transplantation). Substantial headway has been made in the past decade with regard to microsurgical techniques and improved immunosuppression, immunomodulation, and immunotolerance protocols.[56-58] Modern protocols include steroid sparing/avoiding techniques, cell-based immunomodulation strategies, immunosuppression reduction as tolerance increases, and topical therapies that limit overall systemic immunosuppression. Critics remain concerned about the lack of convincing long-term functional data; an unclear and evolving risk-benefit ratio; and potential life-shortening or fatal complications related to immunosuppression, including hyperglycemia, hyperlipidemia, impaired renal function, arterial hypotension, and/or lymphoproliferative disorders. However, early results in a small number of patients (approximately 100 upper limb or hand transplants have been performed worldwide to date) are promising, offering midterm function that is comparable with or, in some cases, better than reimplantation and generally better function than is achievable with currently available prostheses. With such advancements currently being evaluated, hand transplantation may become more widely accepted and feasible in the near future.

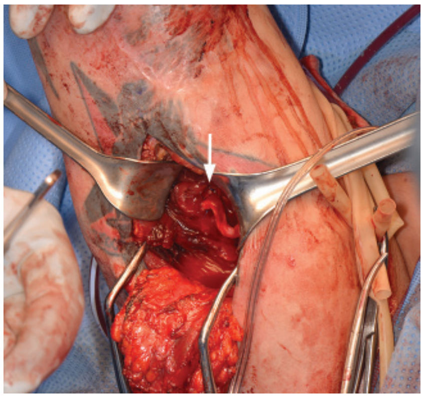

Figure 11 Intraoperative photograph of a posterior targeted muscle reinnervation procedure on a transhumeral amputee. The terminal radial-posterior interosseous nerve has been attached to the deliberately denervated and reinnervated lateral head of the triceps (arrow).

Summary

Advancement in prosthetic design is paralleling the increasing number of amputations. It is important for orthopaedic surgeons to know how to perform "good" amputations to allow patients to achieve the maximum benefits from modern prostheses. Meticulous attention to surgical technical details and familiarity with residual limb options are crucial to achieving the desired outcome.

References

1. Atasoy E, Ioakimidis E, Kasdan ML, Kutz JE, Kleinert HE: Reconstruction of the amputated finger tip with a triangular volar flap: A new surgical procedure. *J Bone Joint Surg Am* 1970;52(5):921-926.
2. Steichen JB, Idler RS: Results of central ray resection without bony transposition. *J Hand Surg Am* 1986;11(4):466-474.
3. Peimer CA, Wheeler DR, Barrett A, Goldschmidt PG: Hand function following single ray amputation. *J Hand Surg Am* 1999;24(6):1245-1248.
4. Puhaindran ME, Athanasian EA: Double ray amputation for tumors of the hand. *Clin Orthop Relat Res* 2010;468(11):2976-2979.
5. Puhaindran ME, Healey JH, Athanasian EA: Single ray amputation for tumors of the hand. *Clin Orthop Relat Res* 2010;468(5):1390-1395.
6. Puhaindran ME, Rothrock CP, Athanasian EA: Surgical management for malignant tumors of the thumb. *Hand (N Y)* 2011;6(4):373-377.
7. Puhaindran ME, Chou J, Forsberg JA, Athanasian EA: Major upper-limb amputations for malignant tumors. *J Hand Surg Am* 2012;37(6):1235-1241.
8. Sakamura R, Nohira K, Shibata M, Sugihara T: Coverage of a large soft-tissue defect of the chest with a free fillet forearm and hand flap. *J Reconstr Microsurg* 2001;17(4):229-231.
9. Bodily KC, Burgess EM: Contralateral limb and patient survival after leg amputation. *Am J Surg* 1983;146(2):280-282.
10. Ziegler-Graham K, MacKenzie EJ, Ephraim PL, Travison TG, Brookmeyer R: Estimating the prevalence of limb loss in the United States: 2005 to 2050. *Arch Phys Med Rehabil* 2008;89(3):422-429.
11. Mazet R Jr: The geriatric amputee. *Artif Limbs* 1967;11(2):33-41.
12. Pandian G, Hamid F, Hammond MC: Rehabilitation of the patient with peripheral vascular disease and diabetic foot problems, in DeLisa JA, Gans BM, eds: *Rehabilitation Medicine: Principles and Practice*. Philadelphia, PA, Lippincott-Raven, 1998, pp 1517-1544.
13. Bohne WHO, Ertl JP: Amputations of the lower extremity, in Chapman MW, ed: *Chapman's Orthopaedic Surgery*, ed 3. Philadelphia, PA, Lippincott Williams & Wilkins, 2001, pp 3149-3173.
14. Smith DG, McFarland LV, Sangeorzan BJ, Reiber GE, Czerniecki JM: Postoperative dressing and management strategies for transtibial amputations: A critical review. *J Rehabil Res Dev* 2003;40(3):213-224.
15. Enneking WF, Dunham WK: Resection and reconstruction for primary neoplasms involving the innominate bone. *J Bone Joint Surg Am* 1978;60(6):731-746.
16. Won H, Maley P, Salim S, Rao A, Campbell NT, Abbott JA: Surgical and patient outcomes using mechanical bowel preparation before laparoscopic gynecologic surgery: A randomized controlled trial. *Obstet Gynecol* 2013;121(3):538-546.
17. Nowroozi F, Salvanelli ML, Gerber LH: Energy expenditure in hip disarticulation and hemipelvectomy amputees. *Arch Phys Med Rehabil* 1983;64(7):300-303.
18. Vancabeke M, Harper L, Penders W, Putz P: Anterior flap for coverage following hip disarticulation for osteomyelitis. *Acta Orthop Belg* 1999;65(2):223-225.
19. Batch JW, Spittler AW, McFaddin JG: Advantages of the knee disarticulation over amputations through the thigh. *J Bone Joint Surg Am* 1954;36(5):921-930.
20. Waters RL, Perry J, Antonelli D, Hislop H: Energy cost of walking of amputees: The influence of level of amputation. *J Bone Joint Surg Am* 1976;58(1):42-46.
21. Torburn L, Schweiger GP, Perry J, Powers CM: Below-knee amputee gait in stair ambulation: A comparison of stride characteristics using five different prosthetic feet. *Clin Orthop Relat Res* 1994;303:185-192.
22. Chiodo CP, Stroud CC: Optimal surgical preparation of the residual limb for prosthetic fitting in below-knee amputations. *Foot Ankle Clin* 2001;6(2):253-264.
23. Hagberg E, Berlin OK, Renström P: Function after through-knee compared with below-knee and above-knee amputation. *Prosthet Orthot Int* 1992;16(3):168-173.
24. Borggreve J: Kniegelenksersatz durch das in der Beinlängsachse um 180 gedrehte Fussgelenk. *Arch Orthop Unfallchir* 1930;28:175-178.
25. Van Nes CP: Rotation-plasty for congenital defects of the femur: Making use of the ankle of the shortened limb to control the knee joint of the prosthesis. *J Bone Joint Surg Br* 1950;32(1):12-16.
26. Hillmann A, Rosenbaum D, Gosheger G, Hoffmann C, Rödl R, Winkelmann W: Rotationplasty type B IIIa according to Winkelmann: Electromyography and gait analysis. *Clin Orthop Relat Res* 2001;384:224-231.
27. Clerici CA, Ferrari A, Luksch R, et al: Clinical experience with psychological aspects in pediatric patients amputated for malignancies. *Tumori* 2004;90(4):399-404.
28. Wallace GF, Stapleton JJ: Transmetatarsal amputations. *Clin Podiatr Med Surg* 2005;22(3):365-384.
29. Tintle SM, Keeling JJ, Shawen SB, Forsberg JA, Potter BK: Traumatic and trauma-related amputations: Part I. General principles and lower-extremity amputations. *J Bone Joint Surg Am* 2010;92(17):2852-2868.
30. Gottschalk F: Transfemoral amputation: Biomechanics and surgery. *Clin Orthop Relat Res* 1999;361:15-22.
31. Pinzur MS, Gottschalk F, Pinto MA, Smith DG: Controversies in lower extremity amputation. *Instr Course Lect* 2008;57:663-672.
32. Smith DG, Fergason JR: Transtibial amputations. *Clin Orthop Relat Res* 1999;361:108-115.
33. Anderson WD, Stewart KJ, Wilson Y, Quaba AA: Skin grafts for the salvage of degloved below-knee amputation stumps. *Br J Plast Surg* 2002;55(4):320-323.
34. Polfer EM, Tintle SM, Forsberg JA, Potter BK: Split-thickness skin grafts for residual limb coverage and preservation of amputation length. American Academy of Orthopaedic

Surgeons 2014 Poster Presentation Abstract. Available at: http://www.abstractsonline.com/plan/ViewAbstract.aspx? Accessed May 20, 2014.

35. Harris AM, Althausen PL, Kellam J, Bosse MJ, Castillo R; Lower Extremity Assessment Project (LEAP) Study Group: Complications following limb-threatening lower extremity trauma. *J Orthop Trauma* 2009;23(1):1-6.

36. Pierce RO Jr, Kernek CB, Ambrose TA II: The plight of the traumatic amputee. *Orthopedics* 1993;16(7):793-797.

37. Tintle SM, Keeling JJ, Forsberg JA, Shawen SB, Andersen RC, Potter BK: Operative complications of combat-related transtibial amputations: A comparison of the modified burgess and modified Ertl tibiofibular synostosis techniques. *J Bone Joint Surg Am* 2011;93(11):1016-1021.

38. Tintle SM, Baechler MF, Nanos GP, Forsberg JA, Potter BK: Reoperations following combat-related upper-extremity amputations. *J Bone Joint Surg Am* 2012;94(16):e1191-e1196.

39. Potter BK, Burns TC, Lacap AP, Granville RR, Gajewski DA: Heterotopic ossification following traumatic and combat-related amputations: Prevalence, risk factors, and preliminary results of excision. *J Bone Joint Surg Am* 2007;89(3):476-486.

40. Harvey ZT, Potter BK, Vandersea J, Wolf E: Prosthetic advances. *J Surg Orthop Adv* 2012;21(1):58-64.

41. Brenner CD: Wrist disarticulation and transradial amputation: Prosthetic management, in Smith DG, Michael JW, Bowker JH, eds: *Atlas of Amputations and Limb Deficiencies: Surgical, Prosthetic, and Rehabilitation Principles*, ed 3. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2004, pp 223-230.

42. Carey SL, Dubey RV, Bauer GS, Highsmith MJ: Kinematic comparison of myoelectric and body powered prostheses while performing common activities. *Prosthet Orthot Int* 2009;33(2):179-186.

43. Kyberd PJ, Chappell PH: The Southampton Hand: An intelligent myoelectric prosthesis. *J Rehabil Res Dev* 1994;31(4):326-334.

44. Dale B, Olson MD, Larntz K: Perceived stability, function, and satisfaction among transfemoral amputees using microprocessor and nonmicroprocessor prosthetic knees: A multicenter survey. *J Prosthet Orthot* 2009;21(1):32-42.

45. Wong CK, Benoy S, Blackwell W, Jones S, Rahal R: A comparison of energy expenditure in people with transfemoral amputation using microprocessor and non-microprocessor prostheses: A systematic review. *J Prosth Orthot* 2012;24(4):202-208.

46. Aldridge JM, Sturdy JT, Wilken JM: Stair ascent kinematics and kinetics with a powered lower leg system following transtibial amputation. *Gait Posture* 2012;36(2):291-295.

47. Aschoff HH, Kennon RE, Keggi JM, Rubin LE: Transcutaneous, distal femoral, intramedullary attachment for above-the-knee prostheses: An endo-exo device. *J Bone Joint Surg Am* 2010;92(suppl 2):180-186.

48. Hagberg K, Brånemark R: One hundred patients treated with osseointegrated transfemoral amputation prostheses: Rehabilitation perspective. *J Rehabil Res Dev* 2009;46(3):331-344.

49. Hagberg K, Häggström E, Uden M, Brånemark R: Socket versus bone-anchored trans-femoral prostheses: Hip range of motion and sitting comfort. *Prosthet Orthot Int* 2005;29(2):153-163.

50. Sullivan J, Uden M, Robinson KP, Sooriakumaran S: Rehabilitation of the trans-femoral amputee with an osseointegrated prosthesis: The United Kingdom experience. *Prosthet Orthot Int* 2003;27(2):114-120.

51. Kuiken TA, Dumanian GA, Lipschutz RD, Miller LA, Stubblefield KA: The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee. *Prosthet Orthot Int* 2004;28(3):245-253.

52. Kuiken TA, Li G, Lock BA, et al: Targeted muscle reinnervation for real-time myoelectric control of multifunction artificial arms. *JAMA* 2009;301(6):619-628.

53. Dumanian GA, Ko JH, O'Shaughnessy KD, Kim PS, Wilson CJ, Kuiken TA: Targeted reinnervation for transhumeral amputees: Current surgical technique and update on results. *Plast Reconstr Surg* 2009;124(3):863-869.

54. Parker P, Englehart K, Hudgins B: Myoelectric signal processing for control of powered limb prostheses. *J Electromyogr Kinesiol* 2006;16(6):541-548.

55. Tintle SM, Baechler MF, Nanos GP III, Forsberg JA, Potter BK: Traumatic and trauma-related amputations: Part II. Upper extremity and future directions. *J Bone Joint Surg Am* 2010;92(18):2934-2945.

56. Brandacher G, Ninkovic M, Piza-Katzer H, et al: The Innsbruck hand transplant program: Update at 8 years after the first transplant. *Transplant Proc* 2009;41(2):491-494.

57. Lanzetta M, Petruzzo P, Dubernard JM, et al: Second report (1998-2006) of the International Registry of Hand and Composite Tissue Transplantation. *Transpl Immunol* 2007;18(1):1-6.

58. Petruzzo P, Lanzetta M, Dubernard JM, et al: The international registry on hand and composite tissue transplantation. *Transplantation* 2008;86(4):487-492.