# BKA with TMR Are Changing the Options in Limb Salvage

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Christopher Attinger and Grant Kleiber

## 10.1 Introduction

When considering salvaging a limb, it is critical to assess the type of function the reconstructed limb is capable of providing. One has to accurately assess the realistic activities that the patient is physically capable of. This then determines which options best meet those goals: the planned reconstructed limb versus an amputation. The function achieved with below knee amputations have improved dramatically with the application of myodesis, vascularized fibular graft, targeted muscle reinnervation (TMR) and the use of ever more sophisticated prosthesis. Because of this, salvaging a limb just to salvage the limb is no longer an acceptable goal. The surgeon's goal is to give patients a *functional* limb that meets their realistic physical goals, whether it be a reconstructed or amputated limb. The younger and/or more athletic patients, the more they will demand of their reconstructed leg. As such, the reconstructed limb may not be able to meet their desired goal and the decision to undergo an amputation may more appropriate. However, the older the patient, the less he/she may demand of the reconstructed leg. As a result, a less than perfectly functional leg may be sufficient to carry on acts of daily living and avoids the necessity of relying on a prosthesis.

We will initially cover the decision-making for amputation versus salvage. We will then cover the basics of doing a below knee amputation focusing on myodesis, ERTL, and TMR.

## 10.2 Preoperative Preparation

The decision to potentially perform an amputation occurs because of inadequate available soft tissue or bone for the reconstruction of a functional limb, inability to restore appropriate arterial blood flow or overwhelming infection. To assess the leg for possible reconstruction, one has to accomplish three things: ensure sufficient blood flow to heal, eradicate any residual infection, and have a functional result in mind that fits the patient's needs.

When facing a diabetic or radiated patient, it is often hard to assess blood flow. One had to keep the angiosome concept in mind at all times to be sure that the area in question is adequately perfused [1]. ABIs are unreliable in diabetics and renal failure patients because of calcified vessels. The most reliable is an angiogram with magnified views of the foot. This also allows the

C. Attinger (✉)
Department of Plastic and Orthopedic Surgery, Medstar Georgetown University Hospital, Washington, DC, USA
e-mail: Christopher.attinger@medstar.net

G. Kleiber
Department of Plastic Surgery, Medstar Georgetown University Hospital, Washington, DC, USA


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surgeon to visualize the rate of flow in each artery. This can be done with very little dye (<10 cc of dye), especially in patients with kidney function at risk. One has to be able to assess the contributions of each of the three arteries to the foot and the arterial-arterial connections between those arteries [2]

It is critical to have a good vascular team to rely on. One needs access to physician(s) who excel in angioplasty, bypass surgery, and venous surgery. Going over the angiogram with the respective vascular interventionist is critical so that he or she understands exactly what type of blood flow is needed for the reconstructive surgery to be successful. This is especially true if microsurgery is one of the possible reconstructive options [3]. Angioplasties tend to have a shorter half-life (30% occlusion rate at 3 months) when compared to that of a bypass and that has to be kept in mind during the reconstruction. The optimal flow to the downstream foot (as measured by TcO2) with bypass surgery occurs at 5–8 days post bypass versus as long as 30 days post angioplasty. The microsurgical anastomosis to a major artery should *always* be end to side so as not to sacrifice distal flow [4]. The exception is when plugging the flap pedicle into a small perforator where end to end is preferable. When doing microsurgery, the venous flow also has to be assessed to make sure that the venous return from the flap travels via the venous system (superficial or deep) that has the least amount of resistance [5].

Dealing with infection can be difficult because diagnosis is affected by the way the specimen is collected, by how the laboratory handles it, by the presence of biofilm and interpretation of the PCR data. In addition, one has to consider the host. The more medically compromised the host, the more vulnerable the host is to residual infection. We recommend removing all exposed tissue after painting the wound with blue dye to accurately demarcate the wound surface [6]. By excisionally debriding to normal red, yellow, and white tissue, one can be certain that one has removed all the surface bacteria. The more extensive the excisional debridement, the more likely one is to also remove any burrowing biofilm that can be as deep as 4 mm under the wound surface. The resection of any indurated tissue at the edges of the wound down to soft normal tissue removes all potentially infected tissue and is more likely to remove residual biofilm. The amount of indurated soft tissue that needs to be resected is always surprisingly thin and may only require 2–4 mm thick cuts. It is critical to obtain pre-debridement and post-debridement tissue cultures (versus culture swabs) to assess the quality of the debridement. Once the post-debridement results are available, the surgeon can then make the decision as to whether to close or not [7]. Working closely with infectious disease for the initial broad-spectrum antibiotics and subsequent narrowing of the antibiotic coverage is critical to minimizing the potential toxicity of the antibiotics on the patient. If bone infection has been resected and the post-debridement bone cultures are negative, one only needs antibiotics for 1 week as per both the IDSA [8] and ISID guidelines.

Finally, one has to decide on the type of reconstruction that will be used. Keep in mind that if an ulcer heals in a diabetic foot, the chances of ulcer recurrence at 2 years can be as high as 80% [9]. The result therefore has to be a functionally sound foot in order to minimize the risk of recidivism. If it is deemed by the surgeon that the function of the salvaged limb will not meet the physical capacity and expectations of the patient, then amputation has to be considered. It can either be a foot amputation or a below knee amputation. It is important to fully discuss those options with the family and the patient. Having a peer amputee and the prosthetist and orthotist talk to the patient about the consequences of shorter foot amputations versus below knee amputation is very productive The patient and the family can then make an intelligent decision as to which to choose.

## 10.3 Below the Knee Amputation

### 10.3.1 Preoperative Preparation

The amputations with the longest 5 year survival at our center include toe amputation, trans-metatarsal amputations and below knee amputations [10]. All other amputations (ray, Lisfranc, Chopart or Syme amputation) lead to higher recidivism and lower 5-year survival due to decreased function. There is no significant difference 5 year survival difference between the below knee amputation and the TMA. Since we recently added TMR to the BKA, the ambulatory rate has risen to 91% at 3 month and the 1 year survival rate was 95% (average non-traumatic BKA had a 35% mortality at 1 year) [11]. These results add to the ever-growing data that regular physical activity is the key determinant to increasing survival [12].

The level of the amputation is dependent on the available, viable soft tissue and bone after debridement of the foot and ankle or drainage amputation. If the leg is ischemic, review of the angiogram is helpful to better assess what angiosomes are well perfused. Even if the popliteal or superficial femoral artery is occluded, the collateral flow can be adequate to heal a below knee operation. The demarcation line between cold and warm tissue usually coincides with the level of ischemic pain. Only using tissue above the lines demarcating pain and temperature has proved to be remarkably accurate in determining amputation levels with only a 2% BKA to AKA conversion rate [13]. It also important that the patient meet with a prosthetist preoperatively so that the patient fully understands what is about to occur. The prosthetist also provides invaluable feedback to the surgeon so that the ideal residual limb can be designed. If possible, it is also very helpful for them to meet with another amputee who has gone through what the patient is about to experience. This pre-amputation consultation is invaluable not only in allaying the fears of the patient but to have a positive outlook and thus ensure the most functional outcome.

Preoperative and perioperative medical management is as important as surgical technique. Diabetes, end-stage renal disease, coronary artery disease, coagulopathy, and chronic anemia are associated with increased surgical complications and should be managed aggressively. Patients with ESRD should dialyzed the day before the amputation. Beta-blockers should be taken the morning of surgery, and perioperative antibiotics should cover the initial infection and re-dosed as needed. Glucose should be kept under 200 during the perioperative period [14].

The level of anesthesia may vary based on the planned procedure. Regional blocks, with sedation, are preferred so that the block can be continued during the first 4–5 days postoperatively. In our recent experience, regional nerve blocks and selected targeted motor nerve reinnervation have been very successful in controlling postoperative pain and minimizing phantom pain.

Amputations performed in the setting of infection should be done in two stages. Two-stage below knee amputation for ischemic and infectious causes have been shown to have significant decreased reoperation rates [15]. It give 24–48 h for the lymphatic system to clear residual bacteria and it limits possible cross-contamination that can occur when done in a single stage. It also gives time to obtain definite culture and sensitivities. When there is lymphedema in the leg, removing the infection will decrease the swelling. In addition, a lymphedema wrap applied by physical therapy to the residual limb post drainage amputation works remarkably well to get rid of the edema and make the residual tissue more pliable for the definitive amputation. If only the foot is involved, the initial drainage amputation should be an ankle disarticulation to minimize bone bleeding. If the ankle is involved, a guillotine amputation is planned above the level of infection. The completion amputation is then performed at least 2–3 days afterward.

## 10.4 Below Knee Amputation

### 10.4.1 Technique

Bickel popularized the use of the posterior myocutaneous flap (PMF) in 1943. Burgess later modified it by recommending that the deep posterior compartment be removed to limit unnecessary bulk in the posterior flap and limit the amount of tissue dependent on presumably diseased posterior tibial and peroneal arteries [16]. Interestingly, in popliteal or trifurcation disease, the sural arteries that feed the gastrocnemius muscles are usually spared and provide the necessary blood flow to the superficial posterior flap. This is reflected in our series of 294 flaps where the ratio of BKA to AKA was 4–1 with a 2% eventual conversion rate from BKA to AKA. Our institution uses a posterior myocutaneous flap (PMF) in which the superficial posterior compartment provides vascularized and durable coverage of the tibial/fibular osteotomies. Tenodesis and myodesis of the superficial posterior compartment serve several functions. Gastrocnemius muscles continue to function as a knee flexor and thus maintain soft tissue bulk and prevent muscle atrophy. A second benefit of the PMF is preventing a suture line and future scar over the distal mid-stump. A final benefit is that the musculature with their insertion restored by the myodesis still functions as a venous pump to help prevent lower leg edema.

The componentry below the socket in the average below knee prosthesis requires at least 8 inches of clearance from the ground. This leaves plenty of amputation length to allow increased leverage of a longer moment arm, increased surface area to disseminate pressure from the interaction of soft tissue with the socket, and it provides additional tissue for an adequate revision BKA should it ever be required. After consulting with the prosthetist, each BKA is planned with a tibial osteotomy at 12–18 cm from tibial tubercle if there is adequate distal soft tissue (Fig. 10.1a). Add 4 cm to the measurement (16–22 cm) if one picks the knee joint line to measure from. Waterproof stockinet and Coban is used to

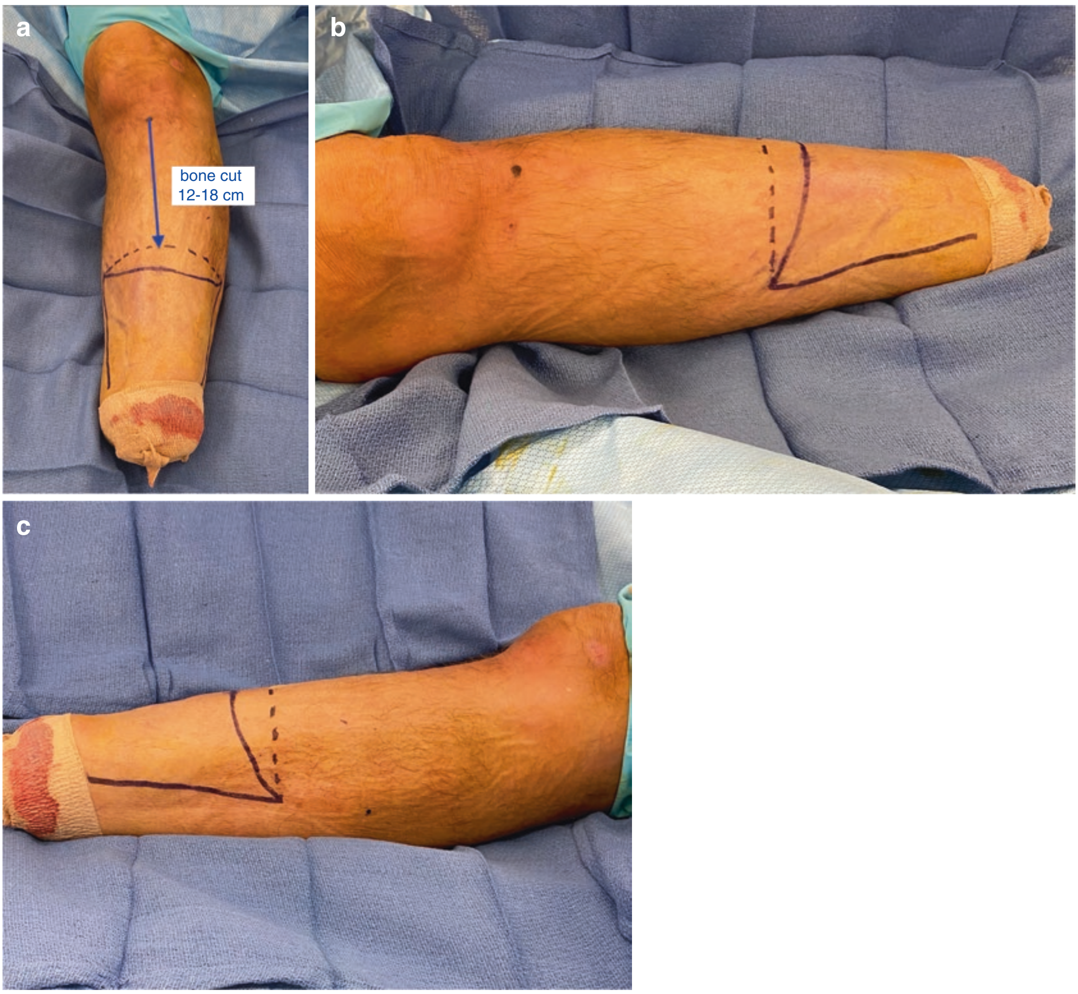


**Fig. 10.1** (**a**) The length of the amputation is measured from the tibial tubercle to the planned bone cut. It should be anywhere between 12 and 18 cm in length. If measuring from the knee joint line, add 4 cm. The actual skin incision line is drawn 2–4 cm. distal to the bone cut line so that the incision does not lie on the bone cut. (**b**, **c**) The medial margin (**b**) stops just below the posterior aspect of the tibia. The lateral margin (**c**) goes just above the fascia separating the posterior from the lateral compartment. Both lines slope up distally to maintain width of distal flap

isolate the distal drainage wound or foot and prevent contamination of the field and proximal clean tissue. A proximal tourniquet is placed on the thigh for the nerve portion of the surgery.

An anterior skin line is drawn at the planned tibial osteotomy site encompassing approximately 2/3 the circumference of the leg (Fig. 10.1a). The medial limit is just below the posterior tibia, and the lateral limit is above the fascia separating the lateral from the posterior compartment. This gives a slightly skewed posterior flap with the medial side being more anterior than the lateral side. The anterior skin incision line is then drawn so that it starts at the same point medially and laterally but extends 2–4 cm distal to the planned tibial bone cut line (Fig. 10.1a). This ensures that the suture line does not fall at the level of the osteotomy site.

Medially and laterally, the skin incision is carried distally with a slight anterior slant toward the ankle to maintain the same flap width as the leg narrows (Fig. 10.1b, c). The skin cuts are through fascia taking great care to ligate or clip the saphenous vein and small arteries and veins (Fig. 10.2a). The saphenous nerve is identified and preserved. The superficial peroneal nerve lies just deep to the superficial fascia and just lateral to the fascia separating the anterior from the lateral compart-

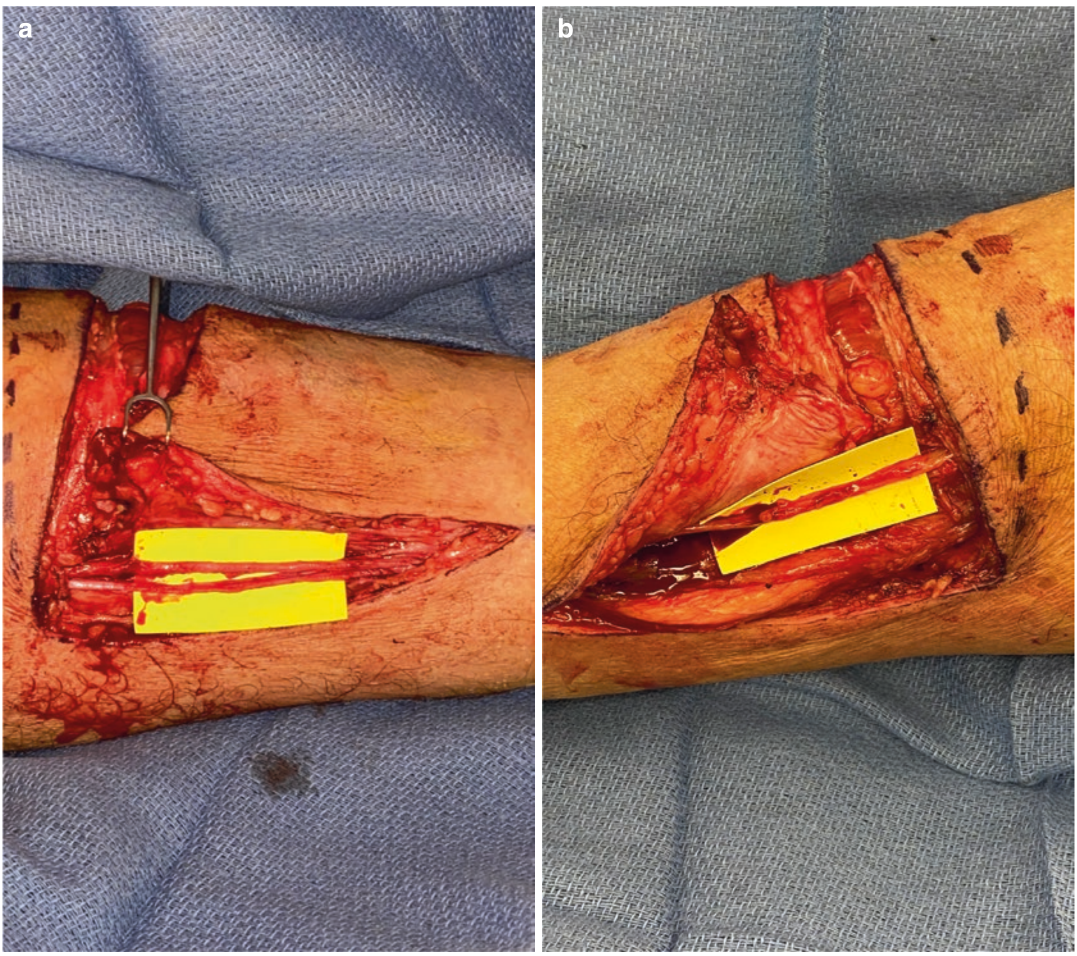


**Fig. 10.2** (**a**) The medial incision is made above the saphenous vein, and the saphenous nerve are preserved. In this picture, 2 branches of the saphenous nerve lie just below the saphenous vein. (**b**) The superficial peroneal nerve is just lateral to the septum dividing the anterior from the lateral compartment. It is dissected out to its full length to the planned distal cut of the posterior flap

ment (Fig. 10.2b). It should be dissected out carefully along its distal length when the incision is made along the lateral compartment and should be identified and preserved. Special attention is paid to preserve the distal lateral compartment peroneus longus and brevis muscles that will be used for myodesis later. The anterior muscle compartment is then cut using electric cautery at just distal to the planned tibial bone cut (Fig. 10.3a). The anterior tibial artery and vein are identified and suture ligated. The deep peroneal nerve is isolated and cut as long as possible (Fig. 10.3b).

The tibia is exposed and the planned osteotomy is verified at pre-planned bone cut distance. An army-navy retractor is passed posterior to the tibia and the osteotomy is made perpendicular to the longitudinal axis of the tibia. The fibular osteotomy is approximately 1.5 cm shorter with a bevel slightly oriented from lateral to medial (Fig. 10.4a–c).

After both osteotomies, a bone hook into the open end of distal tibia provides anterior retraction to expose the deep posterior compartment. A 10 blade is used to sharply dissect the lateral and deep posterior compartment muscles off the distal tibia and fibula (Fig. 10.5a, b). The distal leg is then amputated at a distance that guarantees sufficient posterior flap length to fold anteriorly to close the amputation

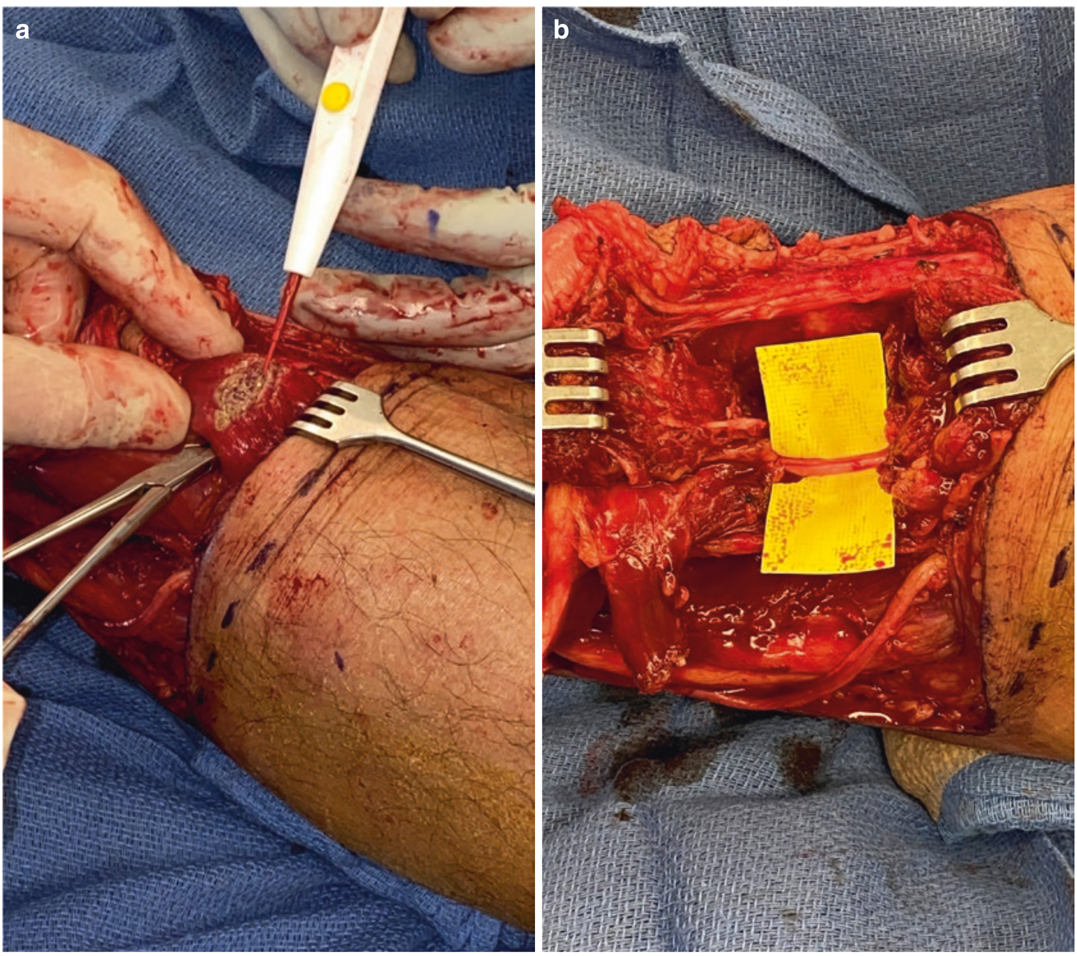


**Fig. 10.3** (**a**) The anterior tibial muscles are cut at the level of the planned tibial bone cut. (**b**) the anterior tibial artery and vein are cut, and the deep peroneal nerve is preserved

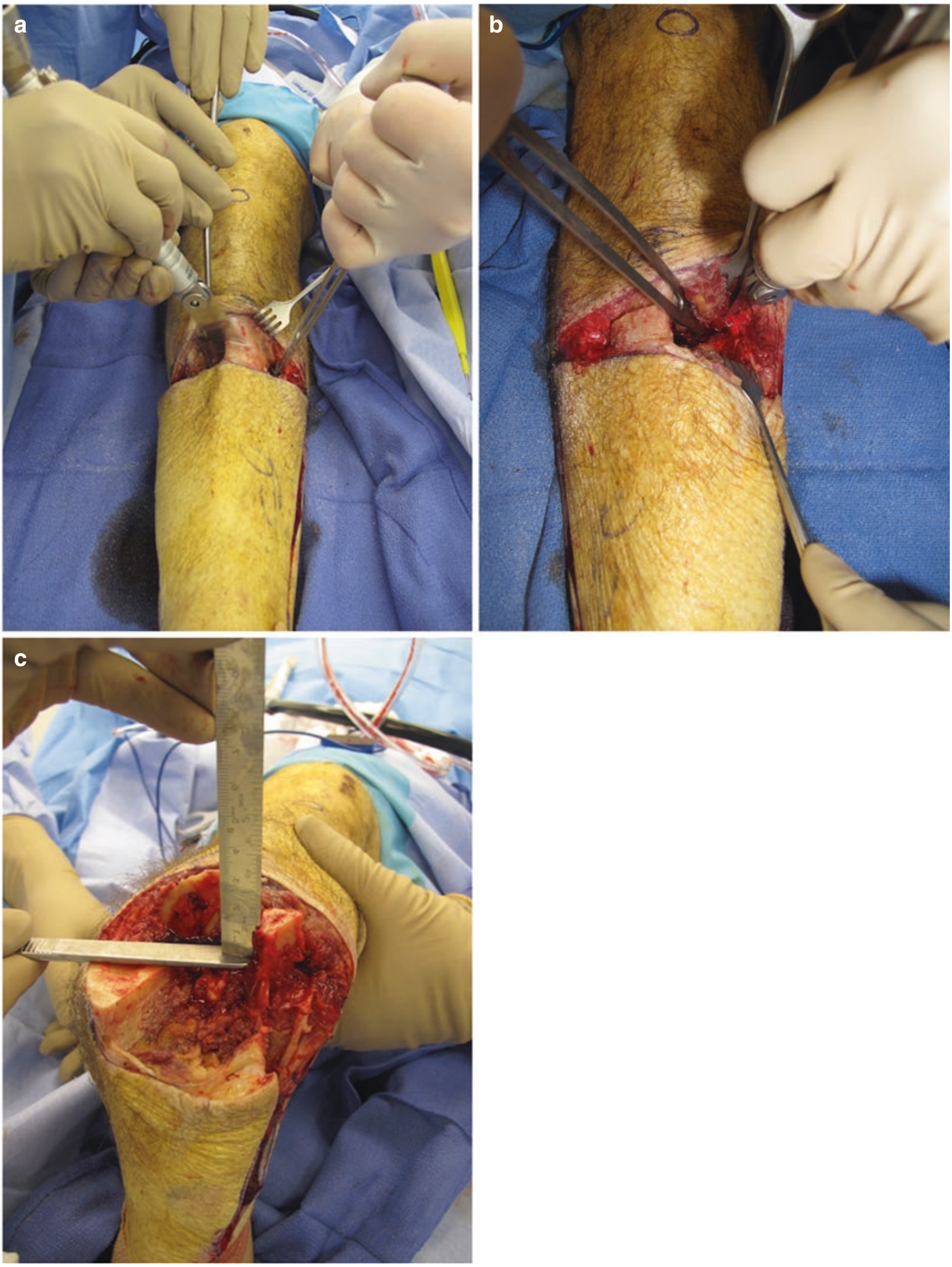


**Fig. 10.4** (**a**) Osteotomy of tibia. (**b**, **c**) The fibular cut is 1–1.5 cm shorter than the tibia and is done carefully not to damage the peroneal artery and nerves

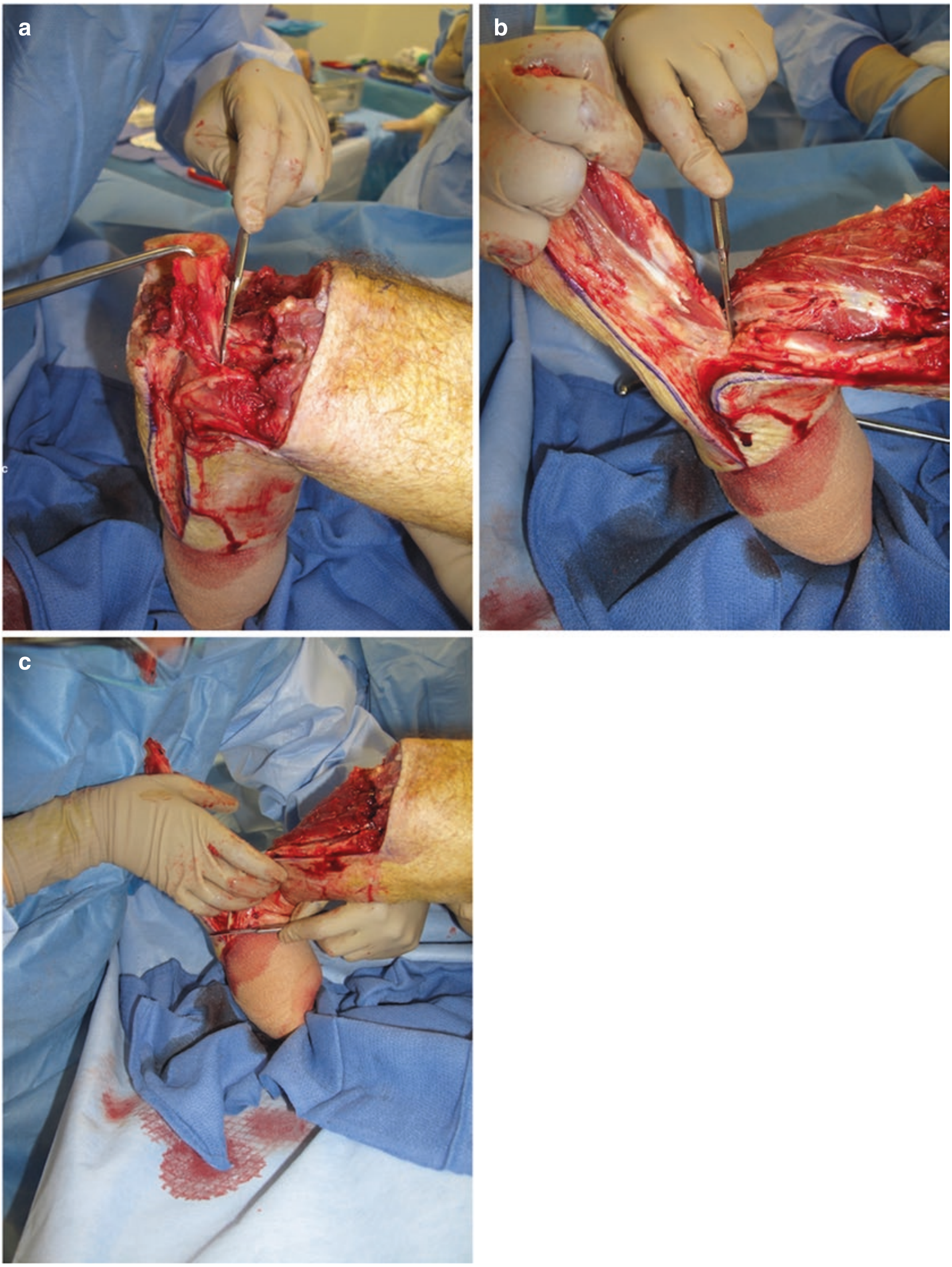


**Fig. 10.5** (**a**, **b**) The posterior flap tissue is dissected off of the tibia and fibula taking great care to preserve the peroneal muscles. (**c**) The leg is cut off at a level where the flap is long enough to easily reach the anterior portion of the tibia for closure

(Fig. 10.5c). After discarding the distal leg, the deep posterior compartment is dissected off of the superficial compartment (Fig. 10.6a, b) and removed with careful ligation of the peroneal and posterior tibial perforators to the superficial posterior department. Then post tibial nerve is dissected out and preserved (Fig. 10.6c). The deep posterior compartment muscles are left a centimeter longer than the tibia for future myodesis to the tibia. The posterior tibial and peroneal arteries are tied off and the posterior tibial nerve is preserved. All four nerves (saphenous nerve, deep peroneal nerve, posterior tibial nerve, and superficial tibial nerve) are carefully preserved for future TMR or traction neurectomy (Fig. 10.7).

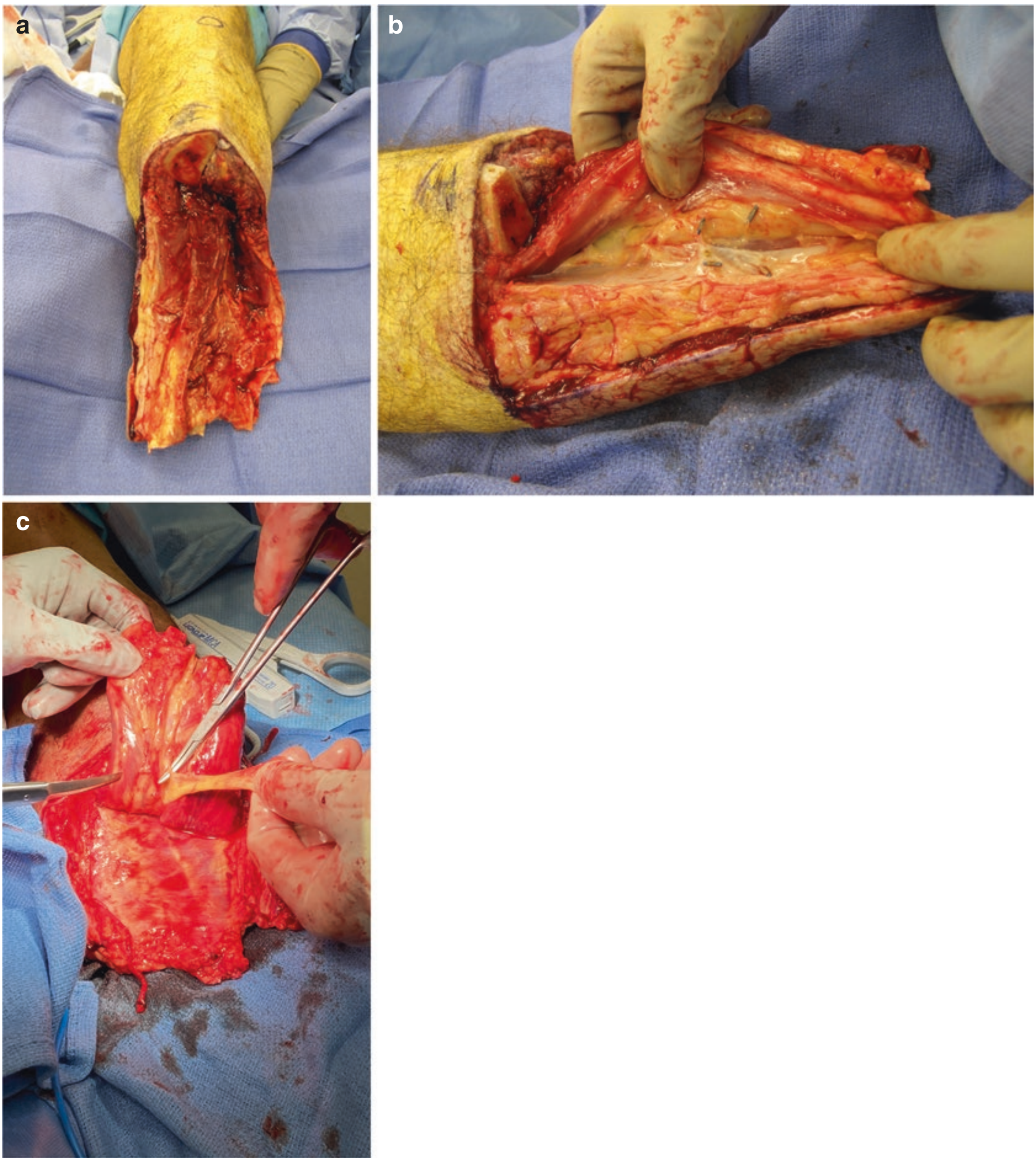

**Fig. 10.6** (**a**–**c**) The deep posterior compartment is then removed off of the posterior compartment fascia taking care to ligate all perforators

**Fig. 10.7** All four nerves (saphenous n., deep peroneal nerve, posterior tibial nerve and superficial peroneal nerve) are carefully preserved for future TMR or traction neurectomy

The peroneal muscles are then freed up from the attachments to superficial posterior compartment muscle fascia all the way up to the cut fibula. Minor pedicles from the peroneal muscles are tied off.

The anterior half of the tibial cortex is then beveled for about 1 cm using a sagittal saw (Fig. 10.8a, b) taking great care to keep the thickness of the remaining cortex at least equal to that of the rest of the tibia. The bevel is then sanded down by brushing the sagittal saw over that area. Three holes are drilled into the medial anterior tibia (left 10, 11 and 12 o'clock and right 2, 1, 12 o'clock) through the anterior cortex toward the center of the medullary canal and will be used for future tenodesis of the soleus and gastrocnemius muscles (Fig. 10.8c). A hole is drilled in the lateral tibial (right 9 o'clock, left 3 o'clock and both at 6 o'clock) to tenodese the peroneal and deep posterior muscles, respectively. Irrigation is performed to get rid of bone dust. New gloves and sterile drapes are placed while a clean table and set of instrumentation are used to avoid any possible contamination with the removed distal stump.

At this point, all the nerves can be addressed with either TMR or traction neurectomy. See nerve section in the final section of this chapter for the technique of TMR.

The peroneus muscles (Fig. 10.9a) are then rotated medially and cut at the level of the lateral tibial border and sewn into the lateral tibial predrilled hole (Fig. 10.9b) using a 0 monofilament. If the muscles are too bulky, the brevis is cut at the level to the fibula and only the longus is used for the myodesis. In that case, a tacking stitch is used to keep the peroneus brevis myodesed to the peroneus longus. The 0 monofilament stitch is then continued back and forth through anterior tibial muscle without incorporating the overlying fascia using a running horizontal mattress suture so that the anterior tibial muscles are myodesed to the freshly myodesed peroneal muscle(s) (Fig. 10.9c). The deep posterior muscles are tenodesed to the 6 o'clock tibial hole making sure that all three muscles are included. In addition, one can further myodese them by attaching the posterior tibial muscles to the inferior border of the tenodesed peroneal muscle (Fig. 10.9d) This maneuver restores the insertion to the anterior tibial muscles and the deep posterior compartment muscles so they maintain their ability to contract against resistance and minimize the loss of muscle bulk over time (Fig. 10.9e).

The posterior flap is then swung up to the level of the anterior portion of the tibia making sure that the soleus covers the entire tibia and a semilunar line is drawn on the soleus muscle at the level of the anterior tibial fascia to mark that level (Fig. 10.10a). One or two drains are placed along the base of the flap. The soleus muscle is then incised along the drawn line with a bovie or ten blade down to Achilles tendon with a slant proximal to distal angle

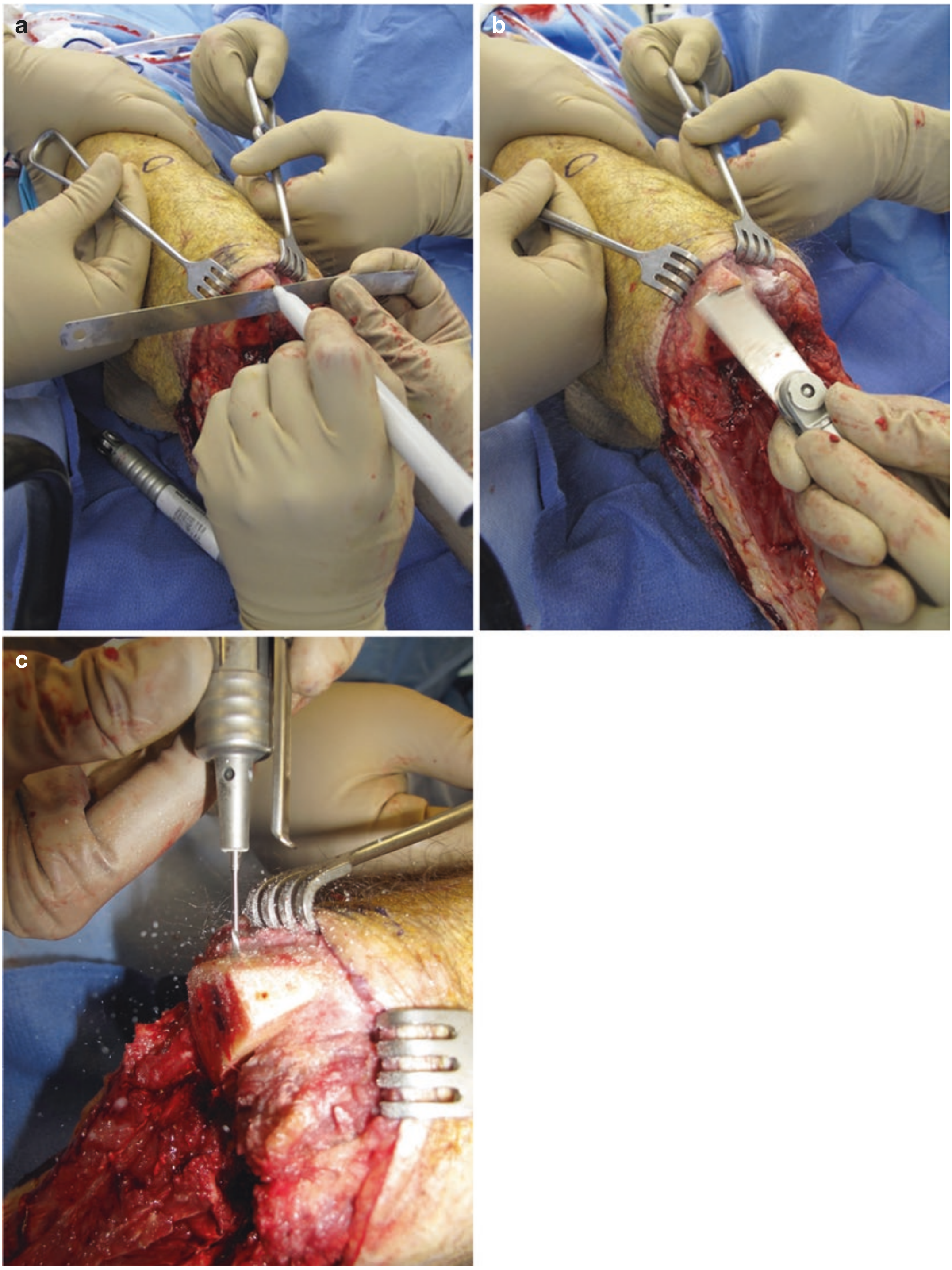


**Fig. 10.8** (**a**, **b**) The anterior portion of the distal tibia is beveled and sanded down. Great care is taken to make the cut high enough to ensure that the circumferential thickness of the tibial cortex remains the same over the entire circumference. (**c**) Three holes are drilled into the medial anterior tibia (left 10, 11 and 12 o'clock and right 2, 1, 12 o'clock) through the anterior cortex toward the center of the medullary canal and will be used for future tenodesis of the soleus and gastrocnemius muscles. A hole is drilled in the lateral tibial (right 9 o'clock, left 3 o'clock and both 6 o'clock) to tenodese the peroneal and deep posterior muscles, respectively

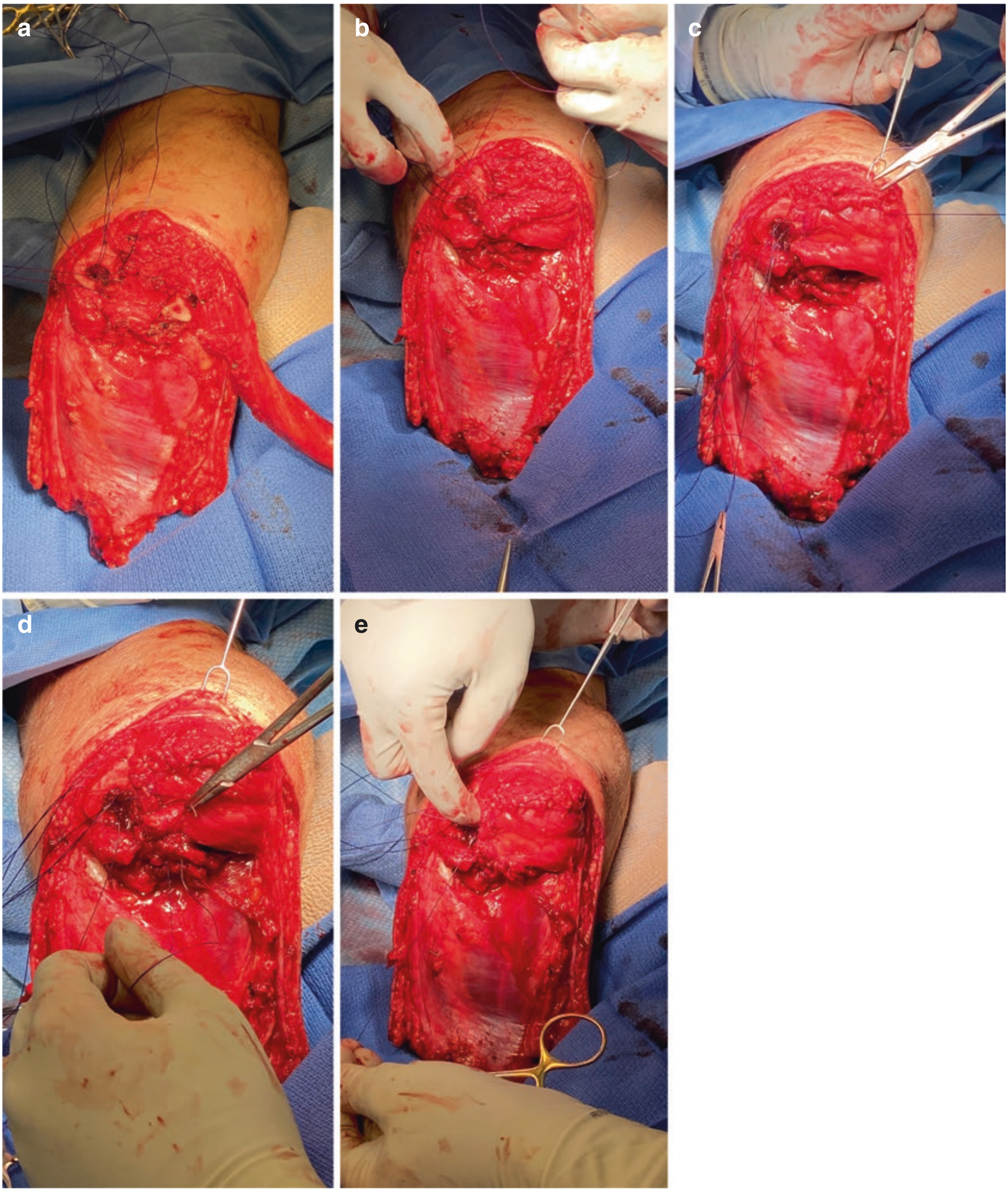


**Fig. 10.9** (**a**, **b**) The peroneal muscle(s) (**a**) are rotated toward the tibia, cut along its lateral border and are then fixed to the lateral tibial cortex hole (**b**) using a 0 monofilament. (**c**) The stitch is then continued through anterior tibial muscle without incorporating the overlying fascia using a running horizontal mattress suture so that the latter are myodesed to the freshly myodesed peroneal muscle(s). (**d**, **e**) The deep posterior muscles are tenodesed to the 6 o'clock tibial hole making sure that all three muscles are included. In addition, one can attach the posterior tibial muscles to the inferior border of the tenodesed peroneal muscle

(Fig. 10.10b) so that when the posterior flap is rotated forward, the distal soleus muscle can be sewn into the anterior tibial cortex. The distal soleus muscle with the fascia-tendinous layer is then sewn into the three previously drilled holes in the tibia with 0 monofilament suture (Fig. 10.10c, d).

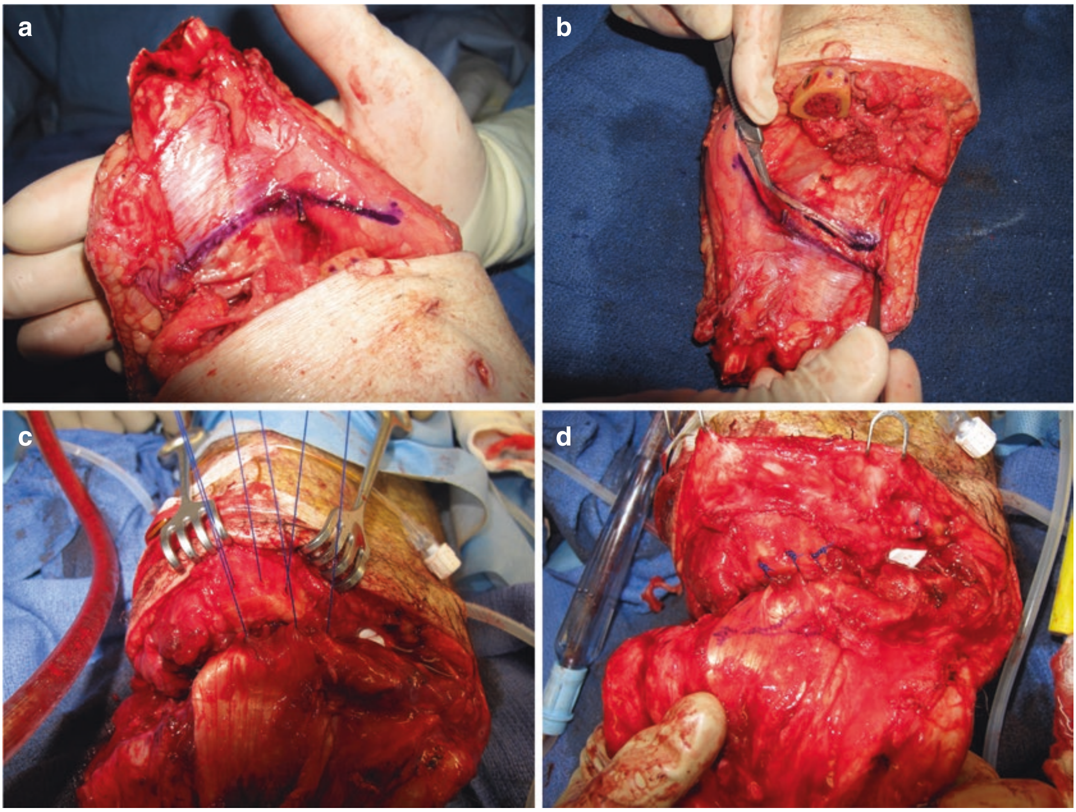


**Fig. 10.10** (**a**) The posterior flap is folded up and a line is drawn at the level of the anterior fascia of the proximal leg. (**b**) The soleus distal to the line is removed either with a bovie or knife. Great care is taken to preserve the underlying Achilles tendon and fascia. (**c**, **d**) Three 0-monofilament dissolvable stitches are placed through the anterior tibial holes. They are sutured into the soleus muscle and underlying fascia. Great care is taken to make sure that the medial part of the soleus muscle covers the entire distal tibia bone with intact muscle

The skin and subcutaneous tissue are then dissected off the distal anterior tibial fascia for a width of about 2 cm (Fig. 10.11a). The Achilles tendon and posterior gastrocnemius tendinous fascia is then cut 2–3 cm distal to the distal end of the soleus tenodesis (Fig. 10.11b) and then sewn to the anterior tibial fascia with a running back and forth with 0 monofilament (Fig. 10.11c, d). The sural nerve and lesser saphenous vein are located at the distal central end of the posterior flap. The nerve is crushed 5 cm from the distal end, buried deep in its tunnel. The lesser saphenous vein is clipped. Skin is cut at a level where the wound can be closed without tension (Fig. 10.12a). Dog ears, if present at the medial and lateral edge of the closure, are removed (Fig. 10.12b) and the suture line re-contoured to create a smooth tapered end so that the leg is ready for a prosthesis as soon as the stitches are removed. The incision is closed with vertical mattress 2–0 monofilament and skin staples are used between each stitch to ensure good skin edge eversion (Fig. 10.12c). The incision line can be covered with an incisional negative pressure device to immobilize the suture line for 7–14 days (Fig. 10.12d). The wound is then dressed and the leg is placed in a knee immobilizer to protect it from falls and prevent possible knee flexion that may result in knee contracture. The skin clips are removed at 1 week and the stitches at 4 weeks (6 weeks for renal failure patients).

Evidence comparing PMF versus Skew or Sagittal flaps show no significant differences, although the level of evidence is poor. In our

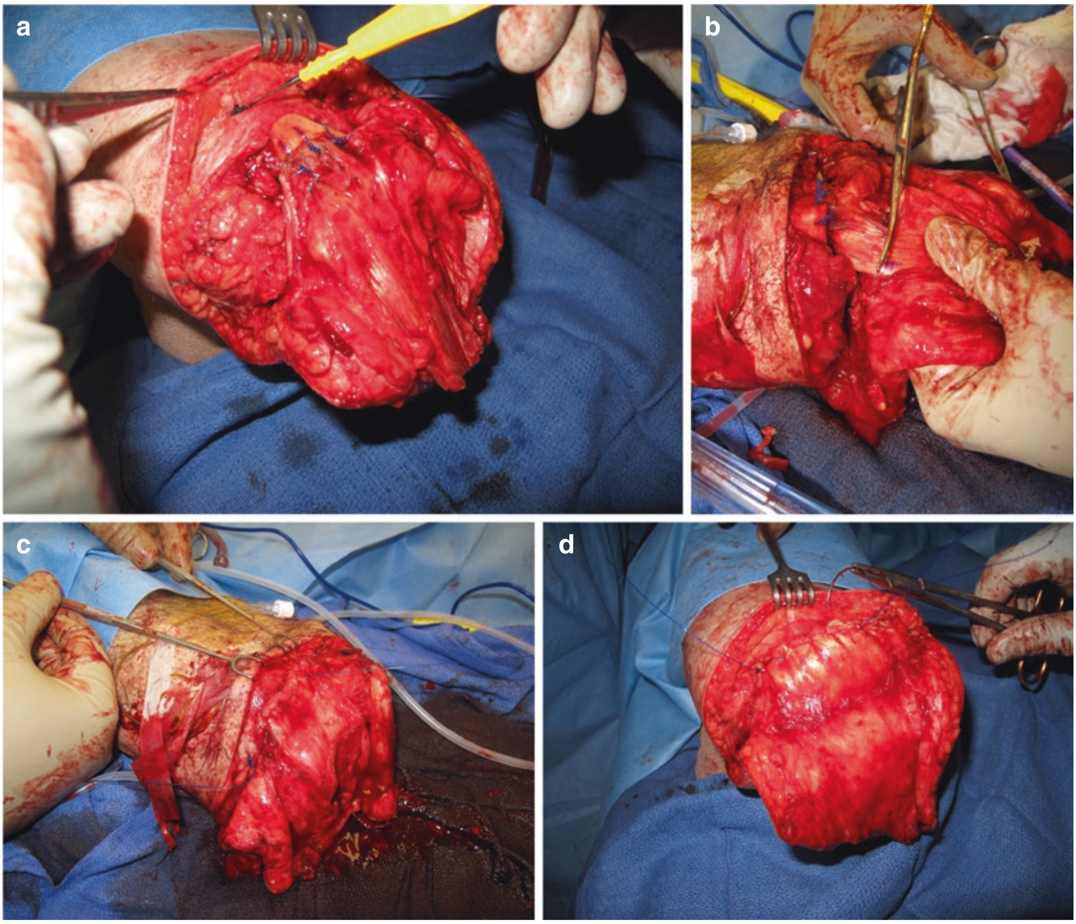

**Fig. 10.11** (**a**) The distal skin and subcutaneous tissue is freed up from the underlying anterior compartment fascia for width of about 2 cm. (**b**) The Achilles tendon and posterior fascia are cut 2–3 cm distal to the tenodesed soleus muscle so they can be sewn into the anterior tibial fascia without tension. (**c**, **d**) The tenodesis of the Achilles tendon to the anterior tibial fascia is performed using a running zero monofilaments horizontal mattress suture in one direction and returned in the other with a running stitch

hands, however, the PMF provides sufficient vascularized soft tissue coverage over the tibial osteotomy to allow us to successfully perform below knee amputations in 80% of all patients who presented with an ischemic or a non-viable or non-functional foot. Without TMR up to 78% of those BKA's resulted ambulatory patients. With TMR, 92% are ambulatory at 3 months. In addition, only 2% of the below knee amputations had to undergo a higher level amputation [9]. This is the highest rate of BKA versus AKA in the literature, suggesting that the vascular supply to the PMF may be superior to that of other flap designs.

### 10.4.2 BKA Using the ERTL Technique

Alternatively, an ERTL modification to the BKA can be performed in patients who have the capacity of being physically active. The ERTL modification for below knee amputation involves placing a vascularized fibular bone graft between the distal tibia and fibula to promote distal bony fusion between the distal tibia and fibula. The distal bones with the interposed fibular graft fuse to form a solid "U" which allows better transfer of leg rotational torque to the artificial prosthetic ankle/foot [17]. It also

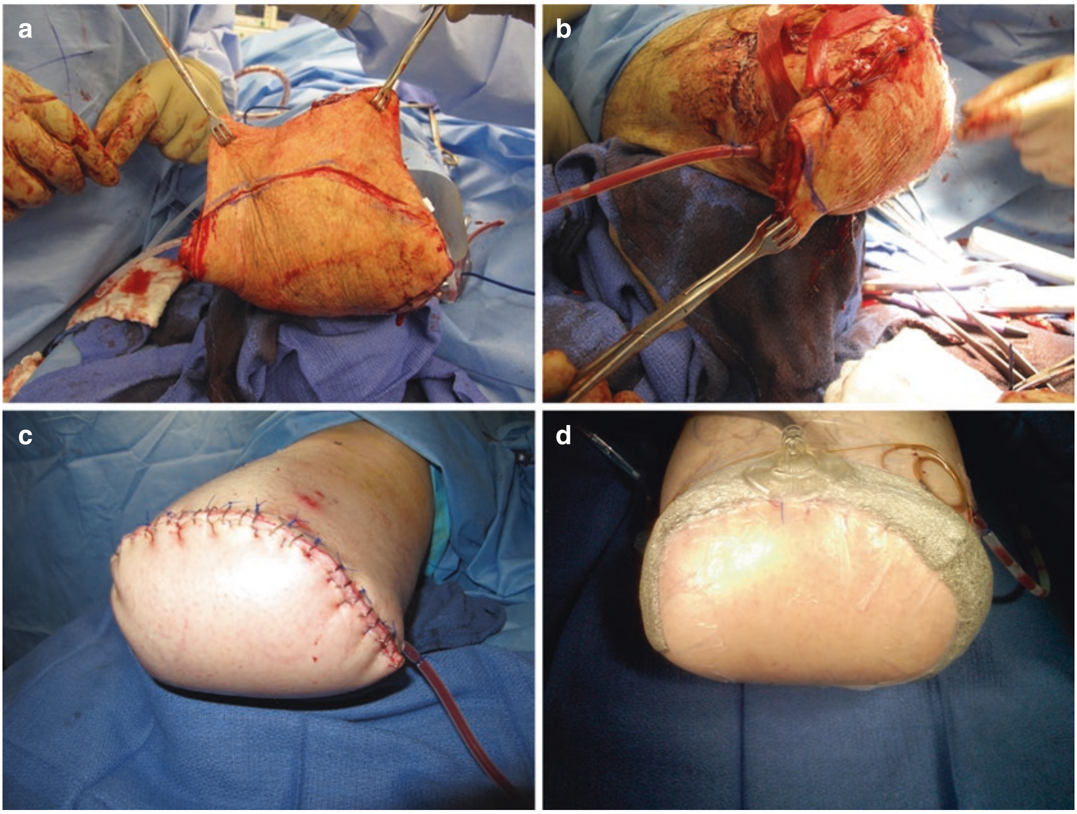


**Fig. 10.12** (**a**) The skin is cut at a level where the wound can be closed without tension. (**b**) Dog ears, if present at the medial and lateral edge of the closure, are removed. (**c**) The incision is closed with vertical mattress 2–0 monofilament and skin staples are used between each stitch to ensure good skin edge eversion. (**d**) The incision line can be covered with an incisional negative pressure device to immobilize the suture line for 7–14 days

allows the distal stump to be end bearing when not wearing a prosthesis.

The initial surgical technique and markings are identical up to the planning of the fibular osteotomy. The distance between the lateral tibia and medial fibula at the planned tibial cut is measured (usually 1.5–2.5 cm) (Fig. 10.13a). The first of two fibular osteotomies is marked at a point distal to the tibial osteotomy that is equal to the width between the medial cortex of the fibula and the lateral cortex of the tibia (Fig. 10.13b). The distal fibula is then cut at that level, and the distal peroneal artery and vein are tied off at the same level. After the distal fibular osteotomy, the distal leg is removed (Fig. 10.5a–c) in the fashion described above.

The proximal fibulectomy is performed after re-confirming the fibular bone graft length is equal to the inter-osseous distance. We recommend a lateral approach to the fibular osteotomy with care when approaching the medial fibular cortex so as not to damage the peroneal artery and the thin medial and posterior cuff of muscle (Fig. 10.13c). The fibular bone graft is rotated into the space between the tibia and fibula to make sure that it fits well in that space (Fig. 10.13d).

The lateral cortex of the tibia and medial cortex of the distal fibula (Fig. 10.14a) are then burred down to aid in bony fusion and stable contact. The vascularized fibular bone graft is then interposed between the distal fibula and tibia and fixated with #20 wires after holes are drilled into both sides of the anterior part of the fibular strut graft, the medial distal fibula and lateral distal tibia (Fig. 10.14b, c). We used to use a cannulated

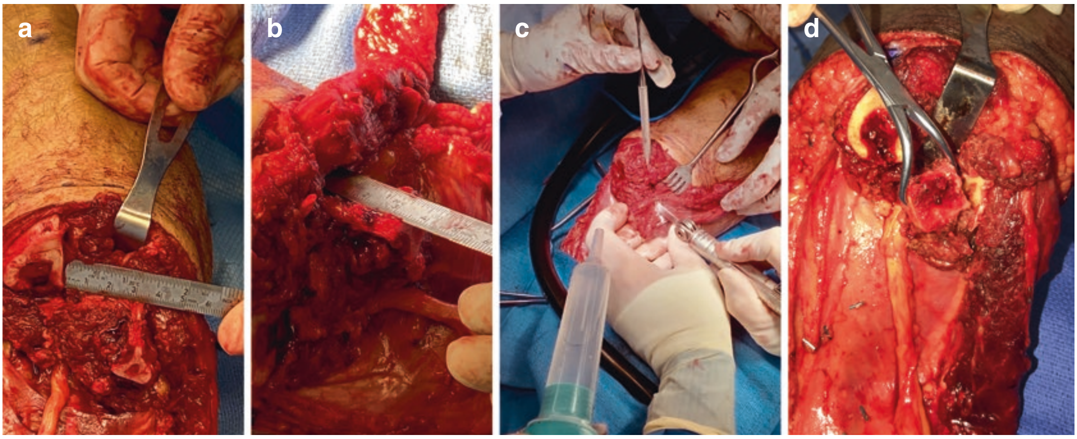

**Fig. 10.13** (**a**) The distance between the lateral tibia and medial fibula determines the length of the distal cut of the fibula. It is usually between 1.5 and 2.5 cm. (**b**) The more distal of two fibular osteotomies is marked at a point distal to the tibial osteotomy that is equal to the width between the medial cortex of the fibula and the lateral cortex of the tibia. (**c**) The proximal fibulectomy is performed after re-confirming the fibular bone graft length is equal to the inter-osseous distance via a lateral approach to the fibula. The medial fibular cortex is approached carefully so as not to damage the peroneal artery and vein and the thin medial and posterior cuff of muscle. (**d**) The fibular bone graft is rotated into the space between the tibia and fibula to make sure that it fits well in that space

screw that had to be later removed in over 50% of the patients because it worked its way out over the following 5 years. We have not had such problems using wire fixation. The result (Fig. 10.14d) should lead to an excellent fusion at 2–3 months of the fibular strut with the distal fibula and tibia (Fig. 10.14e). We therefore no longer recommend using a screw. The myodesis and closure are same as described above for the normal BKA.

### 10.4.3 Postoperative Care

Postoperative care is a critical component in major lower extremity amputations. Pain control immediately the following surgery typically involves patient-controlled analgesia (PCA) via 5 day epidural or regional blocks. While the regional block is the best option, it often cannot used if there is anticoagulation on board. Alternatively, intra-operative use of long-lasting local anesthesia (Exparel) is strongly recommended along the five identifiable nerves.

After lower extremity amputation, there is a significant disturbance in the patient's sense of balance as their center of gravity has been altered significantly. Nursing care and physical therapy play an important role in protecting the patient as they learn to transfer. Falls after amputation can be devastating and frequently lead to reoperation. Nearly one in five amputees will require amputation revisions due to postoperative falls. Thus, it is important to protect the residual limb. A knee immobilizer is placed immediately after each below knee amputation to both protect the distal stump and to prevent knee contracture until the patient is ready for a prosthesis,

Gentle compression in the immediate postoperative period aids with the swelling but should be balanced when there is a question of possible ischemia. Compression should be avoided in patients with severe peripheral vascular disease. One can apply an incisional negative pressure device to the incision to protect it for 5–7 days postoperatively. Alternatively, the dressing is removed on day two to evaluate for signs of hematoma and ischemia. Drains should be observed and output recorded. Once the amount is less than 30 ml daily, the drain may safely be removed. Surgical staples are removed the day of discharge (5 days), and the sutures are typically removed at 4 weeks in clinic (6 weeks with renal failure patients).

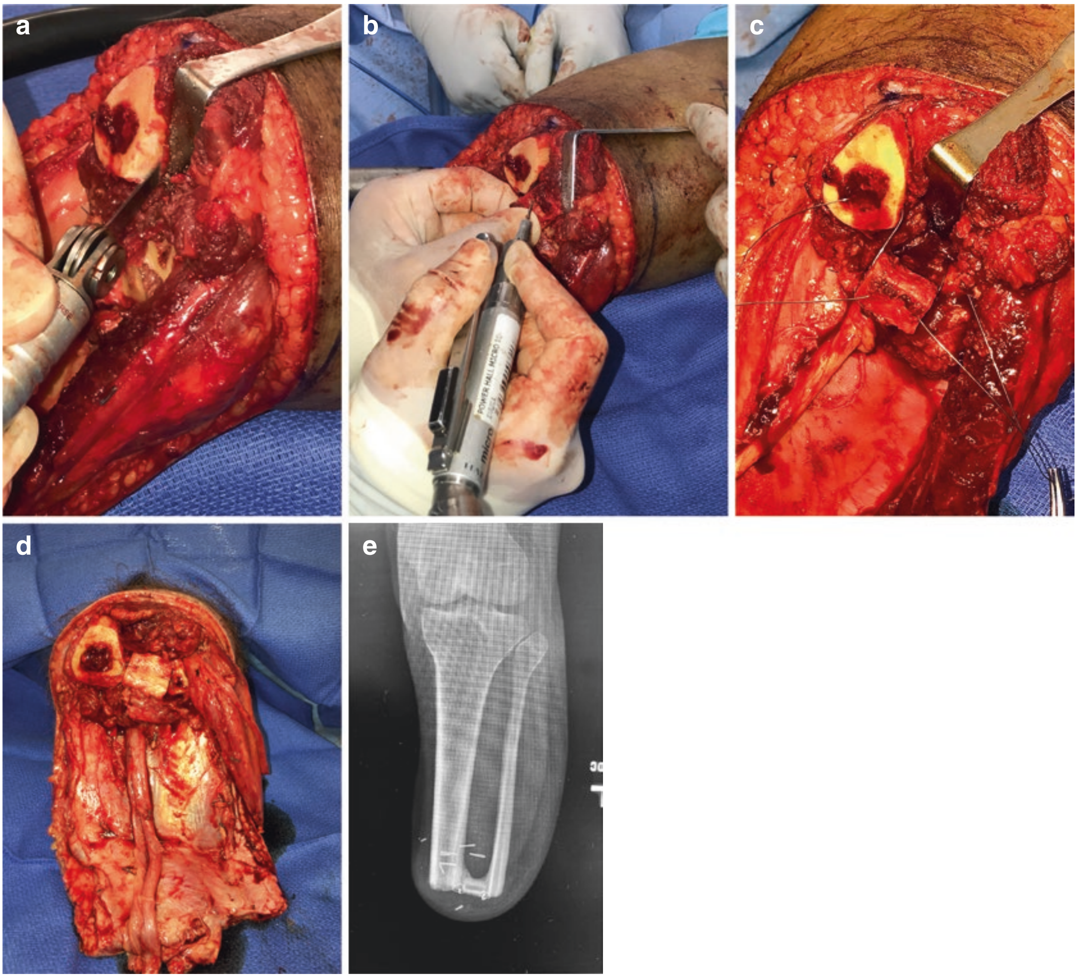


**Fig. 10.14** (**a**) The lateral side of the tibia and the medial side of the fibula are sanded down using the saw to ensure a better fusion of the pedicled fibular graft. (**b**, **c**) Holes are drilled into the lateral tibia and medial fibula and the lateral and medial anterior aspect of the pedicled fibular graft for passage of the wires that will fixate the fibular graft between the tibia and fibula. (**d**) The wires are twisted until the fibular graft is solidly fixated to the tibia and fibula. (**e**) An x-ray of the fixation that occurs at 2–4 months after surgery. The wire is then cut and buried

### 10.4.4 Rehabilitation

The rehabilitation process begins immediately in the hospital. We typically keep each patient 4–5 days for inpatient pain control and evaluation by physical therapy. Physical therapy assesses each patient's strength and ability to transfer safely. Physical therapy determines the amount of assistance needed and recommends acute, subacute, or home-based rehabilitation. Our strong preference is an acute rehabilitation facility and it is important to have a center that is familiar with and trained in caring for amputees. The medical complexity and need for frequent follow up underscore the importance of open communication and a multidisciplinary approach.

The prosthetist now becomes the most important component in caring for amputees after the incision has healed. Once the sutures have been removed, the fitting of the prosthesis may begin. Patients should be educated on the care of the residual limb, compression devices, and the progression from initial prosthetic fitting to final prosthesis. After removal of the stitches, we advocate for fitting and ambulation as soon as it is safe for the patient. This prevents further deconditioning and promotes their return to normal functional status. Rehabilitation is recommended immediately after receiving the prosthesis to aid in teaching how to best use the prosthesis and how preventing injuries from falls.

### 10.4.5 Follow-Up

Reoperation following amputation is unfortunate, but it is relatively common occurring in up to 30% of amputations. Trauma, dehiscence, infection, wound healing, and ischemia all contribute to high reoperation rates. Follow-up is recommended in the 2 and 4 week intervals. At 2 weeks, the residual limb can be examined for signs of infection, dehiscence, or progressive ischemia. The 4-week visit typically involves the removal of sutures and arrangement of prosthetic fitting. If the postoperative course is uneventful, we aim to have each patient ambulating at 6–12 weeks. We then follow up with the patient 3 weeks after he has started using his prosthesis and then every 6 months to reassess the amputation and examine the contralateral foot.

## 10.5 Conclusion

The important lesson is to keep function in mind when making the decision to salvage or amputate a limb. Assuming biomechanical principles are followed, forefoot amputation, including toes, can yield good function. With trans-metatarsal amputation, it is critical to address possible equino-varus deformities. Shorter foot amputations (Lisfranc, Chopart amputations) all require significant AFO (assistant foot orthotic) devices in order to ambulate. These amputations also have to be performed functionally to keep recidivism low. For the less active patients, these shorter foot amputations provide an excellent solution and allow the patients to perform daily acts of living and stay independent. For the active patients, reliance on AFO devices may be too restrictive to allow them to do everything that they may want to do.

If the resulting function of the salvaged foot does not or will not meet the patient's physical needs, then a major amputation should be performed. It has to be done with the same amount of care and attention to detail and function that would have been carried out for limb salvage because the surgeon is actually creating a new, albeit shorter, limb. Focusing on myodesis and tenodesis ensures that the residual muscles remain functional and that the residual limb does not loose mobility and strength. Attention to the distal nerves is critical to minimize postoperative pain and phantom pain. The closure should have a smooth tapered design so that the patient can start wearing prosthesis as soon as the stitches are removed and the prosthesis is ready. Our duty as reconstructive surgeons is to give the patient the best possible leg (reconstructed or amputated) to return to as active a lifestyle as he or she may desire.

## 10.6 Nerve Stabilization in Amputation Surgery

With respect to peripheral nerves, an amputation is a massive neural injury. A complete neurotmetic injury is induced to every nerve of the leg at the amputation level. Often times, these nerves are ignored and left to form neuromas at the level of the weight-bearing amputation stump. An amputation stump neuroma can be severely disabling even in a relatively small sensory nerve such as the saphenous or superficial peroneal nerves, leading to phantom pain and severe residual limb pain. Patients with amputation stump neuromas often complain of pain when wearing their prosthesis, and this can substantially degrade their functional ambulation. The importance of functional ambulation in amputees cannot be overstressed, since non-ambulatory amputees can quickly become deconditioned, and non-ambulatory status is associated with a significantly greater mortality risk [18, 19]. In many ways, the philosophical view of amputation as failed limb salvage perpetuates this failure further downstream, leading to failure to provide a functionally ambulatory stump. Amputation must instead be seen as a form of limb salvage, the goal of which is to provide the patient with a well-padded and pain-free stump-prosthetic interface to allow for functional ambulation.

## 10.7 Pathogenesis of Neuroma Formation

After a nerve transection injury, there is axonal sprouting from the proximal stump. This is initially a disorganized proliferation of axons until continuity is established across the neural gap. This axonal continuity induces a pruning process through which the extraneous axons are removed, and the continuous axons continue distal growth into the downstream neural architecture. If the proliferating axons cannot establish continuity across the neural gap, or if there is no downstream nerve, the disorganized axonal proliferation continues until it is encased in fibrotic tissue and forms a terminal neuroma [20]. This is the case in amputation neuromas, as there is no downstream neural target for axonal growth. When stimulated, neuromas lead to neuropathic pain in the affected neural distribution. In amputees, this is often described as burning, electrical, or shooting pain to specific territories of the phantom leg or foot. When these terminal neuromas form at the weight-bearing stump, they are stimulated by stump-prosthetic interactions from walking or standing.

## 10.8 Incidence and Distribution of Amputation Stump Neuromas

Five nerves are cut in a below knee amputation: the tibial, superficial peroneal, deep peroneal, saphenous, and sural nerves. In more proximal below knee amputations the medial and lateral sural communicating nerves may be running individually. Any of these nerves has the potential to form a terminal neuroma at the amputation stump. In our experience with secondary neuroma management, the superficial peroneal nerve accounts for symptomatic neuroma formation in 76% of patients presenting with secondary amputation stump neuromas, with the saphenous affected in 64% of patients. The tibial nerve, while infrequently involved in neuroma formation, was frequently implicated as a source of plantar phantom pain [21, 22]. Upon review of the original amputation of patients presenting with secondary stump neuromas, the offending nerve was not identified in the operative report in 74% of cases, and failure to recognize a nerve at the time of amputation was associated with a significantly higher risk of stump neuroma formation in that specific nerve [23]. Whichever neuroma prevention technique a surgeon chooses to apply, recognizing the nerves at the time of amputation is the most important step in preventing stump neuroma formation.

## 10.9 Methods for Management and Prevention of Neuromas

Multiple methods exist for management of existing neuromas, but the gold standard after diagnosis of a terminal neuroma is excision of the neuroma. However, after the neuroma is excised back to healthy nerve, the process of axonal sprouting, which initially caused the neuroma begins again. For this reason, neuroma excision is almost always combined with some form of neuroma prevention technique. The most commonly practiced of these techniques is implanting the nerve end into muscle. This was initially thought to lead to reinnervation of the motor endplates by the implanted nerve axons. However, it is now well understood that innervated muscle will not accept new innervation. The success of this technique is likely due to relocating the nerve into a well-cushioned space with an ideal microenvironment, where the resulting terminal neuroma is less likely to be symptomatic. While this technique often results in improvement in symptomatic neuroma pain, the results are rather modest with incomplete resolution of pain [24, 25]. Other methods for neuroma prevention include an implanted device to cap the nerve end, centrocentral coaptation, a dead-end nerve allograft, end-to-side nerve transfer, regenerative peripheral nerve interface, and targeted muscle reinnervation [26]. In centrocentral coaptation, the nerve is longitudinally neurolysed into two fascicular groups, which are then coapted end-to-end distally. Often a conduit or nerve graft is interposed between the coaptation. The goal of this procedure is to establish a nerve gap with axons on both sides, providing neurotrophic factors to guide axonal growth and induce [27]. This technique has been useful for pre-emptive management of the sciatic nerve at the time of amputation [28].

## 10.10 Regenerative Peripheral Nerve Interface

Regenerative peripheral nerve interface (RPNI) was initially described as a method for enhanced myoelectric prosthetic control. The technique involves wrapping a free muscle graft around the terminal end of the nerve, which heals as a graft [29]. The muscle is completely separated from its neurovascular supply to ensure total denervation and wrapped over the terminal nerve as a thin graft. This allows for signal amplification and superficialization, which can be transduced by an implanted or surface electrode for prosthetic control [30–33]. This technique has since been expanded to secondary management of terminal neuromas of the upper and lower extremity [34, 35], and for treatment of post-amputation pain [36, 37]. Recently RPNI has been advocated for prophylactic prevention of amputation stump neuromas at the time of primary amputation [38]. As a technique for nerve stabilization at the time of amputation, RPNI has several advantages. There is an abundance of muscle graft to be harvested from the discarded portion of the amputated limb, leaving no donor site morbidity to the patient. The technique is technically simple and does not require specialized equipment or magnification, and can be performed quickly and efficiently by any surgeon who can identify the terminal nerve ends. Additionally, RPNI provides superior fascicular coverage of the distal nerve end relative to any other technique, and is particularly helpful for management of large nerves, which would have an unacceptable size match for nerve transfer. There are disadvantages to this technique that must also be discussed. The muscle grafts used for RPNI are usually completely separated from their vascular supply, and must survive by imbibition until neovascularization occurs, either from the nerve end or the surrounding tissue. The method by which free muscle grafts survive and heal is not well understood, since muscle has a very low tolerance for ischemia due to its high metabolic activity. There are no other accepted indications for free muscle grafts.

## 10.11 Targeted Muscle Reinnervation

Targeted muscle reinnervation (TMR) is a nerve transfer of a proximal nerve into a distal motor target nerve. Similar to RPNI, this directs the regenerating proximal axons into denervated muscle, in this case through a nerve transfer rather than a muscle graft. TMR was initially described by Dumanian and Kuiken et al. for prosthetic control in proximal upper extremity amputees, redirecting the terminal branches of the brachial plexus into proximal muscle targets around the shoulder girdle. Once these muscles were reinnervated, they were mapped to a surface electrode array to allow for enhanced myoelectric control [39]. Serendipitously, these patients were found to have a substantial reduction in their phantom pain and residual limb pain. TMR has since been applied for management of post-amputation pain [20, 40]. After TMR was proven successful for management of secondary pain after amputation, Valerio and colleagues began to perform TMR nerve transfers at the time of primary amputation, showing superior outcomes in pain prevention [41].

### 10.11.1 Principles

Targeted muscle reinnervation is a nerve transfer, requiring a proximal nerve and a distal (target) nerve. Certain principles should be applied to targeted muscle reinnervation in amputees to optimize outcomes and minimize loss of function. These are similar to the standard principles of nerve and tendon transfers.

1. Expendable Motor Target.

   When selecting a motor target nerve for transfer, it is important that the nerve transfer not lead to loss of function. In a lower extremity amputee, there are many muscles to target since the foot and ankle have been removed. However, considering that the gastrocnemius and soleus muscles have now been repurposed for stump padding, surgeons should consider other motor targets whenever possible to minimize stump atrophy. When a muscle is innervated by more than one motor nerve, one of the redundant nerves may be selected as a target for transfer since native innervation is still preserved.
2. Anatomic Feasibility of Transfer.

   For the nerve transfer to be acceptable, the nerve ends much reach each other to allow for a tension-free coaptation. When possible, the motor target should be within the same muscle compartment as the proximal nerve. This not only allows for a tension-free transfer, but avoids crossing fascial planes, which may lead to entrapment. There are multiple expendable target nerves in each compartment to select.
3. Size Match.

   When possible, target nerves should be selected that are a similar caliber to the proximal nerve. However, this is often not possible, particularly for large nerves such as the tibial nerve. When such a size mismatch exists, the proximal nerve may be split into multiple fascicular groups which can each be independently transferred to different targets. Alternatively, the transfer can be performed to a single smaller nerve, centering the target as best as possible onto the proximal nerve stump, and anchoring the entire coaptation into the denervated muscle surrounding the neuromuscular junction of the target nerve. This creates a combined TMR/RPNI effect.
4. Nerve Transposition with Proximal Transfers.

   When possible, the ends of the proximal nerves should be transposed away from the weight-bearing stump. Target nerves can be identified more proximally, and the transfer can be performed at that level. This prevents the coaptation site from being stimulated during prosthetic ambulation.

### 10.11.2 Author's Technique

During the amputation, the nerve ends are identified and length is preserved (Fig. 10.15). We typically transfer the superficial peroneal (SPN) and tibial nerves, and occasionally the saphenous

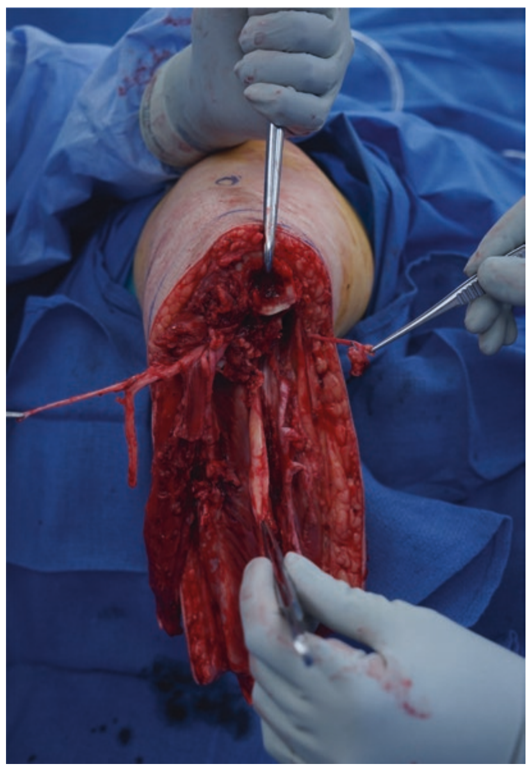

**Fig. 10.15** The tibial, saphenous, and superficial peroneal nerves preserved with length at the time of below knee amputation

nerve. The superficial peroneal nerve is identified most commonly in the anterior corner of the lateral compartment just posterior to the anterolateral septum. Occasionally the nerve may run in the lateral corner of the anterior compartment, and infrequently it is located within the anterolateral septum itself. There may be two branches of the superficial peroneal nerve, in which case each should be identified and preserved.

The knee is positioned flexed and the fibular head is palpated. A two-centimeter incision is made at an oblique angle, one centimeter inferior to the fibular head. The common peroneal nerve (CPN) is identified at this level beneath the crural fascia, as it courses beneath the posterior crural intermuscular septum (PCIS) that separates the lateral compartment from the superficial posterior compartment. The fascia over the lateral compartment is incised at its posterior aspect, and the peroneus longus muscle is retracted superficially away from the PCIS. This allows the surgeon to sharply release the PCIS over the CPN and under the peroneus longus. The nerve may be decompressed further distally, releasing the anterior crural intermuscular septum as well. At this point, an internal neurolysis is performed to separate the common peroneal nerve into its fascicular groups. A nerve stimulator is used to map the fascicular groups to the muscles in the anterior and lateral compartments. We advocate preservation of the tibialis anterior innervation, since this is the largest muscle in the anterolateral leg and is important for padding of the tibial bone stump. Our preferred target is the extensor digitorum longus or peroneus longus (Fig. 10.16). The SPN is then translocated from the distal wound into the proximal CPN incision by passing a clamp retrograde along the SPN, and pulling the nerve out proximally (Fig. 10.17). The SPN and the target nerve will usually match closely in caliber, and the coaptation is performed through the small proximal incision [42].

The tibial nerve is dissected retrograde from the distal amputation wound until a motor branch is identified from the nerve. At this level, any branch from the tibial nerve is a motor branch. We preferentially select target nerves for the deep posterior compartment, since these muscles are cut flush at the amputation level and are not used for stump padding. The tibialis posterior is the most commonly identified target at the amputation level. The motor target nerve is carefully neurolysed from the tibial nerve as far proximally as can be reached, then transected proxi-

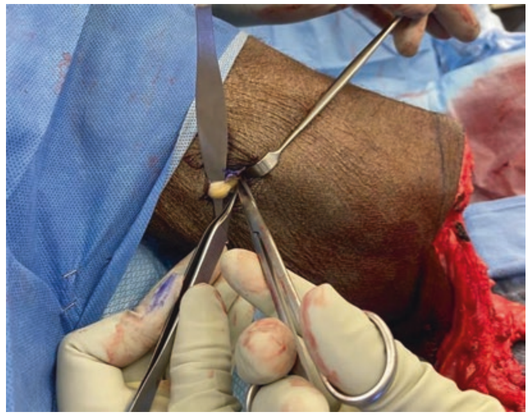

**Fig. 10.16** The common peroneal nerve is exposed and decompressed through a small oblique incision just below the fibular head

**Fig. 10.17** The superficial peroneal nerve is translocated into the proximal wound in preparation for transfer to the extensor digitorum longus motor nerve (looped)

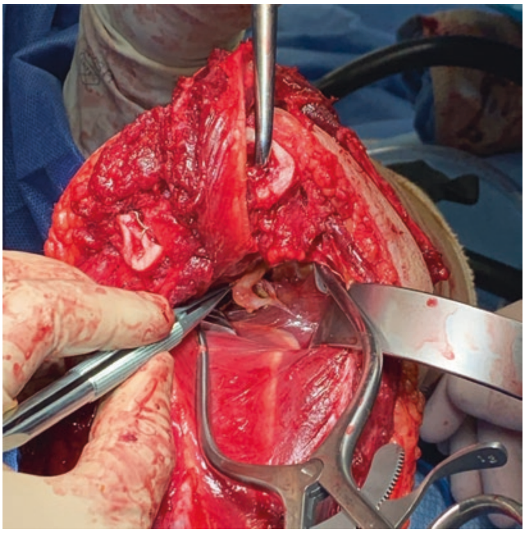

**Fig. 10.18** The tibial nerve is transferred to a deep flexor motor nerve (in this case FHL) through the distal wound, in the interval between the superficial and deep posterior compartments

mally and brought distally into the wound. The tibial nerve is then transected, and an antegrade end-to-end coaptation is performed, usually with significant size mismatch (Fig. 10.18). The coaptation is then anchored to the denervated muscle at the neuromuscular junction with suture or fibrin glue.

If a transfer is performed for the saphenous nerve, it is brought through the fascia to the medial gastrocnemius muscle. Intramuscular dissection is performed until a distal motor nerve branch is identified, usually within a small fat stripe. The target nerve is transected, and coaptation is performed at this level. More often, the saphenous nerve is managed with a crush-and-bury neurectomy, and a more proximal TMR transfer is performed if the patient develops saphenous nerve symptoms, which is rare in our experience. This transfer is performed at the level of the adductor canal to the sartorius or vastus medialis motor nerves.

### 10.11.3 Outcomes

The initial studies mentioned above were mostly conducted on healthy patients having amputations for traumatic or oncologic processes. However, the majority of patients who require amputations have progressive peripheral vascular disease or diabetic foot infections. After performing successful TMR procedures for secondary post-amputation neuroma pain, we designed and applied a TMR protocol for major amputees at our institution, and TMR transfers are now performed concurrently for every major amputation at our center. Compared to patients undergoing standard BKA, significantly fewer patients undergoing TMR reported phantom pain (17 vs. 52%) or residual limb pain (13 vs. 51%). Significantly fewer TMR patients required narcotics for pain control at 3-month follow-up (9 vs. 27%). Significantly more TMR patients were ambulatory with a prosthesis (92 vs. 71%) [43].

## 10.12 Conclusions

Post-amputation pain is often attributable to a failure to recognize and properly managed the nerves transected at the amputation level. Multiple options exist for the stabilization of these distal nerve ends. At our institution, we favor targeted muscle reinnervation nerve transfers at the time of the amputation, which allows for axonal redirection into denervated motor endplates, without leaving non-vascularized tissue in the amputation stumps of patients with peripheral vascular disease or diabetic foot infections. This technique is efficient and reproducible, and can be applied to patients with severe medical comorbidities. When performed at the time of amputation, TMR nerve transfer is effective at preventing phantom limb pain or stump neuroma formation in most patients.

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