Complication Management: Nonunions

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Alan Catanzariti and Kyle Moore

Introduction

The concern related to complications can consume a substantial amount of healthcare providers' time and thought. In surgical disciplines, seemingly minor complications can invoke major frustration and anxiety for both the practitioner and patient. At the core of the near-constant impetus to improve surgical technologies and techniques are the quality of patient care and the goal of reducing complications. The successful management of surgical complications requires a thorough understanding of the pathology in question and the aptitude to instill confidence in the patient regarding the practitioner's ability to deliver effective treatment. Surgeons can manage their fears of complications and begin to better understand the subtle nuances that are unique to successful complication management by developing a comprehensive knowledge base. Nonunion is a complex surgical complication that results in an absence of healing across two opposing bony surfaces. Various anatomic locations in the lower extremities have been identified as having relatively high propensities for nonunion. Nonunion of tibial shaft fractures can occur in 10–60% of cases [1–4]. Hindfoot and ankle arthrodeses are associated with a nonunion rate of approximately 10%, although rates ranging from 6–33% have also been reported for triple arthrodesis [5–8]. The first metatarsophalangeal joint (first MTP) and first tarsometatarsal joint (first TMT) arthrodeses have nonunion rates below 10% [9–14]. Surgical nonunion is not uncommon in the foot and ankle. Thus, surgeons should have a relatively high index of suspicion, particularly in situations in which there is a predisposition to nonunion.

This chapter will focus on the complex facets that are integral to nonunion management in the foot and ankle with a special emphasis on nonunion in elective surgical patients, i.e., those individuals who have undergone previous osteotomy and/or arthrodesis for the purpose of surgical reconstruction and have developed a nonunion. Despite the focus on nonunion in elective surgical patients, the general principles and management techniques discussed can also be applied to the treatment of nonunions with traumatic etiology.

Nonunion is a chronic condition that is capable of causing significant pain, deformity, and instability in lower extremities. Nonunion can arise when a bone sustains injury in the form of a fracture, osteotomy, or resection for joint arthrodesis. Osteotomies, arthrodesis procedures, and fractures are considered to have progressed to nonunion when the biologic mechanisms of bone healing cease to function appropriately [15]. A plethora of time lines and variability in the descriptions of nonunion exist, and surveys have revealed significant inconsistencies regarding the definition of the onset of nonunion [16]. Previous reports have described nonunion as a fracture that is unable to heal within 6–8 months of observation [17–19]. Currently, the Federal Drug Administration (FDA) characterizes nonunion as "established when a minimum of 9 months has elapsed since injury, and the fracture site shows no visibly progressive signs of healing for a minimum of 3 months" [15, 20]. For the purpose of this discussion, we describe nonunion as a multifactorial disease state that is rooted in the body's inability to heal two opposing bony surfaces. Ultimately, these cases necessitate interventions from external sources, either via surgical or nonsurgical means, to facilitate osseous union. Although a preset time frame of 9 months might be helpful in certain situations, we by no means feel that it is necessary to delay treatment until this time frame has passed.

In their 1976 report, Weber and Cech classified fracture nonunion by correlating radiographic findings with biologic healing efforts [21]. These authors subdivided nonunion types into hypertrophic, oligotrophic, and atrophic. Hypertrophic nonunions promote callus formation, maintain sufficient vascularity and biologic activity for healing, and normally only require improved stability to facilitate union.

A. Catanzariti (✉) • K. Moore
West Penn Hospital, The Foot and Ankle Institute, 4800 Friendship Avenue, North Tower, 1st Floor, Pittsburgh, PA 15524, USA
e-mail: acatanzariti@faiwp.com; kmoore6@wpahs.org

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Oligotrophic nonunions exhibit only a minute amount of callus radiographically, and although they do not completely lack biologic activity, they are much less active than desired. Finally, atrophic nonunions are considered to be nearly devoid of biologic activity and are deemed nonviable. This classification system is based on radiological appraisals and has limited value for prognosis and treatment due to the advent of advanced imaging.

Furthermore, it is not possible to discuss nonunion without also establishing a framework for defining delayed union. Unfortunately, the differentiation of delayed union and nonunion can be nebulous. For the purpose of this discussion, we define delayed union as a prolonged time to bone healing compared to the average, "normal" course. The same factors that predispose a patient to nonunion can certainly contribute to delayed union. However, the absence of biologic activity that is encountered in nonunion does not exist to the same degree in delayed union.

Basic Science of Bone Healing

The bony skeleton is the structural framework that serves as the attachment sites of the body's various ligaments, muscles, and tendons. This framework affords protection to some of the most vital organs in the human body and is a storehouse for physiologically crucial nutrient deposits [22]. The bone is one of the few tissues in the human body with full regenerative capacity that is also capable of healing without scar formation [22–24].

Despite its perceived rigidity, the bone has the ability to withstand substantial deformation under tensile, torsional, and compressive stresses. When external forces exceed a bone's capacity to deform, a fracture occurs. Purposeful "fractures" can occur in the forms of osteotomy or joint resection for arthrodesis, and surgeons can capitalize on the regenerative capacity of the bone to provide reconstructive correction.

Almost instantaneously after a traumatic insult occurs, the involved segments of the damaged bone undergo a reparative process via a highly regulated series of events [22–26]. The initial induction and inflammatory phases promote the recruitment of phagocytic cell lines, bone-forming pluripotent mesenchymal cells, and growth factors. The swelling that occurs around the site soon after injury facilitates physiologic splinting of the opposing surfaces. The adjacent bone margins then begin to unite by one of the two distinct healing models that are commonly referred as primary (direct) and secondary (indirect) healing.

The large majority of osseous injuries (which are frequently treated nonoperatively) undergo secondary healing. This healing is characterized by the presence of exuberant bony callus, initial widening of fracture gap due to resorption of the damaged ends, and an overall lack of stable fixation [22, 23, 27]. Within 2–3 weeks of the injury, the fracture site is partially stabilized and gradually bridged by soft, cartilaginous callus [23]. The newly formed collagenous substrate subsequently undergoes ossification that results in a stable bony segment.

In contrast, for the majority of elective surgical reconstructions that involve osteotomy or arthrodesis, primary osseous repair is typically the desired method of healing. This repair is characterized by an absence of callus around the site and a lack of widening of the fracture line. There are a few critical prerequisites to achieving this outcome that has been described by Danis as *soudure autogene* or the autologous weld [28]. First, close anatomic reduction of the adjoining segments and direct contact of the surfaces should be obtained. In regions in which direct bone-to-bone contact is not present, the gaps must be limited to approximately 1 mm of space between the segments [15, 29, 30]. Secondly, stable fixation that is capable of resisting deforming forces and facilitating adequate compression across the fracture site must be delivered. When these criteria are met, the opposing damaged surfaces are recanalized via new Haversian systems instead of being resorbed [31]. Cutting cones will facilitate the ingrowth of new vasculature and the delivery of bone-forming cells and thereby lead to the development of a functionally "bridged" bony segment. Following the union of the damaged segments, the newly formed bone will begin a remodeling phase according to Wolff's law [32].

Etiology of Nonunion

Successful bone healing requires the orchestration of numerous complex mechanisms and factors. At the most basic level, the bone must have adequate vascularity, have sufficient contact with the opposing surface, and be provided with stability around the surgical site to facilitate union. A patient can be predisposed to nonunion when a deviation exists at any level of the elaborate bone healing cascade or when the basic factors of vascularity, surface contact, and stability are lacking. To successfully manage nonunion, surgeons must determine the etiology behind the occurrence and then provide intervention directed at the areas of deficiency. Ultimately, therapeutic interventions for management of nonunion should be directed toward improving the mechanical and biological environment at the nonunion site.

The factors that contribute to nonunion can be subdivided into local factors and host factors (Table 3.1). Local factors can be considered to be any abnormalities that occur at the nonunion site and are frequently correlated with technical error. For example, excessive periosteal stripping or thermal necrosis at the surgical site during bony resection can lead to an avascular local environment, and there is an established

Table 3.1 Summary of factors associated with impaired bone healing

Local factors	Host factors
Infection	Tobacco use
Insufficient fixation	Vitamin D deficiency/ insufficiency
Poor reduction/gapping	Thyroid dysfunction
Malalignment	Parathyroid dysfunction
Poor site preparation/debridement	Diabetes mellitus
Thermal necrosis	Premature weight bearing
Soft tissue interposition	Malnutrition
Soft tissue/periosteal stripping	Arterial insufficiency
	Pharmaceuticals (NSAIDs, steroids)

relationship between local soft tissue injury and an increased incidence of nonunion [33–35]. Moreover, inadequate bone surface contact or malalignment can create gaps that cannot be bridged by normal physiologic processes. Malalignment can also generate abnormal stress across the arthrodesis or osteotomy site during the phases of healing. Poor surgical site preparation due to insufficient removal of the joint cartilage, inadequate penetration of the subchondral plate, or interposed soft tissues can serve as a direct barrier to bony bridging in arthrodesis procedures. Furthermore, inadequate or inappropriate fixation that fails to stabilize the arthrodesis or osteotomy site can lead to excessive surgical site motion. Although micromotion at the bone-to-bone interface has been shown to positively affect healing, gross instability due to insufficient fixation can be detrimental to achieving successful union [23, 36–40].

While not solely a technical error, surgical site infection can be a local factor that also contributes to nonunion. Infection of the local soft tissues can lead to necrosis and a dysvascular environment. Overt bacterial infection of the bone weakens its structural integrity and can cause failure of the fixation construct that leads to instability of the surgical site. Diseased fibrous tissue and interposed necrotic bone segments can be barriers to the ingrowth of healthy vascular channels and can inhibit the delivery of growth factors.

There are numerous preexisting medical conditions that are capable of contributing to the incidence of surgical nonunion. While not directly affecting the surgical site in the same manner as the previously described local factors, certain medical conditions can have adverse effects on the bone healing cascade. For the purpose of this discussion, the authors refer to these patient conditions as host factors. One host factor that is often cited as a cause of nonunion is tobacco use [15, 41–44]. Nicotine has been shown to uncouple the tightly regulated angiogenesis and osteogenesis pathways that are formed during normal bone healing [45]. Prolonged use of tobacco leads to a reduced oxygen-carrying capacity and results in generalized tissue hypoxia. The proliferation and activity of bone-forming osteoblasts are significantly diminished in subjects exposed to nicotine [46–48]. Moreover, the overall bone mineral density of smokers can be significantly less than that of individuals who do not use tobacco products, and this difference is further exacerbated in elderly and postmenopausal patients [49–52]. These combined effects lead to an increase risk of nonunion in smokers that has been reported to be 2–16-fold higher in hindfoot arthrodesis and to a significant increase in overall complications such as wound dehiscence and infection [43, 44, 52].

Endocrine and metabolic irregularities have also been shown to contribute to nonunion. Specifically, vitamin D deficiency, diabetes mellitus, parathyroid disease, thyroid dysfunction, hypogonadism, and malnutrition can have significant implications in the bone healing cascade [53–55]. One specific report of nonunion patients by Brinker and colleagues showed that 31 of 37 (84%) individuals who met their screening criteria suffered underlying metabolic or endocrine abnormalities [55].

The prolonged use of pharmaceuticals, such as nonsteroidal anti-inflammatory drugs (NSAIDs), chemotherapy agents, anticoagulants, antibiotics, and advanced biologic antirheumatic drugs, has been hypothesized to contribute to nonunion [24, 56–70]. Although no absolute agreement exists regarding the roles of medications in elective foot and ankle surgical nonunion, causal links between diminished bone healing and certain pharmacological regimens have been reported in both clinical and laboratory models [24, 56–70]. For example, Jeffcoach and colleagues found a significant increase in complications in patients receiving NSAIDs after suffering traumatic long bone fracture [63]. Various animal model studies have shown significant implications of NSAID use on bone healing due to abnormalities in prostaglandin production at the fracture site [24, 64–67]. The long-term use of corticosteroids can predispose patients to osteopenia by inhibiting osteoblastogenesis and has been cited as one of the most common causes of secondary osteoporosis [24, 61, 62]. The cytotoxic and antiproliferative properties of chemotherapeutic drugs have been shown to inhibit healing in arthrodesis subjects [59, 60]. Furthermore, antibiotics, specifically fluoroquinolones, have been alleged to adversely affect bone healing by altering endochondral ossification and inducing chondrocyte death [68–70].

Patient Evaluation

To formulate a comprehensive treatment plan for a nonunion patient, one must begin by obtaining a thorough history and physical examination. Details of the initial surgery, including time lines before and after the intervention, the pathology that leads to the original operation, previous treatments, and other complications throughout the treatment course, should be reviewed. A complete analysis of the patient's past medical and social histories is essential. Particular emphasis should be placed on comorbidities that are known to adversely affect bone healing, such as diabetes mellitus, peripheral vascular disease, vitamin D deficiency, thyroid dysfunction, malabsorption syndromes, autoimmune disease, and tobacco use. Pharmaceuticals linked to aberrations in bone metabolism, such as immunosuppressive agents, NSAIDs, and high-potency steroids, should also be noted.

A thorough appraisal of the previous clinical, surgical, and inpatient hospital records should be conducted prior to revision surgery. Obtaining a complete copy of the patient's external records is particularly important if complications, such as surgical site infections, wound healing issues, or venous thrombotic events, transpired during the postoperative course. Patients should understand the importance of such records and be encouraged to bring reports and film copies of diagnostic imaging when available.

Furthermore, in-depth understandings of the patient's current pain, disability status, and future treatment goals should be acquired. For example, a patient might seem to be a surgical candidate from an objective standpoint. However, certain medical or social issues might limit or preclude the option of additional surgery. A patient might be unable to proceed with further surgical intervention due to an inability to withdraw from social responsibilities or due to concurrent medical conditions. The provider might be relegated to employing nonoperative care in lieu of surgical therapy. These situations are best elucidated early in the planned treatment course.

Physical examination of the involved lower limb requires a comparison to the contralateral extremity. Disparities of temperature, edema, and erythema should be noted. Inspection of the soft tissue envelope for signs of open lesions, drainage, or skin atrophy should also be performed. Baseline neuromotor and vascular statuses as assessed by palpation of pulses, capillary refill times, and manual muscle testing should be examined and documented.

The suspected or confirmed nonunion site(s) should be palpated for tenderness, and manual stress should be applied to assess apparent gross instability. The ranges of motion of the contiguous joints of the nonunion should be evaluated for crepitation or limitation. Close attention should be given to the presence of tenderness, malalignment, diminished range of motion, and additional signs of degenerative changes at these neighboring joints. Such findings may be useful guides for future treatment. For example, when malalignment exists at a nonunion site, secondary angulation through compensation might occur at the adjacent joints. Such situations can arise when a severe varus deformity exists at a tibiotalar arthrodesis nonunion. Long-standing compensatory eversion at the subtalar joint (STJ) to achieve a plantigrade foot can result in arthrosis that might require realignment arthrodesis during the ankle revision. Revision of the tibiotalar arthrodesis without addressing the subsequent STJ deformity can create a continued source of pain even if ankle union is achieved.

Laboratory testing can be beneficial when evaluating and formulating a treatment plan for a nonunion patient. Updated chemistry and hematology (CMP, CBC) panels should be obtained and reviewed for all patients, especially when a surgical intervention is planned. When a patient's nutritional status is in question, evaluations of the albumin, prealbumin, total lymphocyte count, and transferrin levels can be useful to ascertain the healing potential [71, 72]. Furthermore, due to the roles that vitamin D and calcium abnormalities play in nonunion, blood levels should be obtained for the majority of patients undergoing treatment. Vitamin D levels below 20 ng/mL typically warrant repletion therapy in the majority of cases [73–75].

In situations in which an underlying infectious etiology of the nonunion is suspected, acute phase reactant testing, including erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) tests, can be helpful aids for diagnosis. Acute phase reactants have high sensitivity and specificity in the diagnosis of osteomyelitis [76, 77]. A 2013 report by Stucken et al. compared the utilities of ESR and CRP in the diagnosis of infection in nonunion patients. The authors determined that the combination of ESR and CRP is a significantly accurate predictor of infection in such cases [78]. If suspicions of infection are accompanied by increases in CRP and ESR values, a biopsy of the nonunion site for gram staining, culture and sensitivity, and histologic review should be performed.

Numerous imaging modalities are available to evaluate foot and ankle nonunion including radiographs, radionucleotide scans, linear and computerized tomography (CT scanning), and magnetic resonance imaging (MRI). Depending on the specific nature of a nonunion, one or a combination of these techniques can be employed for evaluation, treatment guidance, and progress monitoring.

Plain film radiographs have become a mainstay tool in the assessment of bone healing after fracture, osteotomy, and arthrodesis. Bone union or arthrodesis is traditionally deemed to have occurred when orthogonal X-rays show trabecular bridging across three of four cortices, and patient complaints of pain and swelling have begun to subside [79, 80] (Fig. 3.1). Standard radiographs have proven to be a particularly valuable tool in the assessment of nonunion. Findings on serial radiographs frequently serve as the first indication that union is delayed or has failed to occur following surgery.

Serial X-rays should be evaluated in a chronological manner. Multiplane projections consisting of the dorsoplantar (DP) and oblique (MO) foot and anteroposterior (AP) and mortise ankle and lateral foot and ankle should be assessed for healing, bone quality, and residual or recurrent deformity. Additional specialized alignment radiographs, such as Saltzman and Harris-Beath views, can be useful to better assess the relationship of the foot/ankle to the lower leg [81, 82] (Fig. 3.2). Disuse osteopenia, sclerosis, bone callus, and progression of radiolucent lines at the suspected nonunion site should be noted and quantified. The presence of hardware loosening, breakage, and/or migration is indicative of excessive surgical site motion and warrants further investigation. The concern about an infectious component should also be heightened when sinus tracks or radiograph signs of infection are present [83, 84].

Fig. 3.1 AP, oblique and lateral radiographs demonstrating bridging across 3 of 4 cortices

Despite the role of plain film X-rays, two-dimensional X-rays cannot adequately or thoroughly discern bony union in all cases. Visualizing trabeculation across an arthrodesis or osteotomy site can be difficult when internal fixation, a bone graft, or bone graft substitute has been utilized. Patients complaining of continued postoperative pain and swelling even after apparent radiographic union has occurred often warrant further investigation beyond standard X-rays. In such instances, three-dimensional imaging modalities, such as CT scanning, have proven to be exceedingly useful. Hindfoot joints exhibit a nonplanar orientation, and the significant superimposition that is present throughout the midfoot can make standard radiographs appear equivocal when evaluating nonunion. The nonplanar and compact natures of these joints can be better evaluated with helical CT scans than with standard films (Fig. 3.3). A 2006 report by Coughlin prospectively compared standard radiographs to CT scans in the evaluation of union in hindfoot arthrodesis. The study reported a significant difference in the reliabilities of the detection of true bone union between CT scans and radiographs [85]. The evaluation of CT scans allows radiologists and surgeons to quantify the percentage of fusion mass, which is difficult with plain radiographs in most instances (Fig. 3.4). It is recommended that a measurement of 50% or more bridging at an arthrodesis site be achieved before it is considered a successful union [86]. Furthermore, a thorough analysis of the adjacent joints can be performed when CT scanning is used for nonunion. When adjacent arthritis is present, the decision to incorporate these joints into the fusion mass during revision surgery might be considered.

If the viability, vascularity, or suspected infection of the nonunion site or adjacent bone is in question, MRI and bone scintigraphy scans have been demonstrated to be useful [87–90]. The sensitivity of MRI in the detection of avascular necrosis (AVN) in the foot and ankle is nearly 100% [87, 91].

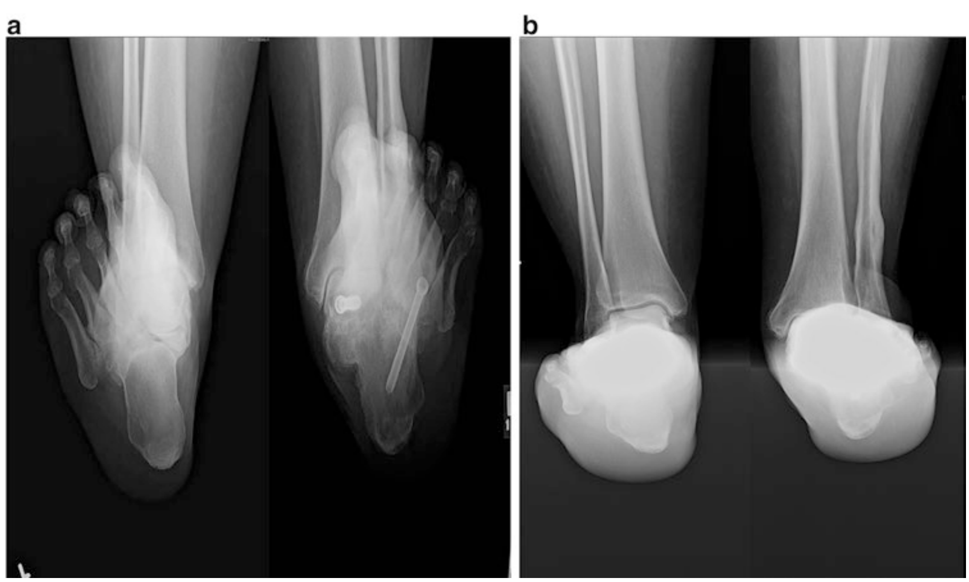


Fig. 3.2 (**a**) Bilateral calcaneal axial radiographs (**b**) Bilateral hindfoot alignment radiographs

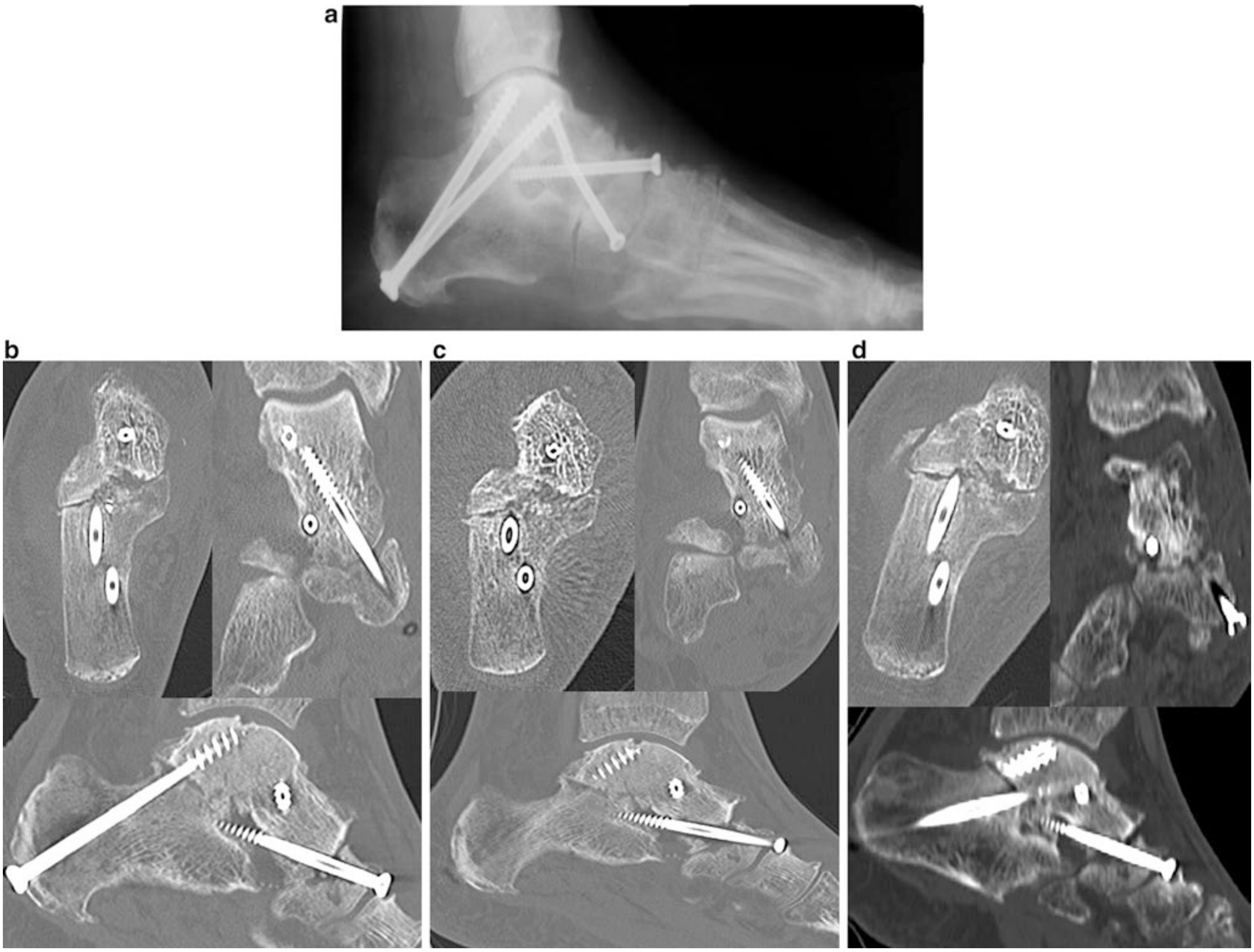


Fig. 3.3 (**a**) Lateral radiograph with fractured screw (inferior-medial to superior-lateral) across talonavicular joint 6-months following selected hindfoot arthrodesis for end-stage adult acquired flatfoot. This view fails to demonstrate evidence of joint consolidation. (**b**) 3-months status post axial and lateral CT scans showing absence of consolidation at both the talonavicular and subtalar joints. (**c**) 6-months status post CT scan with continued absence of consolidation. (**d**) 9-months status post CT scan clearly demonstrating nonunion following an extended course of immobilization, nonweightbearing and electrical stimulation

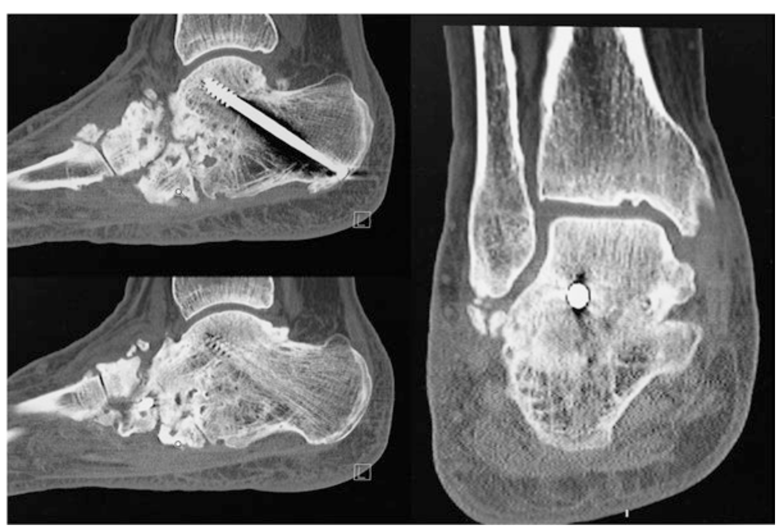


Fig. 3.4 CT scan demonstrating near complete consolidation after subtalar joint arthrodesis

Adjacent articular surfaces remote to the site of nonunion can also be thoroughly assessed for degenerative changes, which can help to guide future surgical planning. However, the use of MRI after surgical reconstruction can be problematic due to artifacts and scatter if ferromagnetic implants have been utilized. In such circumstances, nuclear bone scintigraphy scans (technicium-99m MDP) have been shown to adequately detect both unifocal and multifocal AVNs at acceptable rates and are not hindered by retained hardware. Furthermore, white blood cell-labeled nuclear scans (indium-111) can be utilized in conjunction with traditional scanning techniques to detect underlying infection at the nonunion site. Combining Tc-99m MDP and indium-111 scans increases the accuracy, specificity, and sensitivity of the diagnoses of concomitant bone infections in nonunion patients to greater than 90% [87, 92].

In patients for whom a suspicion of underlying osteopenia or osteoporosis is present, bone densitometry scanning can be a valuable tool. The healthcare community recommends bone density testing (via dual-energy X-ray absorptiometry (DEXA)) for postmenopausal women at the age of 65 and for male and female patients with risk factors such as tobacco use, alcoholism, chronic steroid use, and endocrine disorders that contribute to osteoporosis prior to age 65 [93–95]. When a bone mass deficiency is present in a nonunion patient, the patient might benefit from the utilization of additional orthobiologics or fixation methods, such as locked plating constructs and/or external fixation, which have proven successful in the osteoporotic/osteopenic bone.

Nonunion Management/Treatment Strategies

Treatment strategies should obviously be focused on healing the nonunion. However, nonunions in the foot and ankle are often associated with malunions and deformities. Additionally, the joints in close proximity might be stiff, malaligned, and painful due to compensation, particularly in cases of long-standing nonunions. Therefore, one should employ a global approach that accounts for the entire foot, ankle, and lower leg. The ultimate goal is a well-aligned, painless, and functional foot and ankle. Obtaining this goal can be challenging and is certainly not possible for every patient. Nonetheless, some degree of pain relief and improved function should be expected. The surgeon needs to develop a treatment plan and then determine a realistic prognosis, and the plan and prognosis should be thoroughly communicated to the patient. Patients should understand that the treatment process will be long and cumbersome and will often require multiple surgical sessions. While some nonunions heal rather easily, others require a long period of time to heal.

Patient goals typically include pain relief and normal function. The primary goals for the surgeon include union, normal architecture/alignment, resolution of symptoms, and functionality. The goals must be kept realistic and attainable. Obviously, these goals will vary based on the patient's unique situation and circumstances. Factors such as medical history, prior surgery, anatomic site, compliance, etc. will directly affect the patient's prognosis and should be the starting point of any discussion between the patient and surgeon. The surgeon should provide reasonable options and associated outcomes based on his/her experience and the current literature. Furthermore, the surgeon and patient should agree on the definition of an acceptable outcome. The patient's motivation, disability, social problems, litigation issues, mental status, and desires should be considered before a revision is undertaken.

Revision surgery to address nonunion often requires much thought, thorough planning, patient education, patient optimization, appropriate technology and resources, extended convalescence, advanced imaging, further surgery, and long-term follow-up. Patients should have clear understandings of their problems. Surgical consultation and informed consent should provide clarity and understanding regarding each patient's unique situation. This process might require several visits and various types of educational media for the patient to thoroughly comprehend his or her situation and develop realistic expectations. Such patients and their families should understand the uncertainties associated with nonunion healing, the extended course of treatment, and that multiple surgical interventions might be required.

Appropriate consultation with other services is important prior to surgery. Any issues that might adversely affect patient outcomes should be addressed by the appropriate specialist before surgical intervention.

If preoperative noninvasive lower limb arterial studies demonstrate poor perfusion, a vascular surgery consultation is recommended. These tests might indicate that the proposed surgery might not heal. A vascular intervention can be performed to increase arterial perfusion or might indicate that the patient is not a surgical candidate.

If incision placement is necessary in an area that is predisposed to dehiscence or if soft tissue deficits are anticipated following realignment, a plastic surgery consultation is recommended. A plastic surgeon might suggest an optimal site for incision placement or perform soft tissue reconstruction concomitantly during revision for the nonunion.

Unfortunately, patients with long-standing nonunions might be dependent on oral narcotics. Referral to pain management is helpful both during the course of treatment and ultimately for the detoxification and weaning of the patient off of all narcotic medications [96–98].

Obtaining a preoperative physical therapy consultation is particularly important in situations in which premature weight bearing was a contributing factor to nonunion. A physical therapist can provide gait training that accounts for the postoperative activity expectations and the use of assistive or adaptive devices. Furthermore, such training provides an opportunity for the patient to develop a relationship with a physical therapist who will work with him or her following surgery. Rehabilitation will be necessary following surgery for independent transfer and ambulation. Ultimately, physical therapy will be necessary to address the strengths and ranges of motion of the surrounding joints.

A nutritionist consultation should be considered for patients who are malnourished or obese. It has been clearly established that poor dietary intakes of proteins, particularly albumin, and vitamins can contribute to delayed union or nonunion. Furthermore, a nutritionist can help a severely obese patient reduce his or her weight. Obesity obviously makes the offloading of the surgical site technically very difficult [53, 99–101].

Endocrinology consultations are beneficial for patients with diabetes, particularly those patients with elevated HgA1c levels. Hoogwerf et al. have demonstrated a linear relationship between the incidence of complications and elevated HgA1c levels in patients with diabetes mellitus [102].

Therefore, tight glucose control should be a part of patient optimization when diabetes mellitus is present. Furthermore, in a 2007 report by Brinker et al., the investigators strongly recommended endocrinology referrals for patients with nonunion when technical errors have been excluded [55], i.e., the patient's failure to heal was not caused by underutilization of fixation, fixation failure, or infection. Endocrinology can isolate the metabolic deficiency that contributed to the nonunion and treat the abnormality to optimize the patient throughout their treatment course. These treatments can include the repletion of low vitamin D levels, thyroid hormone, and the optimization of blood glucose.

Depression is not uncommon in patients with chronic medical conditions; thus, patients with nonunions often exhibit signs of clinical depression. Referral to their primary care physician or psychiatrist might be beneficial [103–106].

Although the majority of revision procedures to address nonunion can be performed in one surgical setting, there are situations in which multiple surgeries are required. Factors that influence this decision include prior operative procedures, fixation that necessitates removal, the fixation that will be utilized for the revision, the necessity of harvesting an autogenous bone graft, and the times anticipated for the various parts of the surgery. It is important to anticipate technical difficulties and unforeseen challenges that might develop during surgery. Unfortunately, technical difficulties occur even under ideal circumstances and with the best of plans. Maintaining a surgical schedule that provides a margin to accommodate these unanticipated problems is recommended.

Procedures as simple as removing hardware can be rather difficult even when the appropriate instrumentation and image intensification are available. Such procedures can require a significant amount of time and effort that might be better utilized to address other, more important aspects of the procedure. Therefore, it might be better to stage the surgery so that the fixation can be removed during the initial surgical session and debridement, realignment, fixation, etc. can be performed in the next surgical session. Additionally, if intramedullary nails, large diameter screws, or other types of devices with large diameters are removed, the patient can be permitted a period of time to allow these bony deficits to fill in or consolidate. These processes can be expedited via the use of adjuvant nonsurgical therapies, such as pulsed electromagnetic field and ultrasonic therapies. The goal is to improve bone quality, which might enhance the effectiveness of the fixation that will be used in subsequent procedures.

In situations in which osteomyelitis is suspected, staged procedures are recommended. Although preoperative advanced imaging is helpful in the diagnosis of osteomyelitis, a definitive diagnosis can only be made with bone cultures and biopsy. Because infection will adversely affect bony union, it is imperative that the organisms are identified and appropriate antibiotics are administered if osteomyelitis is present. The primary surgical session can be used to obtain a bone biopsy and cultures to rule out or treat osteomyelitis. Additionally, hardware can also be removed during this initial surgical session.

Staging provides time for the patients to contemplate their upcoming procedures and develop a thorough understanding of their situation. Staging also provides an opportunity to address metabolic deficiencies or issues such as elevated HgA1c or hypovitaminosis D. Additionally, staging can provide time for a patient to implement smoking cessation program if necessary.

Lastly, the staging of procedures gives the surgeon an opportunity to ascertain the patient's ability to comply and to determine whether there are socioeconomic, psychological, family, or other factors that require attention.

Deformity Assessment

Deformity is invariably associated with nonunion in the foot and ankle. In addition to addressing nonunion, surgeries must also address any existing deformity (Fig. 3.5). Deformity, whether secondary to inadequate reduction during the index procedure or due to gradual development following a failed union, must be completely reduced. One of the major surgical goals is to obtain complete realignment. Any residual deformity will result in stress or an unevenly distributed axial load on the nonunion site and increase the risk of failure following revision. Residual deformities can further result in compensatory gaits that predispose surrounding joints to degenerative processes. Thus, deformity assessments must be thorough and comprehensive. Evaluations should include clinical examination, radiographs, and advanced imaging.

Clinical examination should include both static and dynamic assessments. Frontal, transverse, and sagittal plane deformities should be evaluated in both open and closed kinetic chains. Open kinetic chain evaluations of both the nonunion site and the surrounding joints are important.

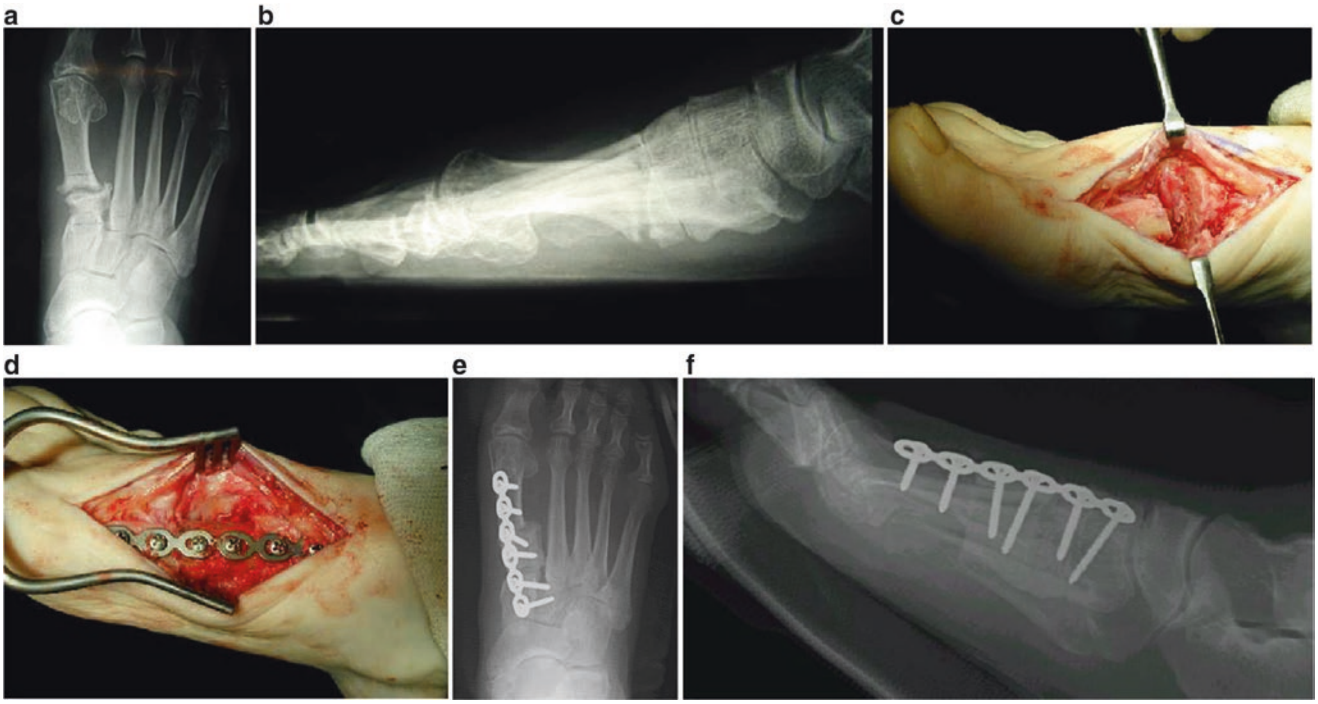
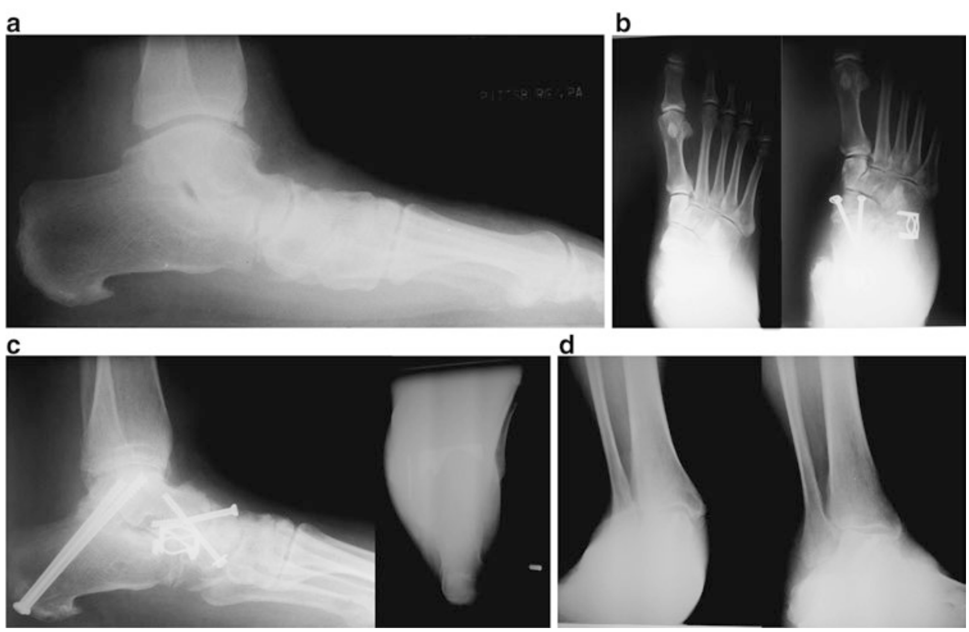


Fig. 3.5 (**a**) AP radiograph showing nonunion following a first metatarsal base osteotomy for hallux valgus reconstruction resulting in severe shortening. (**b**) Lateral radiograph demonstrating significant first ray elevation. (**c**) Skeletal deficit following resection of the nonunion. (**d**) Defect filled with a structural autogenous bone graft and secured with plate fixation. (**e**, **f**) AP and lateral radiographs demonstrating restoration of length and sagittal plane realignment

Fig. 3.6 (**a**) Lateral radiograph of late-stage adult-acquired flat foot with significant angular deformity. (**b**) Preoperative and postoperative radiograph following triple arthrodesis. Note the undercorrection of transverse plane deformity with inadequate talar head coverage by the navicular. (**c**) 6-months status post lateral and axial radiographs demonstrating nonunion. (**d**) AP radiograph of the ankle showing valgus deformity



Compensatory deformities can often develop in adjacent joints. A long-standing nonunion of the subtalar joint (STJ) following arthrodesis for stage III adult-acquired flatfoot with residual valgus deformity might develop ankle valgus (Fig. 3.6). Revision surgery of the STJ nonunion should also address the ankle valgus to obtain complete realignment. Furthermore, one must ascertain whether the ankle valgus is fixed or reducible. An attempt should be made to passively manipulate the deformity into realignment. This determination can be made during open kinetic chain assessment. Closed kinetic chain or weight-bearing assessment is also very important. The level of deformity and the areas of compensation can be determined. The patient should be able to place the foot and ankle into a corrected position during weight bearing. If this cannot be accomplished, then the deformity is fixed. If the patient cannot place the ankle joint into a position that parallels the subtalar deformity at the nonunion site, the joint deformity is fixed and requires correction. If the patient can achieve the corrected position, the joint deformity might resolve with realignment of the nonunion. Reducible valgus deformities of the ankle can be managed with joint-sparing procedures, such as deltoid ligament repair and periarticular osteotomies. However, a fixed deformity might require ankle arthrodesis or total ankle replacement to obtain complete realignment. Another example is the compensatory forefoot supinatus/varus that develops due to an ankle or hindfoot nonunion in valgus deformity. The supinatus/varus might require correction during surgical management of the nonunion. Such deformities will be exposed and magnified following ankle or hindfoot realignment. A fixed supinatus/varus requires surgery. However, a reducible deformity might resolve without intervention following ankle or hindfoot realignment [107].

Plain radiographs are an important part of deformity assessment because they can fully characterize all other deformities associated with the nonunion. Radiographs can be used to evaluate length, angulation, rotation, and translation. It is occasionally important to obtain weight-bearing radiographs of the contralateral extremity as well as the involved extremity. Stress radiology can be helpful in the evaluation of the competence of the collateral ligaments of the ankle.

Shortening is not uncommon with nonunion. One must ascertain the degree of shortening that is acceptable from a functional standpoint. It is important to anticipate the quantity of bony resection that will be necessary to develop a healthy cancellous substrate at the nonunion site. This quantity will have implications in terms of the type and size of bone graft that will be required. Furthermore, this quantity will also influence the type of fixation that is necessary and whether adjacent joints will need to be included in the arthrodesis.

Angular deformities, particularly in the frontal and sagittal planes, can be thoroughly reviewed with plain radiographs. Nonunion following STJ or ankle joint arthrodesis can often be associated with a severe frontal plane deformity. Plain radiographs will demonstrate the extent of the deformity so that plans can be made for realignment during revision surgery of the nonunion. Templates can be helpful when planning realignments for frontal plane deformities. One can determine whether complete realignment is possible based on the extent of the deformity. There are situations in which a complete reduction of a severe deformity can place a compromised soft tissue envelope at risk for wound problems. In such situations, one must accept incomplete realignment or consider shortening the bony segment. Otherwise, one should prepare for possible soft tissue reconstruction.

Nonunions following arthrodeses of the tarsometatarsal, midfoot, and midtarsal articulations are often associated with sagittal plane deformities. Axial loads will invariably result in dorsiflexion deformities. Plain radiographs will demonstrate the degree of deformity so that the surgeon can plan accordingly.

Therefore, plain radiographs are very important for planning deformity corrections during revision nonunion surgeries. These evaluations should be comprehensive, and all appropriate views should be obtained. Radiographs should be obtained with the patient in a full weight-bearing position and should be performed bilaterally, particularly when significant deformities involving the hindfoot and ankle are present.

Although advanced imaging can be quite helpful in the evaluation of nonunion, such imaging has limited utility in terms of deformity assessment. CT scans can be helpful in evaluations of transverse plane deformities, particularly rotational and translational problems. These deformities can be clinically and radiographically difficult to evaluate. A CT scan can provide information regarding the magnitude and direction of the deformity, particularly in cases involving the STJ and ankle joints.

Principles and Techniques for Revision Surgeries of Nonunions

Full-thickness incisions down to the bone should be utilized in virtually all cases. Undermining should be avoided or kept to a minimum to facilitate retraction. The goal is to avoid disrupting the blood supply at the incision site. However, one must be cognizant of the vital structures located in a particular area, particularly nerves and tendons, to avoid damaging them. In situations involving severe deformities that require significant realignment, incisions should be placed opposite the tension side of the soft tissue envelope. Such location might be in areas that are remote from the original incision, which is certainly acceptable. Otherwise, placing an incision on the tension side of the soft tissue envelope can result in wound problems.

Thorough dissection and evacuation of scar tissue is important because it will permit direct access to the nonunion site, which is essential for adequate debridement and joint preparation. Additionally, the removal of scar tissue that contributes to joint contracture allows for manipulation so that alignment can be restored.

The nonunion must be identified and thoroughly evacuated. All devitalized and necrotic tissue should be completely removed. Joint access is very important, and having appropriate instrumentation to facilitate access is helpful. Various types of distracters are available to provide and maintain access to the nonunion site. Following debridement, the host tissue can be prepared with a combination of fenestration and fish scaling. Depending on the specific anatomic site, sharp drill bits should be advanced under constant irrigation into the deep subchondral tissues to create vascular channels. The goal is for blood to enter the nonunion site and deliver cells, bone marrow, growth factors, etc. Following fenestration, the host tissue should be further developed into a healthy cancellous substrate via the use of small, sharp osteotomes. This procedure should be performed aggressively, but care should be taken to preserve the cortical and subchondral bone at the perimeter of the nonunion site so that the structural integrity is maintained. This structural integrity of perimeter bone will be important to facilitate realignment and support a stiff fixation construct. Although many such cases will involve bone grafts or bone graft substitutes, bone grafts cannot manifest biologic activity without an adequate blood supply. Therefore, meticulous attention to preparation of host tissues is important for enhancing union.

The primary goal of fixation is to provide a stable construct that eliminates motion. Motion during healing impedes the consolidation of bony surfaces and the incorporation of bone grafts. Although a firm surgical plan is required in these cases, one must respond to intraoperative findings and developments that require alternative forms of fixation. The surgeon should plan for "alternative" forms of fixation and have these devices readily available. As these revision nonunion cases evolve, adaptability is critically important to achieving the primary goal of stability.

The choice of fixation is often affected by factors such as osteopenia, the location of the nonunion, proximity to surrounding joints, previous fixation, patient compliance, the amount of bone loss following debridement, the patient's ability to tolerate non-weight bearing, the surgeon's technical acumen with specific techniques and devices, and industry/technical support. Situations involving severe osteopenia or bone loss might require super constructs or the sacrifice of nearby joints (Fig. 3.7).

Recent advances in technology have provided many excellent options for fixation. Screws should purchase cortices or compact subchondral bone whenever possible. Locking plate technology is an excellent option for patients with osteopenia or poor quality bone (Fig. 3.8). Alternatively, supplemental external fixators that neutralize the nonunion site are a reasonable option in this same patient population (Fig. 3.9).

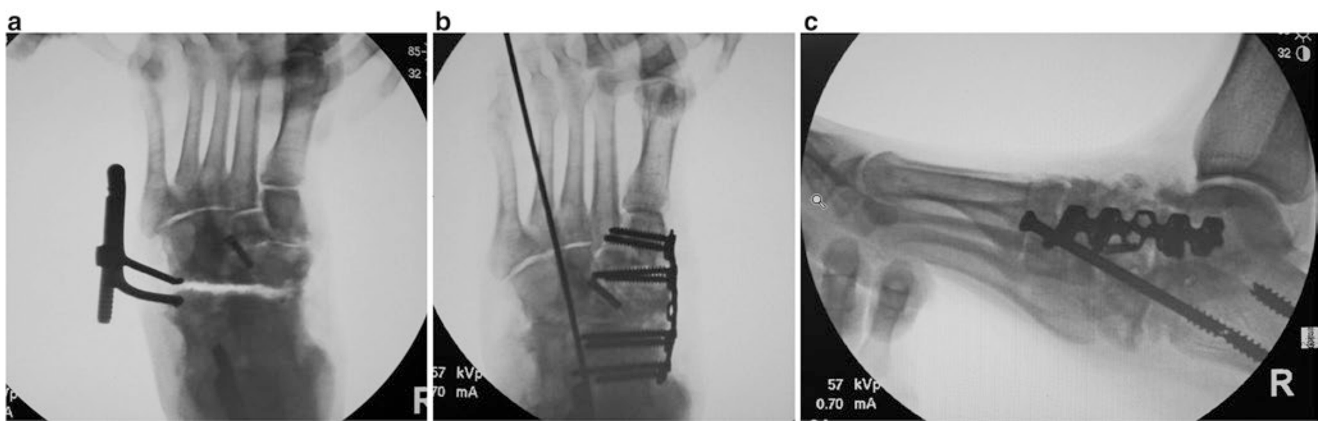


Fig. 3.7 (**a**) Intraoperative AP image following debridement of midtarsal nonunion. (**b**, **c**) Revision of nonunion showing super-construct fixation with a locking plate that extends distally to include the medial cuneiform

Fig. 3.8 (**a**, **b**) Nonunion following naviculocuneiform arthrodesis. (**c**, **d**) Revision with locking plate that extends distally to the 1st tarsometatarsal articulation which was included in the fusion mass

Fig. 3.9 (**a**) AP and lateral radiograph demonstrating severe ankle and subtalar arthritis (**b**–**e**) Plain film radiographs and serial CT scans demonstrating no consolidation across arthrodesis sites (**f**, **g**) Revision tibiotalocalcaneal arthrodesis with intramedullary nail, external fixation and implantable bone growth stimulator (**h**) AP and lateral radiograph demonstrating consolidation of revision tibiotalocalcaneal arthrodesis

Surgical Revision Techniques: Specific Anatomic Sites

First Metatarsophalangeal (MTP) Joint

The incidence of nonunion following the first MTP arthrodesis is relatively low. The incidences are higher in patients with hallux rigidus who develop subsequent end-stage arthrosis and patients with posttraumatic arthritis than in patients with diagnoses of hallux valgus. End-stage arthrosis, whether secondary to hallux rigidus or posttraumatic arthritis, is often associated with a thicker subchondral plate that can be sclerotic and avascular. These patients have a higher predisposition to nonunion than patients with hallux valgus. Therefore, joint preparation must be thorough and adequate such that the subchondral plates are penetrated and methodically broken to enhance blood flow. Some of the reaming systems used for joint debridement might be inadequate in these cases or should be supplemented with drilling techniques and fish scaling rather than used alone.

Patients who have undergone a distal first metatarsal osteotomy for hallux rigidus are also at risk for avascular necrosis (AVN). Advanced imaging to evaluate or rule out AVN can be helpful in this group of patients. One can then plan for appropriate debridement techniques and the use of bone grafts or orthobiologics to augment arthrodesis.

Positioning the hallux in plantar flexion will result in a significant axial load during the propulsive phase of the gait. These patients can develop nonunion, particularly if they begin weight bearing prior to the complete consolidation of the arthrodesis site. One of the reasons that the first MTP arthrodesis has such a low incidence of nonunion is that the hallux is typically positioned in dorsiflexion which offloads the arthrodesis site during weight bearing.

Revision surgery should be based on the reasons for nonunion. Regardless of the factors involved, revision should include thorough debridement and joint preparation, autogenous cancellous bone and/or orthobiologics, appropriate positioning, and a stable fixation construct. A structural bone graft is rarely necessary, and some shortening is certainly acceptable in this situation. The calcaneus or distal tibial metaphysis provides regional sources of autogenous cancellous bone. The authors typically use 6-mm or 8-mm trephines in a percutaneous manner to harvest the bone for first MTP nonunion revisions. Fixation constructs should extend to cortical bone remote from the arthrodesis site via either long screws or a long plate (Fig. 3.10). Although the authors typically permit immediate weight bearing following first MTP arthrodesis, a 6-week period of non-weight bearing is recommended following revision for nonunion.

Tarsometatarsal (TMT) Joint(s)

The first TMT arthrodesis (the modified Lapidus procedure) is a common procedure for hallux valgus reconstruction. Additionally, this joint is often included when global TMT arthrodesis is performed for posttraumatic arthritis and deformity. Nonunions of the TMT joints and all of the midfoot articulations are vertically oriented nonunions that have some shear component in which the osseous segments slide past each other when subjected to axial load. Nonunion of the first TMT joint is often associated with first ray elevation secondary to axial loading. Additionally, shortening is not uncommon with this particular nonunion, particularly in long-standing cases (Fig. 3.11). Therefore, revision goals should include union, sagittal plane realignment, and restoration of length. A structural bone graft might be necessary when shortening is significant (Figs. 3.12 and 3.13). However, the majority of these cases do not require a structural bone graft, particularly when sagittal and transverse realignments are easily achieved. Debridement of nonviable bone and scar tissue, the development of a healthy host environment, autogenous cancellous bone grafts, the use of orthobiologics, and stable fixation are often sufficient to address nonunion of the first TMT joint. Locking plate technology lends itself well to this situation.

Arthrodesis of the lesser TMT joints (second and third) might be required for posttraumatic arthritis or deformity involving the TMT complex. Nonunion of the lesser TMT joints might develop following global arthrodesis (joints 1–3). Fortunately, nonunion following lesser TMT arthrodesis is rarely associated with malalignment. Revision typically requires thorough debridement, host preparation, bone grafting/orthobiologics, and stable fixation.

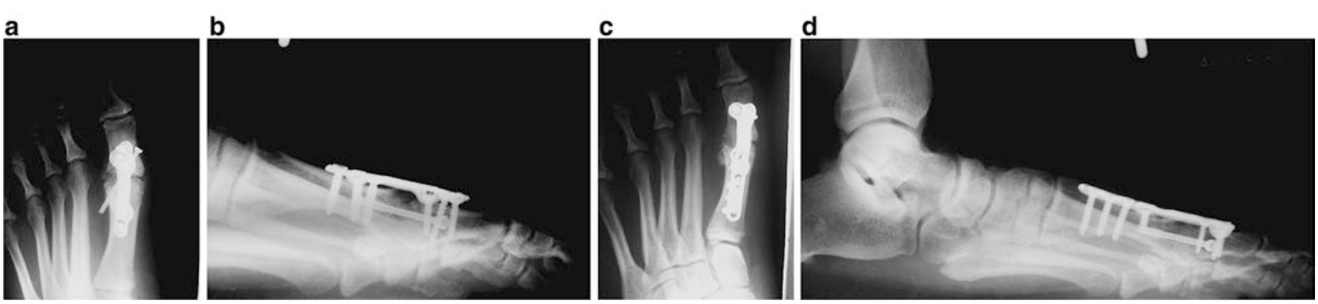


Fig. 3.10 (**a**, **b**) Nonunion status post 1st MPJ arthrodesis (**c**, **d**) Revision with a long locking plate that extends far beyond the arthrodesis site. The goals are to engage quality cortical bone and disperse axial loading over a relatively large implant

Tritarsal Complex

Nonunion is not uncommon following isolated, selected, or triple arthrodeses. Revision surgery should address not only the nonunion but also other associated problems.

Fig. 3.11 (**a**) First ray shortening and elevation following 1st tarsometatarsal arthrodesis. (**b**) Revision with autogenous structural bone graft and plate. Note restoration of length and sagittal plane alignment

These might include undercorrection, malunion, ankle valgus or varus with associated collateral ligament attenuation, medical column instability not recognized during the initial surgery, soft tissue contractures that were not adequately released during the initial surgery, and unrecognized suprastructural issues. The goals of revision surgery are union, restoration of a plantigrade foot, and the preservation of function. Preoperative considerations should include specialized radiographs to evaluate alignment, appropriate advanced imaging, and patient optimization. Intraoperative goals include the development of a healthy cancellous substrate at the nonunion site and realignment. Specialized technology, appropriate instrumentation, bone grafts, orthobiologics, and image intensification help to accomplish these goals. In addition to revision of the nonunion, procedures should include osteotomies, the release of soft tissue contractures, superconstructs, and extended arthrodesis to include other joints whenever necessary.

Nonunion following isolated arthrodesis of the STJ can be surgically managed with isolated revision of the STJ or conversion into a triple arthrodesis. The highest incidence of nonunion following STJ arthrodesis occurs in patients with posttraumatic arthritis following calcaneal fractures. The authors prefer isolated revision of the STJ nonunion in the absence of malalignment and when degenerative changes are absent from the talonavicular (TNJ) and calcaneocuboid (CCJ) joints. This judgment is often based on

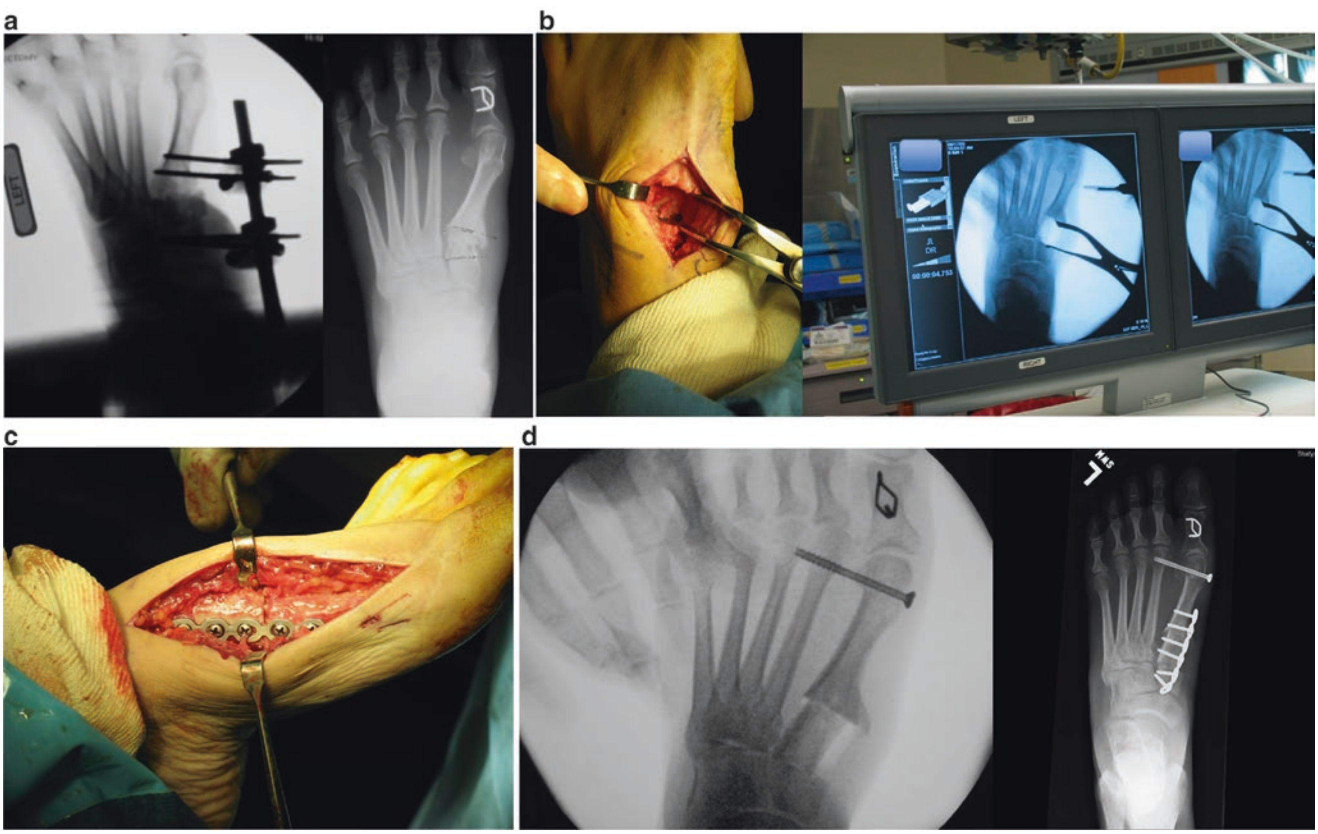


Fig. 3.12 (**a**) Status post 1st tarsometatarsal nonunion with significant shortening. (**b**) Skeletal defect following debridement. (**c**) Structural autogenous bone graft with plate fixation. (**d**) Restoration of length and alignment

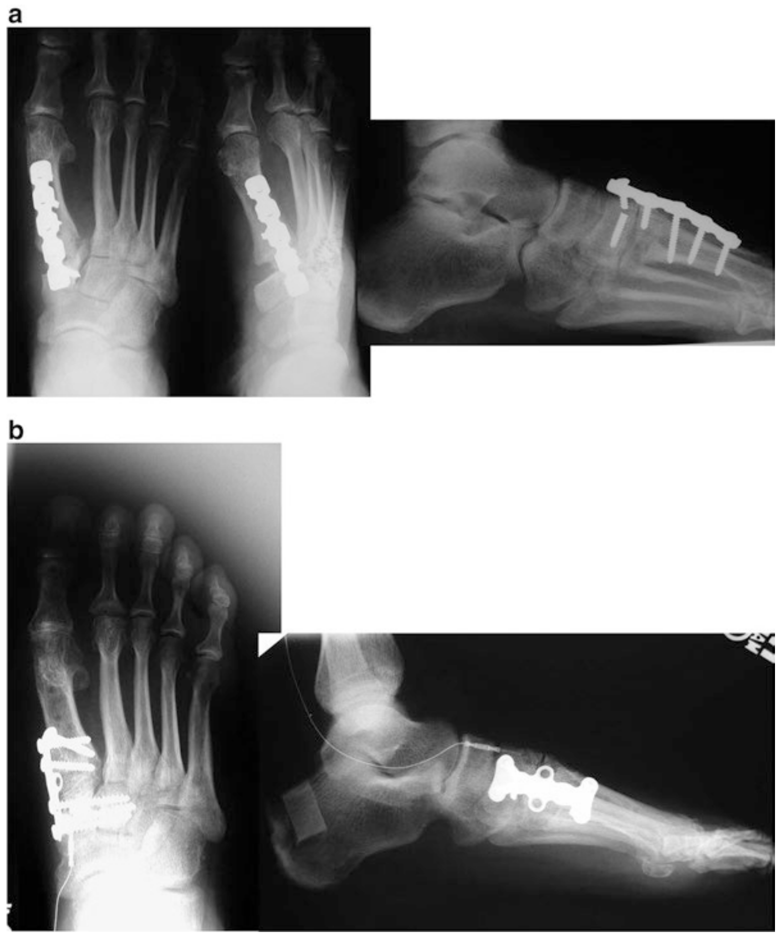


Fig. 3.13 (**a**) Nonunion following 1st tarsometatarsal joint arthrodesis (**b**) Revision 1st TMT arthrodesis with structural graft, locking plate, implantable bone growth stimulator

clinical assessment and preoperative imaging. The fixation construct typically includes large diameter compression screws (Fig. 3.14). The authors prefer multiple screws that engage the cortices or subchondral areas. However, when malalignment is present or there are factors that will adversely affect the fixation construct, we prefer to convert the STJ nonunion into a triple arthrodesis (Fig. 3.15). This procedure enhances the stiffness of the entire tritarsal complex following fixation and provides multiple options for fixation.

The rate of nonunion following TNJ arthrodesis has been reported to be relatively high [108, 109]. Isolated revision is difficult even when the alignment is good. The authors invariably convert nonunions of the TNJ into triple arthrodeses (Fig. 3.16). CCJ arthrodesis enhances the compression of the TNJ and allows easier realignment when deformity is present. Additionally, incorporation of the STJ into the fusion mass adds further stiffness to the entire construct. Complete elimination of all tritarsal motion will enhance the possibility of union during revision TNJ surgery. Our fixation construct of the talonavicular joint typically includes lateral compression screws and a medial locking plate. However, we have also used multiple compression screws that are strategically placed to deliver even compression throughout the arthrodesis site (Fig. 3.18d and e).

Selected arthrodesis for stage III or IV adult-acquired flatfoot has become a common procedure. Although the incidence of nonunion has not been reported, the authors have observed a higher rate relative to triple arthrodesis, particularly at the TN joint [110]. Our preference is to convert nonunions of either the STJ or TNJ into triple arthrodeses (Fig. 3.17).

Nonunion of any or all of the tritarsal joints is possible following triple arthrodesis (Fig. 3.18). The principles of addressing nonunion remain the same. Debridement, joint preparation, realignment, bone graft/orthobiologics, and enhanced fixation are required. A static neutralization external fixator is occasionally used to augment the internal fixation construct if osteopenia is severe or there are concerns about premature weight bearing.

Ankle Joint

Nonunion following ankle arthrodesis is most common in patients who have developed posttraumatic arthritis following pilon and Weber C fractures [111]. Ankle nonunions involve large, transversely oriented adjacent surfaces with

Fig. 3.14 (**a**) Nonunion status post isolated subtalar joint arthrodesis. (**b**) Intraoperative image-intensification confirming nonunion location. Distraction provides access to allow adequate debridement and preparation. (**c**) Fixation construct using compression screws engaging cortical and compact subchondral bone to enhance screw purchase and construct stiffness. Note electrical bone growth stimulator

good bony apposition that are generally stable to axial compression and should proceed to union. The revision of ankle joint nonunion depends on the original surgical approach and fixation. The majority of surgical approaches are either anterior or lateral, and we recommend using the same approach for revision. However, in cases in which a poor soft tissue envelope places the patient at risk for wound problems, an alternative approach should be considered (Fig. 3.19). A posterior approach is a reasonable alternative in these situations.

Debridement of ankle nonunion resulting in substantial bone loss can be difficult to manage. One must determine if

Fig. 3.15 (**a**) Nonunion following subtalar joint arthrodesis. (**b**) Intraoperative identification of nonunion. (**c**) Conversion into triple arthrodesis

Fig. 3.16 (**a**) Nonunion following talonavicular arthrodesis. (**b**) Intraoperative identification of nonunion and conversion into a triple arthrodesis. Fixation accomplished with a combination of screws and locking plates. (**c**) Intraoperative images of final construct. (**d**) 3-months status post surgery

Fig. 3.17 (**a**, **b**) Status post selected hindfoot arthrodesis for end-stage adult acquired flatfoot. Implants traversing the talonavicular joint are short and located along the medial aspect of the joint with virtually no lateral compression. (**c**) CT scan confirms absence of consolidation at the talonavicular joint. (**d**) Conversion into triple arthrodesis. Fixation with screws and locking plates

there will be adequate bone to support an isolated revision of the ankle nonunion following debridement. Obtaining a solid fixation construct without sacrificing the STJ can be challenging with extensive bony debridement, particularly during a second or third revision. Alternatives include tibiotalocalcaneal or tibiocalcaneal arthrodeses (Fig. 3.20).

Although some shortening can be tolerated, excessive shortening can result in significant gait disturbances and

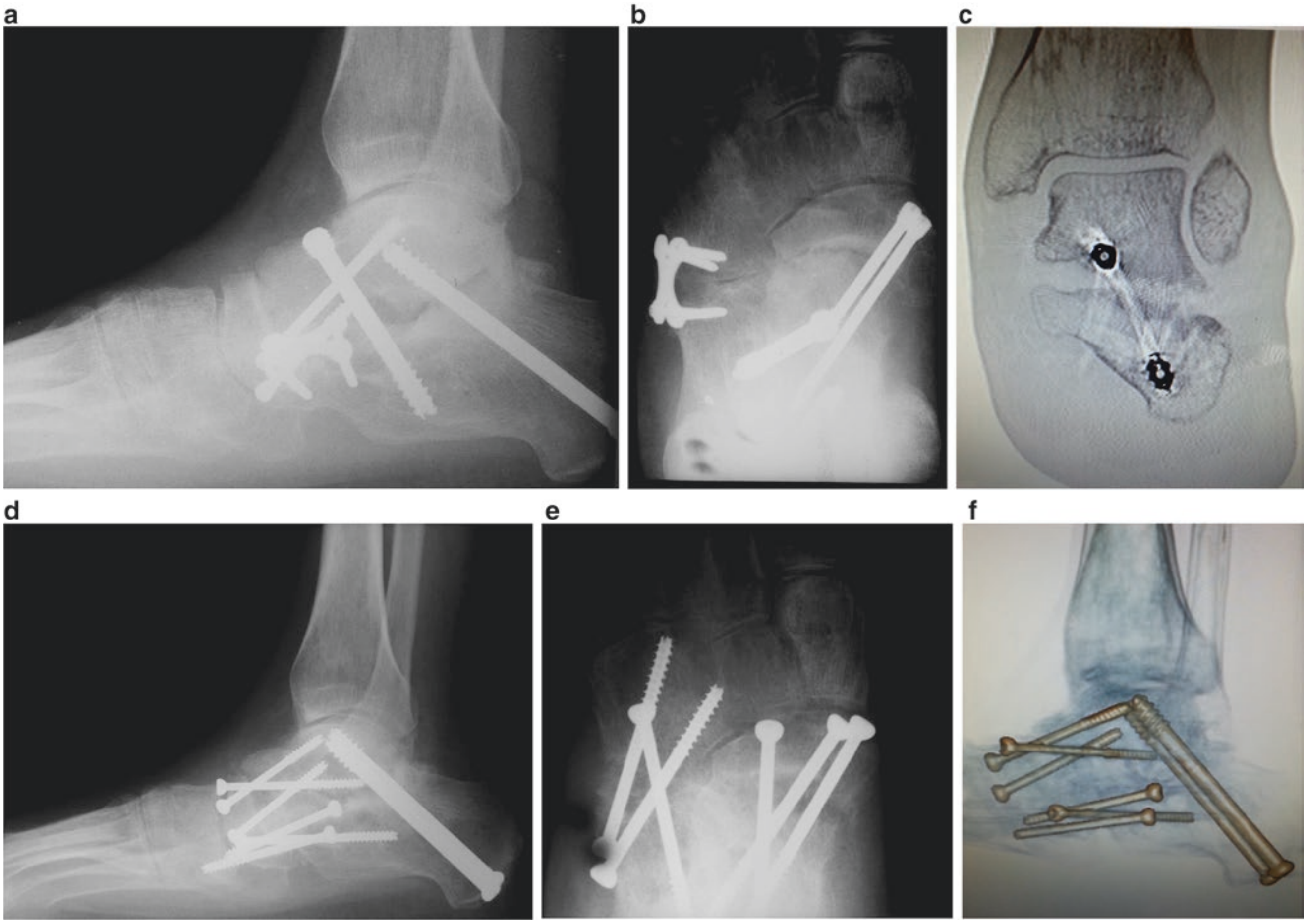


Fig. 3.18 (**a**, **b**) Radiographs demonstrating nonunion of all tritarsal joints following triple arthrodesis. (**c**) CT scan confirmation of nonunion. (**d**, **e**) Status post revisional triple arthrodesis. Note 2-point fixation of all tritarsal joints. (**f**) CT scan confirmation of consolidation

compensatory issues in the suprastructural skeleton. Additionally, acute shortening of the ankle can result in complications such as venous congestion, wound bunching with subsequent breakdown, edema, and tissue necrosis. Autogenous bone grafts or engineered bone might be considered in these cases [112]). Another option is a large segmental allograft, which has no limits in volume. However, large allografts do not always completely incorporate and can be predisposed to fracture. Distraction osteogenesis of the tibia is another option for maintaining length. The advantages of this technique include early weight bearing, stimulation of regional blood flow, and management of large defects (up to 10 cm.). This technique requires technical expertise and patient compliance [113].

The anatomy of the ankle lends itself well to multiple fixation options following nonunion revision. Screws, plates (standard and locking), intramedullary devices, and external fixators provide a range of good options for securing a stiff construct to support revision surgery.

Postoperative Management

Biologic responses are influenced by load and stability. Revisional nonunion surgeries invariably require extended periods of immobilization and non-weight bearing. Physical therapy consultations that provide instructions for non-weight bearing are recommended, especially if the patient is unable to comply prior to surgery. Devices such as knee walkers, wheelchairs, etc. can be helpful for these patients. Patients who lack family support are good candidates for placement into subacute nursing facilities. Deep venous thrombosis prophylaxis is recommended and dictated by risk factors. Patients should resume preoperative supplementation if indicated for any previously diagnosed deficiencies. The use of electrical stimulation or ultrasound might be considered to augment healing following surgery. Progress to union should be monitored with serial radiographs and advanced imaging. The authors typically confirm consolidation with CT scans prior to weight bearing.

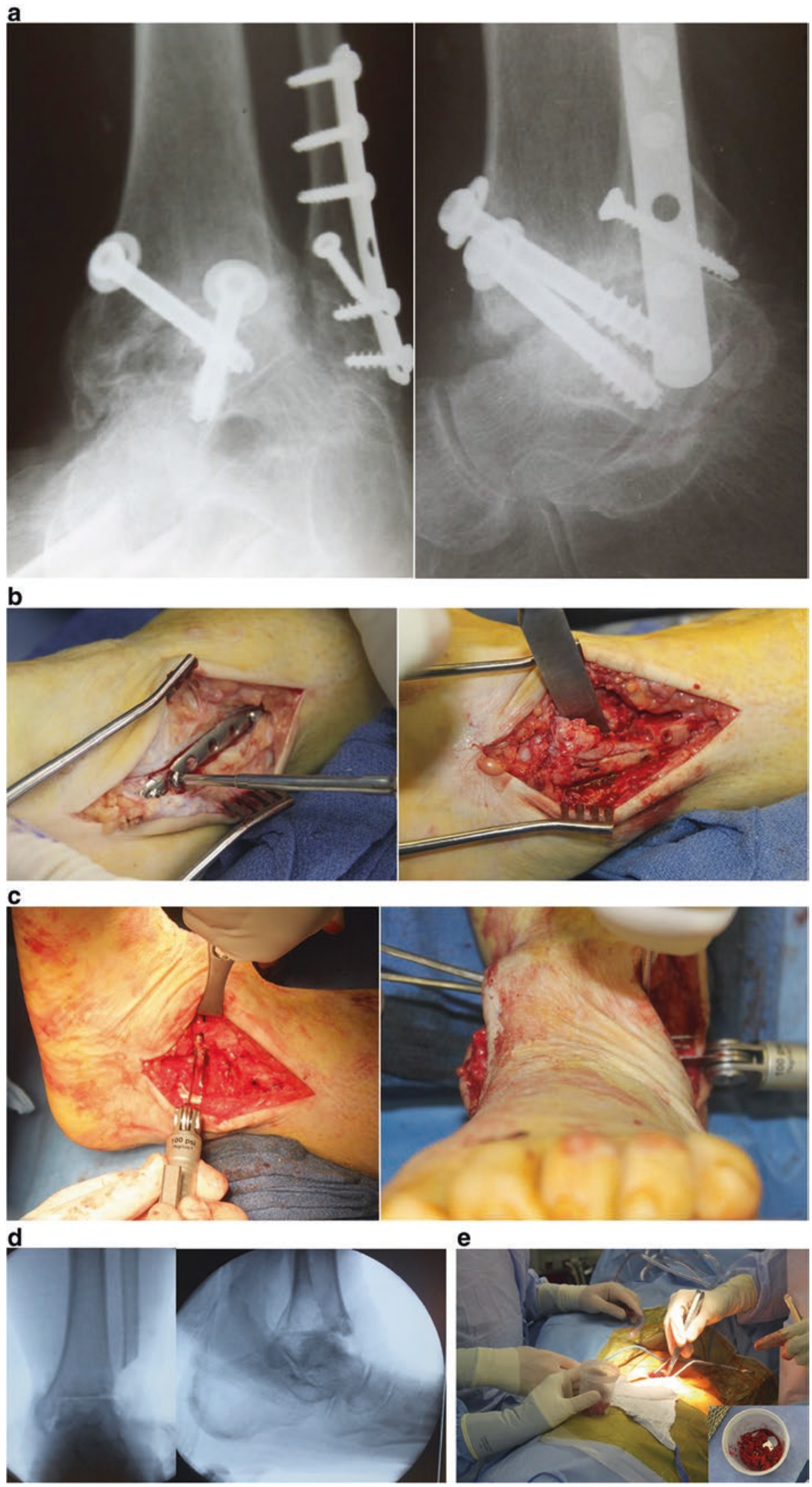


Fig. 3.19 (**a**) Nonunion status post ankle arthrodesis through anterior approach. (**b**) Revision through lateral approach. Removal of hardware and osteotomy of fibula. (**c**) Resection of nonunion. (**d**) Intraoperative images following debridement. (**e**) Harvest of cancellous bone graft from ipsilateral iliac crest. (**f**) Drilling of subchondral plate and packing of bone graft. Note fixation construct using screws that engage cortices and subchondral bone. (**g**) 3-months status post radiographs demonstrating consolidation. (**h**) CT scan confirmation of consolidation

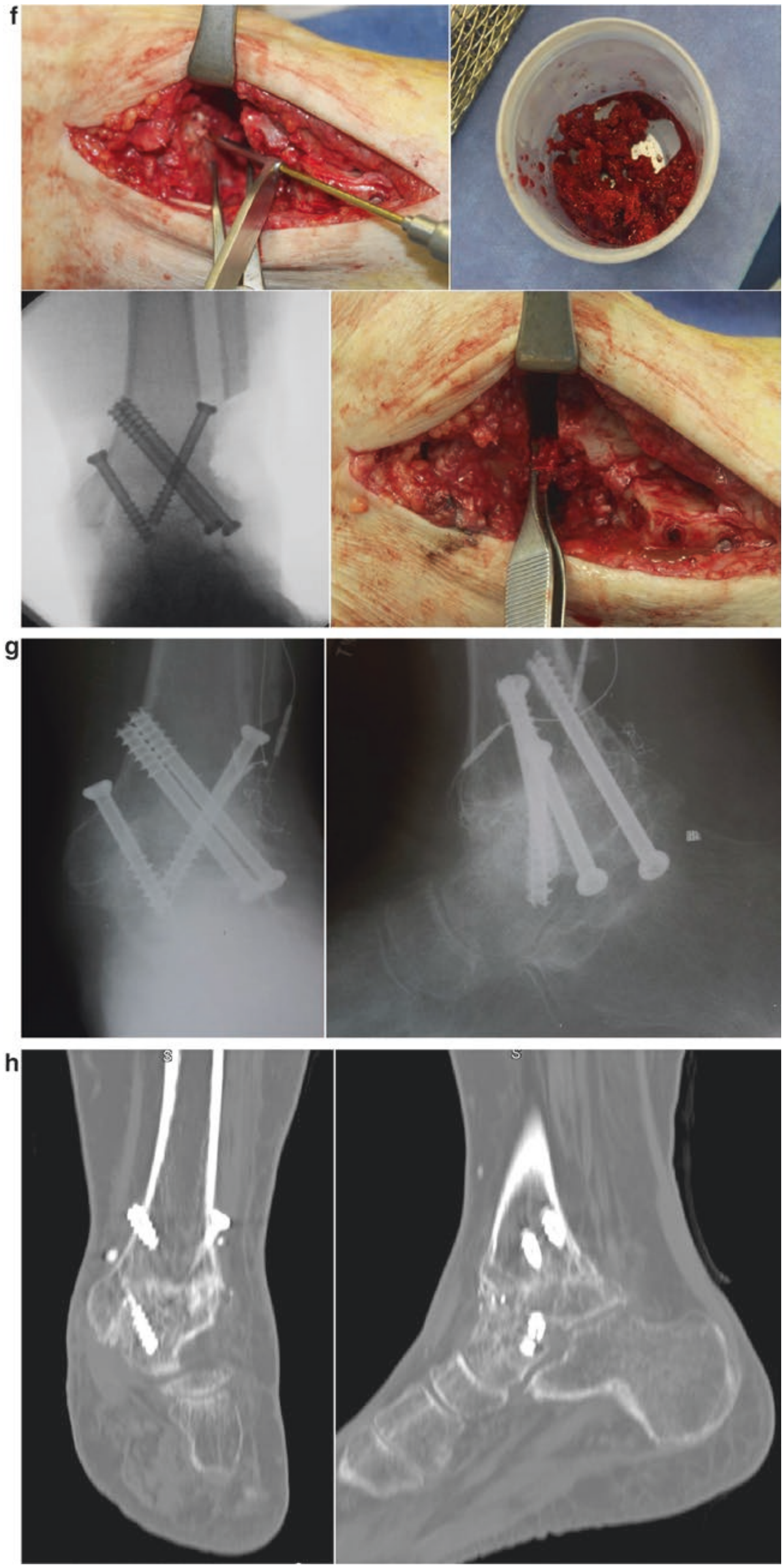


Fig. 3.19 (continued)

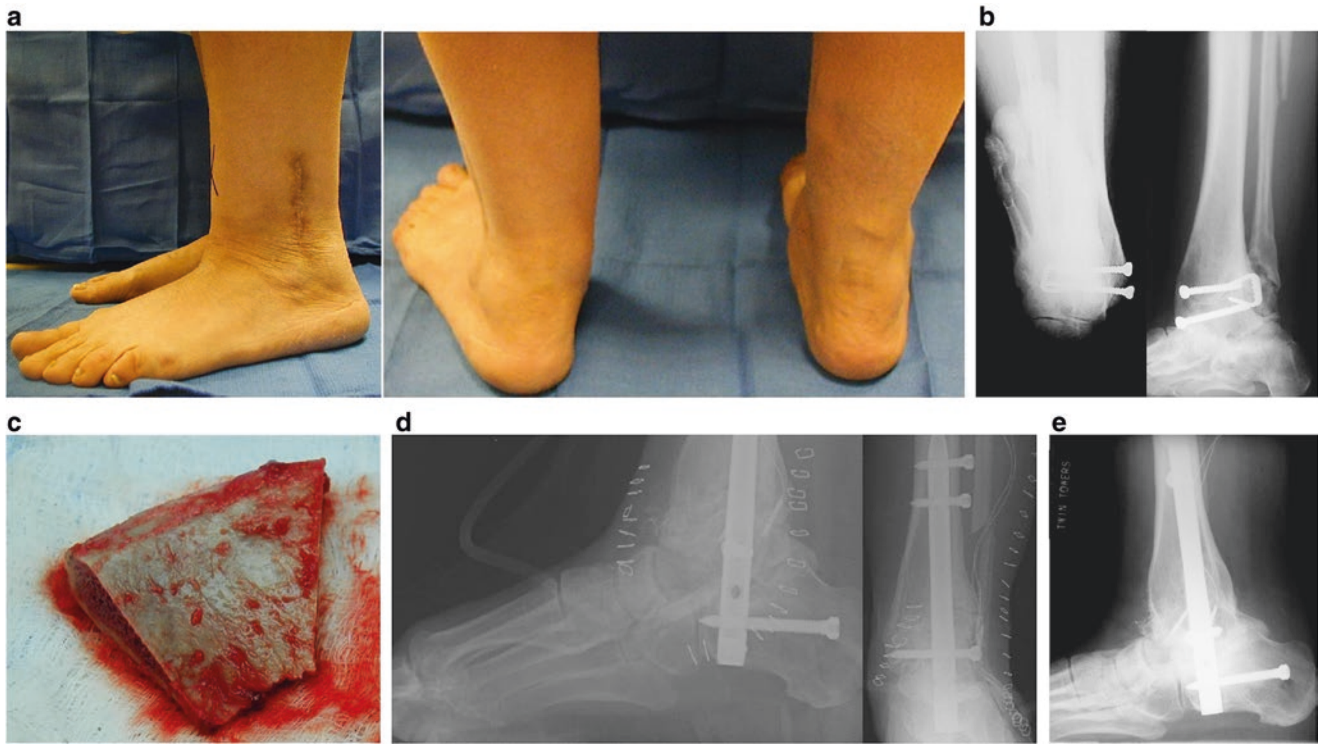


Fig. 3.20 (**a**) Nonunion following ankle arthrodesis with residual valgus deformity (**b**) Radiographs demonstrating nonunion. (**c**) Structural graft harvested from iliac crest. (**d**) Conversion into tibiotalocalcaneal arthrodesis with intramedullary nail. (**e**) One-year status post surgery demonstrating union

Conclusion

Surgical nonunion is a complex condition encountered by foot and ankle surgeons. The successful management of nonunions requires an understanding of bone healing, an awareness of medical conditions that contribute to abnormalities of bone metabolism, knowledge of technical issues that predispose patients to nonunion, and a thorough comprehension of fixation principles. Many cases benefit from a multidisciplinary team approach, and recruiting the assistance of other medical/surgical specialists and allied health professionals is encouraged to achieve successful outcomes.

References

1. Riemer BL, DiChristina DG, Cooper A, et al. Nonreamed nailing of tibial diaphyseal fractures in blunt polytrauma patients. J Orthop Trauma. 1995;9:66–75.
2. Caudle RJ, Stern PJ. Severe open fractures of the tibia. J Bone Joint Surg Am. 1987;69(6):801–7.
3. Sanders R, Jersinovich I, Anglen J, DiPasquale T, Herscovici Jr D. The treatment of open tibial shaft fractures using an interlocked intramedullary nail without reaming. J Orthop Trauma. 1994;8:504–10.
4. Govender S, Csimma C, Genant HK, et al. Recombinant human bone morphogenetic protein-2 for treatment of open tibial fractures: a prospective, controlled, randomized study of four hundred and fifty patients. J Bone Joint Surg Am. 2002;84-A(12):2123–34.
5. Sangeorzan BJ, Smith D, Veith R, et al. Triple arthrodesis using internal fixation in treatment of adult foot disorders. Clin Orthop Relat Res. 1993;294:299–307.
6. Wukich DK, Bowen JR. A long-term study of triple arthrodesis for correction of pes cavovarus in Charcot-Marie-Tooth disease. J Pediatr Orthop. 1989;9(4):433–7.
7. Saltzman CL, Fehrle MJ, Cooper RR, et al. Triple arthrodesis: twenty-five and forty-four-year average follow-up of the same patients. J Bone Joint Surg Am. 1999;81-A(10):1391–402.
8. Maskill MP, Loveland JD, Mendicino RW, Saltrick K, Catanzariti AR. Triple arthrodesis for the adult acquired flatfoot deformity. Clin Podiatr Med Surg. 2007;24:765–78.
9. Goucher NR, Coughlin MJ. Hallux metatarsophalangeal joint arthrodesis using dome-shaped reamers and dorsal plate fixation: a prospective study. Foot Ankle Int. 2006;27(11):869–76.
10. Doty J, Coughlin M, Hirose C, et al. Hallux metatarsophalangeal joint arthrodesis with a hybrid locking plate and a plantar neutralization screw: a prospective study. Foot Ankle Int. 2013;34(11):1535–40.
11. Roukis TS. Nonunion after arthrodesis of the first metatarsal-phalangeal joint: a systematic review. J Foot Ankle Surg. 2011;50(6):710–3.
12. Catanzariti AR, Mendicino RW, Lee MS, Gallina MR. The modified Lapidus arthrodesis: a retrospective analysis. J Foot Ankle Surg. 1999;38(5):322–32.
13. Donnenwerth MP, Borkosky SL, Abicht BP, et al. Rate of nonunion after first metatarsal-cuneiform arthrodesis using joint curettage and two crossed compression screw fixation: a systematic review. J Foot Ankle Surg. 2011;50(6):707–9.

14. Thompson IM, Bohay DR, Anderson JG. Fusion rate of first tarsometatarsal arthrodesis in the modified Lapidus procedure and flatfoot reconstruction. Foot Ankle Int. 2005;26(9):698–703.
15. Brinker MR. Nonunions: evaluation and treatment. In: Browner BD, Levine AM, Jupiter JB, Trafton PG, editors. Skeletal trauma: basic science, management, and reconstruction. 3rd ed. Philadelphia, PA: W.B. Saunders; 2002. p. 507–604.
16. Bhandari M, Guyatt GH, Swiontkowski MF, et al. A lack of consensus in the assessment of fracture healing among orthopaedic surgeons. J Orthop Trauma. 2002;16(8):562–6.
17. Muller ME, Allgower M, Schneider R, Willenegger H. Manual of Internal Fixation: Techniques Recommended by the AO group. 2nd ed. Berlin: Springer Verlag; 1979.
18. Lack WD, Starman JS, Seymour R, et al. Any cortical bridging predicts healing of tibial shaft fractures. J Bone Joint Surg Am. 2014;96(13):1066–72.
19. Nicoll EA. Fractures of the tibial shaft: a survey of 705 cases. J Bone Joint Surg (Br). 1964;46:373–87.
20. Bishop JA, Palanca AA, Bellino MJ, et al. Assessment of compromised fracture healing. J Am Acad Orthop Surg. 2012; 20(5):273–82.
21. Weber BG, Čech O. Pseudarthrosis: pathophysiology, biomechanics, therapy, results. New York: Grune & Stratton; 1976. Print
22. Mandracchia VJ, Nelson SC, Barp EA. Current concepts of bone healing. Clin Podiatr Med Surg. 2001;18(1):55–77.
23. McKibbin B. The biology of fracture healing in long bones. J Bone Joint Surg (Br). 1978;60(2):150–62.
24. Pountos I, Georgouli T, Blokhuis TJ, et al. Pharmacological agents and impairment of fracture healing: what is the evidence? Injury. 2008;39(4):384–94.
25. Lindholm R, Lindholm S, Liukko P, et al. The mast cell as a component of callus in healing fractures. J Bone Joint Surg (Br). 1969;51(1):148–55.
26. Ham AW. A histological study of the early phases of bone repair. J Bone Joint Surg Am. 1930;12(4):827–44.
27. Charnley J. The closed treatment of closed fractures. 3rd ed. Edinburgh and London: E & S Livingstone Ltd; 1975.
28. Danis soudure autogene-Danis R. Théorie et pratique de l'ostéosynthèse. Paris: Masson; 1949.
29. Schenk R, Willenegger H. Zur Histologie der primären Knochenheilung: Modifikationen und grenzender Spaltheilung in Abhängigkeit von der Defektgrösse. Unfallheilkunde. 1977;81: 219–27.
30. Augat P, Margevicius K, Simon J, et al. Local tissue properties in bone healing: influence of size and stability of the osteotomy gap. J Orthop Res. 1998;16(4):475–81.
31. Schenk R, Willenegger H. Morphological findings in primary fracture healing. Symp Bioi Hung. 1967;7:75.
32. Wolff J. The law of bone remodeling [translated from the 1892 original, Das Gesetz der Transformation der Knochen, by P. Maquet and R. Furlong]. Berlin: Springer Verlag; 1986.
33. Chatziyiannakis AA, Verettas DA, Raptis VK, et al. Nonunion of tibial fractures treated with external fixation. Contributing factors studied in 71 fractures. Acta Orthop Scand Suppl. 1997;275: 77–9.
34. Hak DJ, Fitzpatrick D, Bishop JA, et al. Delayed union and nonunions: epidemiology, clinical issues, and financial aspects. Injury. 2014;45(suppl 2):S3–7.
35. Trueta J. Studies of the development and decay of the human frame. London: William Heinemann Ltd.; 1968.
36. Perren SM. Physical and biological aspects of fractures healing with special reference to internal fixation. Clin Orthop Relat Res. 1979;138:175–96.
37. Perren SM. Evolution of internal fixation of long bone fractures. The scientific basis of biological internal fixation: choosing a new balance between stability and biology. J Bone Joint Surg (Br). 2002;84(8):1093–110.
38. Hak DJ, Toker S, Yi C, et al. The influence of fracture fixation biomechanics on fracture healing. Orthopedics. 2010;33(10):752–5.
39. Bassett CA, Herrmann I. Influence of oxygen concentration and mechanical factors on differentiation of connective tissue in vitro. Nature. 1961;190:460–1.
40. Fukada E, Yasuda I. On the piezoelectric effect of bone. J Phys Soc Jpn. 1957;12(10):1158–62.
41. Haverstock BD, Mandracchia VJ. Cigarette smoking and bone healing: implications in foot and ankle surgery. J Foot Ankle Surg. 1998;37(1):69–74.
42. Sherwin MA, Gastwirth CM. Detrimental effects of cigarette smoking on lower extremity wound healing. J Foot Surg. 1990; 29(1):84–7.
43. Cobb TK, Gabrielsen TA, Campbell II DC, et al. Cigarette smoking and nonunion after ankle arthrodesis. Foot Ankle Int. 1994;15(2):64–7.
44. Ishikawa SN, Murphy GA, Richardson EG. The effect of cigarette smoking on hindfoot fusions. Foot Ankle Int. 2002;23(11): 996–8.
45. Ma L, Zheng LW, Sham MH, et al. Uncoupled angiogenesis and osteogenesis in nicotine-compromised bone healing. J Bone Miner Res. 2010;25(6):1305–13.
46. Zheng LW, Ma L, Cheung LK. Changes in blood perfusion and bone healing induced by nicotine during distraction osteogenesis. Bone. 2008;43(2):355–61.
47. Ma L, Sham MH, Zheng LW, et al. Influence of low-dose nicotine on bone healing. J Trauma. 2011;70(6):117–21.
48. Ma L, Zwahlen RA, Zheng LW, et al. Influence of nicotine on the biologic activity of rabbit osteoblasts. Clin Oral Implants Res. 2011;22(3):338–42.
49. Lee S, do Yoon H, Kim KN, et al. Association between urine cotinine levels and bone mineral density in lumbar spine and femoral neck among adult males. Spine. 2014;39(4):311–7.
50. Daniell HW. Osteoporosis of the slender smoker. Vertebral compression fractures and loss of metacarpal cortex in relation to postmenopausal cigarette smoking and lack of obesity. Arch Intern Med. 1976;136(3):298–304.
51. Law MR, Hacksaw AK. A meta-analysis of cigarette smoking, bone mineral density and risk of hip fracture: recognition of a major effect. BMJ. 1997;315(7112):841–6.
52. Scolaro JA, Schenker ML, Yannascoli S, et al. Cigarette smoking increases complications following fracture: a systematic review. J Bone Joint Surg Am. 2014;96(8):674–81.
53. Day SM, DeHeer DH. Reversal of the detrimental effects of chronic protein malnutrition on long bone fracture healing. J Orthop Trauma. 2001;15(1):47–53.
54. Simpson AH, Mills L, Noble B. The role of growth factors and related agents in accelerating fracture healing. J Bone Joint Surg (Br). 2006;88(6):701–5.
55. Brinker MR, O'Conner DP, Monla YT, et al. Metabolic and endocrine abnormalities in patients with nonunions. J Orthop Trauma. 2007;21(8):557–70.
56. Friedlaender GE, Tross RB, Doganis AC, et al. Effects of chemotherapeutic agents on bone. Short-term methotrexate and doxorubicin (adriamycin) treatment in a rat model. J Bone Joint Surg Am. 1984;66(4):602–7.
57. Gravel CA, Le TT, Chapman MW. Effect of neoadjuvant chemotherapy on distraction osteogenesis in the goat model. Clin Orthop Relat Res. 2003;412:213–24.
58. Hausman MR, Schaffler MB, Majeska RJ. Prevention of fracture healing in rats by an inhibitor of angiogenesis. Bone. 2001; 29(6):560–4.
59. Hazan EJ, Hornicek FJ, Tomford W, et al. The effect of adjuvant chemotherapy on osteoarticular allografts. Clin Orthop Relat Res. 2001;385:176–81.
60. Tortolani PJ, Park AE, Louis-Ugbo J, et al. The effects of doxorubicin (Adriamycin) on spinal fusion: an experimental model of

posterolateral lumbar spinal arthrodesis. Spine J. 2004;4(6): 669–74.
61. O'Brien CA, Jia D, Plotkin LI, et al. Glucocorticoids act directly on osteoblasts and osteocytes to induce their apoptosis and reduce bone formation and strength. Endocrinology. 2004;145(4): 1835–41.
62. Weinstein RS, Jilka RL, Parfitt AM, et al. Inhibition of osteoblastogenesis and promotion of apoptosis of osteoblasts and osteocytes by glucocorticoids. Potential mechanisms of their deleterious effects on bone. J Clin Invest. 1998;102(2):274–82.
63. Jeffcoach DR, Sams VG, Lawson CM, et al. Nonsteroidal anti-inflammatory drugs' impact on nonunion and infection rates in long-bone fractures. J Trauma Acute Care Surg. 2014;76(3): 779–83.
64. Endo K, Sairyo K, Komatsubara S, et al. Cyclooxygenase-2 inhibitor delays fracture healing in rats. Acta Orthop. 2005; 76(4):470–4.
65. Gerstenfeld LC, Thiede M, Seibert K, et al. Differential inhibition of fracture healing by non-selective and cyclooxygenase-2 selective non-steroidal anti-inflammatory drugs. J Orthop Res. 2003;21(4):670–5.
66. Giordano V, Giordano M, Knackfuss IG, et al. Effect of tenoxicam on fracture healing in rat tibiae. Injury. 2003;34(2):85–94.
67. Sudmann E, Bang G. Indomethacin-induced inhibition of haversian remodeling in rabbits. Acta Orthop Scand. 1979;50(6 pt 1):621–7.
68. Huddleston PM, Steckelberg JM, Hanssen AD, et al. Ciprofloxacin inhibition of experimental fracture healing. J Bone Joint Surg Am. 2000;82(2):161–73.
69. Mont MA, Mathur SK, Frondoza CG, Hungerford DS. The effects of ciprofloxacin on human chondrocytes in cell culture. Infection. 1996;24(2):151–5.
70. Perry AC, Prpa B, Rouse MS, et al. Levofloxacin and trovafloxacin inhibition of experimental fracture-healing. Clin Orthop Relat Res. 2003;414:95–100.
71. Seltzer MH, Fletcher HS, Slocum BA, et al. Instant nutritional assessment in the intensive care unit. J Parenter Enter Nutr. 1981;5(1):70–2.
72. Cross MB, Yi PH, Thomas CF, et al. Evaluation of malnutrition in orthopaedic surgery. J Am Acad Orthop Surg. 2014;22(3):193–9.
73. Holick MF. Vitamin D deficiency. N Engl J Med. 2007;357(3): 266–81.
74. Dawson-Hughes B, Heaney RP, Holick MF, et al. Estimates of optimal vitamin D status. Osteoporos Int. 2005;16(7):713–6.
75. Malabanan A, Veronikis IE, Holick MF. Redefining vitamin D insufficiency. Lancet. 1998;351(9105):805–6.
76. Rabjohn L, Roberts K, Troiano M, et al. Diagnostic and prognostic value of erythrocyte sedimentation rate in contiguous osteomyelitis of the foot and ankle. J Foot Ankle Surg. 2007;46(4):230–7.
77. Fleischer AE, Didyk AA, Woods JB, et al. Combined clinical and laboratory testing improves diagnostic accuracy for osteomyelitis in the diabetic foot. J Foot Ankle Surg. 2009;48(1):39–46.
78. Stucken C, Olszewski DC, Creevy WR, et al. Preoperative diagnosis of infection in patients with nonunions. J Bone Joint Surg Am. 2013;95(15):1409–12.
79. Sarmiento A, Sobol PA, Sew Hoy AL, et al. Prefabricated functional braces for the treatment of fractures of the tibial diaphysis. J Bone Joint Surg Am. 1984;66(9):1328–39.
80. Whelan DB, Bhandari M, McKee MD, et al. Interobserver and intraobserver variation in the assessment of the healing of tibial fractures after intramedullary fixation. J Bone Joint Surg (Br). 2002;84(1):15–8.
81. Lamm BM, Mendicino RW, Catanzariti AR, Hillstrom HJ. Static rearfoot alignment: a comparison of clinical and radiographic measures. J Am Podiatr Med Assoc. 2005;95(1):26–33.
82. Mendicino RW, Catanzariti AR, John S, Child B, Lamm BM. Long leg calcaneal axial and hindfoot alignment radiographic views for frontal plane assessment. J Am Podiatr Med Assoc. 2008;98(1):75–8.
83. Lew DP, Waldvogel FA. Osteomyelitis. Lancet. 2004;364(9431): 369–79.
84. Cierny III G, Mader JT, Penninck JJ. A clinical staging system for adult osteomyelitis. Clin Orthop Relat Res. 2003;414:7–24.
85. Coughlin MJ, Grimes JS, Traughber PD, et al. Comparison of radiographs and CT scans in the prospective evaluation of the fusion of hindfoot arthrodesis. Foot Ankle Int. 2006;27(10): 780–7.
86. Jones C, Coughlin M, Shurnas P. Prospective CT scan evaluation of hindfoot non-unions treated with revision surgery and low-intensity ultrasound stimulation. Foot Ankle Int. 2006;27(4):229–35.
87. Buchan CA, Pearce DH, Lau J, et al. Imaging of postoperative avascular necrosis of the ankle and foot. Semin Musculoskelet Radiol. 2012;16(3):192–204.
88. Solicito V, Jacobs AM, Oloff LM, Soave R, Bernstein A. The use of radionucleotide bone and joint imaging in arthritic and related diseases. J Foot Surg. 1984;23(2):173–82.
89. Visser HJ, Jacobs AM, Oloff L, Drago JJ. The use of differential scintigraphy in the clinical diagnosis of osseous and soft tissue changes affecting the diabetic foot. J Foot Surg. 1984;23(1):74–85.
90. Jacobs AM, Klein S, Oloff L, Tuccio MJ. Radionuclide evaluation of complications after metatarsal osteotomy and implant arthroplasty of the foot. J Foot Surg. 1984;23(1):86–96.
91. Mont MA, Ulrich SD, Seyler TM, et al. Bone scanning of limited value for diagnosis of symptomatic oligofocal and multifocal osteonecrosis. J Rheumatol. 2008;35(8):1629–34.
92. Palestro CJ, Love C, Bhargava KK. Labeled leukocyte imaging: current status and future directions. QJ Nucl Med Mol Imaging. 2009;53(1):105–23.
93. Baim S, Binkley N, Bilezikian JP, et al. Official positions of the international society for clinical densitometry and executive summary of the 2007 ISCD position development conference. J Clin Densitom. 2008;11(1):75–91.
94. Kanis JA. Diagnosis of osteoporosis and assessment of fracture risk. Lancet. 2002;359(9321):1929–36.
95. Watts NB, Bilezikian JP, Camacho PM, et al. American association of clinical endocrinologists medical guidelines for clinical practice for the diagnosis and treatment of postmenopausal osteoporosis. Endocr Pract. 2010;16(suppl 3):1–37.
96. Goldman B. Use and abuse of opioid analgesics in chronic pain. Can Fam Physician. 1993;39:571–6.
97. Savage SR. Opioid use in the management of chronic pain. Med Clin North Am. 1999;83:761–86.
98. Tennant Jr FS, Rawson RA. Outpatient treatment of prescription opioid dependence: comparison of two methods. Arch Intern Med. 1982;142:1845–7.
99. Einhorn TA, Levine B, Michel P. Nutrition and bone. Orthop Clin North Am. 1990;21:43–50.
100. Guarniero R, de Barros Filho TE, Tannuri U, et al. Study of fracture healing in protein malnutrition. Rev Paul Med. 1992; 110:63–8.
101. Pollak D, Floman Y, Simkin A, et al. The effect of protein malnutrition and nutritional support on the mechanical properties of fracture healing in the injured rat. J Parenter Enter Nutr. 1986;10:564–7.
102. Hoofwerf BJ, Sferra J, Donley BG. Diabetes mellitus—overview. Foot Ankle Clin. 2006;11(4):703–15.
103. Dworkin SF, Von Korff M, LeResche L. Multiple pains and psychiatric distrurbance: an epidemiologic investigation. Arch Gen Psychiatry. 1990;47:239–44.
104. Katon W. The impact of major depression on chronic medical illness. Gen Hosp Psychiatry. 1996;18:215–9.

105. Katon W, Sullivan MD. Depression and chronic medical illness. J Clin Psychiatry. 1990;51:3–11.
106. Krishan KR, France RD. Chronic pain and depression. South Med J. 1987;80:558–61.
107. Evans EL, Catanzariti AR. Forefoot supinatus. Clin Podiatr Med Surg. 2014;31:405–13.
108. Mann RA, Beaman DN. Double arthrodesis in the adult. Clin Orthop Relat Res. 1999;356:74–80.
109. Granata JD, Berlet GC, Ghotge R, et al. Talonavicular joint fixation: A biomechanical comparison of locking compression plates and lag screws. Foot Ankle Spec. 2014;7:20–31.
110. Catanzariti AR, Adeleke AT. Double arthrodesis through a medial approach for end-stage adult-acquired flatfoot. Clin Podiatr Med Surg. 2014;31(3):435–49.
111. Frey C, Halikus NM, Vu-Rose T, et al. A review of ankle arthrodesis: predisposing factors to nonunion. Foot Ankle Int. 1994;15(11):581–97.
112. Stock U, Vacanti J. Tissue engineering: current state and prospects. Annu Rev Med. 2001;52:443–51.
113. Kanellopoulos A, Soucacos P. Management of nonunion with distraction osteogenesis. Injury. 2006;37(Suppl 1):S51–5.