Malunions

Diagnosis, Evaluation and Management

Animesh Agarwal
Editor

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At times our own light goes out and is rekindled by a spark from another person. Each of us has cause to think with deep gratitude of those who have lighted the flame within us.

– Albert Schweitzer

This book was completed amidst the COVID-19 pandemic of 2020 but began several years before. I am thankful to all the authors who persevered over these past couple of years to bring this book to fruition. The journey was difficult and the end seemed unattainable, yet here we are. To Springer Nature, namely Kristopher and Katherine, thank you for sticking with me and seeing this through—I know it was frustrating and at times painful.

I continue to have the most amazing parents, Jagdish and Kusum, who have continued to be the best parents I could have had and even better grandparents to my three children. They continue to support me both professionally and personally.

My kids continue to amaze me especially during these last three months of this crazy pandemic. They have been by my side and understanding during my long hours, business trips, and all my professional obligations. You three keep me going and my fire burning. Thank you Priya, Deven, and Trevor for being exemplary children in school and in life. I have never had to worry about your choices although I always worry about your well-being in this crazy world especially at this time.

I want to thank all those that have supported me professionally as well. My 22 years here at the UT Health certainly have been memorable. I have been extremely fortunate to work alongside Drs. Charles A. Rockwood, Jr., James D. Heckman, and Fred Corley as well as with Drs.

Kyriacos Athanasiou and Mauli Agrawal. All of them believed in me and gave me a chance as a medical student. I wouldn't be here without their faith in me. My fellowship training with Drs. Attila Poka, Robert Ostrum, and Brian Davison was one of the most memorable years of all my training and I am forever grateful for all their advice, training, and support.

My interest in malunions was "ignited" by Dr. Charlie Taylor who developed the Taylor Spatial Frame (TSF). It was my introduction to the TSF and my involvement with TSF courses over the last 20 years that kept the flame going and my interest in the treatment of malunions. So, thank you, Charlie, for your amazing device and all the knowledge and training you have provided to many of us interested in malunion surgery.

Last but not least, I would like to thank my administrative assistant Anna Conti who has been with me for over 15 years of my career. She is a true friend and always has been supportive.

Animesh Agarwal, MD
Boerne, TX, USA
July 2020

Foreword

Dr. Agarwal and his team of experts have created a thorough and very useful textbook that can be employed quite efficiently to assess and treat fracture malunions of all types. This work complements Dr. Agarwal's earlier textbook on nonunions and he has once again built upon the rich San Antonio tradition begun by Rockwood and Green to clearly define the fracture problem and then provide, in an easily understandable manner, a roadmap for treatment.

The chapters in this text cover all the anatomic areas and in every case are written by experts in the field. In addition to thoroughly reviewing the literature, each author, or group of authors, brings a wealth of personal experience to their chapter and presents the "Author's Preferred Treatment" reflecting that substantial clinical expertise. In addition, each chapter has a few representative case examples that effectively illustrate the best treatment for these challenging cases. The solutions each chapter describes are practical and have proven to be effective in the hands of the experts. The reader will be well served by the guidance provided in this textbook when he or she must decide upon the best way to manage a malunited fracture.

Manchester, VT, USA
July 2020

James D. Heckman, MD

Preface

> The only source of knowledge is experience.
> – Albert Einstein

Despite modern fracture techniques and implants, malunions can still occur. They can be quite disabling for the patient and challenging for the orthopedic surgeon. Prevention by adhering to fracture fixation principles is the best way to "treat" a malunion. The principles of malunion management vary according to anatomical site, amount of deformity, functional limitations, and pain. Iatrogenic causes are common but certainly avoidable to a certain degree. Patient factors can come into play as well as injury factors that may make anatomical restoration of length, alignment, and rotation problematic, leading to malalignment. Tips and tricks to restore the proper anatomy at the initial surgery can help to avoid primary malalignment from occurring.

Over the last 22 years of my practice, malunions have been challenging but also very rewarding. Realigning a deformed limb after years of malalignment is especially satisfying when the patient is able to walk better, their pain resolves, and their overall function improves. This text was designed to provide a reference for the basic principles of malunion diagnosis, evaluation, and management. Chapters are divided by anatomical area and common malunion situations are covered, but the principles of deformity analysis and treatment decisions can be applicable to all types of malunions. There is no one solution to each type of malunion, and treatment must be individualized.

The contributors to this text were selected based on their interest and expertise in this subject. Malunion management is learned by doing, and thus surgeons have learned through years of performing these difficult operations, oftentimes by trial and error. Their experience has become the knowledge provided in this book. We hope that it provides the reader with a basis for tackling these difficult problems.

Boerne, TX, USA　　　　Animesh Agarwal, MD

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1 Malunions: Introduction and Brief Overview

Animesh Agarwal

1.1 Introduction

Malunions historically have occurred due to non-operative or closed treatment of fractures. With the improvement of modern fixation techniques, and improvement of implants especially locked plating, malunions are less likely. Unfortunately, however, they still occur despite this. Many still occur from benign neglect in many underdeveloped countries or even closed treatment. Malunions may or may not require surgical intervention, and much of it depends on the patients and their expectations and desires. In cases where the malunion results in limited or poor function of the extremity, surgical correction may be warranted. Malunions in the upper extremity tend to cause functional limitations. In the lower extremity, functional limitations, leg length discrepancies, and post-traumatic arthritis are all sequelae of lower extremity malunions. The malalignment can occur in length, rotation, angulation, translation, or any combination of the above. Each anatomical area has its own parameters that define what is considered a malunion [1]. A complete analysis and characterization of the deformity prior to surgical correction for preoperative planning is an absolute requirement [2]. A common theme throughout the book is that prevention is the best treatment!

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1.2 Patient History and Physical Exam

When first evaluating a patient with a malunion, a complete history is always needed. This includes not only the medical history with comorbidities but especially a surgical/nonsurgical history especially in regard to the involved extremity. It is important to know the trauma mechanism, management for the particular fracture whether it be operative or closed treatment that occurred, and any surgical complications, if any. Obviously with a malunion, either the fracture was treated closed with a less than ideal reduction or, if the fracture was treated with surgical intervention, was the original reduction and fixation acceptable or was there loss of reduction and fixation during the postoperative course? If there was a failure of hardware, loosening, or breakage, how long was the time to failure? In the lower extremity, when did weight-bearing occur, or was there a second trauma? In the upper extremity, was there a particular event that may have led to this failure? It is important to determine whether or not there was any history of infection to include prior culture results, whether the fracture was closed or open, and the number of surgeries the limb has undergone. Although a radiographic "malunion" may be present, there may not be any functional consequences from this; therefore, it is important to determine whether the patient has pain, functional limitations, or both. In general, upper extremity malunions result in functional

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limitations with or without pain, whereas lower extremity malunions can result in leg length discrepancy, gait abnormalities, and, in long-standing cases, post-traumatic arthritis (PTOA) that can develop with varying degrees of pain.

When examining the affected extremity, it is important to evaluate the skin for all healed incisions or traumatic wounds, any open wounds or sinus tracts, and drainage if present. The range of motion of the joints of the involved extremity in the malunion should be noted and compared to the contralateral normal limb if possible. Compensatory fixed deformities may have occurred in adjacent joints and may require treatment in addition to the bony malunion. Addressing both issues should be part of the plan to ensure correction of the functional disability. Determining any limb length discrepancy is especially important in the lower extremity and can be done clinically by exam. In the lower extremity, varying size standing blocks to equalize leg lengths can be used and placed under the affected limb until the patient feels that their legs are equal. Always remember that some of the leg length inequality can be purely due to angulation. Obtaining leg length radiographs with a ruler can also aid in the precision of determining the exact leg length discrepancy but realize that many patients have inherent leg length discrepancies unbeknownst to them. Clinical and subjective equalization of leg lengths with blocks tends to be accurate for each individual. Palpation and stressing the malunion site should be performed to evaluate for any pain or motion. If either of these occurs, the patient may instead have a nonunion which obviously requires a different approach. A complete neurovascular exam should also be performed when evaluating any extremity.

1.3 Risk Factors for Malunion

Malunions can develop for a variety of reasons. Overall, however, the principal cause of the malunion is failure to maintain the reduction of the fracture either with nonoperative or operative means. Obviously, the reduction has to be obtained before one can maintain it with either casting, external fixation, or internal fixation. Factors that can contribute to the loss of reduction include age [3], osteoporosis, noncompliance with weight-bearing, diabetes and Charcot arthropathy, and iatrogenic reasons such as poor surgical technique including suboptimal fixation or casting techniques. Failure to obtain the reduction is obviously provider related. Oftentimes open internal fixation "OIF" is performed without the reduction or "R." Anneberg and Brink described this as "primary malalignment." This is dependent upon the surgeon's abilities and essentially iatrogenic and thus is obvious at the outset. They also described "secondary malalignment" which occurs when there is a change in the fracture reduction during the postoperative period [1]. This can be due to many factors as described above. Segmental bone loss or comminution can contribute to the development of a malunion, especially in terms of rotation and limb length discrepancy because of the lack of cortical contact, making reduction of the fracture much more difficult. Each specific anatomical area also has its own unique risk factors which will be addressed separately in each chapter.

1.4 General Principles

1.4.1 Diagnosis

The diagnosis of a malunion is primarily based on radiographic evaluation. Oftentimes, however, a malunion presents as a cosmetic issue which is what the patient may complain about initially. This may or may not be associated with symptoms. In patients that are obese, the soft tissue envelope may obscure any clinical deformity. Patients may present with joint pain if the deformity is long-standing as they may have developed PTOA (Fig. 1.1).

1.4.2 Radiographic Evaluation

Radiographic evaluation should always begin with an anteroposterior (AP) and lateral imaging of the affected extremity to include both the proximal

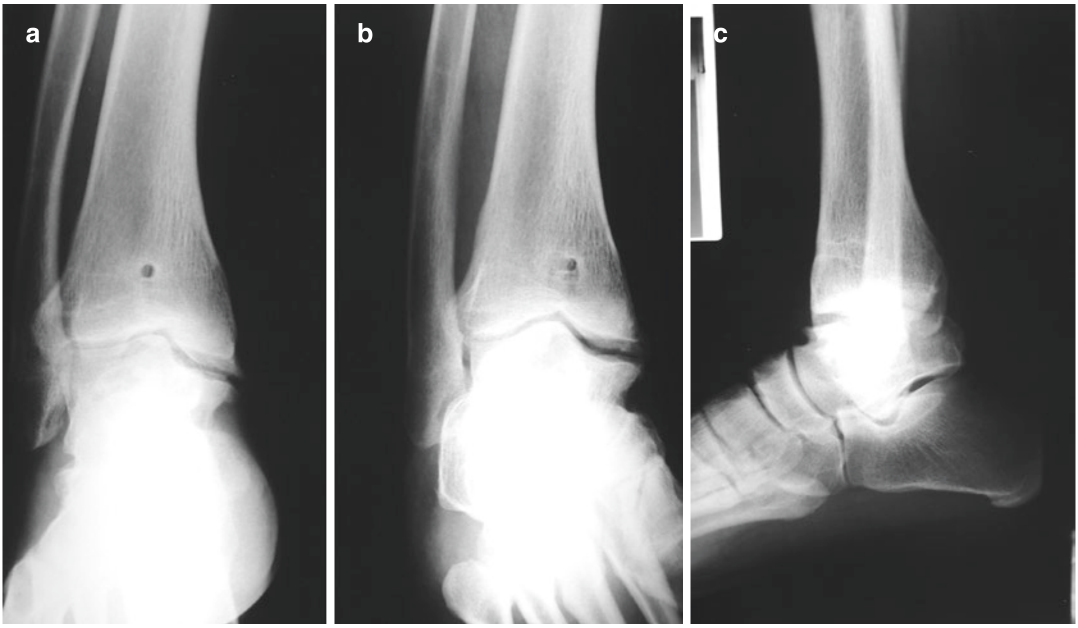

Fig. 1.1 A 35-year-old Latin American male presented with right ankle arthritis. The patient had a right ankle fracture 20 years prior that was casted. He had a varus malunion and had gone on to develop post-traumatic arthritis (PTOA) of the right ankle. He was referred for a fusion. Radiographs of the right ankle. (**a**) Anteroposterior view. (**b**) Mortise view. (**c**) Lateral view. Note the PTOA and varus deformity

and distal joints. If possible, getting the original injury films along with the postoperative films can be helpful in elucidating the etiology of the malunion. The follow-up radiographs after the original fixation can show the progression of the development of the malunion, in some cases, when there is loss of fixation and gradual deformity. In the lower extremity, AP standing of bilateral lower extremities (Fig. 1.2a) and a sagittal long leg standing films of both sides (Fig. 1.2b, c) are helpful to evaluate the mechanical axis of the limbs. Additionally, it is used to evaluate what normal is for that patient from the opposite normal side. In the upper extremity, AP and lateral imaging of the normal opposite can also be helpful for preoperative planning purposes. The current radiographs should be used to determine the limb alignment, anatomical and mechanical axes, center of rotation and angulation (CORA), and joint orientation and then compare to the contralateral normal. This can be done manually or with specific digital templating such as TraumaCAD™ (Brainlab AG, Munich, Germany) (Fig. 1.3). The CORA is determined by the intersection of the center line of the proximal fragment and the center line of the distal segment on both AP and lateral imaging. In cases of short fracture segments, the joint line can be used instead of the center line method (Fig. 1.4). This allows for determination of the deformity parameters in the sagittal and coronal planes. However, often the true maximum deformity and plane of the deformity are somewhere in between. Trigonometric calculations can define the true plane and magnitude of the deformity. Additionally, a no angulation view can be determined via fluoroscopy. An orthogonal view to this angle is the plane of maximum angulation.

If there is concern for a rotational malunion, then CT scanning is the gold standard to confirm the degree of malrotation [4–7], although clinical evaluation should also be performed. In cases where stress examination or palpation of the "malunion" site results in motion and/or pain, a CT scan of the area can also delineate between a malunion and nonunion as fractures with exuberant callus may falsely be diagnosed as malunions when in fact there is incomplete bridging and a persistent nonunion. Additionally, sagittal and

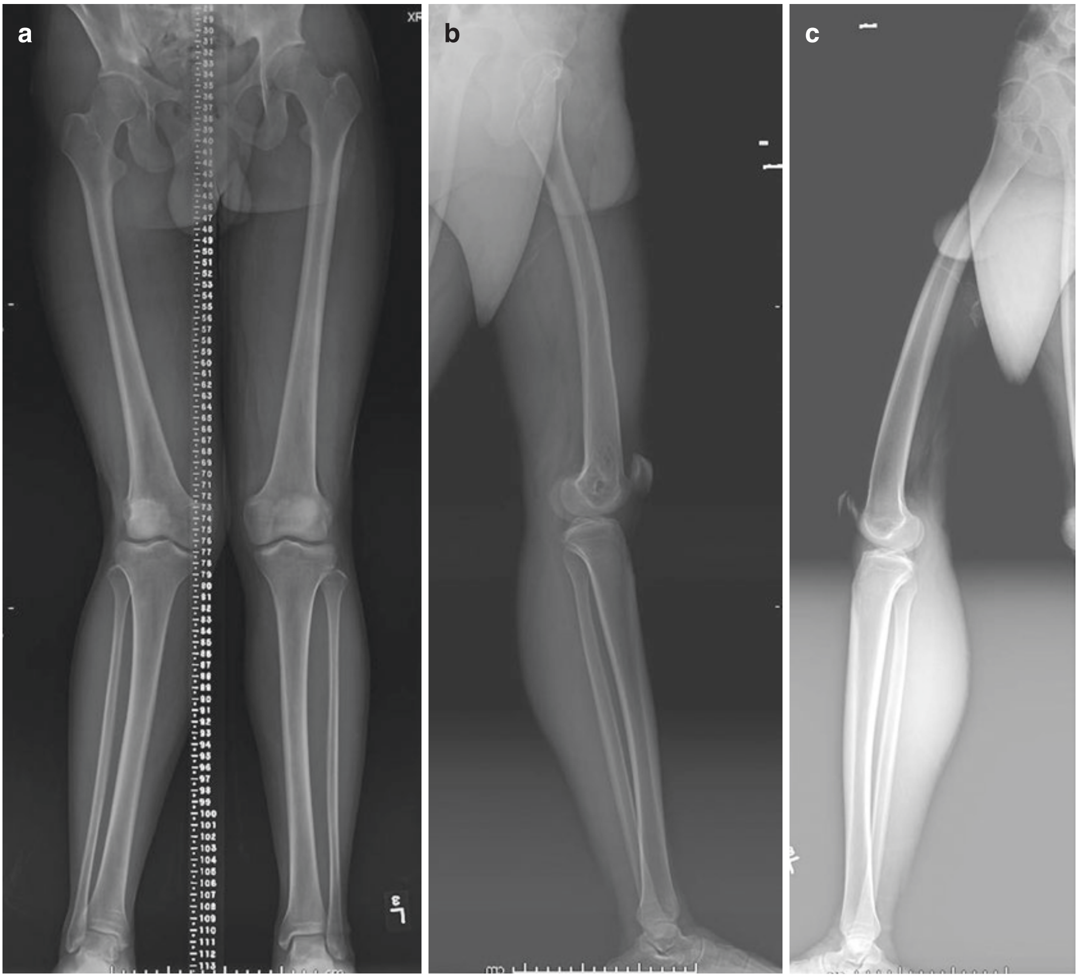

Fig. 1.2 An 18-year-old Latin American male presented with right distal femur valgus deformity after sustaining a fracture several years earlier. (**a**) Anteroposterior standing of the bilateral lower extremities with ruler. (**b**) Standing full-length right (affected) leg sagittal view. (**c**) Standing full-length left (normal) leg sagittal view

coronal reconstructions along with three-dimensional (3D) reconstructions can be useful for preoperative planning as well. If hardware is present, CT scans performed with metal suppression software can be helpful.

Magnetic resonance imaging (MRI) can be useful in some circumstances if there is concern for infection in light of a malunion. The presence of hardware can be problematic, however, but newer software can also limit artifacts from hardware. Otherwise, an MRI is usually not needed for evaluation of a malunion.

Nuclear medicine studies also are usually not needed as well but may be beneficial in cases where there is a history of infection, current draining wounds, or elevated laboratory markers (complete blood count, erythrocyte sedimentation rate, and C-reactive protein). If needed, a bone scan should be performed first and, if positive, followed by an indium scan. If the indium scan is positive, then a colloid scan should be performed to delineate between marrow changes and true infection. Any discordant uptake between the latter two studies indicates probable infection.

1.4.3 Laboratory Evaluation

Laboratory evaluation should always include a complete blood count (CBC), erythrocyte sedi-

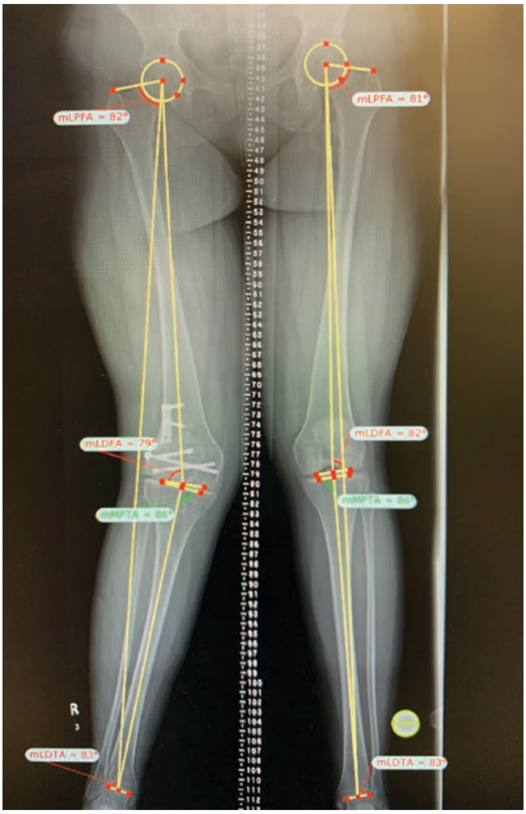

Fig. 1.3 AP standing of the bilateral lower extremities showing TraumaCAD™ deformity analysis. The right side is the abnormal side in comparison to the patient's left side. Joint angles are determined via the program and shown allowing comparison

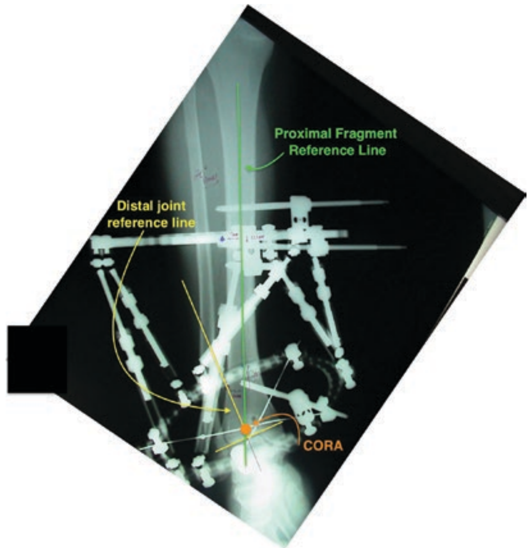

Fig. 1.4 The patient in Fig. 1.1 undergoing gradual correction with Taylor Spatial Frame. The deformity analysis is done with a joint reference line for the extremely short distal segment (*yellow line*). Standard center line for the diaphysis (*green line*). The intersection of the two lines indicates the center of rotation and angulation (*orange dot*)

mentation rate (ESR), and C-reative protein (CRP) along with a full metabolic profile to include vitamin D as well. In some cases where the original fixation was felt to be adequate, yet the patient developed failure of the fixation with loss of reduction after an extended period of time, metabolic studies may indicate reasons for a delay in healing. Any fracture fixation is always a race between the fracture healing and the hardware failing. If adequate time had passed for a fracture that treated properly should have healed, but didn't, leading to a delayed union and/or nonunion with subsequent hardware failure, then laboratory studies may provide some metabolic reason for the issue at hand. Diabetics should have their Hgb A1C checked. Metabolic studies such as thyroid function tests, parathyroid hormone levels, and vitamin D levels can be useful. Many of our trauma patients are vitamin D deficient and may have elevated parathyroid hormone (PTH) indicating secondary hyperparathyroidism which usually resolves with vitamin D replacement.

1.5 Definitions and Classification

A malunion is defined, in general terms, as a fracture that has healed in a non-anatomical position. The malunion can be intra-articular, extra-articular, or both. The malunion can occur in any single plane or be multiplanar, rotational, or with or without limb length inequalities. Classifications for malunions have been described but are unique to each anatomical area and will be described in each chapter along with parameters of what is considered a malunion.

1.6 Ramifications of Malunions

A malunion in and of itself may not be problematic. If there are no functional limitations or pain associated with the malunion, treatment may not be required. Long-standing malalignment in the lower extremity can cause alterations in the mechanical axis with resultant degenerative changes. In the upper extremity, functional limitations can occur due to malunion depending on the bone involved. Cosmetic deformity can also accompany functional limitations, but cosmesis alone may not be an indication for correction. It is important to note that angular deformities not only result in a change in the mechanical axis but also length changes. Varus deformities shorten the limb, and conversely, the limb is lengthened by valgus deformities. Any shortening or lengthening will obviously lead to a leg length discrepancy that has been related to back pain as well as gait disturbances [8].

1.6.1 Lower Extremity Biomechanics

To fully evaluate malunions of the lower extremity, it is important to understand the normal mechanics. In the coronal plane, the mechanical axis of the lower extremity runs from the center of the femoral head to the center of the ankle joint on radiographic examination. The line passes through the knee joint, on average, about 10 mm medial to the center of the knee joint. In the sagittal plane, the center of the femoral head and the ankle are the same endpoints, but the line crosses the knee just anterior to the center of rotation of the knee joint. When looking at the femur versus the tibia, the femoral anatomical axis varies with the mechanical axis by 6° valgus, whereas the tibial mechanical axis and anatomical axis coincide.

Additionally, the joint orientation in both the coronal plane and sagittal plane should be evaluated. For the proximal femur, a line drawn from the center of the femoral head to the tip of the greater trochanter which intersects with the femoral mechanical axis is the proximal femoral orientation angle and should roughly be approximately 90°. The knee joint line is roughly 3° of valgus relative to the mechanical axis, with the distal femur in valgus and proximal tibia in slight varus relative to the mechanical axis (Fig. 1.5).

Incidence of malunions varies from anatomical site but can occur anywhere from any fracture. The issue becomes which ones are clinically relevant to warrant surgical intervention. Each of the subsequent chapters will go in depth into these aspects.

1.6.2 Long-Term Effects of Malunions

It has not been fully established that a malunion will directly result in altered mechanical loads leading to post-traumatic arthritis, although many studies support this. Most likely the etiology is multifactorial, but malalignment after a fracture does seem to contribute especially when the deformity exceeds certain parameters depending on the anatomical area in question [9]. It is fairly clear that intra-articular malunions and incongruities lead to post-traumatic arthritis (PTOA) [10]. Intra-articular malunions will be addressed specifically in each anatomical chapter as the treatment of these varies considerably depending on the joint involved as well as patient age. Prevention, by anatomic reduction and rigid fixation of the articular component, again is the best treatment.

Kettelkamp et al. reviewed 14 patients that had degenerative arthritis of the knee and a history of either a tibia fracture of femoral fracture. They found a strong association between either a valgus or varus deformity at the knee and knee arthritis [11]. In a study of 88 patients followed for an average of 15 years after sustaining a fracture of the lower leg, van der Schoot et al. found a malunion incidence of 49% (malalignment > 5°). These patients had significantly more degenerative changes than those with normal healed fractures. The association was more in the knee and malalignment as opposed to the ankle [12]. Palmer et al. recently published a longitudinal cohort study looking at 1329 knees in 955 individuals. They found that when the medial proximal tibia angle (MPTA) was in varus, there was a significant association with structural progression of arthritis. Additionally, for every one degree increase in varus in the MPTA, there was 21% increase in the odds ratio of joint space narrowing progression in the medial compartment [13]. Mochizuki et al. found a similar association

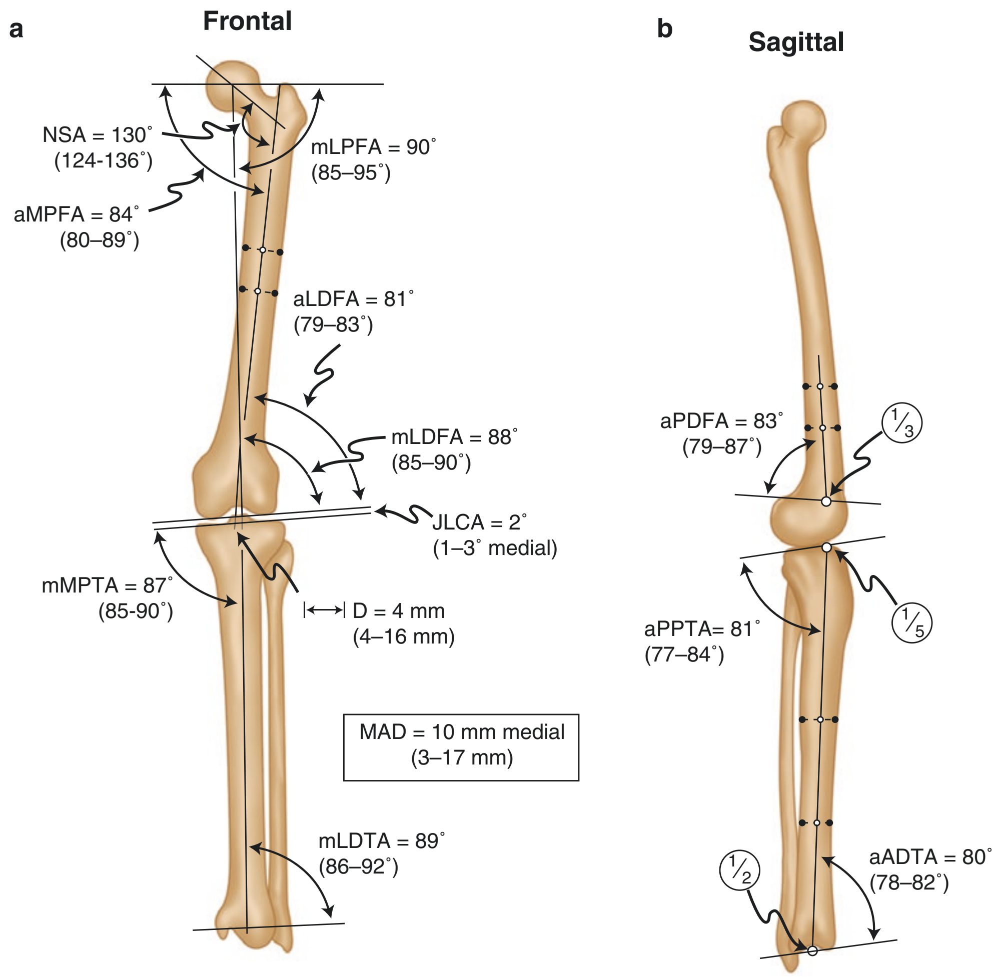

Fig. 1.5 Schematic drawings of normal values for various joint angles when evaluating malunions. (**a**) Normal parameters in the coronal plane. (**b**) Normal parameters in the sagittal plane

with varus tibias and the development of arthritic changes [14]. In a cadaveric skeleton study, Weinberg et al. found an association between malalignment in tibia fractures and the presence of arthritic changes. There were 37 tibia fractures found in 36 skeletons (total inspected 2898), and knee arthritis was found on the injured side when compared to the contralateral limb ($p < 0.001$). Furthermore, if the coronal plane deformity was greater than 5° ($p = 0.006$) and combined with a rotational deformity of greater than 10° ($p = 0.004$), the knee arthritis was even greater. If the tibia was short more than 10 mm, arthritis in the ipsilateral hip was found as well ($p = 0.009$) [15]. In contrast, Philips et al. evaluated 62 patients with femoral shaft fractures and found no association between femoral deformity and knee arthritis. However, the mean coronal plane malunion was only 5° in this group of patients [16]. Milner et al. reported on a 30-year follow-up on a group of tibia fracture patients. They had a 29% coronal malalignment of greater than 5°. They did not find a clear association between arthritis and malalignment [17].

Rotational malalignment can also cause issues requiring surgical intervention. Gugenheim et al. showed in a computer model that femoral rotation, internal or external, can cause frontal plane malorientation. They felt that such malalignment can lead to altered mechanical loads and knee arthritis as well as gait abnormalities [18]. Clinically, rotational deformities have been shown to cause difficulties with demanding activities such as running, sports, and climbing stairs. External rotation of the femur was more problematic than internal rotation [19].

1.7 Management Principles

Each chapter will discuss the specifics of management for each anatomical area. The goal of any malunion surgery is first and foremost to restore function. Pain relief, if due to development of degenerative changes in the joint, may improve once re-alignment occurs. Cosmesis should be a secondary goal only and not the sole reason for surgery. Correction can occur as a single stage or two stages and can be either acute (plates and nails) or gradual (external fixation and internal lengthening nails) [20–25]. If there is any concern for pre-existing infection, then staged surgery is recommended, with the first stage to take out pre-existing hardware and evaluate the surgical site (cultures, etc.). The second stage would be the planned corrective osteotomy and fixation. The author's preference is usually two stages when hardware is present.

1.7.1 Preoperative Planning (Fig. 1.6)

Careful deformity analysis should always be performed as part of the preoperative plan to determine the amount of correction required. Additionally, the osteotomy site and surgical tactic should be carefully planned out [2]. If hardware is present, this includes making sure that instruments to get the previous hardware out are available. There should also be specialty instruments available in the event that failed hardware (especially screws or nails) is encountered. Correction of the deformity requires decisions regarding the location and type of osteotomy as well as the method or implant to stabilize the osteotomy.

1.7.2 Osteotomy Overview

It is important to understand the basic principles and techniques for osteotomies. It is imperative to ensure that the soft tissue envelope at the site of the osteotomy is pristine and without compromise which could lead to wound problems. The ideal location for any osteotomy is in "virgin" bone but as close to the CORA as possible. When the osteotomy is located directly at the CORA, a pure correction occurs without translation to re-establish the mechanical axis. As the osteotomy site moves away from the CORA, increased translation occurs to re-establish the mechanical axis [26] (Fig. 1.7). Metaphyseal bone tends to heal better overall as well as create better regenerate in cases of gradual correction. The osteotomy can be done via a percutaneous technique or open. Our preference is for a Gigli saw osteotomy in gradual correction cases, trying to preserve the periosteum as best possible in the method of Ilizarov. It can also be done with the multiple drill hole technique with an osteotome.

Numerous types of osteotomies have been described [26, 27]. Closing wedge and opening wedge osteotomies result in shortening and lengthening of the extremity, respectively. A dome or neutral wedge osteotomy does not appreciably affect the length. An oblique single-cut osteotomy can also be performed but is much harder to execute when there is a multiplanar deformity and is mathematically derived [28]. One must define the angular and rotational deformities as well as determine the no angulation view for the limb. This allows for single cut and fixation with correction of the malunion. This will preserve the length or restore the length depending on the deformity parameters. In cases of pure rotation or pure leg length discrepancies, or with gradual correction, a transverse osteotomy is sufficient. Opening wedge osteotomies in cases with internal fixation will require some type of bone graft/substitute to be placed into the gap. Distraction osteogenesis is used in cases of gradual correction or leg lengthening to regenerate the bone (Fig. 1.7b–d). Intra-articular osteotomies have also been described extensively when there are intra-articular malunions or incongruities [29].

Fig. 1.6 The TraumaCAD™ preoperative plan for the patient in Fig. 1.2; the planned cut and correction can be seen on the right side of the image

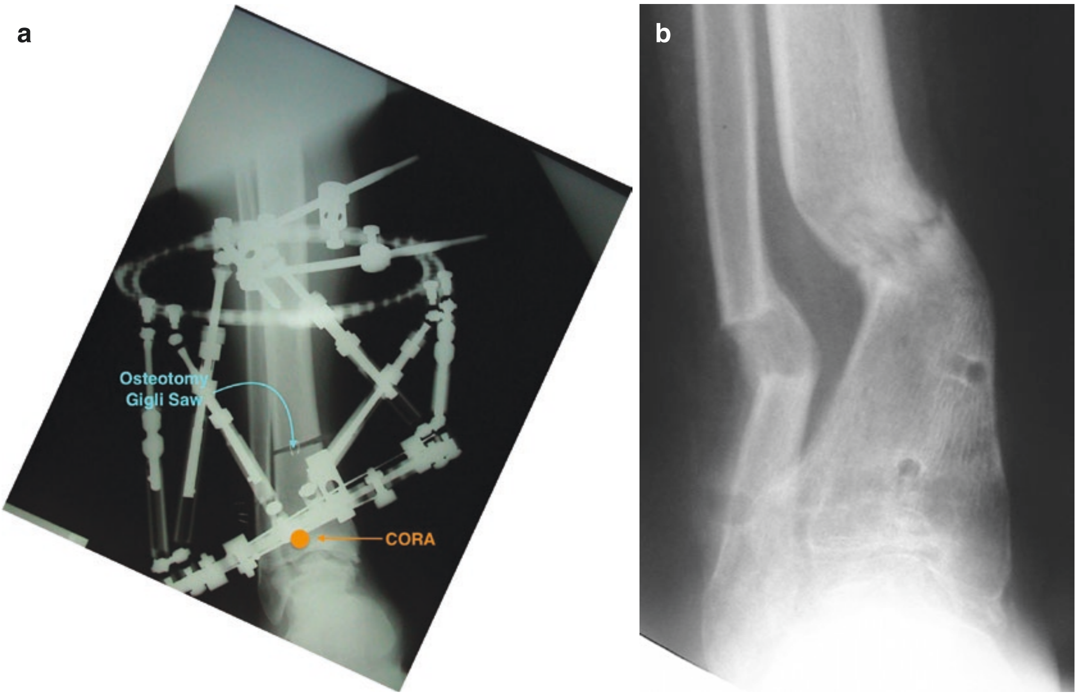

Fig. 1.7 The patient from Fig. 1.1. The osteotomy site is seen proximal to the center of rotation and angulation (CORA) (refer to Fig. 1.4). Due to the distance from the CORA, translation has to occur to allow for re-alignment of the mechanical axis utilizing distraction osteogenesis to create bone regenerate. (**a**) Radiograph orthogonal to the distal ring showing the osteotomy site in relation to the CORA (*orange dot*). (**b**) Anteroposterior (AP) view of the right ankle after correction – note translation. (**c**) Lateral view of the right ankle after correction – note translation. (**d**) AP view of the right tibia showing re-establishment of the mechanical axis of the tibia (*green line*)

1.7.3 Future Technology

Three-dimensional imaging is allowing newer techniques to be used to facilitate malunion management. The use of patient-matched instruments to create patient-specific treatment options are coming to light. Rosseels et al. published their results when using patient-specific 3D printed guides to aid in osteotomy planning. Although their results were satisfactory, they felt that the majority were under corrected [30]. Oka et al. created 3D patient-matched osteotomy jigs using 3D rapid prototyping technology based on the normal contralateral limb. They had 16 patients with upper extremity malunions that underwent 3D corrective osteotomies with patient-matched instruments with excellent results, achieving accurate correction and functional recovery [31]. As 3D printing becomes more prevalent and imaging techniques continue to evolve, the use of such 3D printed cutting jigs to perform precise osteotomies will become more widespread.

1.8 Summary

The best management in treating malunions is their prevention. The surgeon should adhere to basic AO (*Arbeitsgemeinschaft für Osteosynthesefragen*) principles of fracture fixation and first obtain and then maintain a reduction. When the joint is involved, anatomic restoration of the joint and bone grafting as needed to support the joint in cases where it is needed can help mitigate subsidence. In cases of diaphyseal fractures, restoration of length, alignment, and rotation are key. Unfortunately, iatrogenic causes have been shown to be a significant contributor to the development of a malunion. In cases where corrective osteotomy is needed, careful and detailed preoperative planning will help to ensure a successful outcome.

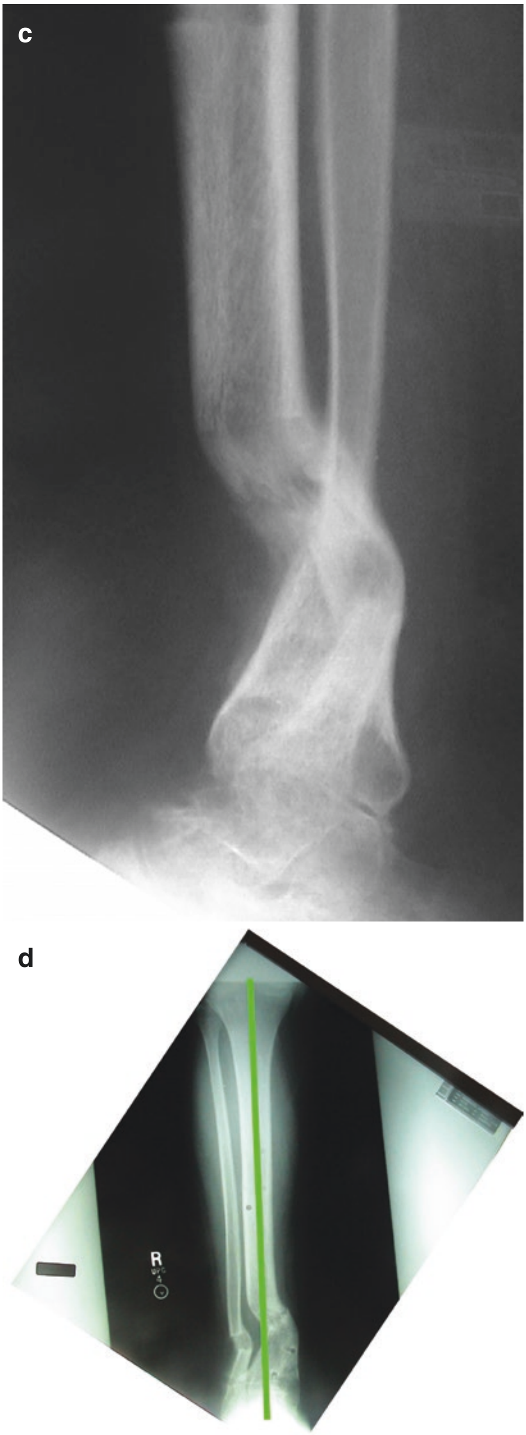

Fig. 1.7 (continued)

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2 Malunions of the Clavicle

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2.1 Clavicle Fractures

2.1.1 Introduction

Clavicle fractures are common injuries encountered by orthopedic surgeons [1–12]. They represent 2–15% of all adult fractures [1–28] and between 35% and 66% of fractures to the shoulder girdle [5, 7, 8, 12, 18, 29]. The incidence of clavicle fractures is bimodal, with a peak incidence in young, active individuals [20, 21, 24] and another peak later in life. Young patients with clavicle fractures are predominantly male, and older patients are typically female [3, 6, 11, 17, 23, 28].

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Two mechanisms of injury can be identified as the most common causes of clavicle fractures [6]. The most common occurs in around 90% of cases [6] and results from a fall [12, 30] or a direct blow [19, 28, 31] to the outer side of the shoulder. The second most frequent mechanism of clavicle fractures tends to occur after a fall onto an outstretched arm [2, 6, 12]. Clavicle fractures in young patients are frequently observed in relation to leisure and high-performance sports [32]. Fractures in the elderly are often acquired during low-energy domestic falls [17, 20] and are also often found in osteoporotic bone [28].

Evaluation of clavicle fractures begins with a thorough history and physical examination and typically progresses to plain radiographs identifying the fracture site and pattern [11]. Fractures of the middle third of the clavicle are the most common [2, 23, 24, 30, 33] and account for 66–85% of all cases [3–7, 12, 16, 19, 24, 28–30, 32]. Injuries to the midshaft occur where the clavicle changes its cross-sectional shape and is devoid of muscular protection [26]. Most shaft fractures (approximately 70%) are displaced [3, 19]. Displacement is much more likely to occur in the middle part of the clavicle compared with fractures of the medial and lateral thirds [17, 23]. There is an increasing incidence of multifragmentary and displaced fractures of the clavicle due to an increased participation by patient populations in high-speed sports [2].

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2.1.2 Initial Fracture Treatment

Traditionally, the majority of clavicle fractures, especially midshaft clavicular fractures in adults [32], have been treated non-operatively [1, 2, 9, 22, 26, 34]. Investigators have cited high union rates and low associated functional deficits as a basis for such management [12]. The goal of non-surgical clavicle fracture treatment is to achieve bony union while minimizing dysfunction, morbidity, and cosmetic deformity [23]. Conservative treatment usually consists of wearing a simple sling [3, 5, 6, 8, 16, 17, 23, 26, 27, 30, 35] or a figure-of-eight bandage [2, 3, 5, 6, 8, 16, 17, 23, 30, 35] until the fracture is healed according to radiographs and clinical assessment [11].

According to the literature, due to a low risk of nonunion or malunion, the following clavicle fractures can be treated non-operatively: fractures with little or no displacement [2, 23, 24], simple fractures, fractures of the medial or lateral third [2], multi-fragmentary fractures with little or no displacement [2, 23, 24], and fractures in low-demand patients [16], patients with low compliance or substance abuse [2], or patients with medical contraindications to surgery [16]. In these patients, conservative treatment is recommended as there is an increased postoperative risk of complications or the benefit of surgery is minimal [2]. Furthermore, conservative treatment offers the advantage of low costs [16]. Despite these benefits, surgery for clavicle fractures is playing an increasingly important role in the clinical setting. This is mainly accomplished through open reduction and internal fixation [26] with either compression plating or intramedullary nail fixation [16]. The goal of surgery is to improve the functional outcome of the shoulder as well as to avoid nonunion and symptomatic malunion by achieving anatomic reduction [3].

2.1.2.1 Initial Outcome

Following conservative treatment of clavicle fractures, union typically occurs within 8–12 weeks [36] with patients regaining function after 3–6 months [22]. Fractures treated conservatively often heal uneventfully and are rarely complicated by significant morbidity [27] such as functional disability [26]. Although clinical results of non-operative treatment have generally been considered favorable [4, 31, 32, 37] resulting in minimal to no persistent symptoms [38], it is widely recognized that not all clavicular fractures treated conservatively will have a good outcome [8, 16, 23, 27, 39]. It is apparent that union alone may not result in clinical success [40], and sequelae following non-surgical treatment of clavicular fractures are not uncommon [41]. A recent, prominent study showed a high prevalence of symptomatic malunion and nonunion following non-operative treatment of displaced midshaft clavicular fractures [42]. Another large clinical study has shown that more than 10% of patients with clavicle fractures that were treated conservatively exhibited unsatisfactory radiologic and cosmetic results and 3–5% of cases suffered significant mobility deficits in the affected shoulder [10].

While it is unclear why there is such a difference between the outcome of clavicular fractures in previous reports and those in more recent studies, there are several possibilities [42]. The earlier reports often included data on clavicular fractures in children, who have inherent healing abilities and remodeling potential [28]. This may have artificially improved the overall results of the data in those reports [28, 42]. Moreover, most of the previous studies based the success of non-operative treatment on radiographic bony union which occurred in more than 95% of the cases [15]. There was a lack of data in the literature regarding functional and especially "patient-based" outcomes following clavicular fractures [22, 34]. Patient-oriented outcome measures and scores report upper extremity functional deficits that might not be detected by surgeon-based scores [28, 42]. Additionally, it is clear that patient-based outcome measures reveal residual impairment after clavicular fractures that surgeon-based or radiographic measures do not [34]. Another relevant issue is changing patient expectations. Most active clinicians are acutely aware that a patient today is more likely to expect a rapid return to pain-free function following a fracture (and be more vocal when this does not occur) than was the case previously [42].

Conversely, it may also be that injury patterns are changing [42].

2.1.2.2 Non-operative Versus Surgical Treatment

While non-operative care remains the standard for the majority of minimally displaced clavicle fractures [3, 12], open reduction and internal fixation has demonstrated superior results when compared with conservative management in recent trials of management of displaced fractures [3, 9, 11]. Surgery has been shown to decrease the rates of malunion [3, 43, 44], nonunion [3, 43, 44], and functional impairment [23, 44]. This could be explained by the fact that surgical treatment with open reduction and internal fixation achieves an anatomic reduction, which non-operative treatment does not in most cases [45]. Despite these recent findings, the optimal treatment for acute, displaced midshaft clavicle fractures is still controversial [3, 12, 24, 25, 43]. Despite patient-based outcome measures revealing an increased incidence of clavicular malunion following non-operative treatment [12], there is limited evidence of these sequelae available from randomized controlled trials [6].

With regard to surgical treatment, fixation and healing of fractures in the middle third of the clavicle are affected by anatomic and biomechanical conditions of the clavicle [46]. As implant technology and surgical techniques have improved, surgical outcomes have been enhanced and fewer complications resulted [1]. According to the Canadian Orthopaedic Trauma Society [42], open reduction and internal fixation (ORIF) of displaced clavicle fractures compared to conservative treatment showed better functional outcome and less cases of malunion and nonunion at 1 year of follow-up. This was confirmed by McKee et al.'s meta-analysis [21] of randomized controlled trials showing, in addition to the above mentioned, a decreased overall complication rate with operative intervention. Additionally, Xu et al.'s meta-analysis [43] showed that patients treated non-operatively were more likely to develop a complication, especially a malunion, than those treated with primary operative repair. Moreover, recent research has suggested that operative intervention has fewer long-term sequelae [22].

Lenza et al. [6] concluded that treatment options should be chosen on an individual patient basis, with careful consideration of the relative benefits and harms of each intervention and patient preferences. Presently, clavicular fracture treatment is largely determined by fracture characteristics [11], stability of fracture segments [23], displacement [23], and localization [11]. When making the decision for surgery, attention must be paid to the patient's psychophysical features and expectations, as well as age and gender [11, 23, 24]. It has been reported that patients within a younger female population tend to be more often unsatisfied by a poor cosmetic result [24]. Physicians should determine whether there have been previous injuries to the ipsilateral clavicle as well as the patient's hand dominance, since these factors may alter the treatment decision [11].

The following factors have been shown to be predisposing to less favorable results after nonsurgical treatment of midshaft clavicle fractures: displacement, comminution, shortening, and fractures of the dominant arm [19]. Nonetheless, cases in which osteosyntheses should be considered as the primary treatment are still under debate [19]. For details about the indications of surgery reported in literature, see Table 2.1 [2, 4–6, 11, 14, 18, 19, 22–24, 28, 44, 47–49].

2.1.2.3 Complications After Initial Fracture Treatment

Complications following fractures to the clavicle are relatively uncommon but include the following: malunion (after non-operative treatment 9–36%; after surgical treatment 0–4%) [3, 16, 21, 25, 42, 50, 51] or nonunion (15–20%) [8, 21, 27], pneumothorax (3%) [27], brachial plexus injury (1%) [27], posttraumatic arthritis (3%) [27], refracture (4%) [21, 27], infection, and complications of surgical treatment [27] (including hardware removal needed in one third of cases because of prominence) [19, 21]).

A malunion of the fractured clavicle indicates that the fracture has healed in a less than ideal position. This is often associated with large callus

Table 2.1 Indications for primary fixation of a displaced fracture of the clavicle

Fracture pattern and inspection	
	Prominence over the fracture [11]
	Significant cosmetic or clinical deformity of the shoulder [23, 28, 47, 48]
	Ecchymosis [11]
	Soft tissue compromise, skin breaks, or tenting [2, 11, 14, 23, 28, 44]
	Impending open fractures [6, 28, 47]
	Open fractures [2, 4–6, 23, 28, 44, 47]
	Segmental fractures [28]
	Comminution [6, 18, 19, 28, 44]
Displacement [18, 23, 48]	
	Of more than 20 mm [4, 23, 28, 49]
	Of greater than 15 mm [2, 23]
	Significant, severe fracture displacement [5, 6, 23]
	>100% of a shaft width [2]
	Cranio-caudal displacement of the fragments greater than 2.3 cm [24]
	Two or more diameters of displacement [22]
	Severe dislocation and angulation [4]
Shortening	
	≥ 13% associated with fragment displacement ≥2 cm [24]
	Greater than 15% [24]
	More than 20 mm [28]
Associated injuries	
	Floating shoulder [23, 28, 44, 47]
	Scapulothoracic dissociation [47]
	Scapular malposition and winging [28]
	Mediastinal structures at risk (because of displacement) [23]
	Ipsilateral upper extremity injuries/fractures [28]
	Multiple ipsilateral upper rib fractures [28]
	Bilateral clavicle fractures [28]
Neurovascular problems	
	Neurovascular injuries [2, 6, 28, 47]
	Post-neurovascular repairs [47]
	Neurovascular compromise [4, 14, 23]
	Progressive neurologic deficit [28]
Patient factors	
	Higher activity level [47]
	Increasing functional demands [48]
	Younger active patients [23]
	Advancing age [18]
	At higher risk of malunion, nonunion, or other sequelae [2]
	Fractures of the dominant arm [19]
	Polytrauma [2, 23, 28, 47]

formation [13, 19, 52] leading to a narrowing of the thoracic outlet with compression of the brachial plexus [19, 30, 34, 35, 38, 52–54] and subclavian vessels [5, 19, 34, 54]. Aside from neurologic symptoms [21] such as nerve paresthesia, brachial plexus neuropathy [27], and ulnar neuropathy [27] and the abovementioned thoracic outlet syndrome [8], malunion of the clavicle can also cause vascular injuries such as thrombosis, pseudoaneurysm, vessel compression [27, 54], and laceration or rupture [5] and the development of Paget-Schroetter syndrome [55] which is a primary upper extremity deep vein thrombosis of either the axillary or subclavian vein. In McKee et al.'s systematic review comparing non-operative with operative treatment of midshaft clavicle fractures [21], the predominant complications in the non-operative group were nonunion, neurologic problems (including brachial plexus irritation and compression), and symptomatic malunion. The most common complications following surgery consisted of local hardware irritation or pin protrusion (treated with removal of hardware) and wound infection [21]. Another study reported additional complications such as plate loosening, plate breakage, infection, painful implants, refracture after plate removal, and discomfort [44].

2.2 Malunion of the Clavicle

2.2.1 Introduction

Historically, clavicle malunion has been assumed to be clinically innocuous [56]; however, malunited fractures are not always benign entities [36] as a malunion can affect the function of the shoulder [31]. Despite the clavicle's "excellent reparative powers" (as reported in literature), restoration of length, translation, and rotational deformities of the clavicle following a fracture does not occur [19]. It is therefore becoming increasingly apparent that clavicular malunion is a distinct clinical entity with radiographic, orthopedic, neurologic, and cosmetic features [28, 42].

2.2.2 Development of Clavicular Malunion

Fracture healing following a displaced midshaft fracture of the clavicle can lead to the development of a clavicular malunion. According to Davies [22], midshaft clavicle fractures generally have greater deformity than lateral fractures ($p = 0.03$) following conservative treatment.

In the literature, authors have stated that "maintaining the alignment after closed reduction of a displaced clavicular fracture is wishful thinking" [19]. Despite the description of more than 200 closed reduction methods in cases of closed fractures of the midshaft clavicle, no methods have been reported as the gold standard in achieving [36] and maintaining a reduction [15, 34, 57]. Therefore, a certain amount of deformity secondary to angulation and shortening [11, 17] is to be expected [1, 10, 12, 15, 17, 19, 34, 36, 46, 50, 58].

According to McKee et al. [57], midshaft fractures of the clavicle heal in pretty much the position noticed on fracture radiographs (displacement and elevation of the medial fragment due to the pull of the sternocleidomastoid muscle with shortening due to the medialization of the lateral fragment) [4, 10, 17, 19, 26, 36, 59]. Consequently, this increases angulation at the sternoclavicular joint [36]. However, this has been recently challenged. Additionally, a rotational component to the deformity can result with the distal fragment and attached shoulder girdle rotating anteriorly in the coronal plane [36, 59]. The weight of the arm causes the distal fragment to displace inferiorly as well [10, 17, 36, 59]. Furthermore, the clavicle fragments seem to heal in a cranially convex position (apex superior malposition) [10].

2.2.3 Incidence of Clavicular Malunion

There is a disparity among the reported rates of symptomatic malunion following conservative treatment of clavicle fractures [39]. Though symptomatic malunions have been reported to be relatively rare [11, 13, 46, 51, 52], recent studies have shown that the rate of malunion after non-operative treatment may be much higher than previously indicated [2].

There are several reasons for the increased incidence. The first reason for this might be the fact that the survival rate of critically injured trauma patients (with more complex fracture patterns) has increased. Secondly, patient expectations have changed, and the follow-ups are more regular and thorough (with possible patient-oriented outcome measures). The recent literature may have excluded outcome information of children (presenting with a fabulous healing potential) which might have further increased the rate of malunion after clavicle fractures [42]. The rate of symptomatic malunion or nonunion of displaced fractures of the clavicle has ranged from 3% to 5% [38]. Fortunately, symptomatic malunion is less frequently observed than nonunion overall [1].

According to Jorgensen et al. [25] and Ban et al. [3], close to 30% of all non-operatively treated patients experienced a symptomatic malunion. Kulshrestha et al.'s randomized controlled trial [50] showed a malunion rate of 36% in the non-operatively treated patients, whereas the rate after surgical treatment was only 4%. The Canadian Orthopaedic Trauma Society reported a symptomatic malunion rate of 0% in cases of surgically treated clavicular fractures and a rate of 18% if patients were treated conservatively [42]. In McKee et al.'s meta-analysis [21] of randomized controlled trials, the malunion rate was 9% among patients treated conservatively, whereas it was 0% in the surgically treated patient group. Liu et al.'s meta-analysis [16] revealed a malunion rate of 0.8% in the surgically treated group compared to 14% found following conservative treatment of clavicular fractures. Leroux et al.'s study [51] revealed a low malunion rate of 1.1% in the 1350 patients initially treated with open reduction and internal fixation of an isolated, closed midshaft clavicular fracture.

2.2.4 Features of Clavicular Malunion

A malunion of the clavicle is a three-dimensional deformity [2, 36]. According to the literature, a symptomatic malunion of the clavicle will display one or more of the following features: shortening [4, 10, 15, 19, 26, 29, 36, 50, 57] (of more than 14–20 mm [26]), medial and inferior displacement [36, 50], anterior rotation [4] (of the distal fragment [36]), a change of angulation [50] (in a horizontal or vertical plane of greater than 20° [58], and/or an axial deviation of 10–30° [10]) [58]. See Table 2.2 [4, 10, 15, 19, 26, 29, 36, 50, 57, 58, 60].

2.2.5 Consequences of Clavicular Malunion

The clavicle has several important functions intrinsic to its length and curvature [29]. Malunion of the clavicle can result in negative consequences to the biomechanics of the shoulder joint [31] as well as the anatomic relationships [29] of the shoulder girdle and the coordination between its elements [10]. In the case of a malunion, the directions of muscle pull (inserting at the clavicle) are changed which can also lead to dysfunction [10].

Due to clavicular shortening, the lever arm of the arm/shoulder girdle also shortens [58] which can change the glenoid orientation [19, 26]. This can possibly increase the shear forces at the level of the glenohumeral joint [19, 31]. Also, the muscular balance is disturbed due to the diminished muscle-tendon tension [19, 31] causing a loss of strength and endurance. This can possibly cause pain [26] and functional problems of the shoulder especially in overhead movements [10, 19, 24] and also a decrease in abduction strength [10] and reduced range of motion [15, 31]. In addition, it has been shown that shortening of the clavicle promotes arthritis of the acromioclavicular joint and increases the risk of refracture [10].

Table 2.2 Features of clavicular malunion

Shortening [4, 10, 15, 19, 26, 29, 36, 50, 57, 60]
Medial and inferior displacement [36, 50, 60]
Anterior rotation of the distal fragment [4, 36, 60]
Angulation of more than 20° [50]
Hyperabundant callus formation [58]

Note: These features are often accompanied by pain and cosmetic or functional complaints [50]. See Sect. 2.2.4

2.2.6 Predisposing Factors for Clavicular Malunion

It is still not clear which patients are more likely to develop late complications following clavicular fractures, such as malunion [8]. Prognostic indicators that would identify individuals who are most at risk for developing malunion following this injury would be very useful in refining operative indications [21]. However, there are no studies thus far that report on predictors for developing symptomatic malunions [25], although in general greater degrees of displacement, especially more than 2 cm of shortening, are associated with a higher incidence of symptoms. In addition, there probably exist as yet unrecognized features of the displaced fracture of the clavicle which predisposes it to become a symptomatic malunion [39]. Patients with a displaced midshaft clavicle fracture seem to have a higher risk of developing residual pain [18], unsatisfying cosmesis, and a dysfunctional shoulder [18, 22, 61]. In the presence of comminution or complete displacement, especially when occurring in females or elderly patients, there seems to be a higher risk of nonunion, malunion, and poor outcome in general [2, 62].

According to Nowak et al. [18], the location of the initial fracture as well as shortening did not predict outcome except for cosmetic defects. They based this on the fact that there is intraindividual variability between clavicles for subjects without previous clavicle injuries. That study indicated that shortening, defined as the difference in length between the injured and non-injured clavicle, seemed unlikely to be a reliable predictor for sequelae [18]. Nevertheless, shortening has been reported to be a critical deficit for the development of a symptomatic malunion in multiple other studies [19, 62]. Although many efforts have been made to quantify and correlate the degree of clavicular shortening with symp-

Table 2.3 Predisposing factors for the development of clavicular malunion with conservative treatment

Displacement [18, 22, 34, 35, 61, 62]	
	Complete displacement [2, 21]
	Two clavicular diameters or more [22]
Comminution [18, 62]	
Female patient [2]	
Older or elderly patient [2, 18]	
Shortening [28, 34, 56, 62]	
	More than 14 mm in females, 18 mm in males [29]
	More than 1.4–2 cm [19]
	More than 1.5 cm [63]
	More than 2 cm [7, 23, 39]

toms, there is still no clear single measure that can accurately predict which patients will be symptomatic with a clavicle malunion [56]. See Table 2.3 [2, 7, 18, 19, 21–23, 28, 29, 34, 35, 39, 56, 61–63].

2.2.7 Prevention of Clavicular Malunions

Appropriate initial management of a clavicle fracture can prevent later complications such as malunion of the clavicle [30]. Many unsatisfactory results attained after conservative therapy for midclavicular fractures can be detected relatively early in a patient's post-injury course and may prompt surgical intervention. Unfortunately, studies have shown that immobilization in extension (i.e., a figure-of-eight bandage) is no better than a sling for midshaft fractures [19, 58]. There is no closed method of reduction shown to obtain and maintain improved alignment in displaced fractures of the clavicle.

In contrast, various authors recommend initial surgical intervention in order to avoid painful sequelae and functional deficits after clavicular shaft fractures [2]. According to the literature, only a percutaneous or open reduction and internal fixation seems to prevent the development of a clavicle malunion in a displaced fracture of the midshaft clavicle, especially in the young, active age group [19, 26]. This is confirmed by the results of Liu et al.'s meta-analysis [16] showing a significant difference in malunion rate between operative and non-operative treatment for clavicle fracture (RR 0.11, 95% CI 0.04–0.29), which indicates that operative treatment reduces the rate of malunion. The meta-analysis of McKee et al. [21] has shown an absolute risk reduction for developing a clavicle malunion of 9% (ranging from a 9% risk with non-operative treatment to a 0% risk with operative care). Additionally, Xu et al. [43] demonstrated with their meta-analysis that operatively treated displaced midshaft clavicular fracture patients had a lower nonunion and malunion rate compared with those treated non-operatively (2% versus 15%). Furthermore, Kulshrestha et al. [50] showed a 4% malunion rate in the operative group versus a 36% rate after non-operative management.

In any case, fracture healing should be monitored and patients be made aware of the risks of returning to full activity levels before complete healing of their clavicle fracture. According to Cooney et al. [5], emergency physicians should properly educate patients concerning the need to follow recommendations restricting strenuous activity, lifting, and load bearing in an attempt to limit re-injury and subsequent complications, both vascular and otherwise. Moreover, patients should be referred for outpatient follow-up to allow for proper monitoring of recovery and fracture healing [5]. See also Sects. 2.1.2.2 and 2.2.6.

2.2.8 Diagnosis and Evaluation of Clavicular Malunions

2.2.8.1 Presentation

Introduction A malunited clavicular fracture has historically been considered a cosmetic problem [11, 35], with functional limitations [34, 46] or symptoms being rare [17, 35, 46, 64]. Previous reports indicated that unless there was a visible deformity, most patients with a malunion would function well and be asymptomatic [13, 34]. More recent studies, in which the outcome measures after clavicular fracture healing were more patient based rather than simply radiological, showed that there were less favorable outcomes of a malunion [1, 4, 11, 43, 58]. Also, non-operative treatment of displaced shaft fractures is associated with a higher rate of functional deficits than previously reported [17].

Symptomatic malunion can result in significant disabling symptoms [13, 36] and become especially problematic in patients with significant fracture shortening [12, 58]. Within the literature, there is a relative consensus about the amount of shortening needed to cause shoulder discomfort and dysfunction, generally agreed to be 15 mm [11, 26, 33] to 20 mm [7, 27, 59] or more. Patients with pain and functional impairment may adapt to a lower functional level in order to overcome the shortcomings caused by the dysfunction [41].

Symptoms Malunion following clavicular fracture may be associated with orthopedic, neurologic, and cosmetic complications [34]. Patients report pain, cosmetic concerns, and muscular, neurovascular, and functional impairment. Complaints vary from mild to serious impairment in daily activities [19], and there is increasing evidence that patients can have substantial dissatisfaction and disability following a clavicular malunion [36, 59]. Although the cosmetic consequences of injuries are rarely a focus of orthopedic reports, it is clear that many young patients are discontent with the appearance of the asymmetric, "droopy" shoulder that can be associated with clavicular malunion [34]. See Table 2.4 [1, 4, 5, 10, 11, 13, 19, 24, 28, 33, 34, 36, 46, 56, 57, 59, 60, 64, 65].

Table 2.4 Symptoms of clavicular malunion

Muscular impairment	
	Weakness [4, 10, 11, 19, 24, 28, 34, 36, 53, 56, 59]
	Fatigue [4, 19, 34, 36, 56, 57, 59]
	Atrophy [10]
Pain [1, 4, 5, 10, 11, 13, 19, 33, 34, 36, 46, 57, 59, 64]	
	Periscapular pain [36, 56]
	Problems with sleeping on the back [19]
Neurovascular impairment [11, 13, 36, 60, 64]	
	Numbness/paresthesia [4, 19, 57]
Cosmetic concerns [4, 5, 19, 60]	
	Bump or prominence [36, 59]
	Deformity [5, 59]
	Sense of displacement [59]
	"Droopy shoulder" [34, 65]
	Shoulder asymmetry [56]
Functional impairment [1, 60]	
	Decreased range of motion [10, 13]

2.2.8.2 Physical Exam

Certain consistent features are seen in patients who present with symptoms [34]: on observation, one will notice the affected shoulder to droop (ptosis) and be "driven in" when the arms are rested at the patient's side [36] (Fig. 2.1). The shortening of the mediolateral length of the clavicle [10, 60] with inferior displacement of the distal fragment [34, 60] and anterior rotation [59, 60] frequently emerges as the characteristic finding. One can measure the relative lengths of the injured and uninjured clavicle by marking the acromioclavicular joint on either side and measuring the distance to the sternal notch [36], as these landmarks are easily palpable [36]. However, at present, there is no validated method for measuring clavicular shortening [2]. The rotational aspect of the deformity could be seen as scapular winging [36]. Observing the patient from behind as they raise and lower their arms in forward flexion will aid in the detection of this aspect of the deformity [36]. At the same time, angulation of the sternoclavicular joint is frequently observed [27]. Objective measures of shoulder strength and endurance often show deficits compared with their uninjured side [36]. McKee et al. [59] reported deficits in strength (specifically endurance strength) following nonoperative care of displaced clavicular fractures [59]. Bony spurs or bulky space-occupying callus has been sporadically reported [58]. Furthermore,

Fig. 2.1 Clinical pictures demonstrating severe shortening and deformity of the right shoulder following a right clavicular malunion. Note the shortened, "ptotic" position of the shoulder

a clavicular malunion at the lateral end of the clavicle with a posterior bony projection reducing the capacity of the supraspinous fossa before it enters the subacromial space can result in rotator cuff impingement syndrome [14]. A summary of clinical findings is provided in Table 2.5 [10, 14, 27, 36, 58–60].

2.2.8.3 Diagnostic Imaging

Radiographs (Figs. 2.2, 2.3, 2.4, and 2.5) Radiographic evidence of a malunion is universal following the closed treatment of displaced fractures of the clavicle [21, 34]. However, the radiographic assessment of deformity is difficult due to the S-curve of the clavicle in the coronal plane [36]. Anterior-posterior radiographs may not accurately reflect the degree of deformity [10, 36]. Nevertheless, radiographs give a rough estimate of deformity by measuring overlap of the fracture

Table 2.5 Clinical findings in cases of clavicular malunion

Ptosis (droop, driven in) of the shoulder [36]
Deformity [60]
Shortening of the mediolateral length of the clavicle [10, 60]
Inferior displacement of distal fragment [60]
Anterior rotation of the clavicle [59, 60]
Scapular winging [36]
Angulation of the sternoclavicular joint [27]
Decreased strength (residual and endurance) [36, 59]
Bone spikes or bulky space-occupying callus [58]
Rotator cuff impingement [14, 60]

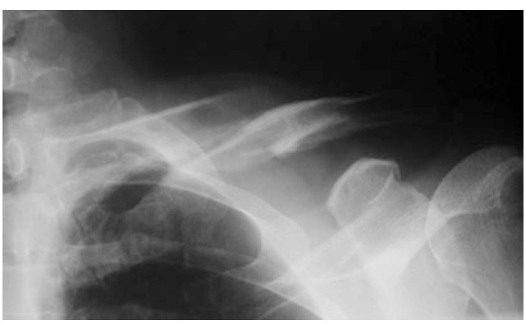

Fig. 2.2 Radiograph of the left clavicle demonstrating the typical shortened, inferiorly displaced position of the distal fragment. This is part of a complex three-dimensional deformity that includes anterior displacement and rotation of the distal fragment

Fig. 2.3 Radiograph demonstrating malunion with shortening and typical deformity

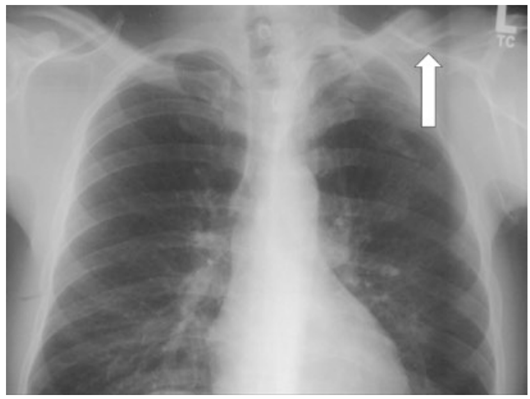

Fig. 2.4 Chest radiograph demonstrating a left clavicular malunion (white arrow) following non-operative treatment of a displaced midshaft fracture of the clavicle. Significant chest/shoulder asymmetry resulted with patient complaints of weakness and thoracic outlet syndrome

Fig. 2.5 An angular malunion in a young 18-year-old patient following closed treatment of an angulated midshaft clavicle fracture. Significant clinical deformity resulted: in addition, this patient is at risk for refracture

fragments as shortening [36]. One can compare the injured and uninjured sides [66] on separate radiographs or compare them directly on a neutrally rotated chest radiograph [36].

According to McKee et al. [59], fractures of the clavicle midshaft usually heal in the same position as initially seen on X-rays. Initial anterior-posterior radiographs of clavicle fractures often demonstrate clavicular shortening [12] with an inferior-posterior [12] displacement or ptosis of the lateral fragment [58]. (See also Sect. 2.2.2.) In clavicular malunion, shortening of the clavicle in the medial-lateral plane (with the abovementioned displacement) is therefore a common radiographic finding in symptomatic patients [34].

Computed Tomography (Fig. 2.6) Computed tomography scanning may also be helpful in the setting of clavicular malunions but is not typically a part of the initial evaluation [11]. It can be helpful to assess the three-dimensional deformity associated with malunions and its effect on scapular orientation [36]. CT scanning is particularly helpful in those fractures located medially, which are difficult to evaluate fully with conventional radiographs [58]. Three-dimensional reconstruction is also extremely helpful in understanding the deformity in the most laterally located fractures that are prone to angulation [58].

Others For diagnostic purposes in relation to clavicular malunion, nerve conduction studies and magnetic resonance imaging (MRI) are used in order to demonstrate dysfunction of, and compression of, respectively, the brachial plexus [8].

Fig. 2.6 This CT scan taken at the scapular level of a patient with a left clavicular malunion demonstrates the result of the malunion with anterior translation and protraction of the left scapula and shoulder girdle (*white arrow*) compared to the normal scapular position on the right side

2.2.9 Management of Clavicular Malunions

2.2.9.1 Non-surgical Treatment

So far, there has been no literature on closed treatment of clavicle malunions, but it seems evident to begin with non-operative measures before considering surgery [19] including physiotherapy or pain medication [19]. If a satisfactory result cannot be achieved, surgical treatment should be discussed with the patient [19].

2.2.9.2 Surgical Treatment

Introduction Although the treatment of malunions of the clavicle continues to evolve [49] and distinct clinical entities can be treated successfully [19], clavicular malunions continue to present challenges for orthopedic surgeons [1, 13, 60]. This is due to the technical difficulty of accurately restoring anatomy to a complex three-dimensional deformity and securing adequate skeletal stabilization [13, 60]. Nevertheless, the treatment of symptomatic malunions by open reduction and internal fixation usually results in high patient satisfaction [49]. The objective of treatment in patients with symptomatic clavicular malunion is to restore the normal anatomic configuration and length of the clavicle, thereby reducing local pressure on the adjacent neurovascular structures, as well as to relieve typical symptoms of malunion, and to improve functional outcome and aesthetic results [64, 67]. In general, the following surgical interventions for treatment of clavicular malunion have been described in the literature: excision of callus, resection of clavicle, claviculoplasty (resection of protruded bone), and corrective osteotomy of the clavicle [53, 60].

Contraindications According to Bosch et al. [46], corrective osteotomy is not indicated in patients with a malunited clavicular fracture who are asymptomatic and function well in their daily activities [67]. Also, some physicians may advise against surgical correction because of the long-standing tradition of non-operative treatment of clavicular fractures and because of an appropriate concern that operative treatment of the malunited fracture is associated with a risk of damage to the underlying neurovascular structures [38]. Other authors have advised not to surgically correct a clavicular malunion in cases of severe osteoporosis or low patient functional demands [40, 67]. For McKee et al. [40], further contraindications for surgical correction of a malunion were inadequate soft tissue coverage, an active infection at or near the operative site, and an unreliable, noncompliant patient. For details of contraindications for surgery, see Table 2.6 [40, 67].

Indications Since many clavicular malunions are asymptomatic, careful patient selection and counseling before surgery (with its inherent risk of complications) is recommended [17]. The careful assessment and selection of patients is mandatory for determining who may benefit from a corrective osteotomy [34]. Despite the abovementioned contraindications and risks of surgical intervention, correction after a malunion seems to be a good treatment option in cases of a symptomatic malunion of a midshaft fracture of the clavicle [4]. Patients with symptomatic clavicle malunions benefit from a corrective osteotomy of the clavicle to restore a more anatomic position [56]. The indications for surgical intervention in patients are primarily clinically based [1]. Thus, symptomatic malunion [36, 60], not asymptomatic radiographic malunion [40], is the indication for operative correction [11]. Most authors would not offer operative treatment for cosmetic reasons alone [34, 36], and for Smekal et al. [7] and McKee et al. [40], dissatisfaction with the appearance of the shoulder girdle [60] must be accompanied by some functional complaints or increased callus formation [60] to warrant surgical correction of a clavicular malunion [67]. Furthermore, difficulty using straps, backpacks, etc. is considered a relative indication for a surgical correction [40]. Correction of the deformity should be considered when there is radiographic displacement or shortening associated with pain [1, 4, 40, 60, 67]. Also, in case of thoracic outlet syndrome or brachial plexus compression, surgical treatment should be considered [60]. Less commonly reported indications for malunion correction reported in literature were supraclavicular nerve entrapment, costoclavicular syndrome, Paget-Schroetter syndrome, subclavian and axillary vein compression, and supraspinatus impingement [60]. For McKee et al. [40], this is indicated by clavicular malunion with substantial shortening (>1 cm, typically 2–3 cm), angulatory deformity (>30° at the fracture site), or translation (>1 cm). Another surgical indication is functional impairment [1, 13, 15] such as weakness and rapid weakness of the shoulder girdle muscle [67], especially in overhead or resisted activities [40]. If there are persistent symptoms of neurovascular compression [40, 46, 60] distally in the arm [13, 67] as a result of either clavicular deformity or massive callus formation after fracture [13, 46], then correction by osteotomy and callus resection is a reliable solution [46]. This is particularly imperative if the signs and symptoms of neurologic compression persist after maturation of the callus [13]. Other reasons for secondary surgical treatment are malunion with sequelae such as arthritic changes of the acromioclavicular joint [4]. For details of surgical indications, see Table 2.7 [1, 4, 11, 13, 14, 23, 34, 40, 41, 46, 60, 66, 67].

Table 2.6 Contraindications for surgical correction of clavicular malunion

Inadequate soft tissue coverage [40]
Active infection at or near the operative site [40]
Radiographic malunion only (no symptoms) [40]
Asymptomatic malunion [67]
Coexisting clavicular nonunion [40, 67]
Unreliable, noncompliant patient [40]
Osteopenic bone, osteoporosis [40, 67]

Timing of Surgical Intervention Surgical correction of a clavicular malunion is an elective operation that can be performed with consistent and reliable results at any time after injury [36], although the optimal timing of surgical correction is unknown [19]. It has been

Table 2.7 Indications for surgical correction of clavicular malunion

Radiographic displacement or shortening associated with the following sequelae:
Pain, discomfort [1, 4, 11, 34, 40, 46, 60, 67]
Shoulder dysfunction [1, 11, 13, 14, 34, 40, 46, 60, 67]
Acromioclavicular arthritic changes [23]
Neurovascular impairment [11, 13, 34, 40, 41, 46, 60, 66, 67]
Cosmetic dissatisfaction [40, 60, 67]

reported that corrective osteotomy performed within 2 years of the fracture seemed to lead to a better outcome than when done once the fracture has healed for a long time [19]. Hillen et al.'s study [4] suggested that better results can be obtained by correcting the deformity within the first year after injury. Leroux et al. [51] reported a median time to osteotomy for malunion (15 cases) of 14 months (range 7.8–15.7 months) after initial open reduction and internal fixation of isolated, closed midshaft clavicle fractures. The systematic review of the surgical treatment of clavicular malunions by Sidler-Maier et al. [60] did not find an impact of time to surgery on the outcome after correction of the clavicle malunion. Nonetheless, it seems to be beneficial to consider early correction of a clavicle malunion, as early surgical correction easier restores the clavicle anatomy with less bony and soft tissue dissection when compared to delayed reconstruction of a clavicle malunion especially for acute displaced midshaft clavicle fractures [39, 60].

Surgical Techniques The systematic review of the current literature by Sidler-Maier et al. [60] has shown that the majority of patients ($n = 77$) in 29 included studies were treated with an osteotomy and subsequent ORIF (open reduction and internal fixation). The next most frequent management choice was debridement, excision, or removal of excess callus or bone ($n = 19$), but also other techniques like resection of the clavicle or nerve exploration and decompression were reported [60]. As for the approach, mostly a supraclavicular incision or a sagittal incision (in Langer's lines) was used. Rarely, a horizontal or transverse incision was used [60].

Corrective Osteotomy Symptomatic malunions may be addressed with open reduction and internal fixation, bone grafting, and corrective osteotomy as needed [11, 19, 60]. In this regard, anatomic restoration is usually achieved by an osteotomy of the malunited site and its realignment [64]. Despite the initial rare use of an osteotomy to restore pre-injury anatomy being recommended in the literature as a therapeutic alternative to correct symptomatic clavicular malunion [10], it has led to rapid reduction of symptoms in the reported cases [10, 33, 46]. Overall, corrective osteotomy has been reported to improve symptoms and shoulder function significantly in cases of malunion [11, 17, 34, 39, 60] and seems to be required to adequately restore the anatomic alignment (length and rotation of clavicle) [60].

Planning of the osteotomy is critical [36]. In general, in order to correct the clavicle malunion, the initial fracture line should be recreated [36] with a microsagittal saw plus/minus osteotomes. Once the osteotomy is done, a drill can be used to enter the medullary canal at each end of the osteotomy. This can increase the healing potential by allowing intramedullary osteo-progenitor cells access to the osteotomy site [36]. The fracture fragments are then realigned [65], the proximal and distal fragments are distracted, and the "original" length of the clavicle can be corrected [17]. There is usually excess bone present due to the healing response after injury [36] which can be morselized and used as bone graft [60]. See also "The Role of a Bone Graft."

Method of Fixation The surgical correction of a malunion is usually stabilized with a pre-contoured clavicle plate or intramedullary pin [1, 52, 60]. In the systematic review of the surgical treatment of clavicle malunions by Sidler-Maier et al. [60], the preferred method of fixation after corrective osteotomy was plate fixation (53 of 77 patients), followed by intramedullary pin fixation ($n = 6$) though no method of fixation seemed to be superior when reviewing the study outcomes.

Plate Osteosynthesis A pre-contoured clavicle plate is typically used for osteosynthesis in this setting and can be positioned on the superior or anterior surface of the clavicle, depending on the surgeon's preference [19]. In addition to being technically easier to apply intra-operatively, the use of a pre-contoured plate decreases soft tissue irritation and reduces the rate of subsequent hardware removal. For example, McKee et al. [34] used a 3.5 dynamic compression plate for fixation and Hillen et al. [4] a pelvic reconstruction plate [60]. According to literature, plate fixation seems to be the standard surgical fixation [68]. This is possibly because, in comparison with intramedullary devices, it provides more stability regarding rotation and distraction [60]. Even if clavicle plates need bigger skin incisions and more soft tissue stripping than intramedullary devices, they appear to have a quick functional improvement 6 months postoperatively [69]. See also "Surgical Technique Described by McKee et al." [40].

Intramedullary Device An intramedullary device has also been reported for stabilization after corrective osteotomy of the clavicle [19, 35, 60, 63] and was described in detail using an elastic stable intramedullary nail (ESIN) by Smekal et al. [52, 67]. Though hardware migration has been a common problem, intramedullary fixation seems to have the shorter operative time [69]. In addition to that, the preservation of the soft tissue envelope and periosteum can accelerate fracture healing [68]. After stable fixation, the shoulder can be mobilized immediately, but resisted activities or strengthening should be limited to prevent hardware failure [19]. The advantages of this technique are the lack of hardware-related problems caused by prominent subcutaneously positioned plates [57] and the fact that bone grafting from the iliac crest is typically not necessary [57]. See also "Surgical Technique Described by Smekal et al." [67].

Claviculectomy Claviculectomy is reserved for cases where multiple reconstructive procedures have failed and the patient is left with residual pain, deformity, and typically an infection [5]. While it is not ideal and should not be considered as a first choice for reconstruction, claviculectomy provides excellent pain relief, restoration of reasonable function, and a very low re-operation rate. Historically, some authors have recommended merely resecting the clavicular segment for the treatment of a clavicular malunion, but this should not be considered as a preferred operation as superior alternatives exist [38]. See also "Surgical Technique Described by Connolly et al." [38].

Callus Excision In cases of malunion causing neurovascular impairment such as thoracic outlet syndrome due to hyperabundant callus, surgical management may include removal of the impinging hypertrophic callus or bone fragment, with corrective osteotomy and subsequent open reduction and internal fixation of the clavicle, followed by rehabilitation [30]. Removal of excessive callus and scar tissue around the clavicle after a malunited clavicular fracture can reduce or relieve disabling paresthesias and pain even if surgery is done several years after the fracture [41]. This is usually done in conjunction with a corrective osteotomy. It has been reported that adequate restoration of the thoracic outlet allows the index finger of the surgeon to pass between the clavicle and the rib [41]. Nevertheless, correction of the excessive callus will not improve the biomechanics of the shoulder joint, though it might be a good surgical treatment option in case of neurovascular impairment due to compression [60].

Claviculoplasty (Resection of Protruded Bone) Fujita et al. [54] reported resolution of thoracic outlet syndrome secondary to clavicular malunion by resection of the inferiorly protruded part of the clavicle formerly compromising the subclavian artery running just beneath the malunion site. However, this procedure alone is generally discouraged if significant deformity exists: it is best reserved for cases with malunited spicules or fragments that extend inferiorly and encroach on the thoracic outlet.

The Role of a Bone Graft In many previous studies in which surgical correction was used to treat clavicular malunion, an intercalary structural bone graft was implanted to re-establish the length and contour of the clavicle [27, 34] as well as to facilitate bone healing [60], although this is often not required [17, 36, 60]. Since the proximal and distal fragments of the clavicle can usually be distinguished as they are embedded in the callus of the malunion [34], the combination of a microsagittal saw and osteotome can be used to recreate the major fracture fragments and return them to anatomic position without using an additional bone graft [34]. This technique also avoids the morbidity associated with harvesting iliac crest bone graft [34]. Nevertheless, the use of bone grafting may be necessary when there is compromise of the local environment [49].

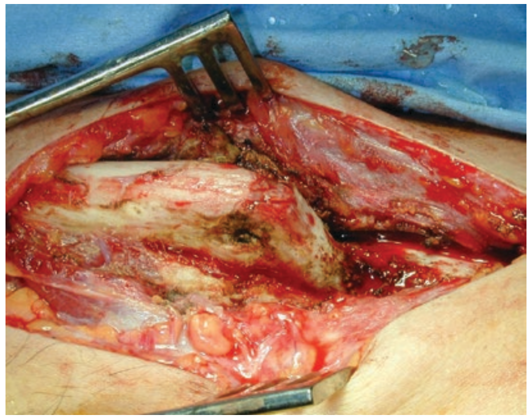

Fig. 2.7 Intra-operative photograph of clavicular malunion prior to osteotomy and correction

Examples of Surgical Techniques

1. Surgical Technique Described by McKee et al. [40] The technique described by McKee et al. [40] to treat clavicle malunion recommends an osteotomy through the original fracture plane. In order to know the exactly required correction (especially the amount of clavicular length), preoperative planning is done (clinically and radiologically).

A bone graft might be needed, should the clinical shortening of the clavicle exceed the radiological shortening to a large amount.

Patients are positioned in a semi-sitting fashion using a beach chair, under general anesthesia, and the involved upper shoulder/arm is draped in a sterile manner. The iliac crest is only draped free when the need for bone grafting is expected. Then, an oblique incision along the upper clavicle border is performed. Once the skin and myofascial layers have been dissected, the malunion can be visualized. The original fracture plane is usually identifiable because of the typical pattern of the fracture ends relative to each other (Fig. 2.7).

The osteotomy is performed after appropriate marking. If the original fracture cannot be easily recognized, an oblique sliding osteotomy can be performed. Osteotomes and a microsagittal saw are both used in a continuously cooled manner (irrigation) to re-establish the previous fracture line.

The proximal and distal fragments are then held together with reduction forceps to recreate normal clavicle anatomy and alignment. The medullary canal is re-opened using a 3.5 mm drill in both the distal and proximal parts of the clavicle. In case of extensive bone loss, a bone graft can be interpositioned between the two fragments. The length and alignment is restored with the opposite side as a reference for length measurement. The relatively flat superior surface of the distal clavicle can be used as a guide to restore rotational alignment. Following re-approximation of the proximal and distal fragments, the osteotomy site is fixed with a pre-contoured plate with a minimum of six cortices of screw purchase in both fragments (three in each fragment) (Fig. 2.8).

At the end, flattening of the bony fragments using a rongeur, and morselized local callus can be put next to the recreated fracture line (osteotomy). A standard closure is performed in layers, and the arm is placed in a sling (radiographic result: Figs. 2.9 and 2.10).

2. Surgical Technique Described by Smekal et al. [67] Surgery is performed under general anesthesia using a beach chair. Skin incision directly over the deformed clavicle. Identification of the osteotomy site is made using X-rays. Osteotomy is performed using an oscillating saw. By means of a 2.7 mm drill, the medullary canal is re-established in both the distal and proximal

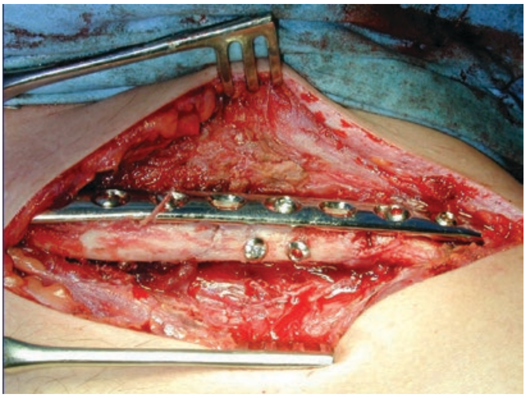

Fig. 2.8 Intra-operative photograph following osteotomy, correction of deformity, lag screw fixation, and plate application

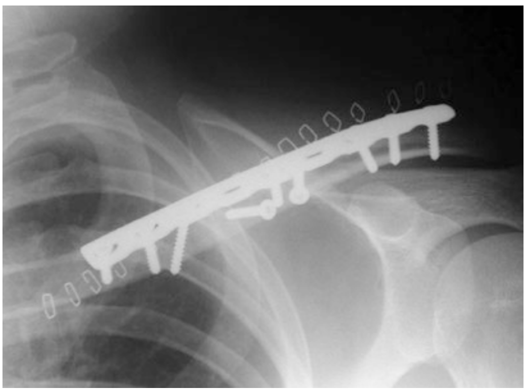

Fig. 2.9 Clavicle radiograph postoperatively. Prompt healing with relief of symptoms ensued

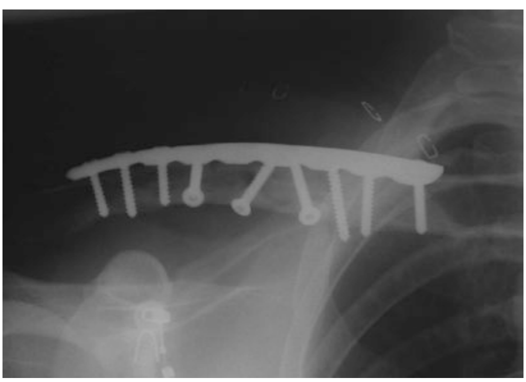

Fig. 2.10 Radiograph taken following corrective osteotomy. This is the preferred surgical treatment for patients with this condition: a "bumpectomy" alone does nothing to correct the underlying structural deformity and resulting scapular malposition/dyskinesia

fragments. At the site of the sternoclavicular joint, a 1.5 cm skin incision is used, and a titanium nail (elastic stable intramedullary nail, diameter of 2.5 mm) is inserted (under rotational movement) from the sternal end of the clavicle. The two fragments are held together by the surgical assistant to ensure restoration of the original clavicle anatomy. Once the nail is in both fragments, it is shorted as much as possible on the medial end of the *clavicle. Then, standard wound closure in layers.*

3. Surgical Technique Described by Connolly et al. [38] Connolly et al. [38] reported a double osteotomy through the antero-superior aspect of the clavicle 2 cm medial and 2 cm lateral to the malunited clavicle fracture site. This clavicle fragment is then elevated superiorly, followed by a complete dissection protecting the underlying clavipectoral fascia. After removal of the midshaft clavicle fragment and excision of exuberant callus, the reshaped middle segment was reinserted in between the distal and proximal fragment followed by fixation using an eight-hole reconstruction plate. Excessive callus was then put superiorly to the reshaped fragment followed by anterior placement of the plate for fixation of the osteotomy.

Postoperative Treatment The postoperative treatment following corrective osteotomy of clavicular malunion with consecutive plating is fairly routine and similar to that used following primary fixation of acute fractures. McKee et al. [34] allowed patients to begin pendulum exercises immediately postoperatively and active-assisted exercises 2 weeks postoperatively, when the sling was discontinued. At 4 weeks, if radiographs showed a stable situation, full active and passive range-of-motion exercises were started [34]. Resistance and strengthening exercises were allowed at 6–8 weeks post-surgical intervention [34]. See also "Surgical Technique Described by McKee et al." [40].

According to Smekal et al. [67], there is no postoperative immobilization or limitations in range of motion. Patients are supposed to use the arm in daily activities [63], but heavy weight-bearing is not allowed for the first 3 months following surgery or until bony consolidation [67]. Contact sports are forbidden until hardware removal has taken place, which is only performed 6 months following bony union. After removal of hypertrophic callus, a NSAID (non-steroidal anti-inflammatory drug) treatment for 3 weeks is recommended in order to decrease the risk for new callus formation [41]. See also “Surgical Technique Described by Smekal et al.” [67]. As far as Connolly et al.’s postoperative treatment is concerned, the operated arm should be supported in a sling for 3 weeks, then starting range-of-motion exercises. See also “Surgical Technique Described by Connolly et al.” [38].

Surgical Outcome The literature suggests that bony union as well as restoration of the length of the clavicle can be reliably achieved after surgical management of clavicle malunions [1, 19, 60]. Generally, the outcome after surgical treatment for malunion of midshaft displaced clavicle fractures has been described as favorable and nearly equal to results of primary fracture fixation [39]. Late reconstruction of a malunion after a displaced midshaft clavicle fracture is reported to be a reproducible and also reliable procedure restoring muscle strength similar to the one seen with initial surgical fixation [39]. Potter et al. [39] found that there were no significant differences between acute fixation and delayed reconstruction (after clavicular fractures) with regard to strength of shoulder flexion, shoulder abduction, and external or internal rotation, although endurance strength and shoulder scores were slightly inferior in the delayed reconstruction group. Furthermore, several reports on the operative treatment of malunited clavicular fractures have been published. See also “Examples of Surgical Techniques.”

All of these reported good results and generally satisfied patients [19]. Resolution of symptoms and improved function with a high degree of patient satisfaction have been noted following clavicular osteotomy, correction of deformity, and internal fixation [34, 35, 40, 60]. Extension osteotomy combined with autogenous bone grafting seemed to produce particularly good results in those patients with flexion or anterior translation deformity at the malunion site [46]. By lengthening the clavicle, normal anatomy is restored with proper tension on the muscles about the shoulder girdle [63]. It also corrects the cosmetic deformity and yet is minimally invasive to the soft tissue about the clavicle [63]. According to Cooney et al. [5], excellent functional outcomes are reported after total claviculectomy as a salvage procedure as long as the trapezius muscle function is intact preoperatively. Nowak et al.’s study [41] shows that removal of excessive callus in patients with persistent symptoms even several years after the fracture has a good outcome.

The systematic review of the surgical treatment of clavicle malunions by Sidler-Maier et al. [60] showed that all of the included studies had a favorable outcome after clavicle malunion correction though comparing the outcome of the studies was difficult because of different outcome assessment methods. Performing a corrective clavicular osteotomy, Bosch et al. [46] and Skutek et al. [70] reported similar University of California, Los Angeles (UCLA) scores. Both showed a comparable improvement regarding Constant and Murley scores, similar to what Nowak et al. [41] presented with a callus resection. Smekal [57], McKee et al. [34], and Hillen et al. [4] all reported similarly improved Disabilities of the Arm, Shoulder, and Hand (DASH) scores (values twice as good postoperatively versus preoperatively) after corrective osteotomies. Unfortunately, as the time to union had only been reported in some of the included studies (also varying, and not mentioned how often X-rays had been performed), a comparison of the different surgical techniques was not possible in this regard.

Complications After Surgery Surgical management of symptomatic clavicular malunion is associated with a number of potential complications [1, 4, 60] such as persistent malunion, hardware complication or fixation failure, nonunion [19, 60], and fracture deformity or callus causing brachial plexus or subclavian vessel compression [1]. Whereas hardware needs to be removed in about one third of cases after fracture healing having used open reduction and internal fixation for initial clavicle fracture because of prominence [19], a second operation to remove the hardware after malunion correction might be necessary [4] in about 5–10% of cases because of irritation, infection, or failure of fixation [19, 60]. It is not mandatory, but done at patients' request only, and can possibly be minimized through the use of a pre-contoured plate. In general, patients with surgical treatment of clavicle malunion present a good healing potential. The overall complication rate reported in Sidler-Maier et al.'s systematic review [60] comparing studies with surgical treatment of clavicle malunions was less than 6% and mostly found after correction osteotomy, which was the technique most often applied, including loosening of reconstruction plate, non-union, and infection [4, 34, 70]. Nowak et al. [41] had one refracture after callus removal ending in a nonunion. Table 2.8 provides a summary of possible complications after surgical malunion correction [1, 4, 19, 53, 60].

2.2.10 Conclusion

Clavicle fractures are common injuries encountered by orthopedic surgeons. Improper fracture healing following a displaced midshaft fracture of the clavicle can lead to the development of a symptomatic clavicular malunion. Clavicular malunion is a distinct clinical entity that generally develops in higher-demand patients with more severely displaced fractures and has orthopedic, neurologic, cosmetic, and functional symptoms. A corrective osteotomy that re-establishes the pre-injury anatomy of the involved clavicle, especially the restoration of length, and subsequent fixation with a pre-contoured plate to prevent rotation and allow early range of motion seems to be the standard surgical procedure for this condition [60]. It is a reliable operation with a high success rate and low complication rate.

Table 2.8 Complications after surgical management of clavicular malunion

Persistent malunion [1]
Failure of fixation [60]
Hardware complication [1, 4, 19, 53, 60]
Nonunion after surgery [1, 53, 60]
Excessive callus formation [1, 53]
Neurovascular compromise [1]
Infection [19, 60]

Conflict of Interest The authors Claudia C. Sidler-Maier, MD, and Laura A. Schemitsch have declared that they have no conflict of interest. Michael D. McKee, MD, FRCS (C), reports personal fees as a designer from Stryker and as a consultant from Zimmer, Acumed, and ITS, outside the work. In addition, Dr. McKee receives royalties from Stryker for a patent. Emil H. Schemitsch, MD, FRCS (C), reports grants and personal fees from Stryker, Smith & Nephew, and Zimmer; personal fees from Amgen, Bioventus, Acumed, Sanofi, and Pendopharm; and non-financial support from ITS, outside the work.

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3 Malunions of the Proximal Humerus

Christopher B. Hayes, Ryan L. Anderson, Gillian L. S. Soles, and Philip R. Wolinsky

3.1 Introduction

3.1.1 Proximal Humerus Fractures

Proximal humerus fractures are one of the most common orthopedic injuries comprising 4–5% of total fractures [1, 2]. Decreasing bone mineral density as patients age has been linked to the increasing incidence of these fractures in the aging population [3]. Age-related fractures are expected to rise as the population continues to age with an estimated threefold increase by the year 2030 [4]. Following successful union of these fractures, a proportion develop painful deformities that can result in poor functional outcomes. As fracture rates increase, the rate of malunion would similarly be expected to increase.

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Fortunately, most types of malunion are generally well tolerated in the low-demand elderly patient and can be managed non-operatively. Difficulty occurs in attempting to predict which patients will develop symptomatic malunion and, as such, may benefit from early surgical intervention. For those surgical candidates presenting in a delayed fashion, the challenge then lies in deciding between the numerous surgical treatments that will result in the best outcome while minimizing complications.

3.1.2 Epidemiology

Currently the majority of proximal humerus fractures can be managed non-operatively. Iyengar et al. attempted to more clearly determine the rates of complications following non-operative treatment of proximal humerus fractures. They performed a systematic review of 12 studies comprising 650 patients with a mean age of 65 years who underwent non-operative treatment of proximal humerus fractures. They found the most common complication of non-operative treatment to be varus malunion with an overall incidence of 7%. However, when including only three- and four-part fractures, the rate of malunions rose to as much as 23% suggesting that malunion rates are heavily dependent on the original Neer fracture classification [5].

Locking plate technology was anticipated to be the solution to combat failure of non-operative

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treatment in three- and four-part fractures. Unfortunately, even with the use of locking plate fixation, high rates of malunion have persisted with rates as high as 63% [6]. Sprout et al. performed a systematic review including 12 studies with 514 patients and found a rate of varus malunion of 16.3% for proximal humerus fractures treated with locking plate fixation [7]. These studies did not include malunions involving the tuberosities or humeral head likely underestimating the true incidence of malunion associated with locking plate fixation.

Regardless, due to variable treatment patterns, evolving technology, and changing treatment indications over the past 20 years, the incidence of malunions of the proximal humerus has not been clearly defined; however, estimates have ranged between 4% and 20% [8].

3.1.3 Classification

There have been limited classification schemes for proximal humerus malunions developed over the years with minimal consensus on proposed schemes. Initially, Beredjiklian et al. developed the first and most simple classification during their experience treating different malunions. They found a high rate of concomitant bony deformity and soft tissue abnormalities that affected subsequent outcomes and based this classification on this fact. The authors defined bony deformities as type I with tuberosity malposition greater than 1 cm, type II with incongruity or step-off of the articular surface greater than 5 mm, and type III with malalignment of the articular segment greater than 45° in any plane. They further defined soft tissue abnormalities as those with soft tissue contractures, rotator cuff (RC) tears, and subacromial impingement. This was the first classification system of proximal humerus malunions that provided a basis for determining obstacles to correction and identified both bony and soft tissue considerations that need to be corrected to achieve satisfactory results [9]. Additionally, this allowed comparison to be drawn between various types of malunions with different treatments. This classification system, although useful in describing structural malunions and associated soft tissue pathology, has not been widely applied.

Subsequently, Boileau et al. proposed a different classification system for sequelae of proximal humerus fractures based on the dominant bony abnormality. They suggested that sequelae of proximal humerus fractures could be grouped into two categories: intracapsular pathology or impacted fractures and extracapsular pathology or disimpacted fractures. These categories were defined further with type I sequelae dominated by head collapse and minimal tuberosity malunion all with Ficat III–IV stage avascular necrosis, type II sequelae demonstrating locked dislocation or fracture-dislocations, type III sequelae with surgical neck nonunion, and type IV sequelae with severe tuberosity malunions where reconstruction cannot be addressed without tuberosity osteotomy. This classification system is often used when addressing sequelae of proximal humerus fractures with arthroplasty [10].

The system proposed by Beredjiklian helps to characterize problems associated with malunions of the proximal humerus giving the practitioner the forethought to think about not just the bony anatomy but also the soft tissue envelope that can lead to less than satisfactory outcomes when attempting to treat these rare and difficult injuries. Boileau proposed a complementary system that assesses prognostic factors that predict poor outcomes particularly category three or four sequelae that require an osteotomy of the tuberosities. Unfortunately, neither of these systems provides full direction in determining the optimal treatment, likely due to the heterogenous nature of this injury, complications, and subsequent difficulties in management.

3.2 Patient Evaluation

Patients commonly present with complaints of pain, loss of motion, limited function, or a combination thereof. It is paramount to determine the main complaints and specific goals of the patient to maximize patient satisfaction and help determine an individualized treatment plan. Defining initial fracture pattern, mechanism of injury, and presence of dislocation are important in anticipating concomitant soft tissue abnormalities. Previous treatments, including surgeries and rehabilitation programs, may reveal possible contributing factors to the development of malunion. Current medical comorbidities such as osteoporosis, diabetes mellitus, or tobacco use should be recognized as these conditions typically contribute to poor healing potential. Social history including work status and type, mental status, and activity level should be elicited as these factors play a role in postoperative rehabilitation protocols and may help guide the treatment plan. Finally, functional status and goals of care should be ascertained to determine optimal treatment with either operative or non-operative management.

3.2.1 Clinical Examination

A detailed physical examination is important to help clarify the etiology of the patient's complaints, whether it be pain, weakness, or loss of motion. On inspection, patients may have shoulder girdle muscular atrophy, abnormal shoulder contours, or scapular winging. A significant number of patients will have undergone several surgical procedures prior to presentation. Scars should be appreciated and can give clues to prior surgical approaches utilized and subsequent scarring or soft tissue injuries that can be anticipated. Presence of sinus tracts or poorly healed wounds may indicate continued or prior infection. Regardless of prior procedures, the most common complaints of symptomatic malunions are often pain and limited range of motion.

Pain is often absent at rest and occurs with either passive or active motion. Impingement of malunited tuberosities typically causes pain at extremes of motion. The position of the arm and degree at which pain is elicited should be documented. Pathology of the rotator cuff and long head of the biceps should be investigated during examination. The long head of the biceps tendon is a common pain generator of the shoulder but often goes underappreciated [11] and can often mimic other pathologic conditions of the shoulder [12]. Malunion of the greater tuberosities can distort the shape of the bicipital groove leading to disease and degeneration of the biceps tendon [13]. Painful biceps tendon pathology presents with anterior shoulder pain and point tenderness within the bicipital groove. Several tests have been described in aiding to determine long head of biceps pathology. Yergason's test is positive with elicitation of pain with resisted supination with the elbow at 90°. Speed's test is positive with elicitation of pain with resisted forward elevation of a fully extended elbow and supinated forearm. Unfortunately, no tests nor combinations of tests have been reported as reliable measures in detecting long head of biceps pathology [12]. Selective injections can be utilized to aid in diagnosis including injection of the bicipital groove to help differentiate painful stimuli [14].

Range of motion and strength testing are often influenced by pain and should be intensely scrutinized. Determination of underlying causes of painful motion can be difficult as soft tissue and bony abnormalities often coexist and both cause similar clinical pictures. Nevertheless, differentiating active and passive motion can be exceptionally helpful in determining major causes of limited motion. Loss of both active and passive motions typically occurs with soft tissue contractures and bony impingement. Depending on the chronicity of malunion, patients will often have some degree of soft tissue contracture. Capsular contractions cause decreased range of motion with variable production of pain. Beredjiklian found 81% of patients treated for proximal humerus malunions to have capsular contractures that required release at time of surgery at a mean time of 2.5 years from initial injury [9].

Malunited fractures may cause diminished active and passive motion due to bony impingement. Lesser tuberosity fractures may heal in a medial malunited fashion blocking internal rotation with impingement on the glenoid or coracoid process [15]. This can be tested by using the coracoid impingement test by passively placing the shoulder in crossed-arm adduction, forward elevation, and internal rotation to bring the malunited tuberosity in contact with the coracoid or glenoid [16]. Varus impaction generates relative medialization of the greater tuberosity leading to early subacromial impingement and limited abduction [17]. Differences in range of motion from contralateral comparison or elicitation of pain may indicate symptomatic impingement. Similarly, displaced greater tuberosity fractures may heal in a posterior-superior fashion blocking forward flexion and abduction and causing pain with impingement on the acromion [9, 18]. This can be tested with several examination maneuvers including the Neer impingement sign, Hawkins-Kennedy impingement test, Jobe's test, or Yocum's test in an attempt to separate signs of impingement from rotator cuff tears. The Neer sign involves the reproduction of pain during passive abduction of the arm with resolution of the pain following injection of a local anesthetic into the subacromial space. Hawkins-Kennedy impingement test involves the passive positioning of the shoulder at 90° in the scapular plane with elicitation of pain with internal rotation of the arm. Jobe's test involves active forward flexion of the shoulder against resistance with the arm internally rotated, so thumbs are pointing toward the floor with elicitation of pain or weakness as a positive test. Yocum's test involves positioning the patient's hand on the contralateral shoulder and actively elevating the elbow past the horizontal plane with elicitation of pain upon elevation. These tests have all shown appropriate sensitivities over 53% albeit with low specificity that affects their discriminatory ability. The true power in these tests is their ability to rule out impingement and rotator cuff tears with negative tests especially when used in combination with each other [19–22]. With positive impingement tests, it is prudent to evaluate for other causes of shoulder pain with advanced imaging.

On the contrary, loss of active motion with preservation of passive motion is indicative of a rotator cuff tear or nerve injury. Careful physical examination to assess for neurovascular injury should be performed. Axillary and suprascapular nerves are commonly injured in proximal humerus fractures. Tavy et al. investigated 143 consecutive proximal humerus fractures for associated nerve lesions with electromyograms. They found a 58% incidence of axillary nerve and 48% incidence of suprascapular nerve lesions. Neurologic injuries were also more common among patients with displaced fractures compared to nondisplaced fractures. Interestingly, despite high rates of nerve lesions, muscle weakness recovered well in all patients with no effect on amounts of shoulder stiffness [23]. Moreover, rates of axillary nerve injury associated with glenohumeral dislocation may be as high as 65% [24]. Axillary nerve function can be determined by assessing sensation over the lateral deltoid and functional deltoid muscle contraction. Supraspinatus nerve function is determined by testing infraspinatus and supraspinatus muscle strength. Any patient with evidence of neurologic insult should be considered for further testing with electromyography and nerve conduction studies.

Weakness or early fatigue may also be present, due to altered shoulder biomechanics from malunited greater tuberosity or underlying rotator cuff tears. Alteration of the rotator cuff attachment from greater tuberosity malunion can lead to abnormal shoulder mechanics. Biomechanical studies have determined that even 5 mm of superior displacement of the greater tuberosity can increase the force required of the deltoid for abduction by 16% and 1.0 cm superior displacement increases this by 27% [18]. Standard strength testing of the supraspinatus, infraspinatus, and subscapularis should be evaluated. Comparing abduction strength to the contralateral side is often useful in determining maximal shoulder strength. When distinct differences in strength and function exist between normal and affected sides, the integrity of the rotator cuff musculature should be evaluated. Rotator cuff injuries are common following proximal humerus fractures and subsequent malunions. Up to 42% of patients can be expected to suffer a rotator cuff tear within 1 year of a proximal humerus fracture [25]. Similarly, during treatment for proximal humerus malunion correction, Beredjiklian found 48% of patients had significant rotator cuff tears [9]. In some situations, rotator cuff dysfunction including weakness of shoulder girdle musculature involves atrophic changes of the muscle due to prolonged disuse. Willis et al. demonstrated some degree of rotator cuff atrophy in all patients they treated, with significant supraspinatus and subscapularis atrophy in 13% and infraspinatus atrophy in 7% [26]. In these situations, advanced imaging should be considered to improve detection of potentially deleterious rotator cuff tears.

The complex nature of proximal humerus malunions must not go unrecognized, and a thorough examination to determine causes of pain, restricted motion, and function must be undertaken in order to properly treat these complicated problems.

3.2.2 Radiographic Imaging

Imaging of a proximal humerus malunion should begin with plain radiographs. This includes the standard trauma series – anteroposterior (AP), scapular Y, and axillary views. Supplemental internal and external AP views can provide additional information [27]. The AP view allows for calculation of the glenohumeral angle (defines the amount of valgus tilt of the head fragment) and the amount of varus or valgus malalignment based on the neck-shaft angle [8]. The neck-shaft angle is also used during preoperative planning for a lateral closing wedge osteotomy [28]. The axillary view is useful for evaluating the glenoid and concentricity of the glenohumeral joint. Some authors also used a scanogram to determine proper length of the humerus in planning for placement of a prosthesis and determining proper tension of soft tissues during reconstruction [27]. Willis et al. also state that templating radiographs are a valuable tool to assist preoperatively in determining reverse shoulder arthroplasty implant position and describe strategies to alter surgical technique to accommodate bony deformities [26]. It may also be helpful to classify the type of fracture sequelae for anticipated surgical prognosis as described by Boileau et al. [29].

Although plain films allow for a thorough assessment of the malunion characteristics, there are often combined osseous deformities that cannot be adequately quantitated on radiographs [9]. CT allows for a more detailed evaluation of the bony malunion, size and degree of tuberosity displacement, glenoid surface and remaining bone stock, humeral head integrity, and volume and quality of rotator cuff muscles. It also allows for better appreciation of rotational deformities, although the bicipital groove has been shown to be unreliable for use in guiding humeral retroversion during prosthetic implantation, in favor of fracture jigs [30]. CT is especially useful in determining whether a humeral head-sacrificing procedure will be necessary, including glenohumeral incongruity, humeral head Avascular Necrosis (AVN), or extensive damage to the articular surface of the head as sequelae from post-traumatic arthritis or head impression defects involving >40% of the articular surface [27]. Three-dimensional CT reconstruction allows for even greater appreciation of deformities [28]. As previous studies have shown poorer outcomes in patients undergoing Total Shoulder Arthroplasty (TSA) requiring tuberosity osteotomies [31], fully appreciating the degree of tuberosity malunion is critical in deciding between potential surgical interventions.

Finally, MRI is useful for detecting early osteonecrosis and assessing the status of surrounding soft tissue structures, including the rotator cuff, capsule, long head of biceps tendon, and labrum [28]. As was reported by Beredjiklian et al. [9], 79 percent of patients with malunion were found to have both osseous and soft tissue abnormalities, and any unaddressed pathology resulted in worse outcomes. Soft tissue pathology is readily seen on MRI, and the status of the rotator cuff is critical in deciding between arthroplasty techniques. In addition to deficient RC musculature, shoulder instability has also been shown to be associated with poor outcomes in patients undergoing TSA [31]. It is also important to obtain a reference EMG prior to performing any procedure in patients with a clinical nerve deficit [8].

3.2.3 Laboratory Testing

Depending on the initial treatment, various laboratory studies may be appropriate prior to any planned surgical procedures. If the possibility of infection from prior procedures exists, preoperative laboratory testing including a complete blood count with differential, C-reactive protein, and erythrocyte sedimentation rate should be performed. However, it should be noted that these studies are non-specific markers of systemic inflammation and may be elevated for concomitant processes. If these are elevated and concern for prior infected hardware exists, then the gold standard for diagnosing infection would be surgical cultures. When there is no concern for infection, no specific laboratory testing is required.

3.2.4 Surgical Timing

Determining optimal timing for when a patient qualifies as a surgical candidate to address a presumed malunion can be challenging. Several studies have demonstrated that acute treatment routinely results in improved outcomes. Tanner and Cofield reported on late arthroplasty for proximal humerus fractures demonstrating higher complication rates (43% vs 34%) when arthroplasty was performed in a delayed fashion, attributing these results to surgical difficulty and extensive scarring. Frich et al. demonstrated in reviewing 42 arthroplasties performed on acute or chronic proximal humerus fractures, 60% of acute arthroplasties achieved good or excellent results with reliable pain relief compared to 22% of chronic arthroplasties achieving good results often with unreliable pain relief [32]. Similarly, Seidl et al. determined from a study of 40 patients undergoing reverse total shoulder arthroplasty for proximal humerus fracture, patients treated acutely demonstrated 100% tuberosity healing rate with an average Single Assessment Numeric Evaluation (SANE) score of 80.9 and external rotation 28° compared to only 42% tuberosity healing rate with an average SANE score of 69.1 and external rotation of only 18° when treated in a delayed fashion. However, determining which patients will develop symptomatic malunions is difficult. Many patients will regain good shoulder function with mild disability despite poor reduction and radiographic appearance [33]. Additionally, shoulder motion has been shown to steadily improve for up to a year after proximal humerus fracture but rarely improves after that time point [34]. Thus, the simplest treatment for proximal humerus malunions is prevention [8], although clearly factors in addition to bony alignment must contribute to poor functional outcomes in delayed fractures necessitating further operative treatment.

Despite the strikingly poor outcomes associated with delayed fracture treatment, the effect of surgical timing of established malunions on patient outcomes has variability in the literature. Average time to surgery following malunion varies between 19 months [35] and 7.6 years [31]. Beredjiklian et al. initially determined improved satisfactory outcomes for malunion treatment when treated within a year of injury. A satisfactory result was obtained in 84% of patients treated within 1 year; conversely, in those treated over 1 year from fracture, only 55% achieved a satisfactory result. They concluded that a delay in treatment over 1 year might allow scar tissue maturation and disuse atrophy leading to unsatisfactory results [9].

On the other hand, several subsequent studies have been unable to verify their claim and have even concluded that no association between timing and outcome exists particularly when treated with arthroplasty [31, 36, 37]. Both Benegas and McKee were able to demonstrate good results with osteotomies even in patients that had been delayed an average of 65.5 and 23 months from injury, respectively. Furthermore, good results with arthroscopic management have also been demonstrated even with mean times to surgery of 9 and 19 months from injury.

Despite a paucity of data indicating optimal timing, ideally a malunion of the proximal humerus should logically be addressed once it has been identified and determined to be symptomatic, and patient improvement has ceased in order to limit soft tissue contractures and atrophy of the rotator cuff.

3.3 Treatment Options

3.3.1 Non-operative Treatment

Multiple studies have consistently demonstrated satisfactory results with non-operative treatment in functionally low-demand patients [5, 33, 34, 38, 39]. Iyengar et al. performed a systematic review of 12 studies regarding proximal humerus fracture treatment. They were able to demonstrate, among one- and two-part fractures, exceptional healing rates and average active forward flexion as high as 151°. Three- and four-part fractures demonstrated comparatively high healing rates with marginally reduced active forward flexion of 127°, lower shoulder outcome scores, and a much higher complication rate with a 23 percent incidence of varus malunions and 14 percent incidence of avascular necrosis. After 1 year following proximal humerus fracture, prospective non-operatively treated patients demonstrated a side-to-side difference in Constant scores of only 8 points with the suggestion of worse improvement being influenced by fracture pattern. Additionally, overall post-injury Disabilities of the Arm, Shoulder, and Hand (DASH) scores were only 10 points lower than their pre-injury level. Interestingly, these differences were slightly higher for those that experienced a fracture-related complication most notably episodes of shoulder impingement [34]. Court-Brown et al. reviewed both varus and valgus proximal humerus fractures discovering a 100% fracture union rate and 80% good or excellent outcomes at 1 year. Additionally, Neer and Constant scores gradually improved throughout the succeeding year. Interestingly, subjective assessments of strength, reach, and stability showed greater improvement than objective assessments, and patients considered their improvement to be about 90% of the contralateral side. Despite their perceived improvements, the average abduction and flexion power in valgus fractures only returned to 75% of the normal side. Similarly, in the varus group, flexion returned to 70%, and abduction returned to 53% of normal at 1-year follow-up. Multiple regression analysis demonstrated no effect of increasing varus angulation on overall outcomes. These studies also demonstrated that increasing age was associated with lower shoulder scores and lower objective shoulder measures including motion and strength [38, 39]. Most patients dress themselves and partake in personal hygiene by 4–5 weeks, return to household chores by 8 weeks, and return to shopping at 8 weeks. Few differences were perceived between functional outcomes and those that were treated with physical therapy at 1-year follow-up [39].

It should be inferred from these studies that non-surgical management of displaced proximal humerus fractures and subsequent malunions can yield satisfactory outcomes in the majority of patients, regardless of age. Almost all proximal humerus fractures will heal with varying degrees of malunion as is inherent to non-operative treatment. Regardless of radiographic studies, most patients will consistently improve in shoulder function up to 1 year with some residual loss of motion and strength that are relatively well tolerated regardless of the utilization of physical therapy. Interestingly, younger patients often obtain better objective outcomes than their older counterparts albeit with similar or worse subjective measures. Thus, non-operative management of proximal humerus fractures commonly results in asymptomatic malunions of the proximal humerus; however, development of a symptomatic malunion is always a concern during the treatment process.

Even though patients demonstrate an amazing tolerance for proximal humerus malunions, studies have suggested that higher complication rates and worse outcomes occur during delayed operative treatment compared to prompt acute fracture management [32, 40]. Frich et al. examined the functional outcomes of 42 proximal humerus fractures treated with arthroplasty for either acute or chronic fractures. When treating this cohort of patients, acute management within 13 days of fracture provided satisfactory pain relief in all fractures, whereas those treated on an average delay of 14 months had unpredictable pain relief. Additionally, those treated acutely had 60% good to excellent results, whereas those treated as chronic fractures had only 22% good results. Furthermore, only 13% in the acute treatment group had outcomes graded as poor, whereas the chronic treatment group had 40% poor results [32]. Thus, appropriate surgical management can be expected to decrease the number of malunions that require treatment. Despite early appropriate treatment, secondary displacement, non-compliance, and loss of fixation can lead to loss of reduction and development of malunion. Unfortunately, by the time a symptomatic malunion has been recognized, significant time has typically elapsed causing increased scarring and stiffness. Despite the possibility of poorer outcomes compared to acute fractures, patients with persistent dysfunction and pain can successfully be treated with surgery. These patients should be counseled that the goal of surgery is to improve pain and function rather than completely restore it.

3.3.2 Surgical Treatment

The techniques used to address proximal humerus malunions are guided by the underlying deformity and the integrity of the articular segment [29]. Surgical options can be classified into two large categories: humeral head-sacrificing and humeral head-sparing [9, 10]. The mainstay of treatment thus depends on the integrity of the blood supply to the humeral head and the preservation of the articular cartilage. In the absence of articular step-off, avascular necrosis, or glenohumeral osteoarthritis, head-preserving techniques can be utilized. The main head-preserving procedures consist of surgical neck osteotomies, tuberosity debridement and/or repositioning, and soft tissue releases. Head-sacrificing procedures are utilized when significant osteoarthritis, avascular necrosis, or intra-articular step-offs are identified on preoperative imaging. These techniques have all been well described and include hemiarthroplasty, total shoulder arthroplasty, and more recently reverse total shoulder arthroplasty. Regardless of surgical technique, the highest priority should be in determining the limiting factors a patient presents with and tailoring treatment specifically to each patient. It can be difficult to determine whether symptoms are related to soft tissue contracture, bony impingement, or a combination of these, and failure to address the underlying etiology will undeniably result in a poor outcome [9].

3.3.2.1 Osteotomy

When the articular surface of the humeral head is congruent and sufficient bone stock remains, specific morphological alterations of the proximal humerus may be adequately addressed with an isolated osteotomy.

3.3.2.1.1 Tuberosity Osteotomy

Greater tuberosity osteotomy is a viable option for patients with limited shoulder motion and evidence of subacromial impingement with greater than 1.5 cm of greater tuberosity displacement as evidenced by CT imaging. Early reports of isolated tuberosity osteotomy produced good outcomes. Morris et al. treated six patients with greater tuberosity osteotomy and repositioning of the displaced fragment. They found that repositioning of the fragment led to substantial improvements in shoulder function [41]. Beredjiklian et al. demonstrated similar results with successful treatment of ten patients with congruent joint surfaces but malposition of the greater or lesser tuberosity. These patients were managed with tuberosity osteotomy with greater than 1.5 cm of displacement. Nine patients had satisfactory results at 1-year follow-up. The remaining patient treated with osteotomy and fixation with intramedullary rod subsequently developed avascular necrosis and required a total shoulder arthroplasty 4 months after the index procedure. When compared to other deformities, this group of patients had the highest success rate and best results following successful correction of both osseous and soft tissue abnormalities. They did not specify what soft tissue procedures these patients required but did mention that many required capsular releases, subdeltoid and subacromial releases, and subscapularis releases with or without lengthening. Their results demonstrate that successful osteotomy can provide good outcomes as long as all soft tissue and osseous abnormalities are addressed at the time of surgery. Interestingly, when the osseous abnormality was not addressed in two patients and only manipulation was performed, a poor result occurred. Isolated acromioplasty was also adequate to treat malpositioned tuberosities with less than 1.5 cm of displacement in their series of patients.

3.3.2.1.2 Surgical Neck Osteotomy

Varus deformity of the proximal humerus is common [5, 33, 34] and typically occurs with some degree of apex anterior angulation [42]. This combination of deformity often leads to limited active abduction and forward flexion with variable production of pain due to subacromial impingement. Whereas isolated acromioplasty may adequately treat patients with less than 1 cm of tuberosity malpositioning [9], patients with varus deformity rarely improve with this treatment. As such, efforts at treatment with surgical neck osteotomy have been attempted with limited numbers of patients. Solonen and Vastamaki first described a technique of surgical neck osteotomy in 1985 for treatment of humeral neck varus deformity. Their initial case series included seven patients treated with lateral closing wedge osteotomy through the surgical neck and fixated with preformed AO T plates. Five patients achieved normal or near-normal shoulder motion. Average forward flexion improved from 91° to 147° at 5-year follow-up, while average abduction improved from 64° to 134°. Two patients experienced little to no improvement with continued poor function following osteotomy. Interestingly, these two patients also had several factors that likely precipitated failure including capsular contracture, rotator cuff atrophy, and poor compliance with rehabilitation postoperatively [43]. Benegas et al. reported on five patients treated similarly with lateral closing wedge osteotomy fixed with a pre-contoured T plate. They reported a range of varus proximal segments between 28 and 37°. Following osteotomy and fixation, they reported an average improvement in forward flexion of 94°, and all but one patient improved to full flexion strength, with improvement of UCLA shoulder scores (3 excellent and 2 good outcomes) and 100% satisfaction with the procedure [44]. Although these small case series demonstrated good union rates following proximal humerus osteotomy, there remains concern that there is a higher loss of fixation with T plates in older osteoporotic bone [45]. To avoid concerns regarding bone quality, McKee et al. utilized an angular blade plate for fixation, which also allows improved compression at the osteotomy site. They reported an average 40-degree varus neck-shaft angle preoperatively with average correction of 33° postoperatively. Average active forward flexion improved by 30°, and shoulder pain was improved in all patients. Unfortunately, two cases of surgical neck nonunion occurred when compression with the articulated tension device was not utilized. These two failures subsequently required revision surgery including revision to total shoulder arthroplasty in one and an additional bone grafting procedure in the other [42].

When more complex malunions present, an isolated uniplanar osteotomy may not adequately correct all bony deformities. Russo et al. attempted to treat 13 complex proximal humerus malunions with biplanar and triplanar osteotomies and reported good early functional results. They used only screws, Kirschner wires, and bone suture as well as corticocancellous iliac crest bone graft. They reported improvements in forward flexion and abduction with an average of 67 and 80° at 4.5 years, respectively. However, three cases of avascular necrosis of the head (23%) developed, drawing into question the safety of this procedure [46].

Recently, a description of custom-made osteotomy guides from 3D printed deformities has been utilized with good success, although the price of such a tool was not discussed and may be prohibitive. In all cases, careful dissection with precise wedge cuts must be performed for obtaining optimum bony contact to maximize healing rates. These guides are created from 3D printed models generated from a CT scan and designed to secure to the proximal humerus to allow reproducibly precise cuts capable of addressing complex deformities. This case report demonstrated a simple osteotomy jig that was created to provide correction of a complex biplanar deformity. The authors were able to achieve improvement in motion with forward flexion to 160°, abduction to 140°, and external rotation to 65°. Postoperative Constant score improved from 17 to 74 with excellent satisfaction [47].

These procedures are very technically demanding and have associated risks but, however, can be rewarding especially in the younger patient with a well-preserved articular segment. Blade plate fixation is optimal to allow higher amounts of compression and decrease theoretical concern for T plate failure in poor-quality bone. If these plates are utilized, care should be taken to compress the osteotomy site with an articulated tension device to help improve healing rates. Rotational misalignment can be avoided by carefully planning cuts to realign the bicipital groove with the biceps tendon or through utilization of a 3D printed custom guide. Patients can expect improvements in both pain and function as long as healing of the osteotomy occurs.

Proximal humerus osteotomy is a viable option for younger patients with good bone stock yielding good return of function and high union rates. Due to small numbers, short-term follow-up, and few patient-reported outcomes, these studies provide limited prognosis regarding this treatment option. Regardless, they do highlight the need to address all forms of osseous and soft tissue abnormalities and attempt to restore the proximal humeral anatomy to allow efficient and unrestricted subacromial motion.

3.3.2.2 Greater Tuberosity Debridement and Rotator Cuff Advancement

Just as arthroscopic rotator cuff repair has become increasingly attractive, with advancements in techniques and technology, expanded indications for arthroscopic malunion treatment have also shown promising results. Arthroscopy allows direct visualization of the greater tuberosity, soft tissue abnormalities, and the resulting passive mechanics of the shoulder joint to identify both intra- and extra-articular causes of pain and limited motion, including impinging structures, rotator cuff tears, biceps tendon pathology, labral tears, and chondral defects. When it comes to the osseous abnormalities of proximal humerus malunions, arthroscopy is best suited at addressing greater tuberosity malunions and associated soft tissue abnormalities. Depending on the patient complaint and activity level, various arthroscopic techniques can be performed alone or in concert to address various pathologies. Displacement of the greater tuberosity tends to occur after proximal humerus fractures often leading to a more posterior and superior position which may result in early impingement and weakness with forward flexion and external rotation from loss of normal cuff tensioning [18]. Prior to arthroscopy, greater tuberosity displacement less than 15 mm from anatomic position was successfully treated with acromioplasty alone, whereas malunions with greater than 15 mm of displacement generally required an open osteotomy with repositioning [9]. Tuberoplasty represents an early attempt at utilizing arthroscopy principles to treat tuberosity malunions causing impingement. Calvo et al. first described an arthroscopic tuberoplasty technique that involves the arthroscopic resection of excessive greater tuberosity bone with preservation of the rotator cuff insertion. They described taking advantage of partial-thickness tears as openings through which to debride bony protuberances causing impingement. This was performed in two steps: the first being intra-articular resection of the bone up to the insertion of the rotator cuff, followed by introduction of a longitudinal split within the supraspinatus tendon allowing detachment of anterior and posterior cuff insertions and eventual bone resection [48, 49]. This approach allows for the removal of intra-articular sites of bony impingement that would be inaccessible through an open approach. Herrera et al. reported on eight patients treated with tuberoplasty utilizing rotator cuff detachment and reattachment combined with arthroscopic acromioplasty. All patients had between 5 and 10 mm of greater tuberosity malunion displacement. There were no noted complications, and results were deemed excellent in one case, good in six, and poor in one. Pain ratings improved in all patients with significant improvements in range of motion of 50° forward flexion and 20° external rotation [48]. An alternative tuberoplasty technique involves the complete detachment of the rotator cuff from the displaced fragment with electrocautery followed by reshaping using a powered burr and re-tensioning of the rotator cuff combined with an arthroscopic acromioplasty. Burckhardt et al. performed re-tensioning of the repair in nine patients that resulted in improvement in motion with average increases of 43° forward flexion and 12° external rotation. Pain scores improved in all patients, UCLA scores improved from 12 to 30, and American Shoulder and Elbow Surgeons (ASES) scores improved from 41 to 81 at last follow-up. This represented three excellent results, three good results, and three fair results [35]. These two combined techniques appear to allow improvements in function and pain with low morbidity. The limitation of arthroscopy is that it is likely only useful in treating patients with minor tuberosity displacements less than 15 mm although studies to support this claim are lacking. Ji et al. [50] and Kim et al. [51] have described similar techniques that include tuberosity osteotomy with fixation using the suture bridge technique, which allows bone-to-bone healing without taking down the entire rotator cuff insertion.

Malunions of the lesser tuberosity are less commonly described in the literature, and their treatment is even more scarce. Only case reports of arthroscopic treatment exist in the literature. One case report describes successful treatment of a four-part proximal humerus malunion with a medially displaced lesser tuberosity causing glenoid impingement. Arthroscopic decompression of the lesser tuberosity with capsular release was performed resulting in return of motion and decreased pain [15]. A similar case report describes the successful treatment of a malunited lesser tuberosity causing subcoracoid impingement. Arthroscopic coracoplasty was performed with similar improvement in pain and function [52].

These techniques are extremely technically complicated and require expertise in arthroscopic shoulder surgery and intricate rotator cuff repair techniques that should not be attempted without formal training. Isolated lesser tuberosity malunions can be successfully treated with arthroscopic decompression of the offending impingement while avoiding violation of the rotator cuff. Unfortunately, the reliability of these procedures is currently unknown.

3.3.2.3 Arthroplasty

While varus or greater tuberosity malunion has shown encouraging results with osteotomy, intra-articular incongruity is poorly tolerated. Beredjiklian et al. demonstrated early failure and poor results with attempted osteotomy of malunions with intra-articular head incongruity. When incongruity is not corrected, patients uniformly experienced unsatisfactory results due to pain and poor function. When shoulder arthroplasty was performed with good deformity correction, average pain scores improved from 1.6 to 4.2, and average functional scores improved from 41 to 70 percent. In contrast, when adequate bony correction was not obtained, pain scores only improved to 2.8, and functional scores did not improve. Additionally, shoulder motion improved by 32° with adequate correction and decreased by 15° with inadequate correction. These results correspond to a 74% rate of satisfactory results following treatment with shoulder arthroplasty. However, these early reports demonstrated complication rates approaching 30% chiefly related to intra-operative fracture and postoperative instability [9]. Cofield et al. paralleled these findings in an analysis of 49 shoulders undergoing prosthetic replacement for acute or chronic fractures. In the chronic fracture grout, three early complications occurred, related to nerve and rotator cuff injury, and six late complications occurred, related to tuberosity or rotator cuff healing and reflex sympathetic dystrophy, representing a 32% complication rate. They attributed complications to extensive scarring and anatomical distortion leading to increased surgical difficulty [40]. Thus, shoulder arthroplasty can provide improvements in pain and function but with an extraordinarily high complication rate.

Despite relatively high rates of complications in early reports, overall improved outcomes have universally been demonstrated with variable complication rates when treating these difficult sequelae with prosthetic replacement [9, 10, 36, 37, 40, 53, 54]. Dines et al. performed a retrospective review of 20 patients treated for post-traumatic changes of the proximal humerus with modular hemiarthroplasty or total shoulder arthroplasty. Unfortunately, these groups were not separated to allow for head-to-head comparison. Regardless, overall HSS scores improved from an average preoperative score of 26.3 to 77 postoperatively. Additionally, 90% of patients reported satisfactory pain relief at rest with 63% reporting no pain at rest. Furthermore, 75% of patients reported satisfactory pain with activity. Range of motion demonstrated average forward flexion of 111° and external rotation of 30° postoperatively. Patient outcomes were judged by

HSS scoring and revealed 20% excellent, 50% good, 20% fair, and 10% poor results [36]. Bouileau et al. subsequently reviewed 71 sequelae of proximal humerus fractures treated with either hemiarthroplasty or total shoulder arthroplasty. Average pain scores were 10.7 out of 15, active anterior elevation improved 28° to a total of 102°, and active external rotation improved 34° from preoperative 0°. Similarly, they demonstrated overall functional results as good or excellent in 42%, fair in 25%, and poor in 33% as judged by Constant score. Satisfaction with the procedure was high, with 81% declaring themselves as satisfied or very satisfied with their result, and these results correlated with Constant scores [10]. Mansat et al. evaluated 28 patients undergoing shoulder arthroplasty for sequelae of proximal humerus fractures. They reported overall functional results as excellent in 25%, satisfactory in 39%, and unsatisfactory in 36%. Satisfaction with the procedure was again high with 75% declaring satisfied or very satisfied, whereas 7% thought they were worse than before the procedure. Average Visual Analogue Scale (VAS) pain scores improved from average 1.8 to 11, average Constant activity levels improved from 6.2 to 14, and average Constant mobility levels improved from 11 to 23. Active anterior elevation improved from 71 to 107°, and active external rotation improved from −8 to 20° [37]. Cofield et al. evaluated 109 patients treated with hemiarthroplasty or total shoulder arthroplasty for proximal humeral malunion. They noted pain scores improved from 7.8 to 3.1, average active elevation increased from 69° to 109°, and average active external rotation increased from 8° to 39°. Overall functional results demonstrated 52% excellent or satisfactory improvement [31]. It should be noted that although on average patients' range of motion and functionality improved, no average postoperative forward flexion was greater than 120° or 34° external rotation. Additionally, pain and activity levels all improved but were not "normal."

In contrast to general agreement that proximal humerus malunions gain significant improvement in pain, mobility, and function, very little agreement on the ideal prosthesis persists. Dines et al. demonstrated at average follow-up of 33 months that HSS functional scores improved more for hemiarthroplasty (79.7) than total shoulder arthroplasty (70.3). Further, when comparing postoperative motion, hemiarthroplasty again outperformed total shoulder arthroplasty with an average improvement to 114° compared to 103°. Conversely, Boileau and Mansat both demonstrated no difference in functional scores between those treated with total shoulder or hemiarthroplasty at 19 and 47 months, respectively. Cofield et al. found similar results with arthroplasty and total shoulder arthroplasty albeit greater improvements in pain scores for those receiving total shoulder arthroplasty. Additionally, they found that complaints of pain at last follow-up were significantly correlated to presence of glenoid wear and rotator cuff tears in the hemiarthroplasty group.

Several factors have been suggested to impact overall outcome following shoulder arthroplasty for proximal humerus malunions. Dines et al. reported more improvement in HSS scores when patients were younger than 70 (HSS score 83.3) compared to those over 70 (HSS score 71.4). However, Bouileau, Mansat, and Cofield all found no significant differences in overall functional outcomes based on age. Time to arthroplasty was initially demonstrated to have a significant effect on surgical outcomes by Beredjiklian demonstrating 84% satisfactory results when treated prior to 1 year and only 55% satisfactory results when treated further than 1 year from fracture. However, Dines, Bouileau, Mansat, and Cofield all disputed this finding later and were unable to find any differences between patient outcomes based on time to prosthesis.

The only agreed-upon negative factor associated with poor functional outcome following shoulder arthroplasty is utilization of a greater tuberosity osteotomy. Dines et al. found significantly higher HSS scores for patients that were treated without an osteotomy of the greater tuberosity (82.3) compared to those treated with an osteotomy of the greater tuberosity (73.6). Similarly, Bouileau et al. noted patients that required a greater tuberosity osteotomy had worse functional recovery with less active flexion with a mean of 82° compared to 123° without an osteotomy. Conversely, lesser tuberosity osteotomy has no significant effect on anterior elevation compared to those without, achieving an average of 132°. Additionally, complication following greater tuberosity osteotomy led to significantly worse function as judged by Constant scores. Mansat et al. found significantly worse functional outcomes with Constant score of 36 and unsatisfactory results when greater tuberosity osteotomy was required for treatment with arthroplasty. Finally, Cofield et al. attempted to avoid the use of greater tuberosity osteotomy by altering the insertion point of the prosthesis or altering the prosthesis to allow passage without osteotomy. These patients trended toward having worse active elevation (101° vs 115°) and external rotation (34° vs 42°) and more unsatisfactory Neer scores (46% vs 34%) compared to those that did not require osteotomy. Further analysis revealed that of the 31 shoulders that required osteotomy, 35% did not heal or were resorbed and 19% of these demonstrated unsatisfactory Neer result ratings. Furthermore, they found that radiographic signs of instability including humeral head translation had much poorer outcomes compared to those without subluxation. Range of motion suffered in this group with average active elevation of 94° compared to 131° in those without, average external rotation of 10° compared to 47° in those without, and 78% unsatisfactory outcomes in this subgroup of patients. Interestingly, Mansat et al. found the most important factor affecting overall function and pain was the integrity of the rotator cuff. In their study, eight patients had rotator cuff tears, and half of these were unable to be repaired at the time of surgery. These patients demonstrated significantly worse postoperative pain and mobility including anterior elevation and external rotation. This correlated with a 14% result of excellent or satisfactory results compared to 77% when an intact cuff was present.

Although successful outcomes have clearly been demonstrated when proper patient selection is performed, complications are still common. Beredjiklian initially described 12 complications in 11 patients representing a 28% complication rate. These comprised both intra-operative complications, including fracture during canal preparation, and early postoperative complications, including component subluxations requiring revision hemiarthroplasty and humeral component loosening. Late complications occurred in patients that sustained attritional re-tears of the rotator cuff. Cofield and Tanner described their early experiences as well and found 12 complications in 27 shoulders comprising 44% complication rate, including 2 early dislocations, an intra-operative nerve injury, 5 rotator cuff injuries, and 2 tuberosity malunions. They attributed most of these complications to surgical difficulty due to extensive scarring and anatomy distortion. Subsequently, Dines et al. noted their complication rate dropped to 10% owing to a modular prosthesis design that allowed individualized soft tissue tensioning and centering the humeral component within the glenoid. Interestingly, they reported 2 complications in 20 shoulder arthroplasties both related to instability, 1 with superior subluxation related to a greater tuberosity nonunion and the other with posterior subluxation related to postoperative neuropathy. Interestingly, Bouileau et al. demonstrated a 27% complication rate of shoulder arthroplasty even with a modular prosthesis design. Their major complications echoed those of Beredjiklian with five perioperative fractures, nine complications related to the greater tuberosity (loss of fixation, nonunion, and osteolysis), one anterior instability, one neurologic injury, and two late infections. Both infections occurred after prior attempts at fixation. By altering their surgical technique to avoid tuberosity osteotomies for traditional shoulder arthroplasty implantation, Cofield et al. reported a 17% complication rate. They reported one brachial plexopathy and two hematomas. The remaining 13 complications required 10 re-operations. They reported nine patients experienced postoperative instability requiring six re-operations, two incidents of painful glenoid erosion requiring total shoulder arthroplasty, one deep infection, and one periprosthetic humerus fracture. They also performed Kaplan-Meier survival analysis and determined a 94.8% retention at 5 years, 90.1% at 10 and 15 years, and 85.1% at 20 years. Interestingly, despite advances in surgical technique and prosthesis design, outcomes of surgical treatment did not significantly improve between those treated between 1976 and 1997 and those treated between 1998 and 2007.

With the high rate of failures reported for patients requiring greater tuberosity osteotomy, alternative treatment options have been investigated. Ballas et al. attempted to avoid osteotomy by utilizing a newer stemless prosthesis that avoids the need for humeral canal preparation, thus circumventing the need for greater tuberosity preparation. In all of the included 27 patients, the prosthesis was successfully implanted without tuberosity osteotomy. All clinical outcomes improved following surgery with an average improvement in active elevation from 81° to 129° and external rotation from 5° to 40°. Additionally, Constant scores improved from 27% to 62% [55]. These results demonstrate that even when tuberosity malunion is ignored, good results with improvement in pain and function can be obtained. While these newer stemless prostheses are attractive for these reasons, currently there only exists short-term data on their use prompting the need for more long-term studies.

Shoulder arthroplasty for proximal humerus malunion has proven to be a technically challenging treatment option. It requires an intimate knowledge and appreciation of proximal humerus anatomy and associated soft tissue abnormalities. While arthroplasty generates reproducible results, favorable deformities do not exist. Rather, all bony and soft tissue abnormalities must be addressed to obtain satisfactory results. Thus, in the setting of humeral head incongruity, osteonecrosis, or degenerative changes, arthroplasty can result in satisfactory results [9, 10, 32, 37, 40, 56]. Despite these successful results, shoulder arthroplasty remains a highly technical procedure wrought with complications [10, 29, 36, 37, 53, 54]. The most common acute complications are related to the degree of technical challenge. Scarring and contracture create an environment that limits exposure and makes implantation difficult leading to intra-operative fracture and iatrogenic rotator cuff injury. Delayed complications are typically related to the integrity of the rotator cuff. Greater tuberosity nonunion, capsular failure, or rotator cuff tears were common complications between all studies and associated with poor outcomes and high failure rates. If the greater tuberosity or rotator cuff tendons are damaged in any way, one can expect a high likelihood of poor function and dissatisfaction with the procedure. Prior to performing shoulder arthroplasty to address a proximal humerus malunion, the rotator cuff should be inspected and confirmed to be of good quality to support surgical repair to avoid major perioperative instability that may produce a poor result. Additionally, the risks of greater tuberosity osteotomy should be deeply considered and consequences of nonunion discussed with the patient prior to surgery. Stemless prostheses represent newer technology that appears to be safe with equivalent outcomes; however, without long-term data, these procedures should be left to those with particular experience.

3.3.2.4 Reverse Shoulder Arthroplasty

On the basis of poor results using total shoulder arthroplasty for sequelae of proximal humerus fractures due to the frequent need for osteotomy, reverse shoulder arthroplasty has been investigated as an alternative surgical option. Since the inception of reverse total shoulder arthroplasty, the indications for its use have expanded. Reverse total shoulder arthroplasty was first described as a salvage procedure; however, recent literature has supported its use in several areas including proximal humerus malunions [26, 57–60]. Reverse total shoulder arthroplasty has been advocated for when there is poor bone stock to support a total or hemiarthroplasty, little or no reconstructable glenoid component, and chronic atrophied rotator cuff tears. Due to a high failure rate due to instability of conventional total shoulder arthroplasty, Bouileau first advocated for their use in patients requiring greater tuberosity osteotomies. Much like total shoulder arthroplasty and hemiarthroplasty, Martinez et al. investigated the effectiveness of reverse shoulder arthroplasty for the treatment of proximal humerus malunions. Surgical technique focused on soft tissue release and resection of prominent tuberosity malunion and attempted to achieve 20°

of stem retroversion. This resulted in a significant increase in Constant scores from 28 to 58, increased active forward flexion from 40° to 100°, abduction increase from 41° to 95°, and external rotation increase from 15 to 35°. Similar to conventional arthroplasty, their complication rate was 27%. One case of glenoid loosening occurred requiring conversion to hemiarthroplasty, one superficial infection, one transient axillary nerve palsy, three periprosthetic fractures, and six prosthetic dislocations. Four dislocations required revision to hemiarthroplasty, whereas increasing humeral offset successfully treated the other two dislocations. Despite this high complication rate, a satisfaction rate of 87% was achieved; the only unhappy patients were those that experienced postoperative dislocation and revision. Due to a high risk of dislocation, the authors cautioned surgeons to attempt repair of the subscapularis [57].

Willis et al. demonstrated similar outcomes with a lower complication rate. They reported 62.5% excellent rating and an 18.75% good and satisfactory rating with no reported failures. ASES scores significantly improved from mean 28 preoperatively to 63 postoperatively. Pain scores significantly improved from 7 to 3 VAS score and 15 to 35 ASES score. Functional scores also significantly improved from 0 to 5 VAS score and 15 to 27 ASES score. Overall motion improved for all movements including forward flexion from 53° to 105°, abduction from 48° to 105°, and external rotation from 5° to 30°. The authors noted that in order to avoid a greater tuberosity osteotomy, all patients required alteration of the humeral preparation. This included retroverting the humeral stem to greater than 30° to accommodate the deformity, and glenospheres were sized as large as possible to maximize soft tissue tensioning while lateralizing the humeral component to avoid bony impingement. Amazingly, they reported no clinical complications but noted two cases of notching and a single instance of proximal humeral resorption; but no adverse outcomes were presented for these patients [26].

Walch et al. performed their own review of 42 patients with four-part proximal humerus malunions at short to intermediate term 4-year follow-up. In their series of patients, similar results were again attained with improvements in pain from 3.8 to 11.6, Constant scores from 19.7 to 54.9, and improved range of motion including forward flexion from 53.6° to 120.5° and external rotation from −5° to 9°. These outcomes resulted in a 98% satisfaction rate with ratings of very good in 43%, good in 45%, satisfactory in 10%, and unsatisfactory in 2%. Interestingly, they found no difference between those with a subscapularis repair and those without. Four complications occurred yielding a 9.5% complication rate. Only one dislocation occurred which was the result of trauma. Postoperative radiographs were monitored, and a high rate of scapular notching was found, but this finding is of unknown clinical concern as the Constant scores appear to be unaffected at their intermediate time point [58].

While only short to intermediate data exist on the use of reverse total shoulder arthroplasty to treat these difficult fracture sequelae, early reports suggest this treatment is safe and effective. Additionally, reverse arthroplasty yields similar but slightly worse overall function with similar pain relief compared to conventional shoulder arthroplasty. Retroverting the humeral stem and increasing the glenosphere size to tension the soft tissues can achieve a high degree of satisfaction with a low short- to intermediate-term complication rate.

3.4 Conclusion

Fractures involving the proximal humerus are a common entity with the majority resolving with uneventful unity. Small study sizes present in the available literature make it difficult to estimate the true incidence rate of malunion; however, variable rates have been quoted with greater incidence with increasing Neer fracture type. Despite the popularity of proximal humeral locking technology, rates of malunion have experienced little alteration. Malunions of the proximal humerus present unique challenges that must be addressed including subacromial impingement, capsular contractures, rotator cuff tears, avascular necrosis, post-traumatic arthritis, and proximal humeral deformity.

Patients developing symptomatic malunions have few prognostic factors to allow for prediction of future surgical needs. Most patients experience improving motion and pain for up to 1 year following proximal humerus fractures. The most common unifying feature of malunion development is continued pain and motion limitation after fracture healing. Once malunion has been identified to be symptomatic, efforts should be made to address the offending deformities as soon as possible to avoid further soft tissue contracture and limit rotator cuff muscle atrophy that may adversely affect patient outcomes. Interestingly, no literature supports the need for early malunion correction with most reports reporting equal outcomes for patients regardless of time to surgical intervention.

Treatment options vary widely depending on patient-specific complaints and proximal humeral deformity. Non-surgical management can yield satisfactory outcomes but is best reserved for low-demand elderly patients. Operative treatments are based on the combination of specific malunion geometry, patient-reported complaints, and viability of the articular surface. Surgical options include head-sparing procedures, including arthroscopy and osteotomy, and head-sacrificing procedures, including hemiarthroplasty, total shoulder arthroplasty, and reverse total shoulder arthroplasty. Arthroscopy is reserved for patients with little deformity isolated to malpositioned tuberosities with complaints of tuberosity impingement. When more significant deformity is present, osteotomies can improve proximal humerus deformity and provide good improvement in pain and function when successful osteosynthesis is achieved. Patient factors that portend better bone quality are thought to improve these outcomes such as younger age and lesser medical comorbidities; however, the small studies that have addressed this treatment regimen have not specifically studied these variables. When the humeral head is no longer viable, conventional arthroplasty options including hemiarthroplasty or total shoulder arthroplasty provide similar results with improvements in pain and function albeit conditional to greater tuberosity osteotomy healing and successful cuff repair. Unlike conventional arthroplasty, alternatives to avoid complications associated with greater tuberosity osteotomy have been investigated with similar improvements in pain and function. Reverse shoulder arthroplasty can successfully be implanted with little proximal humerus preparation resulting in good short-term follow-up with the advantage of avoiding greater tuberosity osteotomy. Nevertheless, additional research is required to determine long-term outcomes following treatment of proximal humerus malunion.

3.5 Case Discussions

3.5.1 Case 1

A 71-year-old male who sustained a surgical neck fracture of humerus after a ground-level fall. Plain films obtained at time of injury include AP, scapular Y, and axillary views (Fig. 3.1a), which demonstrate a varus angulated fracture with typical apex anterior angulation on lateral imaging. Significant medical comorbidities precluded surgical intervention, and he was treated expectantly with non-operative care in a sling.

Subsequent imaging at 3 months (Fig. 3.1b) demonstrated sustained varus positioning, but pain control had markedly improved. Physical therapy was initiated with initial motion of 30° forward flexion and abduction. Range of motion slowly improved, and at 4 months, he demonstrated 90° forward flexion and abduction but with noted weakness. Imaging shows robust callus formation (Fig. 3.1c).

Final follow-up imaging demonstrates residual varus angulation (Fig. 3.1d). Patient had no complaints of pain but still experienced difficulty with certain overhead activities. Final range of motion demonstrated 130° of forward flexion and 90° of abduction. He declined any further treatment and was extremely happy with his progress and was able to fulfill all activities of daily living.

Fig. 3.1 (**a**) Initial AP, scapular Y, and axillary lateral imaging of a two-part surgical neck proximal humerus fracture. (**b**) Radiographs at 6 weeks demonstrating callus formation at the prior fracture site and maintained alignment. (**c**) Radiographs at 3 months demonstrating maturing callus. (**d**) Radiographs at final follow-up with varus malunion

3.5.2 Case 2

A 58-year-old male sustained a proximal humerus fracture from a ground-level fall. He was a very active individual with no prior shoulder pain. Initial imaging demonstrated a complex proximal humerus fracture with varus alignment and relative elevation of the greater tuberosity (Fig. 3.2a). He initially refused any type of surgery. Patient was lost to follow-up for 1 year and returned with a healed malunion of the proximal humerus and significant arthritic wear of the humeral head and glenoid surface (Fig. 3.2b). He complained of difficulty with overhead activity and pain with motion of the shoulder. Aggressive physical therapy did little to improve his symptoms. An MRI

Fig. 3.1 (continued)

was obtained which demonstrated an intact rotator cuff (Fig. 3.2c). He continued to complain of pain and restricted motion and underwent total shoulder arthroplasty (Fig. 3.2d). During the procedure, tuberosity realignment was not performed, and the prosthesis was placed in an orientation to lateralize greater tuberosity offset and achieve a more anatomic alignment. Postoperatively he did very well with improvement in both pain and range of motion. At 1 year, he has overhead motion to 150° with external rotation to 30° and remains pain-free.

3.5.3 Case 3

A 39-year-old female sustained a three-part proximal humerus fracture after a ground-level fall.

Fig. 3.1 (continued)

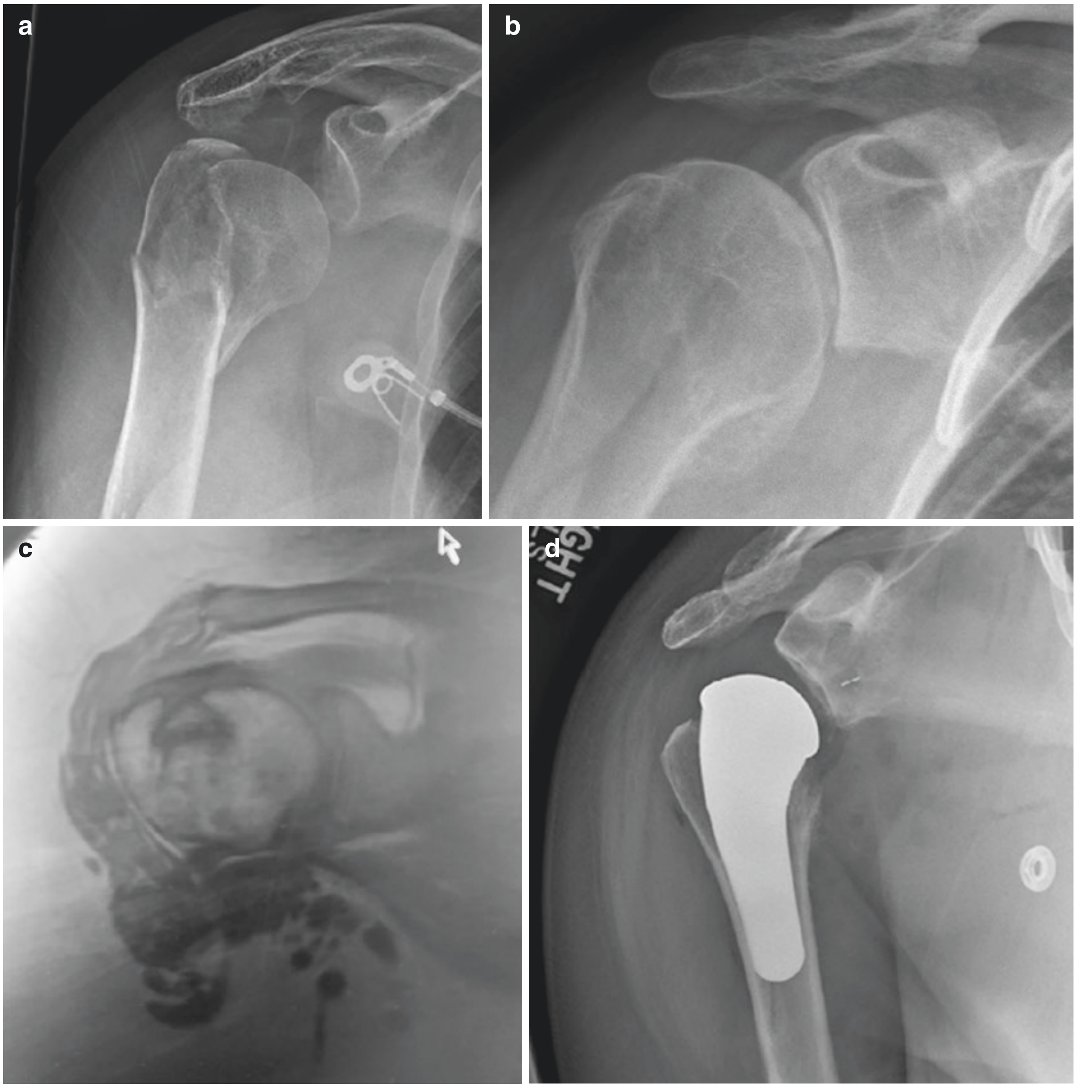

Fig. 3.2 (**a**) Initial AP imaging of a three-part proximal humerus fracture with varus malalignment. Relative superior greater tuberosity elevation is demonstrated due to inferior displacement of the humeral head fracture fragment. (**b**) Successful healing of prior proximal humerus fracture with development of glenoid and humeral head arthritic wear and large inferior humeral osteophyte. (**c**) Select T1 MRI cut of the humeral malunion demonstrating intact rotator cuff attachments to the displaced greater tuberosity. (**d**) Successful total shoulder arthroplasty with anatomic positioning of the previously displaced tuberosity. (Courtesy of Srinath Kamineni)

Initial imaging demonstrated a displaced three-part proximal humerus fracture involving the surgical neck and greater tuberosity (Fig. 3.3a). Her outside orthopedic surgeon attempted non-operative treatment with sling immobilization. She apparently did well for several months but returned 1 year later after successfully healing her proximal humerus fracture but with a malunion (Fig. 3.3b). She began to experience increasing pain in the shoulder. She exhibited signs of impingement on clinical exam and complaints consistent with early arthritis. Overall, her malunion morphology would have been amenable to corrective osteotomy of the greater tuberosity and advancement of her rotator cuff; however, an MRI was obtained (Fig. 3.3c) demonstrating focal areas of avascular necrosis

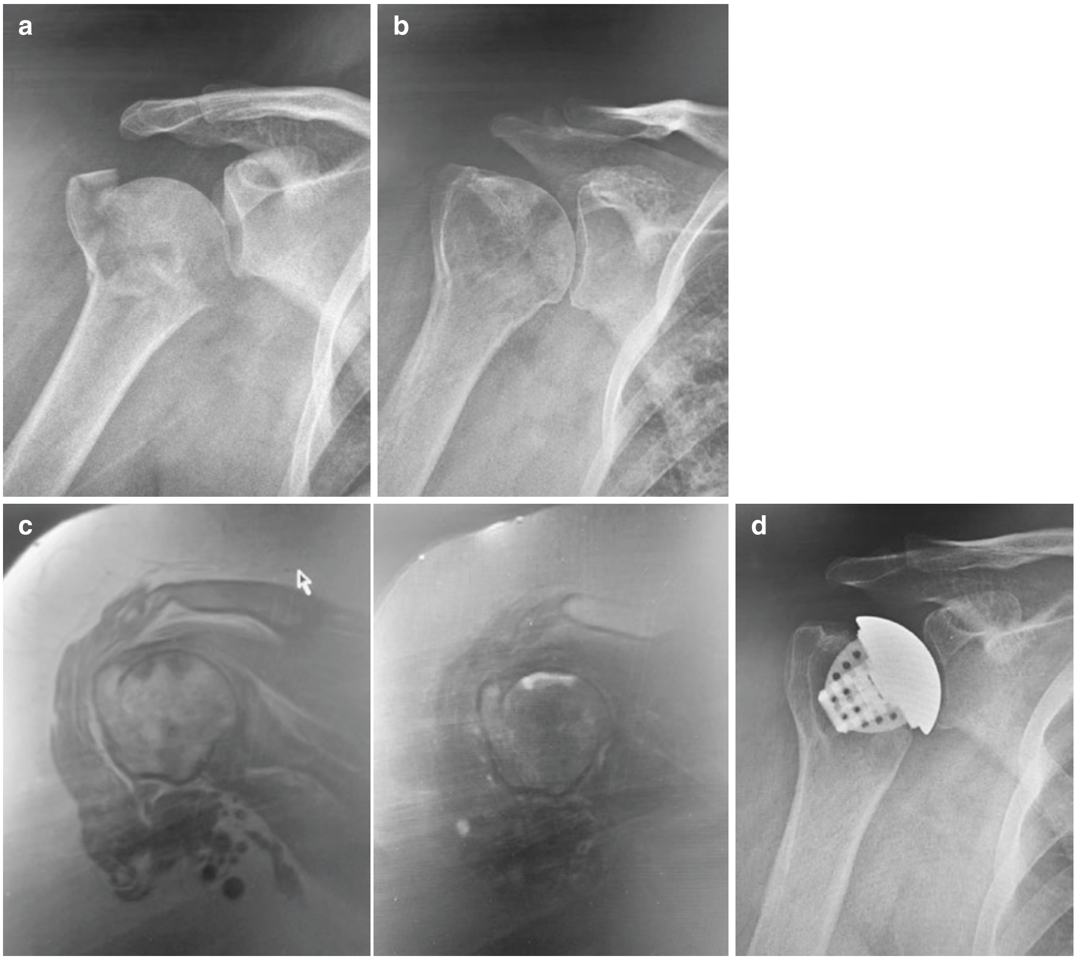

Fig. 3.3 (**a**) Initial AP imaging of a valgus impacted three-part proximal humerus fracture with displaced greater tuberosity fragment. (**b**) Imaging upon initial evaluation with healed proximal humerus malunion with displaced greater tuberosity fragment. (**c**) T1 and T2 imaging of proximal humerus malunion with focal areas of increased signal on T2 and decreased signal on T1 indicative of avascular necrosis. (**d**) Short stem hemiarthroplasty with improvement in greater tuberosity positioning and alignment. (Courtesy of Kaveh Sajadi)

with full-thickness cartilage loss on the humeral head. Glenoid articular cartilage appeared well maintained. Due to her young age, she underwent short stem hemiarthroplasty to preserve her rotator cuff and preserve proximal humeral bone stock (Fig. 3.3d). The prosthesis was placed in an orientation to avoid greater tuberosity osteotomy with restoration of anatomic alignment. She has done very well postoperatively with significant improvement in pain and motion. Last follow-up at 1 year after surgery exhibited significant improvement in both forward flexion and external rotation with no pain.

3.5.4 Case 4

A 62-year-old male sustained a proximal humerus fracture and underwent open reduction and internal fixation at an outside institution. Postoperatively he reportedly underwent extensive rehabilitation with little improvement in pain or motion. At 6 months, he was experiencing exquisite pain with all movement and still experienced continued difficulty with forward flexion and external rotation. Imaging demonstrated a complex proximal humerus malunion with greater tuberosity malunion and persistent

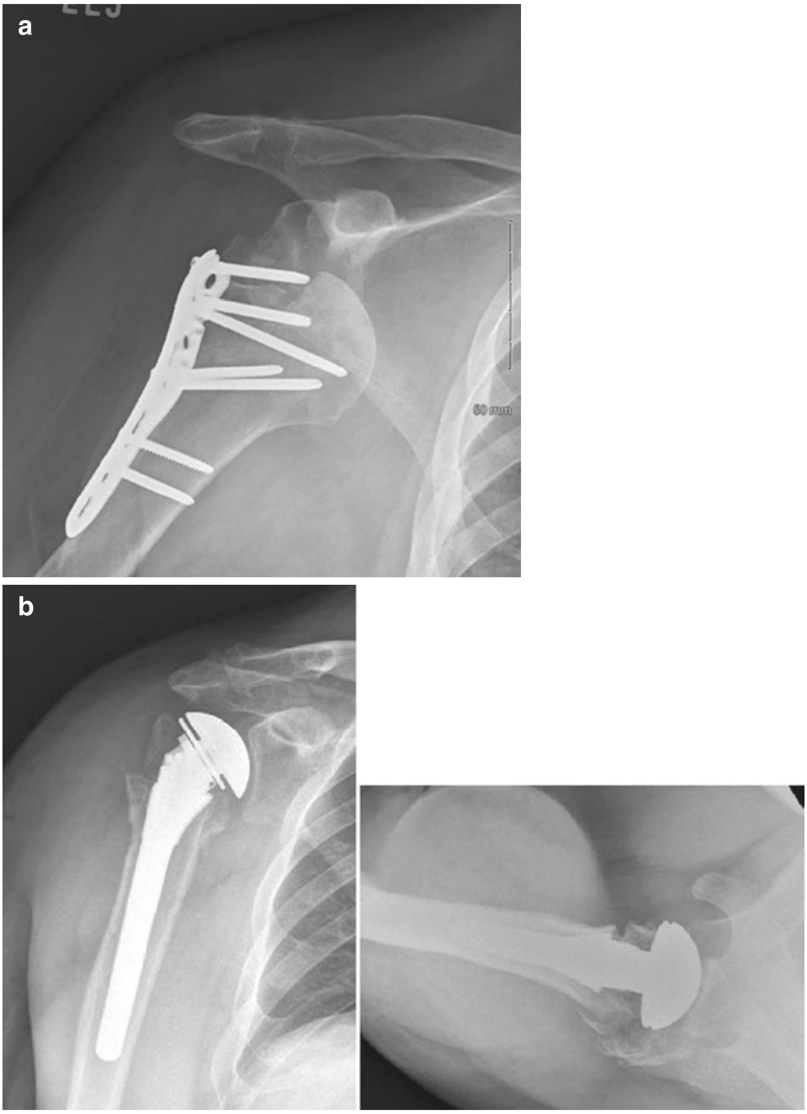

Fig. 3.4 (**a**) Initial AP imaging of healed proximal humerus fracture with intact plate and screw fixation and malpositioned greater tuberosity and anterior dislocation of the humeral head. (**b**) Subsequent revision to hemiarthroplasty with a repositioned greater tuberosity fragment over the lateral flange of the humeral prosthesis. (**c**) Radiographs obtained at 3 months demonstrating greater tuberosity resorption, maintained reduction of prosthesis on lateral imaging, but persistent elevation of the humeral head prosthesis on AP imaging. (**d**) Subsequent conversion to reverse total shoulder arthroplasty. (Courtesy of Srinath Kamineni)

anterior dislocation (Fig. 3.4a). Glenoid bone stock remained intact without significant cartilage wear. The original surgeon then decided to perform removal of the hardware, and a hemiarthroplasty was performed with osteotomy and repositioning of the malunited greater tuberosity (Fig. 3.4b). Postoperatively pain improved, but he reportedly continued to display reduced range of shoulder motion, including 90° flexion and 30° external rotation. Radiographs at 3-month follow-up (Fig. 3.4c) demonstrated resorption of the greater tuberosity fragment with superior migration indicative of rotator cuff failure. He was subsequently referred to our institution for further evaluation and possible revision. He continued to have complaints of difficulty with overhead

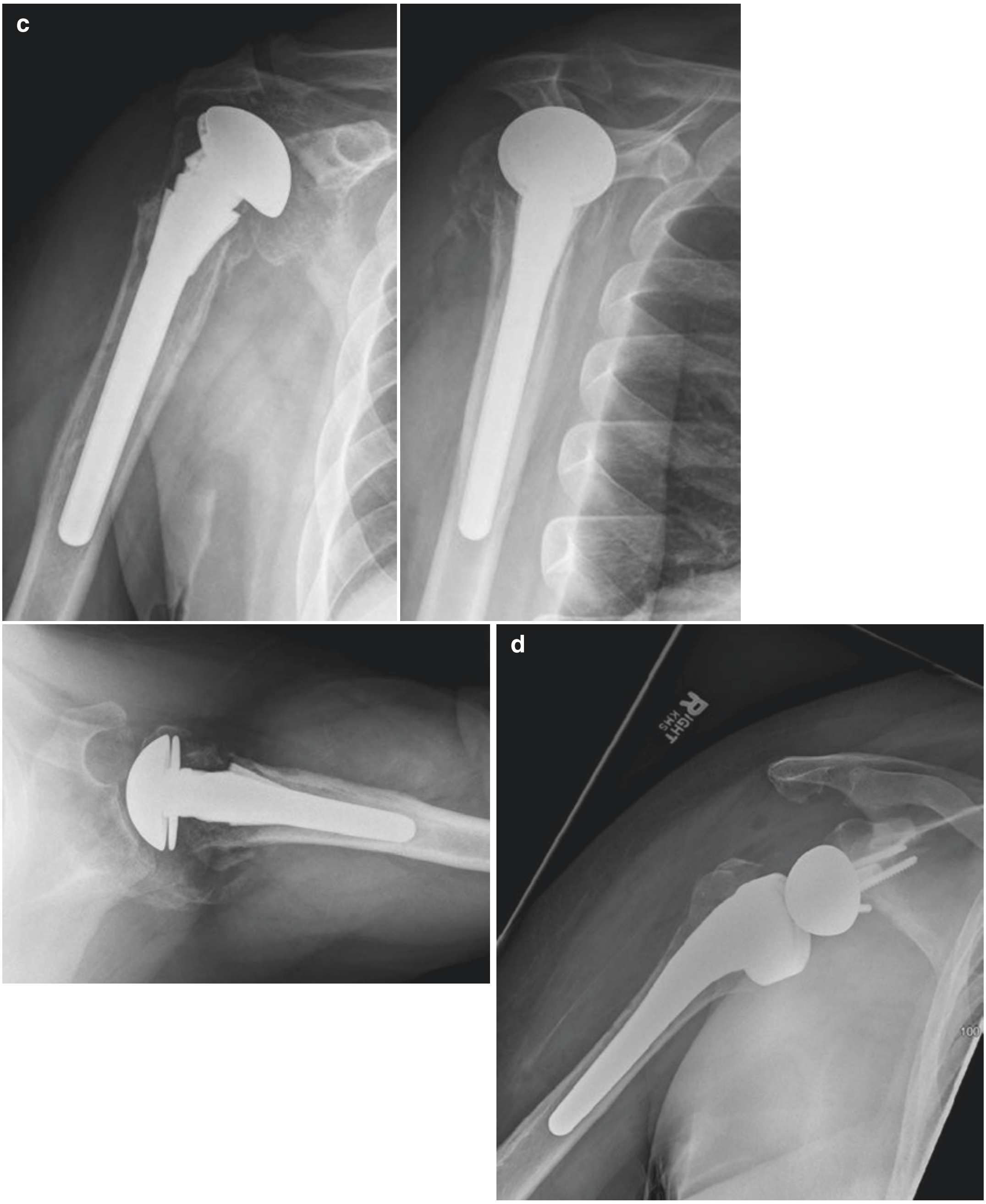

Fig. 3.4 (continued)

activity and worsening shoulder motion but did not wish for any further surgery at that time. He continued to exhibit poor motion with about 70° of forward flexion and inability to comb his hair or brush his teeth and 6 months later returned requesting revision surgery. He subsequently underwent explant of his hemiarthroplasty and conversion to reverse total shoulder arthroplasty (Fig. 3.4d). Afterward, he was able to regain forward flexion to 90° with significant improvement in his ability to perform activities of daily living and remained pain-free at 1 year.

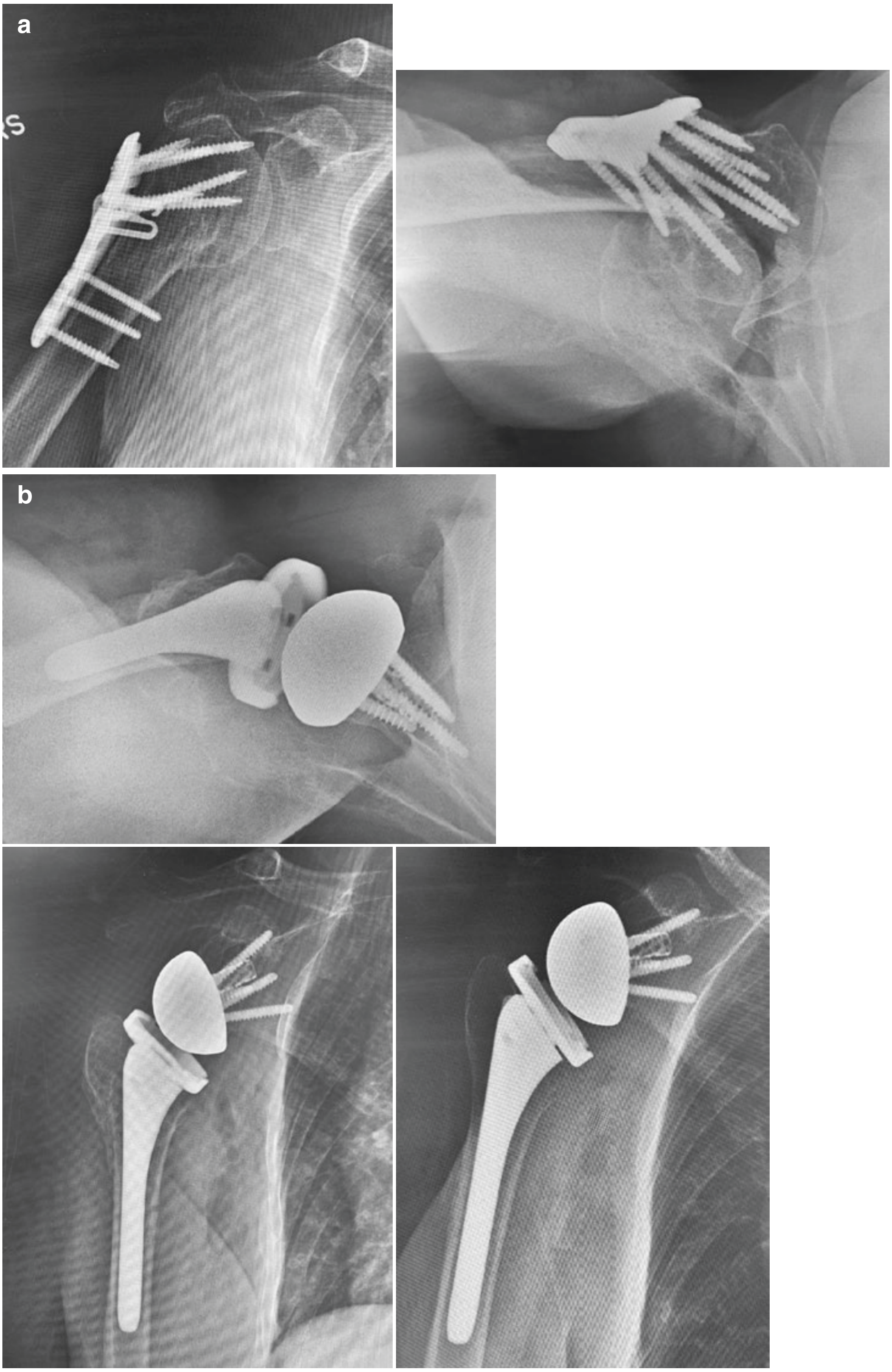

Fig. 3.5 (**a**) Initial AP and lateral imaging of healed proximal humerus fracture with varus malunion and proximal humeral plate and screws. (**b**) Subsequent conversion to reverse total shoulder arthroplasty. (Courtesy of Kaveh Sajadi)

3.5.5 Case 5

A 73-year-old female sustained a proximal humerus fracture and underwent open reduction and internal fixation at another institution 3 years prior. Her pain initially improved after her fracture surgery, and she was able to undergo extensive postoperative rehabilitation. She complained of continued pain with external rotation and continued to have significant weakness. Imaging upon presentation demonstrated a varus proximal humerus malunion with posterior superiorly malpositioned greater tuberosity (Fig. 3.5a). She attempted several rounds of physical therapy targeted at rotator cuff and anterior deltoid strengthening. Despite her attempts, she continued to have difficulty with washing her hair, feeding herself, and putting on shirts. On physical examination, she displayed active forward flexion to 80° with preserved passive forward flexion to 130°. She also had limited active and passive external rotation with signs of posterior glenoid impingement. Additionally, she demonstrated significant rotator cuff weakness with obvious signs of posterior shoulder atrophy on physical examination. Due to her age and significant rotator cuff atrophy, a reverse total shoulder arthroplasty was recommended. She eventually decided to proceed with surgery, and a reverse total shoulder arthroplasty was performed (Fig. 3.5b). Postoperatively she did very well with significant improvement in range of motion. At 1 year, she was very happy and able to wash her hair, dress herself, and feed herself independently.

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4 Malunions of the Humeral Shaft

Jacob J. Triplet and Benjamin C. Taylor

4.1 Introduction

4.1.1 Humeral Shaft Fractures

Humeral shaft fractures account for roughly 3% of all fractures with a reported incidence of 13 per 100,000 per year; a higher incidence in elderly patients has been shown with reported rates as high as 100 per 100,000 persons per year [1–7]. Most often it follows a direct blow or indirect twisting injury. Fractures of the humeral shaft account for nearly 20% of adult humeral fractures [4]. Defined as the area between the upper margins of the pectoralis major tendon or the surgical neck of the proximal humerus to the region of the supracondylar ridge [8], these fractures most often demonstrate a bimodal age distribution with occurrence following high- and low-energy trauma in young and elderly osteoporotic patients, respectively [9, 10]. Often, the fracture pattern helps the surgeon to understand the load applied at the time of injury. Transverse, oblique, spiral, butterfly, and comminuted fracture patterns suggest a tension, compression, torsional, bending, or high-energy loading force, respectively [2, 7].

Understanding of the humeral shaft anatomy is imperative in guiding management. The humerus changes to a triangular shape distally, and the medullary canal tapers to an end about the supracondylar region. The blood supply to the humeral shaft is primarily derived from the brachial, profunda brachial, and posterior humeral circumflex vessels [11]. The humeral diaphysis is dependent on these perforating branches of the brachial artery, and the main nutrient artery enters the medial aspect of the humerus just distal to the midshaft. The radial nerve is particularly vulnerable following humeral shaft fractures. Accompanied with the profunda brachial artery, the radial nerve courses along the posterior aspect of the humeral shaft in a proximal-medial to distal-lateral direction, emerging between the brachialis and brachioradialis muscles. Fractures of the humeral shaft place the radial nerve at risk of injury and entrapment [12–14]. A radial nerve palsy should be suspected with a spiral distal one-third fracture pattern (Holstein-Lewis fracture) (Fig. 4.1); an 18% occurrence has been reported [15]. Additionally, the musculocutaneous nerve lies deep to the biceps muscle and may be injured following humeral shaft fractures. Several muscles attach to the humeral shaft, serving as deforming forces following a fracture. The humeral shaft serves as the origin of the brachialis, triceps, and brachioradialis muscles. It also acts as the insertion site for the deltoid and coracobrachialis, in addition to the three powerful adductors and internal rotators: pectoralis major, teres major, and latissimus dorsi. These deforming forces, along with the patient's body habitus, play an important role in overall limb alignment

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Fig. 4.1 A spiral distal third humeral shaft fracture is commonly referred to as a Holstein-Lewis fracture

Fig. 4.2 Humeral shaft fractures typically displace in a varus position due to muscle pull and body habitus

Fig. 4.3 Open humeral shaft fractures are associated with an increased rate of neurovascular injury as well as postoperative complications

following humeral shaft fracture. Most often, the limb will present in a shortened and varus-angulated position (Fig. 4.2).

With a thorough knowledge of the humeral shaft anatomy, proper management of humeral shaft fractures may be better undertaken. Managing these fractures often depends on several factors. First, open versus closed fracture presentation often dictates the need for operative management; nearly 5% of these injuries are open (Fig. 4.3) [9]. Although reports of conservative management following open humeral shaft fractures have been reported [16], the gold standard is a formal irrigation and debridement of the open wound followed by operative stabilization of the fracture. However, it has been shown that infection rates following non-operative and operative management of these fractures are approximately 3.2% and 4.7%, respectively [17]. Additionally, neurovascular compromise often demands surgical intervention; it is important to be aware that radial nerve palsy is common following these injuries and is not an operative indication alone [3, 14, 18]. Most often, radial nerve palsies are observed for up to 6–12 months to monitor for nerve recovery. Arterial injury may also potentiate an ensuing compartment syndrome or even hemodynamic instability. In such cases, close monitoring and clinical judgment should dictate the need for operative intervention. Concomitant injuries such as those seen in polytrauma and bilateral humeral shaft fractures or in cases of a floating elbow (Fig. 4.4) most often necessitate operative stabilization as well. An understanding of the fracture characteristics is important to recognize at the time of injury. Certain fracture characteristics may benefit from operative stabilization [19]. In cases of segmental injury of the humeral shaft, displaced, comminuted, and those fractures with intra-articular extension may undergo surgical intervention to enhance appropriate alignment and mitigate the risk of malunion or nonunion. Limb alignment following closed reduction and splint application helps predict whether conservative management will be successful. As the humerus is the most freely moveable long bone, anatomic reduction is not required for successful outcomes with non-operative management. However, an acceptable limb alignment is required if non-operative management is to be pursued. Acceptable limb alignments that favor non-operative measures are less than 30° of varus-valgus angulation, 20° of anterior-posterior angulation, and 3 cm of shortening [20, 21]. The patient's body habitus, especially those with large pendulous breasts, plays an important role in overall limb alignment and may reduce successful outcomes with conservative management. If overall limb alignment following closed reduction and immobilization does not meet this criteria, operative stabilization should be considered to circumvent the risk of a functionally limiting malunion or nonunion. In the setting of a pathologic fracture, operative stabilization may be recommended [4]. Lastly, it is widely accepted that in cases of humeral shaft nonunion, operative stabilization with bone grafting should be performed to optimize outcome (Fig. 4.5) [22, 23].

If operative management of a humeral shaft fracture is to be utilized, there are several surgical modalities available (Fig. 4.6) [4, 24–27]. Plate osteosynthesis remains the gold standard for the operative treatment of humeral shaft fractures requiring surgical stabilization [4, 27–29].

Fig. 4.4 Fractures of the humeral shaft and forearm are referred to as floating elbow injuries and are an indication for surgical fixation

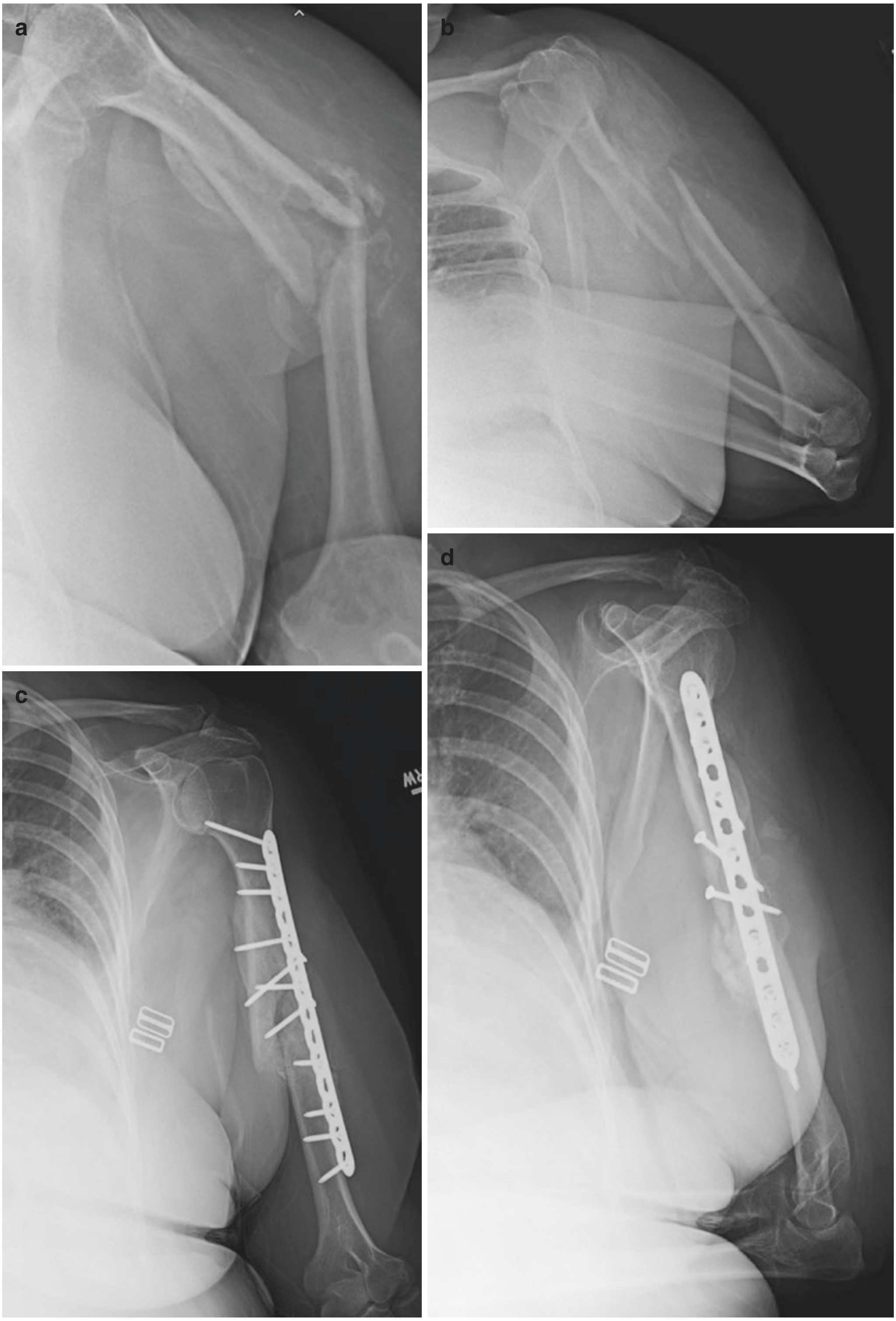

Fig. 4.5 AP and lateral radiographs showing a humeral nonunion from a morbidly obese 44-year-old female with a 9-month history of pain after an acute fracture treated with a simple sling (**a,b**). After the patient underwent treatment of her nonunion with realignment, iliac crest autograft placement, and plating (**c,d**)

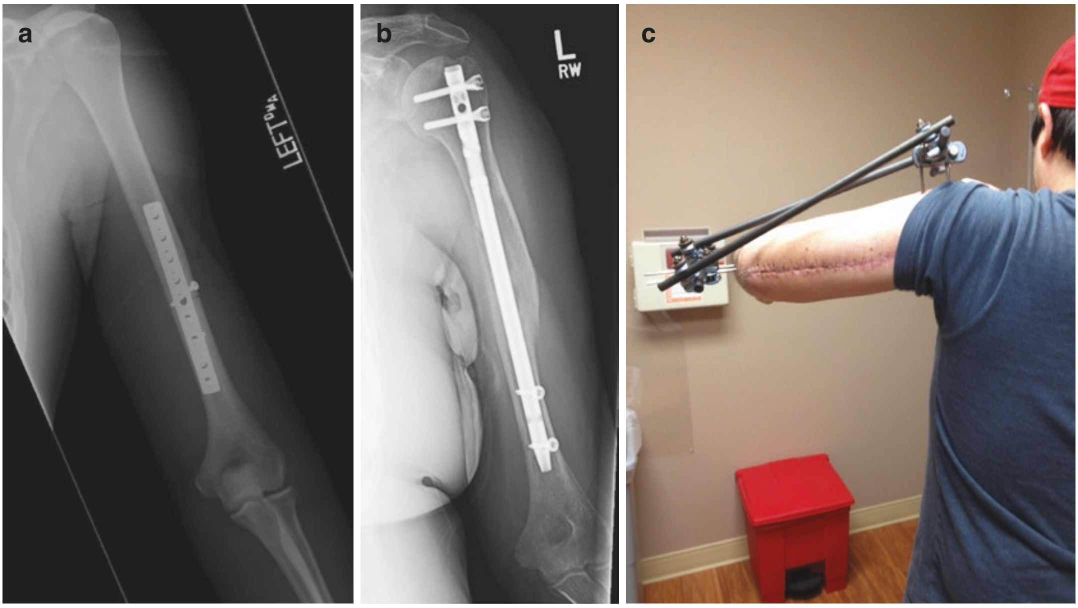

Fig. 4.6 A representative example of treatment of humeral shaft fractures with plating (**a**), intramedullary nailing (**b**), and external fixation (**c**)

Additionally, intramedullary nailing is another popularized and viable treatment modality for humeral shaft fractures, [3, 30], and it is important to note that both antegrade and retrograde humeral intramedullary nails are available [26, 31]. Also, while less commonly applied in the treatment of primary operative stabilization of humeral shaft fractures, external fixation is an available treatment modality and is especially beneficial in cases where "damage control orthopedics" are merited or in cases requiring a temporizing fixation [32]. External fixation is also useful for humeral shaft fractures with concomitant burns or in the setting of large open contaminated wounds. Additionally, use of the Ilizarov fixator has been reported to have success in the setting of humeral shaft nonunion [33–37].

Nonetheless, despite the several surgical treatment modalities available, the majority of humeral shaft fractures are managed conservatively, with reported union rates exceeding 94% [14]. Described by the Egyptians more than 3500 years ago with the use of splints, nonoperative management of humeral shaft fractures tends to yield favorable outcomes [20]. Again, obtaining an acceptable overall limb alignment is important to optimize outcomes with conservative management. With widespread motion at the adjacent shoulder and elbow joints, shortening, axial, angular, and/or rotational malunion of the humeral shaft is often well tolerated with little functional or cosmetic deficits [2]. Following acute injury, humeral shaft fractures are most commonly managed initially with a closed reduction and application of a coaptation or posterior elbow splint or a hanging arm cast (Fig. 4.7) [38]. Dependent on swelling and patient comfort, approximately 2 weeks later, a prefabricated fracture brace is often utilized (Fig. 4.8); this has reproducibly demonstrated success [16, 39–41]. In the setting of humeral shaft fractures, functional fracture bracing provides the benefits of gravity and allows for a hydraulic soft tissue compression, adequate bony alignment, and fracture site motion leading to the promotion of osteogenesis [42, 43]. Moreover, functional bracing allows for the early preservation of shoulder and elbow motion, a reduced cost, and improved patient comfort and hygiene [8, 12, 14, 40]. In a review of the literature, Papasoulis et al. reported an average of 10.7-week time to union of humeral shaft fractures managed conservatively with

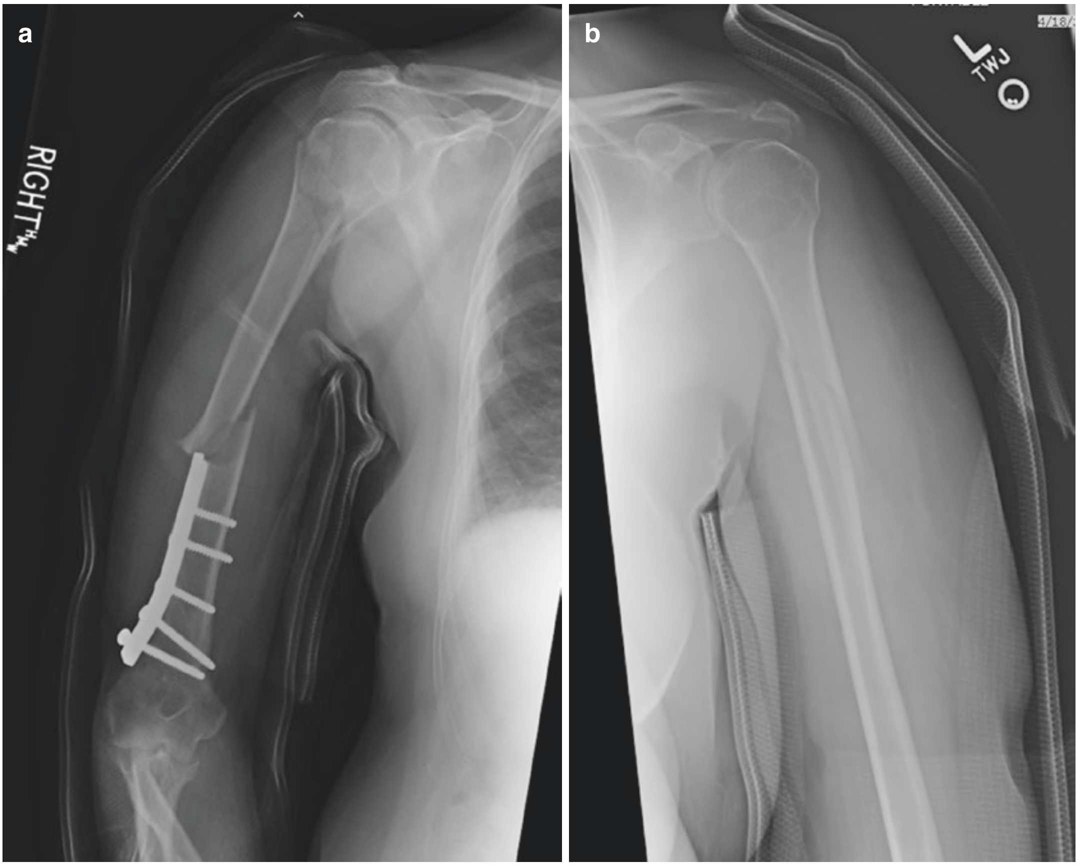

Fig. 4.7 (**a**) A 53-year-old female with a segmental humeral fracture in a coaptation splint approximately 4 h after injury. (**b**) An example of an inadequate coaptation splint, with the medial limb of the splint not extending to the humeral shaft fracture

functional fracture bracing [14]. A longer time to union has been reported with functional brace treatment in cases of open humeral shaft fractures, averaging 13–14 weeks [8, 14, 44]. With excellent results reported, functional bracing is considered the gold standard for treatment of humeral shaft fractures (Fig. 4.9) [14, 30, 38].

4.1.2 Defining Malunion

Although a malunion may simply be defined as a malunited fracture that has healed in a non-anatomical position, a more encompassing definition is needed to help guide treatment. First, one must scrutinize the initial fracture reduction. Close scrutiny of humeral shaft fractures is important as alignment, length, rotation, and angulation may lead to healing in a malunited position. Second, determining the location of the fracture is essential, whether it is diaphyseal, metaphyseal, or intra-articular. Fractures with intra-articular extension often will require operative intervention, as anatomic reduction of articular surfaces is necessary for proper function of the involved joint. Assessment of whether the humeral shaft fracture is simple or complex is also key; this refers to those fractures that occur in a single plane compared with those that occur in multiple planes. Generally, malunion of the humeral shaft is defined as >20° of angulation in any plane (anterior/posterior or varus/valgus) or shortening of ≥2.5 cm [38]. However, in addition to the >20° of angulation in anterior/posterior

Fig. 4.8 (**a–c**) A properly applied fracture brace (Sarmiento brace), with either a regular or over the shoulder version (for proximal fractures) (**c**). Unfortunately, patients may present with the brace worn improperly (**d**), where the brace is not holding the fracture at all

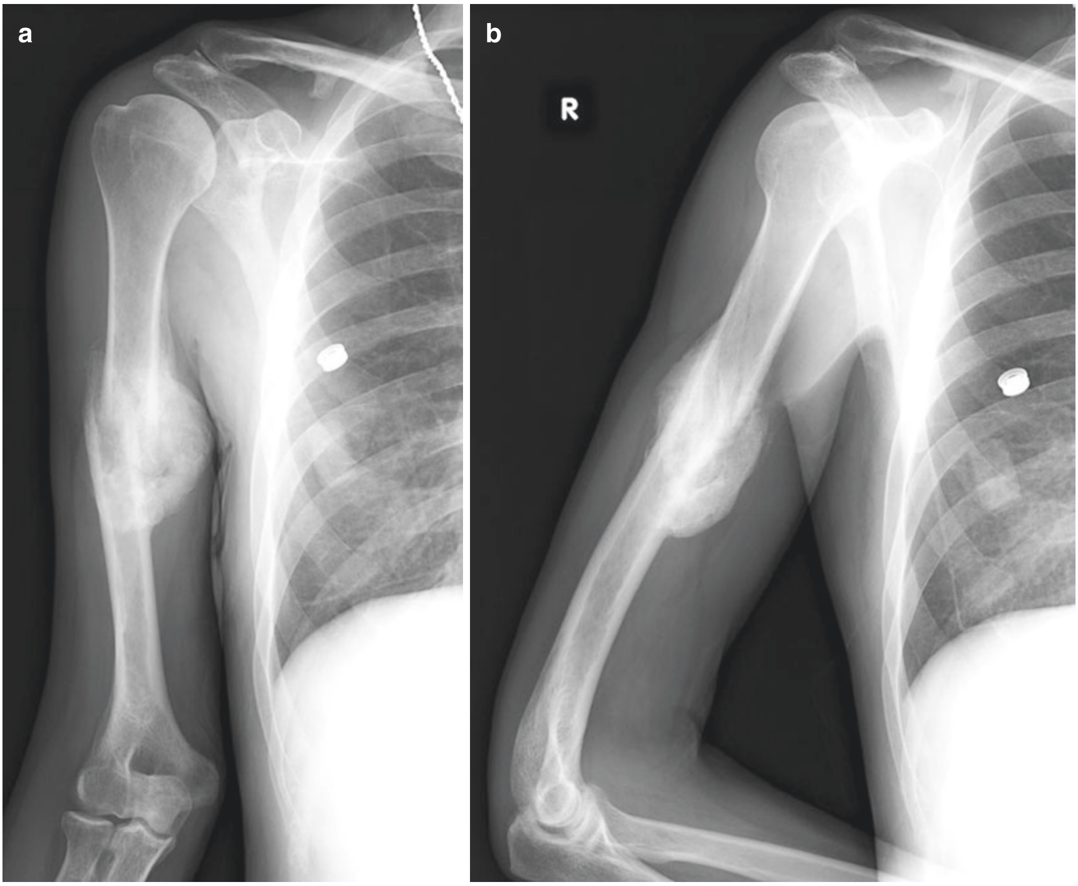

Fig. 4.9 (**a,b**) Closed treatment of humeral shaft fractures generally results in abundant callus formation due to motion and secondary bone healing

plane, other reports assert that >30° of angulation in the coronal plane and >3 cm of shortening/bayonet apposition constitute a humeral shaft malunion as deformity less than these may be well tolerated with minimal functional or cosmetic deficit (Fig. 4.10) [20, 21].

4.1.3 Distinguishing Malunion from Nonunion

It is critical to distinguish between malunion and nonunion of humeral shaft fractures. As the causality of both malunion and nonunion usually differs, the surgical intervention required to treat each can also vary. To distinguish between the two, serial imaging of the humeral shaft fracture is often necessary, as it will reveal the progression to fracture union or nonunion. Demonstration of insufficient bridging between bone edges, lack of callus progression, or loss of acceptable bone alignment when evident within 6 months will often satisfy the general criteria for humeral shaft nonunion [22, 45]. Several factors are associated with nonunion following conservative treatment. Among these are noncompliance with bracing, morbid obesity, unfavorable fracture pattern (i.e., transverse), open or pathologic fractures, history of alcohol abuse, significant angulation, soft tissue interposition, comorbidities (diabetes, rheumatoid arthritis, osteoporosis), anti-inflammatory medication use, and smoking [46]; however, most commonly a nonunion has a multifactorial origin [22]. Nonunion of the humeral shaft is relatively uncommon with a reported range of 3–5% following operatively treated humeral shaft fractures [8, 47, 48]. However, there are scattered reports that cite nonunion rates as high as 50% following operative intervention [4, 40, 49, 50]. In humeral shaft nonunion that occurs following operative stabilization, the most common cause has been shown to be inadequate fixation (Fig. 4.11) [22]. It has been demonstrated to occur following improper reduction or fracture site distraction, inadequate plate size or implant choice, incorrect bone fixation in osteoporotic bone, poor screw purchase, or other technical errors [15, 51]. Humeral shaft nonunions have been reported to occur in as many as 23% of humeral shaft fractures following conservative management in some series [10, 17, 40, 50], with other series demonstrating excellent union rates [8, 42]. Proximal third injuries, Arbeitsgemeinschaft für Osteosynthesefragen (AO) type A humeral fractures, and periprosthetic fractures have been shown to have the highest nonunion rate (Fig. 4.12) [14].

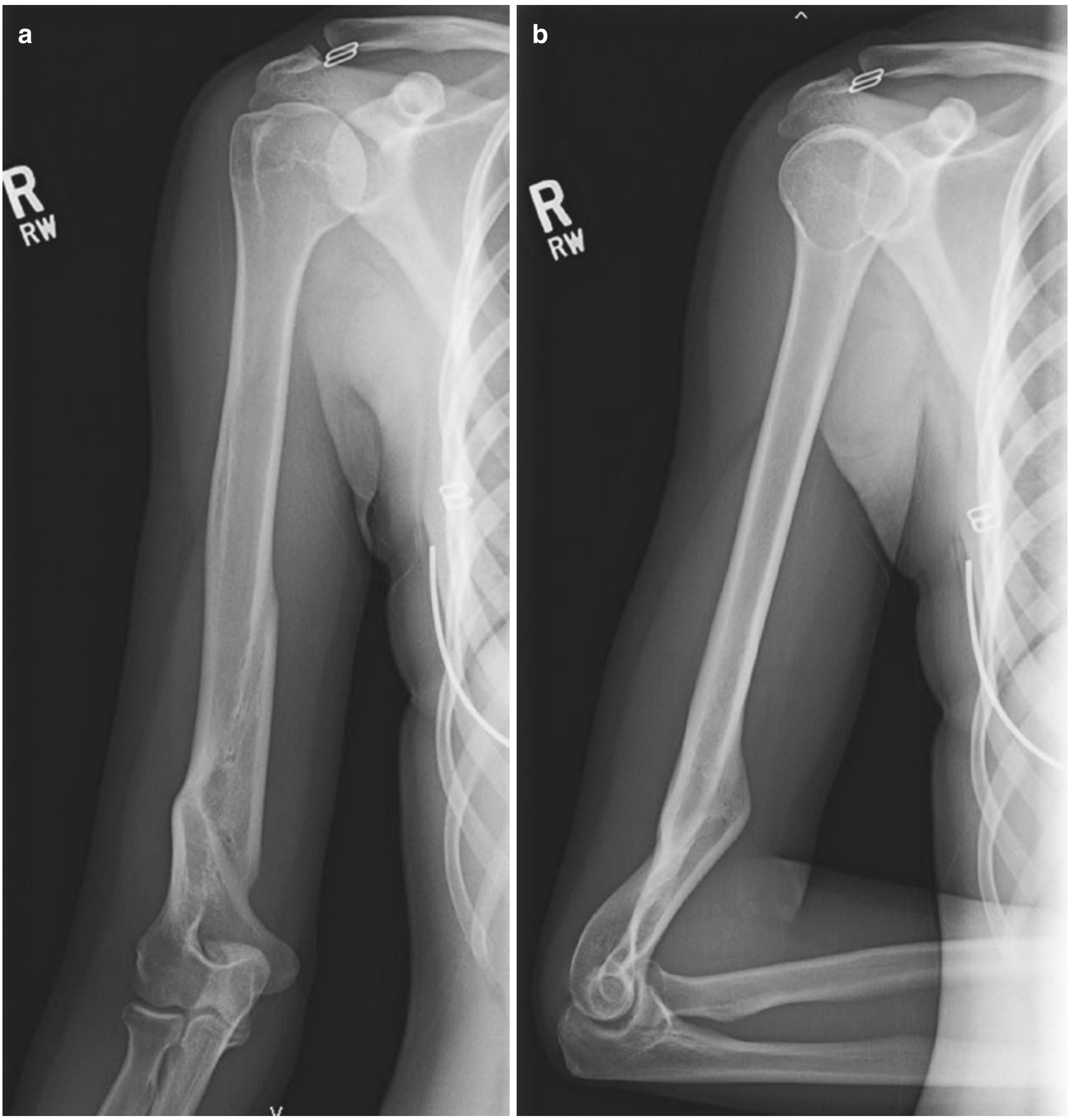

Fig. 4.10 A healthy, active female sustained a distal humeral shaft fracture with some displacement and healed uneventfully (**a,b**). Her motion remains unrestricted (**c–e**), with a nearly imperceptible difference between her two upper extremities

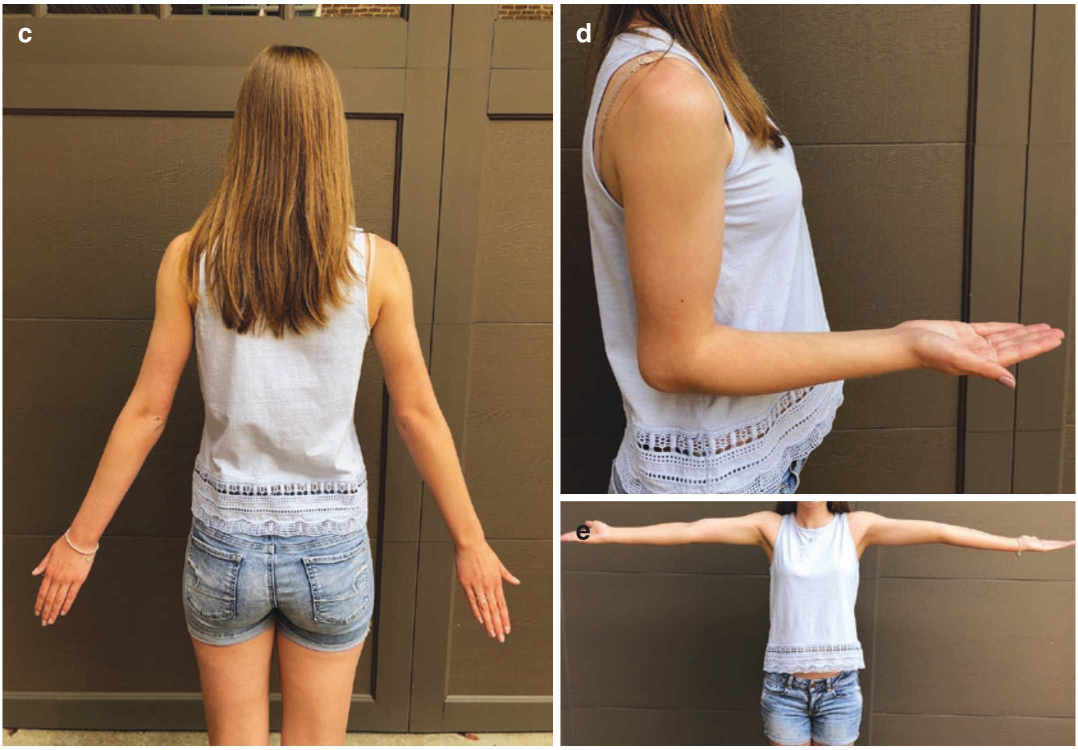

Fig. 4.10 (continued)

Generally, two distinct types of nonunions are frequently described. They either demonstrate fragment ends that are hypervascular or hypertrophic with capability to obtain biologic reaction or that are avascular or atrophic and incapable of biologic reaction [45]. Irrespective of the type of nonunion, either may be complicated by the presence of infection, soft tissue injury, articular incongruities, or non-acceptable overall limb alignment [45]. These worsen the prognosis of the nonunion and often require extensive multistage surgery and/or amputation. Understanding of the need for stability or biology, along with assessment of bone loss, is imperative [22]. Often these fractures will respond well to open reduction and internal fixation with bone grafting [22, 23]. Following operative stabilization, union is achieved in approximately 90–98% of cases following plate fixation and in as much as 91–98% following intramedullary nailing in some series [52]. Humeral shaft nonunions have a substantial associated economic cost [53, 54].

Much more common to occur than humeral shaft nonunion is humeral shaft malunion. The vast majority of humeral shaft fractures will be managed with conservative measures, most commonly with the use of functional bracing. Justification of non-operative management of these fractures is supported in the literature with excellent union rates [14]. Although union rate is high in these patients, more than 85% of patients will demonstrate a residual deformity of <10° [14]. Therefore, some degree of malunion is to be expected following conservative management. However, the degree of malunion is important to consider despite the humerus being able to accommodate a significant amount of deformity with little functional or cosmetic deficit. Additionally, malunion may also occur following operative stabilization of humeral shaft fractures. In these cases, the malunion is more likely to occur from improper reduction at the time of fixation, improper construct, noncompliance, or significant comminution or bone loss.

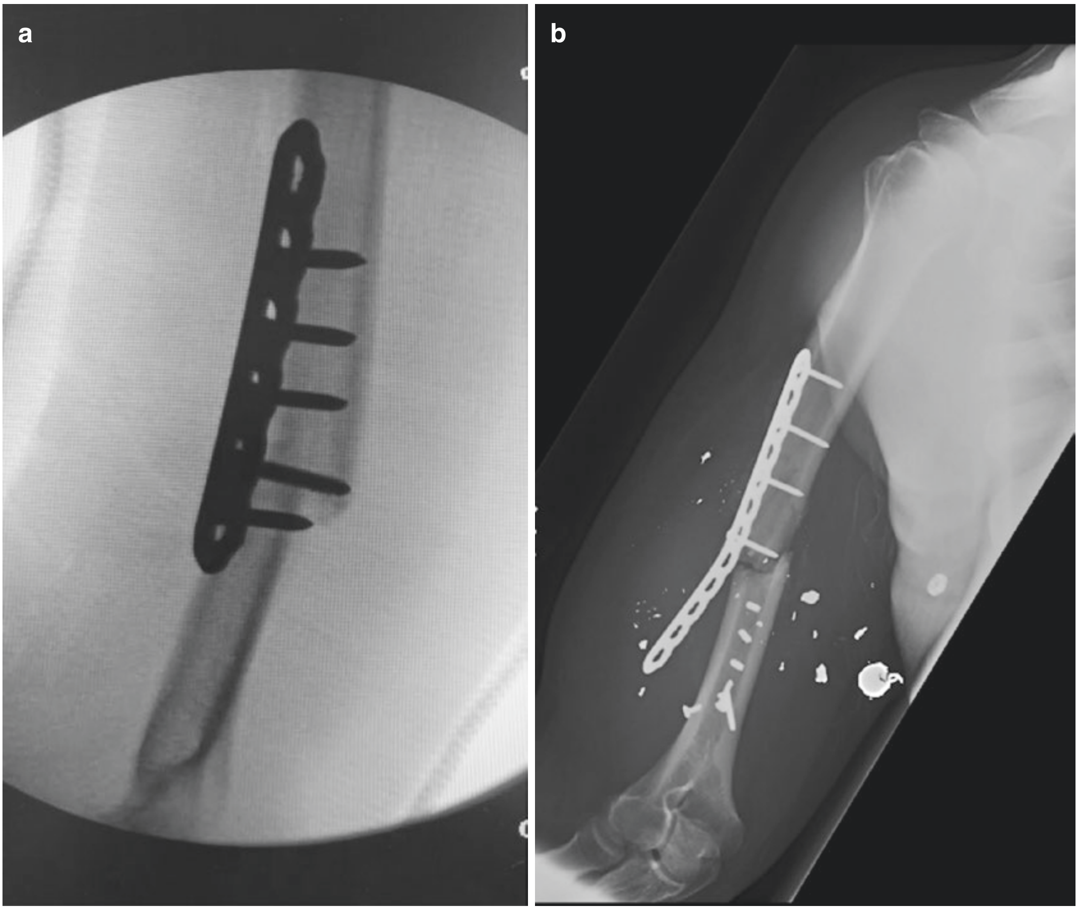

Fig. 4.11 Inadequate fixation can consist of the use of fixation constructs that are too short (**a**) or even with use of small fragment implants in muscular, noncompliant patients (**b**)

4.1.4 Incidence of Malunion

As previously discussed, the incidence of humeral shaft malunion is much more common than nonunion and is to be expected in most cases, particularly those managed by means of non-operative treatment. Several reports have demonstrated that a residual deformity of <10° is found in more than 85% of patients treated with conservative measures following humeral shaft fractures [14]. While humeral shaft malunion may ensue following either operative or conservative management, a higher incidence of residual deformity, most commonly in the frontal plane leading to varus angulation, has been demonstrated after non-operative treatment [12, 14, 17, 38, 44, 50, 55–57]. Applying a more stringent definition to humeral shaft malunion of >20° of angulation in any plane (anterior/posterior or varus/valgus) or shortening of ≥2.5 cm [38], a general incidence of 4.4%, with some literature reporting rates as high as 16% following non-operative management, has been reported, potentially leading to functional impairment and/or cosmetic deformity [14, 17, 38, 50, 55, 56, 58].

4.1.5 Ramification of Malunion

The humeral shaft is very accommodating of deformity. Several studies have demonstrated that angular deformity <20° is well tolerated both functionally and cosmetically [14, 16, 42, 50, 55]. However, some studies have demonstrated

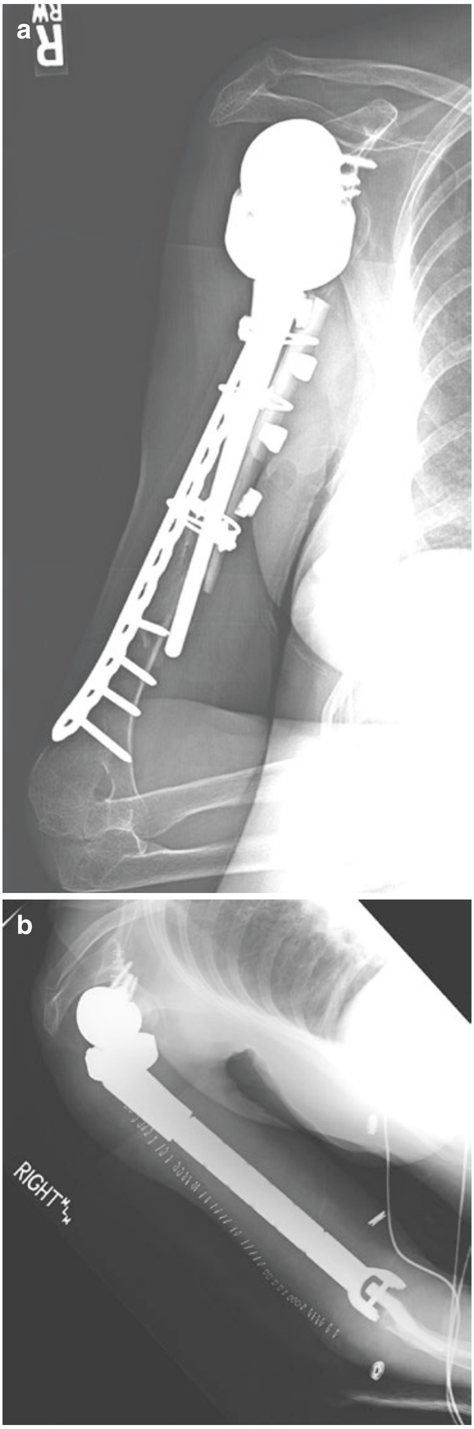

Fig. 4.12 A 59-year-old female underwent right shoulder arthroplasty and five subsequent revisions for loosening and humeral shaft fracture. Due to the poor quality and limited amount of distal bone in the humerus (**a**), a total humeral replacement was performed (**b**)

that the degree of radiographic malalignment may not correlate with functional outcomes [50]. In a recent study, Devers et al. [38] evaluated functional outcomes of malunion of non-operatively treated humeral shaft fractures, and they reported good functional outcomes in patients with malunion following conservative management. However, they also demonstrated that 25% of patients reported trouble with overhead activity and 75% reported noticeable cosmetic deformity, with many of these citing it as a major reason for dissatisfaction. Cosmetic deformity of humeral shaft malunion is a serious concern in patients managed conservatively.

One concern following malunion of humeral shaft fractures treated with non-operative management is a limitation in shoulder motion, particularly external rotation [55, 59, 60]. This has been demonstrated to be more pronounced in elderly patients compared with those younger than 45 years of age [55]. Previously, Sarmiento et al. postulated that loss of external rotation of the shoulder may be influenced by shrinking of the capsule [59]. In a study investigating 67 humeral diaphyseal fractures, Fjalestad et al. demonstrated a 38% loss of external rotation of the shoulder following conservative management with functional bracing [55]. With the use of computed tomography (CT), consolidation of the fracture in a malrotated position was frequently encountered. Although use of the CT was not definitive in demonstrating a clinically significant correlation among the CT-measured angular difference between the involved and uninvolved extremity with loss of external rotation, it suggested that the malrotation likely influences these findings. They postulated that the timing between the injury and the application of the functional brace might influence this. Patients with loss of external rotation compared with those without external rotation deficit had an earlier application of functional bracing (12 versus 16 days, respectively). Therefore, early functional bracing may reduce the incidence of conservatively treated humeral shaft malunions and subsequently reduce external rotation deficit. They further elaborated that malunion with retroversion of the distal fragment was observed in patients who maintained their initial form of immobilization for a prolonged period of time before functional brace application. As the initial form of immobilization is likely to cause internal rotation of the forearm and distal fragment of the humerus relative to the proximal fragment, it was postulated that this would lead to a loss of external rotation. With the shoulder evaluated in an abducted position of 90°, loss of external rotation was observed in 20% of patients. They concluded that the loss of external rotation of the upper extremity following humeral shaft fractures treated with functional bracing is likely due to both the malrotation of the consolidation and changes within the shoulder capsule. Conversely, other studies have reported a 10–15-degree loss of internal or external rotation of the shoulder following non-operative treatment with little functional impairment and good patient satisfaction [38]. It has been shown that in addition to impairment of external rotation, abduction of the shoulder and extension of the elbow may also be affected [14].

4.2 Causes of Malunion

Malunion may occur following both conservative and operative treatments of humeral shaft fractures. Several factors may be associated with malunion following conservative treatment. Among these are noncompliance with bracing, body mass index, unfavorable fracture pattern (i.e., transverse), significant angulation, soft tissue interposition, comorbidities (diabetes, rheumatoid arthritis, osteoporosis), anti-inflammatory medication use, and smoking [46]. Additionally, as previously mentioned, time to application of functional bracing has been postulated to be a risk factor for humeral shaft malunion [38]. However, studies have shown that malunion of the humeral shaft is frequently encountered even in patients who are compliant with functional bracing [38]. Moreover, potential risk factors such as obesity and comorbidities did not differ significantly from patients who healed without humeral shaft malunion [38]. Similar to nonunion, in cases of malunion after operative treatment, the most common cause is believed to be inadequate fixation. Improper reduction or fracture site distraction, inadequate plate size or implant choice, incorrect fixation in osteoporotic bone, poor screw purchase, or other technical errors are likely to contribute to consolidation in a malunited position.

4.2.1 Patient Considerations

Patient factors are important in consideration to properly manage humeral shaft malunion. Age of the patient, consideration of socioeconomic factors, functional demand, and soft tissue integrity are often first to be considered. As previously mentioned, systemic factors and medical comorbidities such as smoking, diabetes control, and nutritional status may have an effect on outcome [46]. Understanding that malunion is often present in patients with osteopenia is an important consideration as it may redirect treatment selection.

First, patients should be educated on treatment options. They should understand that the majority of humeral shaft fractures may be successfully treated with conservative management. However, they should be made aware of the probability that some degree of malunion will ensue and that in most instances it is not associated with functional or cosmetic deficit. Nonetheless, it is imperative that the patient recognize the possibility of cosmetic deformity and potential limitations in motion, particularly external rotation [38, 55]. Although several factors are important to consider, functional demand of the patient and expectations following treatment are perhaps the most important in the setting of humeral shaft malunion. Patients with significant medical comorbidities or those with low functional demand may tolerate a malunion well. Malunion of the upper extremity tends to be better tolerated than those occurring in the lower extremity. Reports have demonstrated a lack of significant pain, good functional outcomes, and patient satisfaction with malunion following non-operative management [38].

4.3 Evaluation and Treatment

4.3.1 History

Obtaining a proper history is imperative in properly managing patients with humeral shaft malunions. Understanding of the original injury, patient medical comorbidities, ability to comply with the initial treatment modality, functional demands, and investigating for evidence of infection are important to ensure proper treatment. As mentioned above, several factors may contribute to the incidence of humeral shaft malunion, but many reports have demonstrated that no significant differences are observed between those with malunion and those without [38]. Additionally, humeral shaft malunions have been reported to occur in up to 16% of patients treated with functional bracings who were compliant with treatment [38]. However, more recently a 37% fracture brace failure rate and a 27% conversion rate to operative intervention have been reported following conservative management [61].

One should also always consider the possibility of a re-fracture through a previously united humeral shaft fracture and ask whether the patient had experienced any trauma since the initial injury that must be investigated. Lastly, patient outcome measures are important to obtain, particularly the ability to perform activities of daily living. As malunion of the humeral shaft has been demonstrated to affect shoulder motion [55, 59], it is important to evaluate for these shoulder limitations, and quite often, patient-reported outcome measures are useful in obtaining subjective data [62, 63].

4.3.2 Physical Examination

As with any examination in orthopedics, a thorough evaluation of the involved extremity should be performed. Begin with observing any cosmetic deformity at rest and with motion. Next, assess active range of the motion of both the shoulder and elbow. With the understanding that shoulder motion may be impaired following nonoperative management of humeral shaft fractures treated with functional bracing, motion should be assessed in several planes. Fjalestad et al. demonstrated a functional loss of external rotation in these patients that differed when assessed at 90° of abduction [55]. Flexion, extension, abduction, adduction, and internal and external rotation of the shoulder should be assessed and compared to the contralateral upper extremity. Elbow motion of flexion, extension, pronation, and supination are important to evaluate, as these motions are needed to perform activities of daily living. Most importantly, patients that are unable to perform activities of daily living may necessitate operative intervention to correct the deformity. In a recent study, Namdari et al. defined functional shoulder range of motion for activities of daily living [64]. They demonstrated that shoulder range of motion needed to perform functional tasks for flexion, extension, abduction, cross-body adduction, abduction at 90°, and internal rotation with the arm at the side were 121, 46, 128, 116, 59, and 102°, respectively. Next, reassessing shoulder and elbow motion passively should be performed. This is important to assess potential capsular changes of the shoulder which would limit both active and passive motions [59]. Again, while obtaining complete shoulder motion is ideal, findings re-confirm that some degree of motion loss may be well tolerated to perform activities of daily living [64]. All of this information is consolidated to evaluate any limitations of the patient.

4.3.3 Laboratory Evaluation

In the setting of malunion of the humerus, laboratory work may be helpful in certain instances. As these patients have consolidation of the fracture, usually an extensive workup to investigate nutritional, infectious, or other causative etiologies is not merited, as they are in cases of humeral shaft nonunion. However, in cases where nonunion versus malunion is difficult to discern, a thorough workup is recommended. Basic infectious labs such as a complete blood count (CBC) with differential, erythrocyte sedimentation rate (ESR), and C-reactive protein (CRP) are recommended.

In suspected cases of malnutrition, metabolic labs including albumin, vitamin D, parathyroid hormone (PTH), serum calcium, phosphate, and alkaline phosphatase should be considered.

Bone quality is important to assess when considering operative intervention for a humeral shaft malunion. Bone density is often appreciated on radiographic imaging. However, it is important to note that when poor bone quality is recognized on plain radiographs, significant deterioration has already occurred. In fact, it is well established that one must lose approximately 30–50% of bone mass before being able to be detected on plain radiographs [65]. In such cases, CT imaging or dual-energy X-ray absorptiometry (DEXA) should be considered. The DEXA scan provides detailed information regarding bone mass while minimizing radiation exposure associated with CT imaging.

4.3.4 Radiographs

High-quality radiographs are the cornerstone of monitoring for malunion following either conservative or surgical management of humeral shaft fractures. Again, from the time of the initial injury, radiographs should be scrutinized for initial fracture reduction, alignment, length, rotation, and angulation of the fracture fragments, number of planes in which any deformity occurs, and location of the fracture, whether it is diaphyseal, metaphyseal, or intra-articular. As discussed, fractures with intra-articular extension often will require operative intervention, as anatomic reduction of articular surfaces is necessary for proper function of the involved joint. Obtaining fracture union is dependent on the biological environment and mechanical properties of the fracture [66]. As previously conferred, discerning between humeral shaft malunion and nonunion is imperative as treatment options and workup differ. An understanding of how to properly assess union is important, and this is complicated in that quantifying union radiographically may be challenging as bone bridging occurs in varying patterns such as periosteal, endosteal, and intercortical [67]. Generally, fracture union is defined as the radiographic presence of bridging callus in at least three of the four cortices on both the anteroposterior (AP) and lateral X-ray [68, 69]. In general, once consolidation of the fracture has been established, the deformity that ensued should be quantified; malunion of the humeral shaft is defined as >20° of angulation in any plane (anterior/posterior or varus/valgus) or shortening of ≥2.5 cm [38]. However, in addition to the >20° of angulation in anterior/posterior plane, other reports assert that >30° of angulation in the coronal plane and >3 cm of shortening constitute a humeral shaft malunion as deformity less than these may be well tolerated with minimal functional or cosmetic deficit [20, 21].

4.3.5 CT/MRI

As described previously, diagnosing malunion of the humeral shaft is often accomplished with high-quality radiographs. Thus, advanced imaging such as computed tomography (CT) or magnetic resonance imaging (MRI) is not needed in such cases. Most often, functional limitations or cosmetic deformity will dictate the need for surgical intervention. However, advanced imaging may have a select role in preoperative planning for surgical correction of humeral shaft malunion. CT imaging allows for better assessment of fracture consolidation as bone bridging may be better assessed than on plain radiographs; this also helps distinguish between malunion and nonunion. Moreover, CT and MR imaging are useful in cases to assess for infection or pathologic lesions. CT imaging may better assess deformity than plain radiographs as landmarks are more reproducibly visualized. By using the transepicondylar axis (TEA), one may assess the degree of rotational malunion of the humeral shaft fractures. Therefore, it may provide usefulness in preoperative planning that will require an osteotomy. Lastly, magnetic resonance imaging (MRI) is useful to assess soft tissue structures and aid in measurement of limb alignment. Recently, a methodology of presurgical planning to utilize complex deformity of long bones with a single-cut osteotomy has been publicized [70].

4.4 Treatment

4.4.1 Initial Treatment of Humeral Shaft Fracture

4.4.1.1 Non-operative Management of Humeral Shaft Fractures

As the vast majority of humeral shaft fractures will be managed with conservative measures, a thorough understanding of the primary non-operative treatment modality should be discussed. Despite the non-operative treatment options available, at the time of injury, the initial treatment modality is closed reduction followed by the application of a coaptation or posterior elbow splint, sling and swathe, or a hanging arm cast [38]. Often, a formal closed reduction is not needed, as gravity and the weight of the arm are likely to accomplish this. However, frequently a valgus mold to the splint is necessary to counter the varus-producing deforming forces. This is especially true in patients with a large body habitus or breasts, which potentiates the varus angulation of the deformity. One must understand the deforming forces and expected displacement of fracture fragments based on location of the fracture. Fractures occurring proximal to the pectoralis major insertion should result in a proximal fragment that is abducted and externally rotated by way of the rotator cuff muscles; the distal fragment will have medial and proximal displacement from the deltoid and pectoralis major muscles. Those fractures occurring between the pectoralis major insertion and the deltoid tuberosity will lead to medial displacement of the proximal fragment from the pull of the pectoralis major, teres major, and latissimus dorsi muscles; the distal fragment will lead to lateral and proximal displacement as a result of the deltoid muscle. Lastly, fractures occurring distal to the deltoid tuberosity will cause abduction of the proximal fragment by the deltoid muscle; the distal fragment will be medially and proximally displaced from the biceps and triceps muscles.

Hanging arm casts depend on traction by the weight of the arm in the cast to help aid in fracture reduction. Generally, this treatment option is reserved for shortened and displaced midshaft humerus fractures with spiral or oblique fracture patterns. Transverse and short oblique fracture patterns are a relative contraindication, as distraction is likely and may impede healing. Coaptation splinting acts similarly to a hanging arm cast with increased fracture stabilization and less potential for distraction and is best for acute injuries. Additionally, while transverse and short oblique fracture patterns are a relative contraindication to the hanging arm cast, these fracture patterns are well tolerated in the coaptation splint, but maintaining the position of the splint and axillary irritation are common complaints. A Velpeau dressing, also referred to as thoracobrachial immobilization, is another conservative treatment modality that is generally indicated in elderly patients with minimally displaced fractures that do not require a reduction, and the benefit of this treatment is reported comfort. Finally, the shoulder spica cast is rarely utilized but is indicated in fractures requiring abduction and external rotation.

Although several non-operative treatment modalities have been presented to manage humeral shaft fractures conservatively, the most popularized is the use of the functional brace. Popularized by Sarmiento [16], and often referred to as the Sarmiento brace, functional bracing has demonstrated good results, which have been both reproducible and reliable [8, 10, 40, 42, 43, 56, 59]. Again, as the shoulder and elbow allow for a significant amount of motion, malunion in several planes and shortening are often well tolerated with little functional or cosmetic deformity [2]. Therefore, obtaining anatomic alignment after the injury is not necessary. However, obtaining an acceptable overall limb alignment is important to optimize outcomes with conservative management. Due to these factors, conservative management capable of obtaining an acceptable overall limb alignment following humeral shaft fractures should yield good results. Historically, this was definitively managed with bandages, U-casts, hanging arm casts, or coaptation, posterior, or abduction splinting [38, 71]. However, some of these treatment modalities require elbow immobilization. Elbow stiffness may subsequently ensue; this is a major disadvantage with these forms of non-operative management. Therefore, a conservative treatment modality that preserves elbow motion while allowing for adequate fracture alignment is ideal. These limitations with current non-operative treatment modalities were recognized, and the design of the functional brace was implemented to circumvent them.

In the setting of humeral shaft fractures, the functional, or Sarmiento, brace provides the benefits of gravity and allows for a hydraulic soft tissue compression, adequate bony alignment, and fracture site motion leading to the promotion of osteogenesis [42, 43]. Additionally, it circumvents shoulder and elbow motion restrictions and has demonstrated a reduced cost and improved patient comfort and hygiene [8, 12, 14, 40]. However, the functional brace is usually not well tolerated in the acute period. Dependent on swelling and patient comfort, approximately 2 weeks after the injury and application of temporary immobilization, most commonly with a coaptation splint, a prefabricated fracture brace is often utilized [16, 39–41]. However, timing of functional brace application may be important to reduce the incidence of external rotation limitations [55]. In general, early functional bracing will likely yield favorable functional outcomes without significant cosmetic deformity. In a recent review of the literature, it was reported the time to union averaged 10.7 weeks following humeral shaft fractures managed conservatively with functional fracture bracing [14]. In cases of open humeral fractures, a longer time to union has been demonstrated with functional brace treatment, averaging 13–14 weeks [8, 14, 44]. In their review of 922 patients, Sarmiento et al. demonstrated an overall union rate of 97% [8]. Other reports have demonstrated similar results; in a study evaluating 233 patients, Zagorski et al. demonstrated a 98% union rate with 95% excellent functional results [44]. However, more recently, non-operative management has been demonstrated to have a 37% fracture brace failure rate and a 27% conversion rate to operative intervention [61].

The functional fracture brace is designed to be worn throughout the day. Although the average time to union has been reported to average 10.7 weeks, several factors play into the duration of brace use [55]. Rehabilitation is usually started quickly after the application of the functional brace beginning with active non-weight-bearing exercises of the hand and elbow along with pendulum exercises of the shoulder. Assisted exercises of the shoulder and gradual weight-bearing are usually started around 3 and 6 weeks, respectively [4].

Time to union may be affected by several variables, and often chief among these is the overall health of the patient. Tobacco use, vasculopathies, and diabetes often require a prolonged duration of non-operative treatment to achieve fracture union. Therefore, success of the functional brace is very much dependent on the compliance of its use, with hours per day, duration of treatment, and using the brace in an appropriate manner. Additionally, noncompliance with functional bracing may result in functionally limiting or a cosmetically noticeable malunion or nonunion (Fig. 4.13). Some studies have questioned conservative management as nonunion rates have been reported to be as high as 50% in some series [4, 17, 39, 40, 50]. Concerns of malunion after non-operative treatment have led to an increase in surgical intervention, with some emerging evidence supporting this [4, 19, 30]. In short, with excellent union rate, good reported functional outcomes, and acceptable cosmetic deformity following conservative management with functional bracing, it is generally the gold standard for treatment of humeral shaft fractures [14, 30, 38].

4.4.1.2 Operative Stabilization of Humeral Shaft Fractures

While the vast majority of humeral shaft fractures are managed with conservative measures, operative stabilization has several indications. Among these are the polytrauma patient, pathologic fractures, unacceptable closed reduction or failed conservative management, associated vascular injury, concomitant forearm fractures (floating elbow), segmental fractures, those with intra-articular extension, bilateral humerus fractures, open fractures, nonunion, and neurological injury following penetrating trauma.

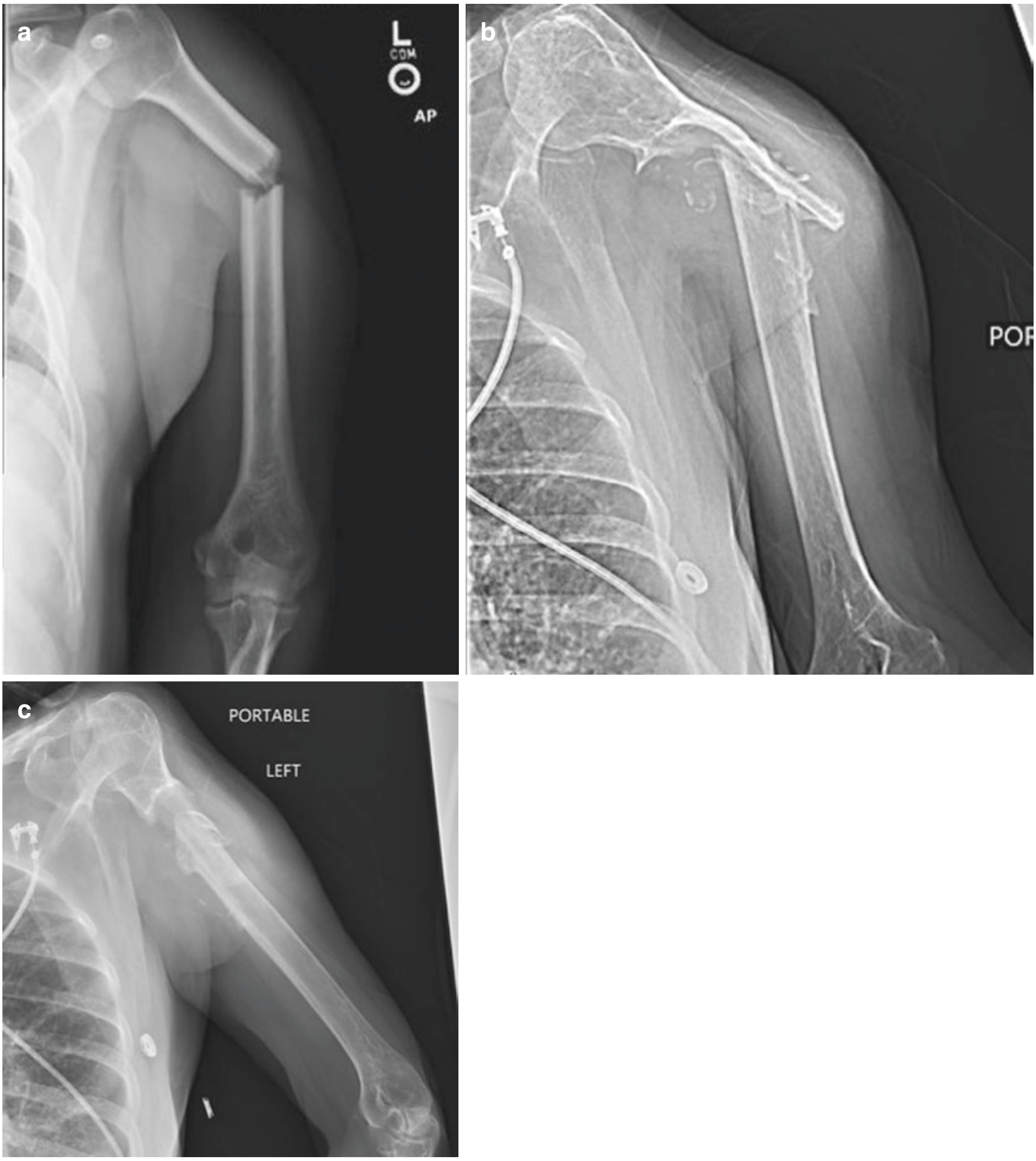

Fig. 4.13 A 72-year-old male sustained a proximal humeral shaft fracture (**a**) and refused splinting or bracing. Follow-up radiographs at 4 months post-injury in the emergency room (due to an unrelated fall) (**b**). He again refused any orthopedic treatment, but final radiographic evaluation (again in the emergency room due to an alcohol-related incident) at over 3 years post-fracture (**c**) revealed a well-aligned atrophic nonunion that was minimally symptomatic per his report

Several surgical techniques are available. Open reduction and internal fixation (ORIF) offers direct fracture visualization and reduction while providing fixation without rotator cuff violation. Intramedullary fixation is ideal for segmental fractures that would require a large and potentially morbid approach, pathologic fractures, or significantly osteoporotic bone. However, with antegrade nailing, shoulder pain is a common complaint due to rotator cuff violation, and the axillary, lateral antebrachial cutaneous, and radial nerves are at risk with locking screw insertions. External fixation may be indicated in cases of infected nonunion, burns, or significant soft tissue injury, but pin site infections, neurovascular injury, nonunion, and cosmesis are reported complications with this technique.

Union rates following operatively treated humeral shaft fractures have been reported, with union rates as high as 98% [4, 18, 26, 72, 73]. Few studies have compared operative and conservative treatment of humeral shaft fractures [3, 74–76]. Currently, multicenter randomized controlled trials comparing operatively treated humeral shaft fractures with conservative management are lacking [4]. Ongoing trials are attempting to evaluate patient-reported outcome measures and cost-effectiveness comparing those that are conservatively managed with those that undergo surgical stabilization. Similarly, in a retrospective review of 186 patients evaluating time to union and complications between conservative and operative management of humeral shaft fractures, Mahabier et al. showed variable time to consolidation with similar rates of delayed union. However, no direct comparison evaluating malunion was made [3]. In a multicenter prospective observational cohort study of 47 patients treated with either a functional brace or retrograde unreamed humeral nail, van Middendorp et al. reported a >90% union rate in both groups with no difference in pain, range of motion of the shoulder or elbow, or return to work. However, operatively treated patients had greater shoulder abduction strength, elbow flexion strength, functional hand positioning, and return to recreational activities at 6 weeks; but no differences were found at 1 year [75]. They concluded that despite early benefits in the operatively treated group, those managed conservatively may expect similar functional outcomes and satisfaction at 1 year. Again, malunion was not primarily investigated in this study.

Several investigators have evaluated operative stabilization of humeral shaft fractures with different types of plate fixation and/or intramedullary nailing [27, 29, 77–84]. In a meta-analysis of randomized controlled trials and nonrandomized studies, Dai et al. compared dynamic compression plating with locked intramedullary nailing of humeral shaft fractures, and they reported no significant difference with respect to nonunion and revision rate [27]. Similarly, Ouyang et al. concluded similar treatment effects on humeral shaft fractures between these treatment modalities [79]. In a prospective study comparing interlocking nails with locking compression plating for humeral shaft nonunions, Singh et al. concluded that both implants yield good functional outcomes and acceptable rates of complications [85]. Padhye et al. evaluated plating, nailing, Ilizarov external fixation, and use of nonvascularized fibular cortical strut grafting in the treatment of humeral shaft nonunions, and they concluded that compression plating yielded the best results [37]. They also noted that the Ilizarov external fixator is ideal for temporary fixation in infected nonunions and that non-vascular fibular cortical struts are beneficial when additional stability is needed. Irrespective of the surgical management of humeral shaft fractures, there are risks associated with them; among these are nonunion, infection, and radial nerve palsy, all of which have a less than 10% reported incidence [4, 18, 72, 86].

4.4.2 Treatment of Humeral Shaft Malunion

Treatment of humeral shaft malunion is dictated by several factors. Most importantly, functional demands of the patient should be considered in selecting treatment. As previously discussed, the humerus is well accommodating of malunion, often having little functional limitation or cosmetic deformity. However, in cases of functional limitation or cosmetic deformity, patient expectations and ability to perform activities of daily living should be assessed. Even in the presence of a functionally limiting or cosmetically deformed malunion of the humeral shaft, continued nonoperative management should be considered. This is ideal in patients with low functional demand and surgically limiting comorbidities, those in palliative care, or patients not interested

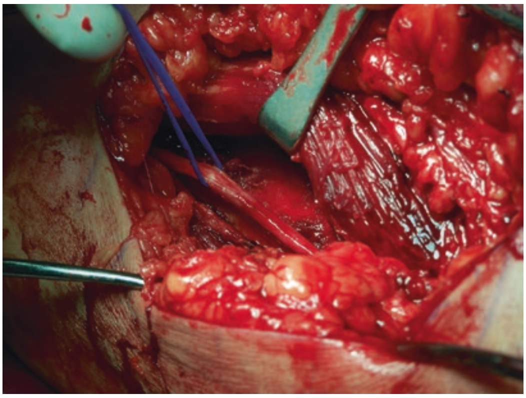

Fig. 4.14 The radial nerve must be identified in all humeral shaft malunion or nonunion cases, and patients must be aware preoperatively concerning the risk of radial nerve palsy

in surgical intervention. In other cases, surgical intervention may offer correction of the malunion to improve functional limitations or obvious cosmetic deformity. However, the surgical insult is not without its own risks.

Operative intervention increases the risk of radial nerve injury, which is confounded by exposure limitation of the radial nerve from callus. Most often the nerve is identified distally between the brachialis and brachioradialis, and proximally it lies medial to the spiral groove. It is important to dissect the nerve free from the malunion site prior to definitive surgical intervention (Fig. 4.14). Transient sensory or motor radial nerve dysfunction may occur following surgical exposure.

4.5 Author's Preferred Methods of Treatment

1. *Asymptomatic*: No treatment necessary and follow-up is generally on an as-needed basis.
2. *Symptomatic Malunion with Atrophic-Appearing Union Site*: Osteotomy of the malunion is carried out in a closing wedge when possible, as the humerus can tolerate shortening without creation of significant functional deficit. Shortening will also allow improved bony apposition of the osteotomy site. If restoration of length is necessary, an opening- or sliding-type osteotomy would be recommended. Contralateral humeral radiographs can be of help when planning surgical realignment, and CT scans of both humeri can be useful to assess the rotational correction needed. If the previous union site is relatively atrophic appearing, autologous bone grafting is recommended, and either iliac crest graft or intramedullary femoral graft (DePuy Synthes Reamer-Irrigator-Aspirator, Warsaw, IN, USA) is generally utilized.
3. *Symptomatic Malunion with Hypertrophic-Appearing Union Site*: General recommendations are similar to those of less robustly healed, with the exception of the use of autologous bone graft; this is typically only utilized if a defect is present after osteotomy fixation.
4. *Use of External Fixation*: Although technically possible, circular external fixation for humeral malunion is not typically utilized but can allow controlled restoration of length, alignment, and rotation of the humerus. Patients must be advised of the nature of these devices and the time required, as this is highly life-altering during the correction.
5. *Arthroplasty*: In cases of patients with advanced adjacent joint arthritis (especially glenohumeral) or adjacent arthroplasty, correction of the malunion may require an osteotomy cut close to or even through an arthroplasty stem. In these instances, revision or tumor prostheses are employed and provide a method of correction of the malalignment that does not require fracture healing. Patients can generally begin very early range of motion, but in instances of distal humeral/elbow replacement, permanent lifting limitations are a required consequence of the procedure.

4.6 Case Discussions

4.6.1 Case 1

A 68-year-old male with a past medical history significant for Parkinson's disease presented to the emergency department approximately 1 h after falling down two steps and landing on his right arm. He was found to have a humeral shaft fracture (Fig. 4.15). He was placed into a coaptation splint and sent to an upper extremity specialist for further management. Due to his Parkinson's disease and acceptable alignment of fracture fragments, non-operative management was selected, and 11 days after injury, he was placed into a Sarmiento brace. Approximately 4 weeks later, the Sarmiento brace was discontinued, and the patient was transitioned to a simple sling. He was weaned from his sling around 5 weeks later and was in formal therapy during this time; he remained non-weight-bearing of the right upper extremity but was allowed to increase weight-bearing over the next several weeks.

At 5 months after the injury, the patient was free of any restrictions and instructed to follow up on an as-needed basis. At this visit, patient had full painless range of motion about the elbow with minor residual stiffness of the shoulder. Final radiographic imaging of the humeral shaft malunion was obtained (see Fig. 4.15). Despite the humeral shaft malunion, the patient was satisfied with his outcomes and his decision of non-operative management.

4.6.2 Case 2

A 67-year-old female sustained the right proximal humeral shaft fracture as shown in Fig. 4.16a as the result of a fall from a ladder while cleaning. As this was an isolated injury and no neurovascular deficits were seen, this was treated conservatively initially in a coaptation brace and then switched to a fracture brace at 19 days after injury (Fig. 4.16b). She began a simple elbow, forearm, and hand self-directed therapy program and then was weaned from her fracture brace approximately 4 months after injury.

At nearly 11 months after injury, she was referred for second opinion after being displeased with the cosmesis of her arm. She had returned to work and was able to perform her mostly secretarial tasks without complaint. She noted mild pain with any heavy lifting as well as some shoulder stiffness and objective loss of overhead abilities. Repeat radiographs are shown in Fig. 4.16c, d. Given her questionable union, a CT scan was ordered and did show bridging callus across the fracture site, albeit a small amount. Laboratory evaluation, including infectious and metabolic labs, was all within normal limits, with the exception of 25-hydroxyvitamin D, which was 22 ng/mL. She also declined any current tobacco use and did not have any history or medicine use otherwise concerning for bony healing ability.

Due to her frustration with the appearance of her arm, she declined non-operative treatment to increase her bone mass at the fracture site and requested corrective osteotomy. Now at almost 1 year post-fracture, she underwent an osteotomy through the previous primary fracture line, as the proximal comminution and fracture extensions had healed without issue. The intercalated segment was left in a malunited position to avoid iatrogenic stripping, and an osteotome was used to separate the two primary fragments. The edges were further cut with an oscillating saw to create a congruent bony apposition, and the long precontoured proximal humerus plate was applied via an anterolateral exposure to the shoulder and humeral shaft.

Postoperatively, she was happy with the appearance of her extremity, but recovery was complicated by a radial nerve palsy (complete motor, partial sensory); this fully recovered by her 6-month follow-up visit. She began unrestricted range of motion of the entire upper extremity immediately postoperatively, with lifting restrictions of no more than 10 pounds for the first 6 weeks. At final follow-up 1 year postoperatively, she continues to work and reports improved upper extremity function and appearance.

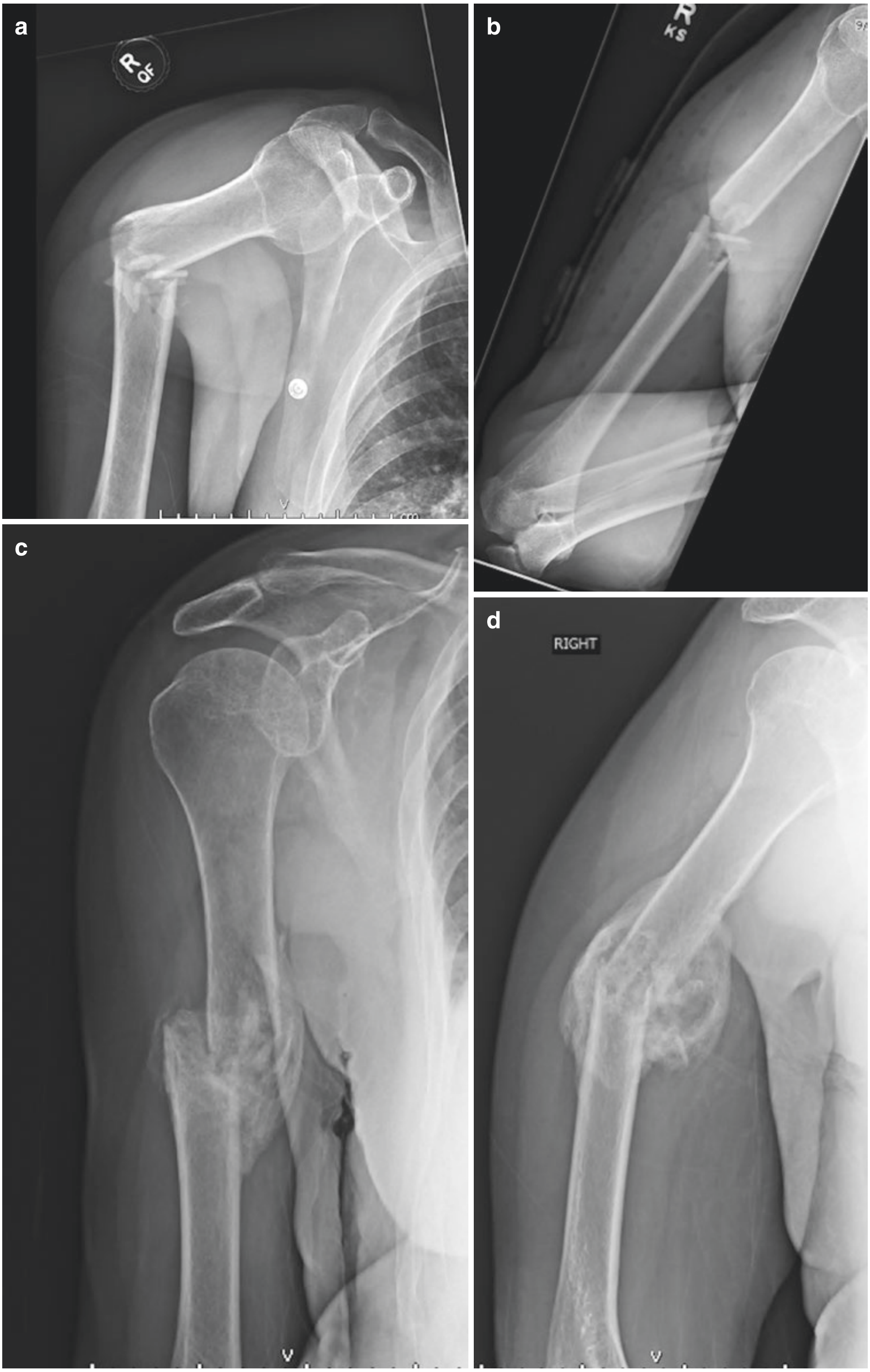

Fig. 4.15 A mildly comminuted humeral shaft fracture (**a**) with the same fracture in an extended fracture brace (**b**). Final follow-up of the asymptomatic malunion (**c,d**)

Fig. 4.16 A proximal humeral shaft fracture (**a**), with extension into the proximal metaphysis. After placement in an extended fracture brace, some expected varus is seen (**b**). Atrophic-appearing malunion (**c,d**). Final follow-up radiographs of the osteotomy and fixation construct (**e,f**)

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5 Malunions of the Distal Humerus

Joseph Borrelli Jr., Tracey A. DeLucia, and Tsuyoshi Murase

5.1 Introduction

Distal humerus fractures are defined as those fractures that involve the distal aspect of the humerus, at or below the level of the metaphyseal/diaphyseal junction, and these fractures may be extra-articular or involve the articular surface of the distal humerus. Typically, distal humerus fractures that occur in the skeletally immature patients are further classified as to whether they occurred from an extension force on the elbow or a flexion force on the elbow. Identifying the cause of the fracture is important for understanding the fracture pattern and structures at risk of injury as a result of the fracture and may give insight into which reduction techniques would be most successful. Also, identifying the position of the distal fracture fragment will give insight as to whether the posterior or anterior periosteal sleeve is intact and therefore how best to use this intact sleeve to aid in the reduction of the fracture fragments.

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Fractures of the distal humerus in skeletally immature patients are commonly classified according to Gartland. In 1959, Gartland described a simple classification scheme to emphasize principles underlying treatment of patients with a supracondylar humerus fracture and discussed a method of injury management that has proven to be practical and effective with time [1]. Gartland described a rotatory and translational deformity, with posterior displacement (extension) of the distal fragment occurring most often. He noted three types of extension injury based on the degree of displacement: type I, nondisplaced; type II, moderately displaced; and type III, severely displaced injury; flexion-type injuries were considered separately (Fig. 5.1) [2]. Treatment of pediatric supracondylar humerus fractures has evolved since Gartland's first description; however, current treatment recommendations from the American Academy of Orthopaedic Surgeons remain based on the modified Gartland classification [3]. In general, type I injuries are immobilized with a cast for 3–4 weeks, with radiographic alignment checked at 1 week. Type IIA injuries can be treated with closed reduction and casting or percutaneous pinning, whereas type IIB injuries should have closed reduction and percutaneous pinning to prevent coronal and/or rotational malalignment. Type III and IV injuries also are treated with closed reduction and percutaneous pinning, as are flexion-type injuries, with possible open reduction and

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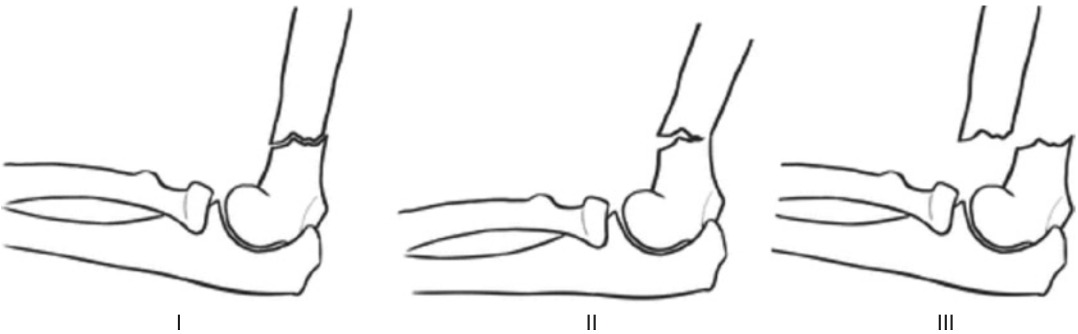


Fig. 5.1 Gartland's distal humerus classification scheme (From Lasanianos et al. [3], with permission Springer Nature)

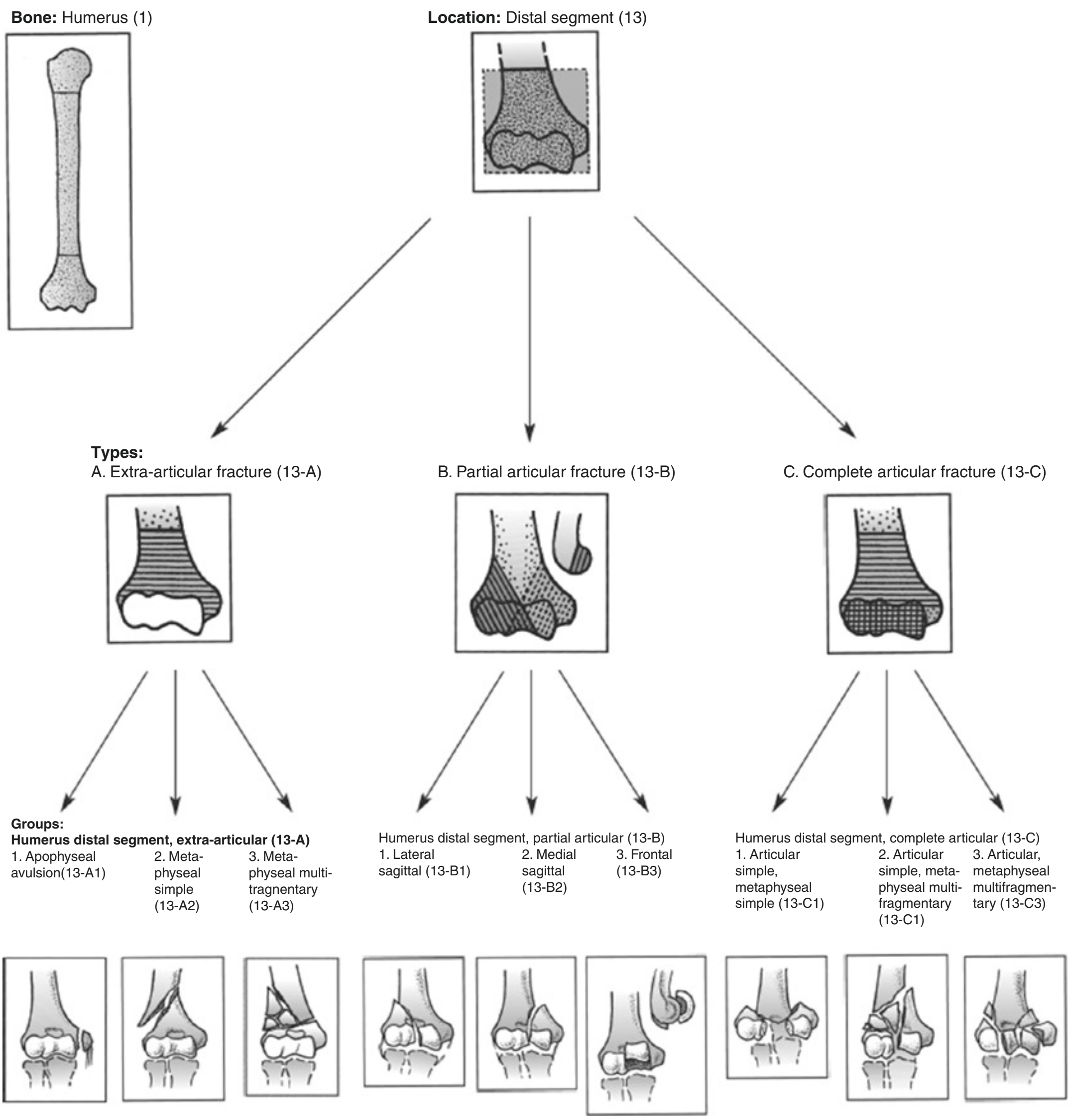


Fig. 5.2 AO distal humerus fracture classification scheme (From Athal [5] with permission Wolters Kluwer)

internal fixation (ORIF) if closed reduction is unsuccessful [2].

In patients, in whom the distal humeral growth plate has closed, these fractures are routinely classified according to the Arbeitsgemeinschaft für Osteosynthesefragen (Association for the Study of Internal Fixation)/Orthopaedic Trauma Association (AO/OTA) classification system that is designed to make documentation of these fractures more accurate and consistent and guide treatment and help in predicting outcomes [4]. Fractures of the distal humerus that are entirely extra-articular are referred to as AO/OTA type 13-A, where the humerus is labeled as no. 1, the supracondylar area of the humerus is labeled as no. 3, and the extra-articular nature of the injury is designated "A." Adult fractures that involve only a portion of the distal humerus are referred to as "partial articular" and classified as AO/OTA type B, and those fractures in which the entire articular surface has been fractured off of the distal "complete articular" fractures are classified as AO/OTA type C (Fig. 5.2) [5]. In general displaced fractures of the distal humerus in healthy adults are treated with open reduction and internal fixation using a combination of plates and screws. The choice of the various approaches and implants available for the treatment of distal humerus fractures is beyond the scope of this chapter. Suffice it to say that if these fractures are malreduced and poorly stabilized or fracture reduction is subsequently lost during the healing process, a distal humerus malunion will develop.

Fractures of the distal humerus are serious injuries that are often difficult to treat no matter how or in whom they occur. Because the anatomy of the distal humerus is so complex, retoring the normal relationship between the distal humerus and the proximal ulnar and radius is essential to restore the normal functioning and appearance of the arm. Additionally, the proximity of the surrounding neurovascular structures to the distal humerus challenges surgeons further during the acute management of distal humerus fractures and during the treatment of distal humeral malunions. A very common time for these fractures to occur is during time of accelerated growth of the distal humerus, and these fractures commonly result from a fall onto the outstretched hand, generally while the child is climbing or playing on elevated structures. Distal humerus fractures in this patient population are most common between the ages of 2 and 12 years, with >50% occurring in children between the ages of 3 and 6 years [6]. Distal humerus fractures are also relatively common in young adults between the ages of 18–45 years. These individuals are generally associated with high-energy trauma commonly occurring in motorcycle or motor vehicle crashes [7]. Distal humerus fractures in these young adults involved in high-energy trauma come in a variety of different fracture patterns. The fracture patterns are generally thought to depend on the mechanism and intensity of the forces applied either directly to the elbow or indirectly through the forearm, wrist, and hand. This trauma can result in fracture patterns, which range from simple extra-articular, transverse fractures to comminuted, open, displaced, contaminated fractures involving the distal humerus in addition to the articular surface. The third most common age group for distal humerus fractures to occur in is older individuals, generally with accompanying poor bone quality. Fractures in this age group (65+ years old) are generally the result of a ground-level fall (GLF). Due to the underlying poor bone quality, these fractures are often comminuted and displaced and may involve the articular surface of the distal humerus [8, 9].

5.2 Fracture Treatment

The need for management of these fractures in children depends upon the initial displacement of the fracture, the perceived stability of the fracture reduction, the presence of complicating factors (vascular injury, neurologic injury, and the integrity of the surrounding soft tissue envelope), and the surgeon's ability to obtain and maintain an acceptable reduction throughout healing. In certain cases, this treatment involves closed reduction and the application of a long arm cast. A certain percentage of young patients can be managed nonoperatively with acceptable outcomes. However, those patients with unstable distal humerus fractures involving the articular surface, and those where an acceptable reduction cannot be obtained or maintained, benefit from surgical intervention [10]. There are numerous successful means to reduce and stabilize these fractures; a description of all is beyond the scope of this chapter. Suffice it to say that surgical intervention generally involves closed reduction and percutaneous pin fixation or, occasionally, open reduction and percutaneous pin fixation or even internal fixation. Unfortunately, a portion of these patients go on to develop a malunion of the distal humerus which when severe is associated with limited upper extremity motion, limited function, as well as a cosmetic deformity and potentially delayed neurologic compromise [10]. The management of distal humerus fractures in adults and older individuals has evolved over the last several decades. Prior to the latter half of the twentieth century, nonoperative treatment was considered a viable management strategy for most patients with distal humerus fractures. Nonoperative treatments included no treatment (bag of bones), traction methods to obtain and maintain reduction, and manual reduction with subsequent cast immobilization. In most of these cases, the fractures went on to heal but often with associated deformity and joint stiffness, which produced decreased upper extremity function [11, 12].

Early attempts at surgical management of these fractures focused primarily on re-approximation of the fracture fragments and occasionally limited internal fixation. Unfortunately, these "limited techniques" often lead to compromised functional outcomes and significant complications including: malunion, nerve injury, vascular injury, infection, and elbow stiffness. The introduction of modern internal fixation techniques by the AO and others has ushered in a new era of management for these fractures resulting in fewer malunions and improved functional outcomes [13–15]. Yet, fractures of the distal humerus in adults and older adults continue to trouble the treating surgeon. Several biomechanical investigations have established that the most rigid fixation constructs using readily available small fragment plates involve placing these plates either at 90° to one another (medial and posterolateral) or parallel to each other along the posteromedial and posterolateral aspects of the distal humerus after reduction of the fracture [16–18]. Several authors have reported good results with these techniques while stressing the need to obtain rigid internal fixation of the medial and lateral column while preserving the blood supply to the fracture fragments as well as the surrounding soft tissues [19, 20]. In general, patients with distal humerus fractures that undergo ORIF by surgeons familiar with state-of-the-art techniques while using newer, readily available implants do not routinely go on to develop symptomatic malunions. The development of symptomatic distal humerus malunions in adults requiring osteotomy and revision surgery is uncommon.

Therefore, the majority of this chapter will focus on the treatment of symptomatic malunions of the distal humerus resulting from distal humerus fractures that occurred early on in life.

5.3 Distal Humerus Malunions

Malunions of the distal humerus are known to negatively influence one's elbow range of motion and when severe make it difficult for individuals to perform their activities of daily living. Also, moderate to severe malunions of the distal humerus can create an unpleasant appearance of the limb, particularly with full elbow extension/hyperextension. Malunions can also negatively affect ipsilateral forearm rotation, making it difficult for individuals to accurately position the hand in space thus further limiting upper extremity function. With varus deformity of the distal humerus being the most common coronal plane deformity, the carrying angle of the limb is either decreased or even reversed further affecting one's ability to carry objects at their side.

5.3.1 Evaluation

Prior to considering any treatment options for the malunited distal humerus, a complete history and physical examination must be undertaken. The surgeon should gain insight into when the initial fracture occurred, if it was a closed or open fracture (and if so the degree of contamination and soft tissue injury), how the fracture occurred, and how it was initially and ultimately treated. A detailed history of all surgical interventions that were undertaken in the past must be ascertained as well as any complications that may have occurred as a result of these treatments. It is important to note a history of and number of re-operations or closed manipulations. Initial injury complications such as compartment syndrome and associated vascular or neurologic injuries (including repairs) should be discussed. A history of infections or delays in the healing of the previous incisions as well as if the patient received any oral or intravenous antibiotics longer than is routinely recommended for operative fixation of a closed fracture is important in the overall evaluation.

With regard to a physical examination, both the malunited and the contralateral limbs must be examined. Firstly, the range of motion of the ipsilateral shoulder, wrist, and hand should be assessed. Following this detailed evaluation, the overall appearance of the upper extremity should be documented including photographs of the malunited limb and the previously uninjured limb. The range of motion of the ipsilateral and contralateral elbow and forearm should also be assessed and clearly documented and compared. The appearance and location of previous incisions and traumatic wounds should also be definitively determined. Muscle strength and a detailed sensory examination of the ipsilateral limb should be performed and the findings documented.

5.3.2 Diagnosis: Radiographic Examination

Detailed plain radiographs of the malunited distal humerus should be performed. These images should include an AP, lateral, oblique, and radial head views of the elbow and a PA and lateral X-ray of the forearm and humerus. Similar radiographic views of the contralateral side should also be obtained for comparison and preoperative planning.

A computed tomography (CT) scan of the affected elbow including all of the humeral deformity and the entire elbow joint and proximal forearm should be obtained. CT images should include axial, coronal, and sagittal images of the area of interest and ideally three-dimensional (3D) of the distal humerus and elbow joint to allow a more complete three-dimensional assessment of the deformity.

Magnetic resonance imaging (MRI) of the elbow is generally not necessary unless there is reasonable concern for the presence of infection or the status and position of previously repaired, or transposed, neurologic or vascular structures.

Indications for surgical intervention are soft and usually depend upon the appearance and function of the limb as most malunions of the distal humerus do not cause pain. However, when severe, the consequences of cubitus varus are real and worsen with time and use of the extremity. These consequences include an increased risk of lateral condylar fractures, pain, tardy posterolateral elbow rotatory instability, tardy ulnar nerve palsy, internal rotational malalignment, and poor cosmesis. Historically, treatment for cubitus varus has been considered for cosmetic reasons only. Recent reports, however, show that the consequences of cubitus varus may also be indications for operative reconstruction. Lateral condylar fractures following cubitus varus remain a common complication seen by pediatric orthopedists. Furthermore, cubitus varus is thought to shift the mechanical axis medially and lead to external rotational torque. Chronically present, this torque stretches the lateral collateral ligament, leading to posterolateral rotatory instability (PLRI). Additionally, some children may even develop posterior shoulder instability. Finally, subluxation of the ulnar nerve and medial head of the triceps over the medial epicondyle can produce pain, snapping, and parenthesis [20–28].

5.3.3 Treatment: Indications and Options

The treatment of supracondylar humerus fractures in children continues to be a topic of discussion and controversy.

Complications of a supracondylar fracture and its treatment have included vascular compromise, compartment syndrome, neurological deficit, elbow stiffness, pin tract infections, myositis ossificans, nonunion, osteonecrosis, loss of reduction, and malunion [29]. Cubitus varus malunions remain the most common complication of the more displaced supracondylar humerus fractures [1]. Modern techniques of repairing supracondylar fractures have significantly reduced the incidence of cubitus varus malunion. However, despite modern orthopedic treatment, malunions continue to occur. The consequences of cubitus varus have included an increased risk of lateral condylar fractures, pain, tardy posterolateral rotatory instability, tardy ulnar nerve palsy, internal rotational malalignment, and poor cosmesis [29]. Historically, treatment for cubitus varus has been considered for cosmetic reasons only. Recent reports, however, show that these other consequences of cubitus varus may also be indications for operative reconstruction.

Lateral condylar fractures following cubitus varus remain a common complication seen by pediatric orthopedists [30]. Furthermore, cubitus varus is thought to shift the mechanical axis medially and lead to external rotational torque. Chronically present, this torque stretches the lateral collateral ligament, leading to posterolateral rotatory instability [26, 27, 30–32]. Finally, subluxation of the ulnar nerve and medial head of the triceps over the medial epicondyle can produce pain, snapping, and paresthesias [30, 32, 33]. The distal humerus malunion typically includes elements of varus, internal rotation, and hyperextension. The accuracy of the initial reduction of the fracture best predicts the incidence of subsequent deformity [34].

Numerous osteotomy techniques for treating supracondylar humerus malunions have been described. Traditional approaches include French, dome, and wedge osteotomies. Bellemore et al. reported their use of a supracondylar osteotomy on 16 patients using a modified French method. This technique, originally described in 1959 as a lateral closing wedge through a posterior approach, uses an intact periosteal hinge medially and two screws with a wire loop laterally to control the distal fragment [34]. Bellemore et al. found this technique to be safe and satisfactory, with no infections or neurovascular complications [35]. Kanaujia et al. reported the use of a dome osteotomy to treat varus supracondylar malunions in 11 children. They performed this procedure through a posterolateral approach and the use of Ikuta's fixation device and crossing Kirschner wires for fixation. The correction was satisfactory in all of the cases, and there was no serious complication [36]. Additionally, the use of various wedge osteotomies has been reported for the treatment of supracondylar malunions. Voss et al. and Wong et al. described lateral closing wedge osteotomies through lateral approaches in 36 and 27 patients, respectively [37, 38]. In general, all 63 patients did well postoperatively although Wong et al. had concerns regarding prominence of the lateral condyle in 14 patients.

Other described techniques for the correction of supracondylar malunions include step-cut, interlocking wedge, and arc osteotomies. DeRosa and Graziano used a step-cut technique of distal humerus valgus osteotomy using one cortical screw for fixation in 11 patients. They found no radial or ulnar nerve injuries, nonunions, infections, or hypertrophic scars [39–41]. The most common means of stabilization of the osteotomies have included casting alone, internal fixation, Kirschner pin fixation, and on occasion external fixation. These various types of osteotomies address only the varus or extension components of the malunion, leaving a residual rotational malalignment and at times disappointing results [42]. Three-dimensional osteotomies address varus, internal rotation, flexion/extension, and lateral translation [43].

A study of 25 patients who were randomized and underwent either the French (lateral closing wedge osteotomy) or a dome osteotomy found improved rotational correction using the dome method, but this technique was associated with an inadequate angular correction, nerve palsy, loss of motion, and circulatory compromise [44]. Ippolito et al. performed 24 supracondylar osteotomies and reported 6 immediate postoperative complications, including ulnar nerve palsy, hematoma, and circulatory disturbance. Disappointingly after an average follow-up of 23 years, they found that all but 2 of the patients lost correction, 14 of the patients were dissatisfied with the appearance of the scar, 12 of the patients had measurable atrophy of the affected arm, and 10 of the patients had loss of motion [45].

Oppenheim et al. performed 45 corrective supracondylar osteotomies in 43 children with a 24% complication rate, including neurapraxia, sepsis, and cosmetically unacceptable scarring [46].

Newer techniques of percutaneous pin fixation versus casting alone and closer postoperative observation for correction of the deformity have decreased the complication rate to less than 15% [47].

5.4 Case Presentations

5.4.1 Case 1: Supracondylar Humerus Fracture

Patient is a 6-year-old female who sustained a supracondylar humerus fracture of her dominant right arm in a fall from a swing. Upon examination, she was found to have a Gartland type II fracture with minimal extension deformity without a coronal plane deformity (Fig. 5.3). She was treated in a long arm cast for 4 weeks.

At 4 weeks, new radiographs showed that the fracture had angulated into more extension but the fracture was allowed to heal in this position (Fig. 5.4). After fracture union, the patient regained her motion over the next several months, but she developed a recurvatum deformity of the right elbow (Fig. 5.5a) but regained normal range of motion (Fig. 5.5b).

The patient presented at 1 year post-injury with complaints that she could not put weight on the arm due to it bending backward and she could not flex her elbow enough to reach her hair. She had no pain in her right arm. On physical examination, she was found to have 25° of recurvatum deformity and only 1000 of elbow flexion of her dominant right elbow.

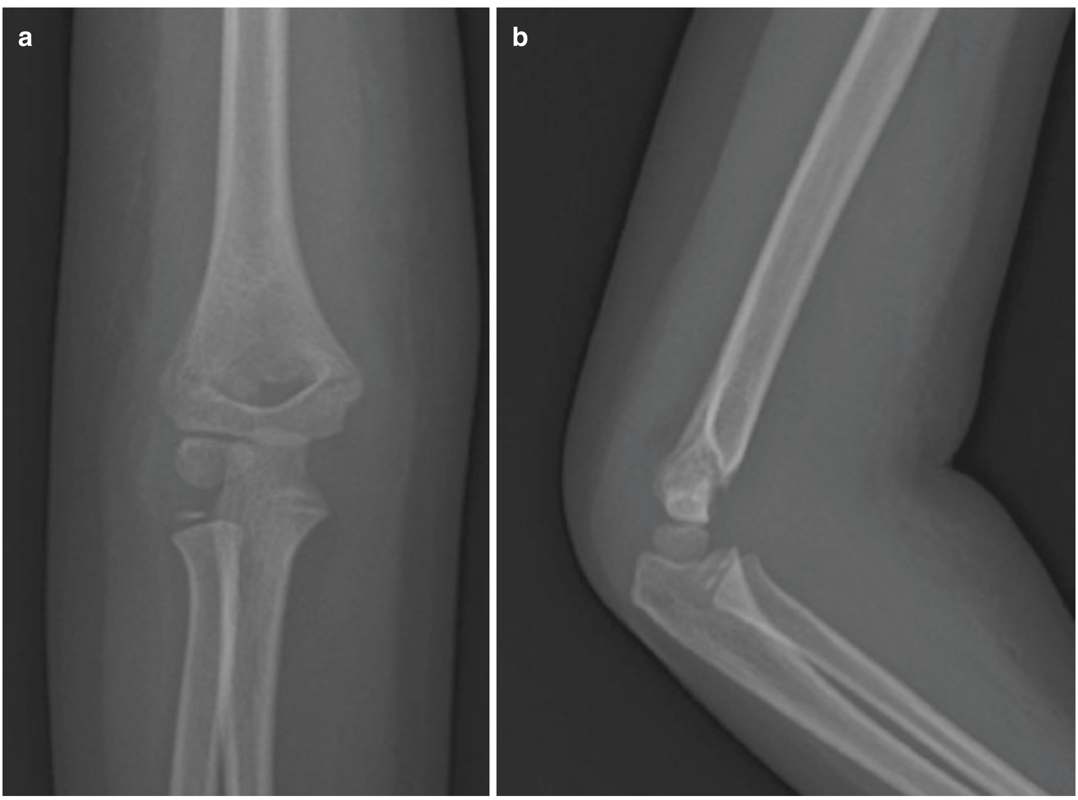


Fig. 5.3 Anteroposterior (**a**) and lateral (**b**) radiographs of the right elbow showing a displaced extension-type supracondylar humerus in a child (Gartland type II)

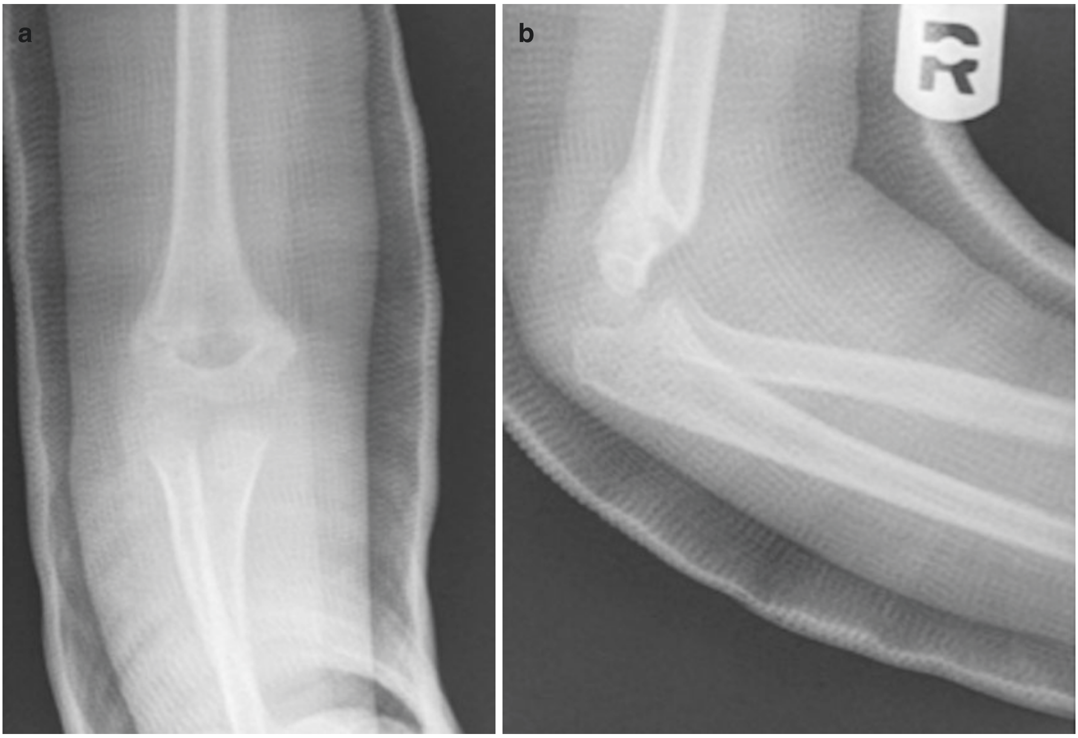


Fig. 5.4 Anteroposterior (**a**) and lateral (**b**) radiographs of the right elbow with the supracondylar fracture having healed with considerable extension deformity

Radiographs at that time demonstrated significant extension deformity of the distal left humerus (Fig. 5.6a, b) but good coronal plane alignment as compared to the contralateral uninjured elbow (Fig. 5.6c, d).

After a thorough preoperative plan was developed and the potential risks and benefits of surgical correction were explained to the patient and her parents, a corrective, anterior closing wedge osteotomy of the distal humerus was undertaken.

Author's Preferred Technique The patient was anesthetized and placed supine on the operating room table. A pneumatic tourniquet was applied to her right proximal arm, and the arm was prepped and draped in the usual sterile fashion. Preoperative motion was assessed under fluoroscopy. A lateral approach to the distal humerus was performed through an incision positioned between the brachioradialis and the lateral head of the triceps. Care was taken to avoid injury to the radial nerve. A subperiosteal exposure was created to allow for small Hohmann retractors to be placed anteriorly and posteriorly around the distal humerus to provide adequate exposure and protect the surrounding soft tissues of the arm. A 1.6 mm Kirschner wire (K-wire) was placed perpendicular to the shaft of the humerus at the level of maximal deformity, and a second K-wire was placed proximal to the first, in a 300° cephalad to caudal orientation to guide the osteotomy. The osteotomy was made through the anterolateral cortex and approached, but did not pass through, the posterior cortex. At this time, two 2.0 mm K-wires were placed percutaneous into the lateral epicondyle and passed up to the level of the osteotomy, and these K-wires were placed in a divergent position, under fluoroscopic guidance. Osteoclasis was then performed with gentle elbow flexion to complete the osteotomy of the posterior humeral cortex while maintaining the integrity of the periosteum. Once the extension deformity was corrected and confirmed by fluoroscopy, the

Fig. 5.5 Clinical photographs of the patient demonstrating a recurvatum deformity of the right elbow (**a**) and limited flexion of the right elbow (**b**)

K-wires were advanced across the osteotomy and into the distal humeral diaphysis medially (Fig. 5.7). Final elbow range of motion was confirmed to be 0–130° and the exposure irrigated and closed in layers with absorbable sutures. The K-wires were then cut and bent 90° and wrapped with Xeroform gauze and their bases. A long arm cast was placed and univalved in the operating room prior to the patient being awoken (Fig. 5.8). Plans were made for cast and K-wire removal at 4 weeks post-op in the office.

After K-wire removal, a long arm cast was replaced for an additional week to allow for additional healing of the osteotomy. Weight-bearing and sports were prevented for 8 weeks after final radiographs to allow for recovery of elbow motion and strength and further healing of the osteotomy. At that point, the patient had a well-healed incision (Fig. 5.9), full pain-free elbow motion from 0° to 135° (Fig. 5.10), and a nicely aligned and healed distal humerus (Fig. 5.11).

5.4.2 Case 2: Supracondylar Humerus Fracture with Varus Alignment

Patient is a 16-year-old male who had sustained an elbow injury involving his nondominant left arm in a fall in Columbia, South America, at the age of 10. He was treated in a long arm splint for 2 months and went on to heal his apparent

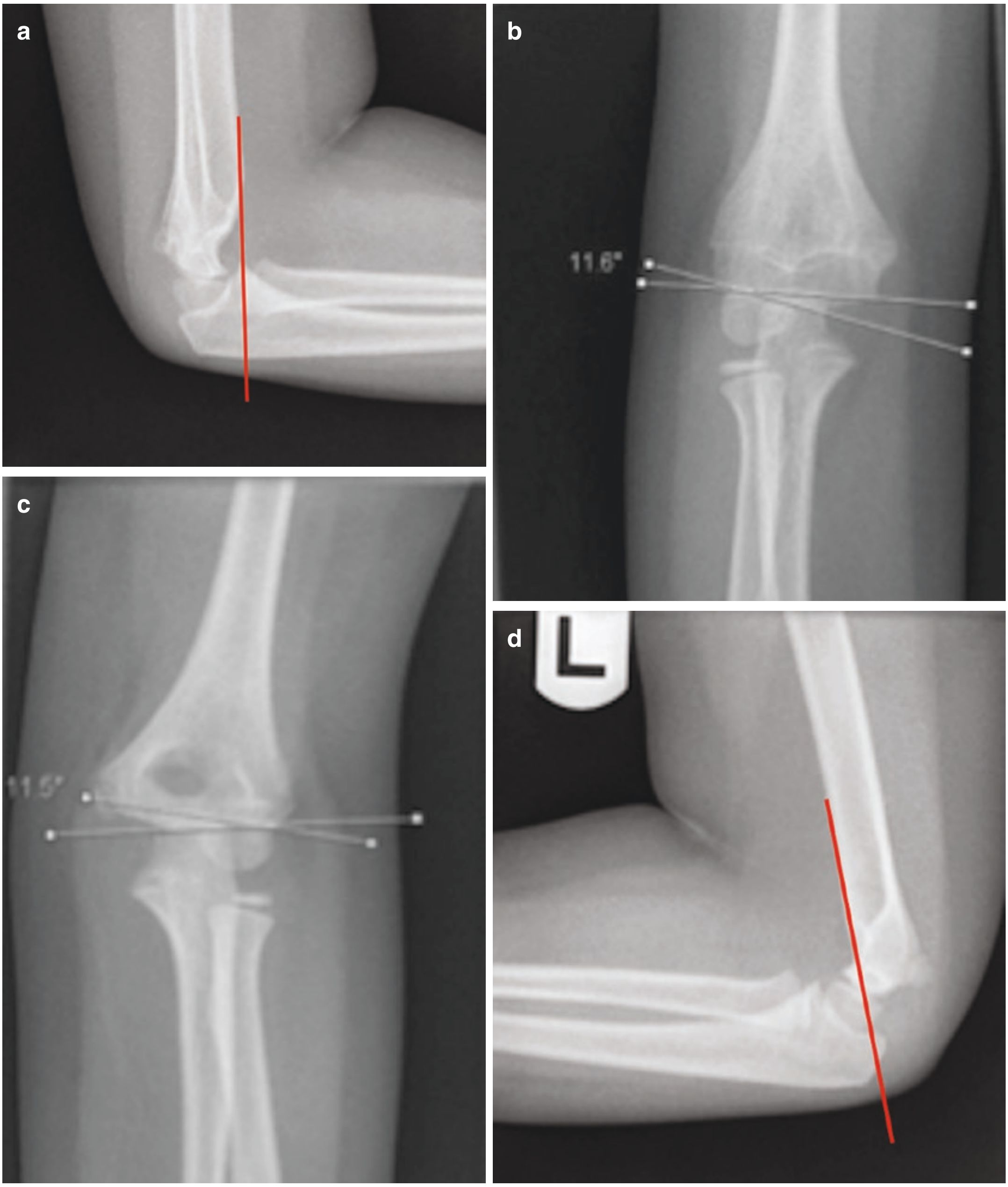


Fig. 5.6 Anteroposterior (**a**) and lateral (**b**) radiographs of the right elbow 1 year post-injury. The anterior humeral line (*red line*) does not pass through the capitellum (**a**). No varus or valgus deformity is appreciated (**b**). Anteroposterior (**c**) and lateral radiographs (**d**) of the contralateral left elbow with the anterior humeral line (*red line*) passing through the capitellum (**d**). Each elbow has Baumann's angle of 11° (**a**,**c**)

supracondylar humerus fracture with considerable varus alignment.

Upon presentation, the patient denied elbow pain or instability and had full range of motion of his left elbow, but with an obvious varus "gun stock" deformity. His elbow motion was −5 to 130° of flexion, with full forearm supination and pronation, but with obvious deformity. Radiographs demonstrated a 25° varus deformity of the left distal humerus and 10° of valgus, of

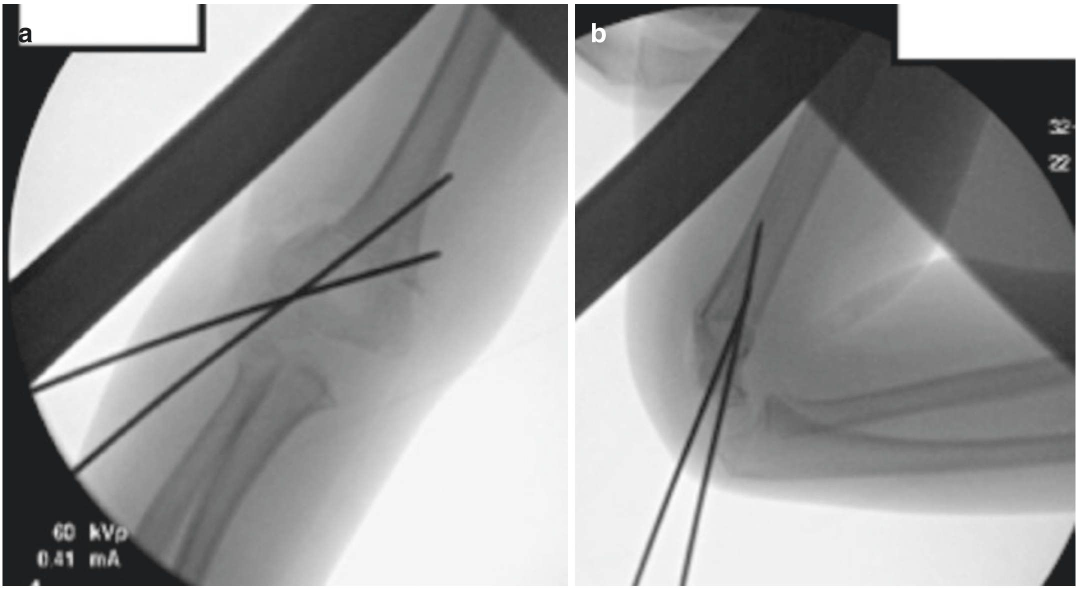


Fig. 5.7 Intraoperative fluoroscopic anteroposterior (**a**) and lateral (**b**) images of the right elbow without change in Baumann's angle (**a**) and correction of the extension deformity (**b**)

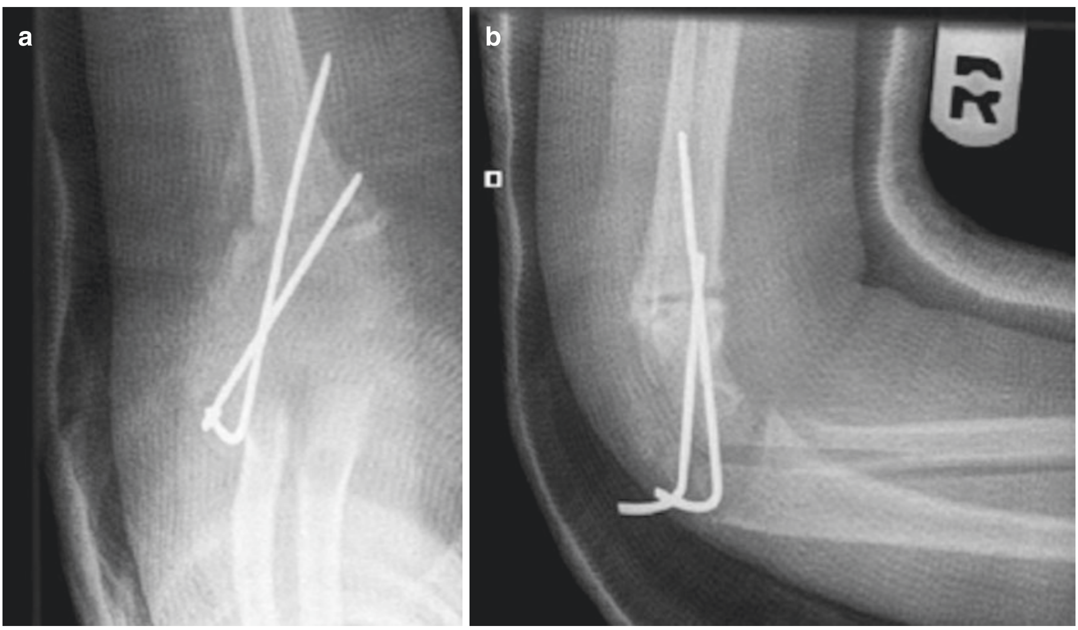


Fig. 5.8 Anteroposterior (**a**) and lateral radiographs (**b**) of the right elbow 4 weeks after osteotomy and correction of extension deformity with the arm maintained in a long arm cast

the right humerus (Fig. 5.12). Baumann's angle could not be measured as his physeal plates had already closed. After a thorough review of his radiographs and physical examination, the potential treatment options as well as the risks and benefits were explained to his parents, and plans were made for a valgus-producing, closing wedge osteotomy of his distal humerus. Careful attention

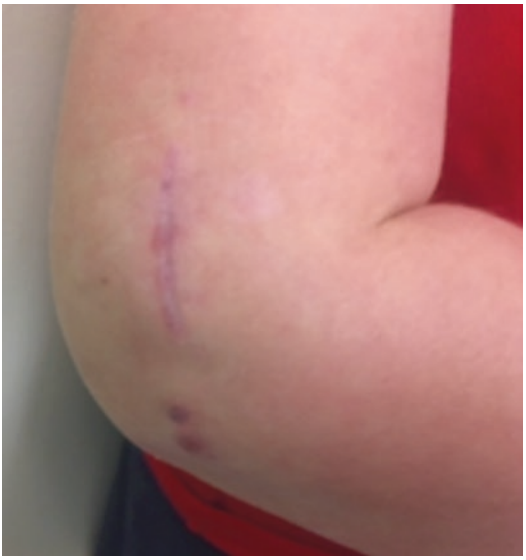


Fig. 5.9 Clinical photograph of the right elbow after the K-wires and long arm cast had been removed

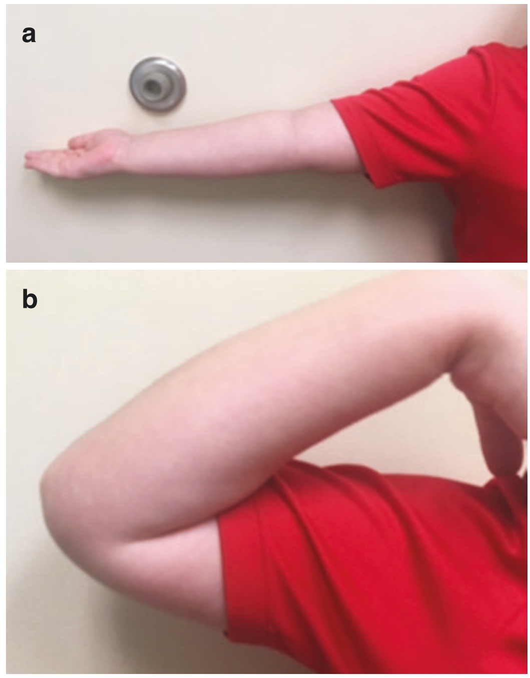


Fig. 5.10 Clinical photographs 8 weeks postoperative demonstrating full elbow extension (**a**) and flexion (**b**)

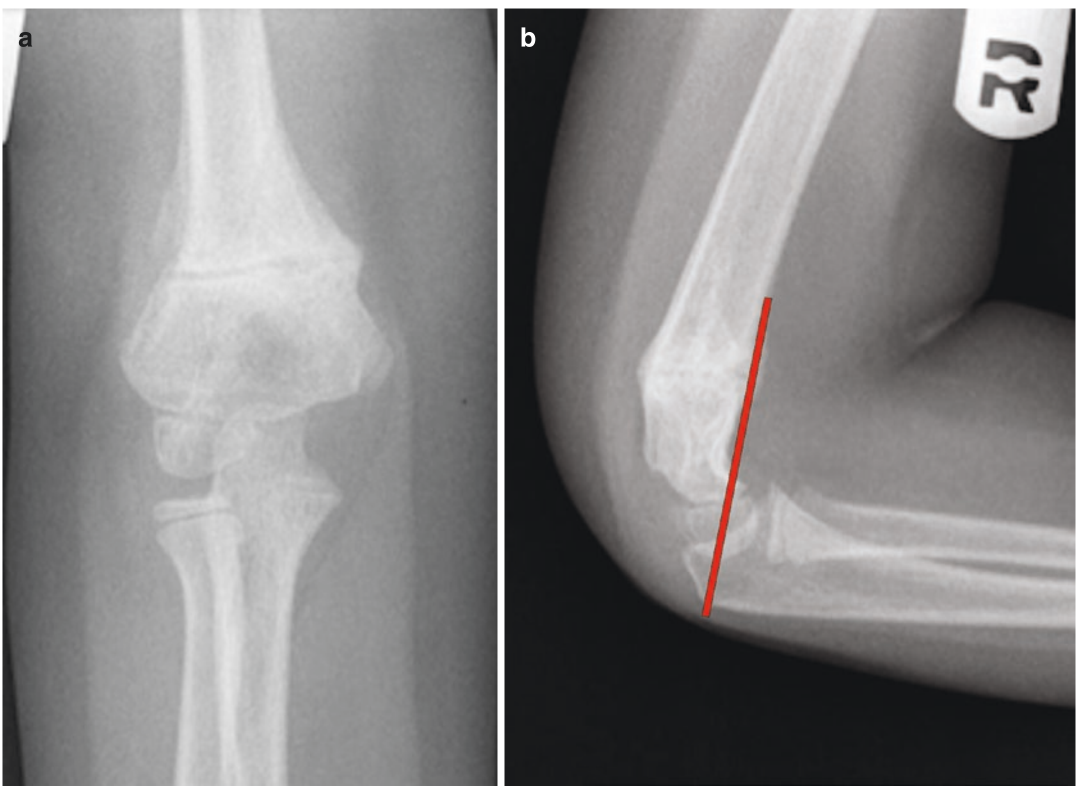


Fig. 5.11 Anteroposterior (**a**) and lateral radiographs (**b**) of the right elbow after correction of the deformity and healing of the osteotomy. The anterior humeral line *(red line)* now transects the capitellum

Fig. 5.12 Clinical photograph of a 15-year-old male with a "gun stock" deformity of his left elbow (**a**). Anteroposterior (**b**) and lateral radiographs (**c**) of his left elbow demonstrating a 25° varus malunion of the distal humerus

was made to avoid overcorrection of his varus deformity in an effort to avoid stretching of his ulnar nerve, in this 6-year-old deformity.

Author's Preferred Treatment After exposure of the lateral distal humerus in the supine position, two 1.6 mm K-wires are inserted from lateral to medial across the humerus at the level of the previous fracture/deformity. A single K-wire is placed perpendicular to the long axis of the humeral shaft, and then the second was placed at a 25° angle to the first with the tips of the K-wires meeting at the medial cortex. These K-wires are placed with fluoroscopic guidance. An oscillating saw was then used to create the 25° closing wedge osteotomy at the level of the maximum deformity. In each case, the saw was passed to the level of the medial cortex but not through it. Prior to completing the final osteotomy, two 2.0 mm K-wires were placed percutaneously through the lateral humeral epiphysis to the osteotomy level. At this point, osteoclasis of the distal humerus was performed by gentle manipulation of the arm to close the osteotomy and translate the distal segment medially to avoid a prominent lateral condyle. The K-wires were then advanced across the osteotomy to provide stability to the osteotomy, and a third K-wire was added, to further stabilize the distal humerus osteotomy site. A long arm cast was applied and univalved in the operating room (Fig. 5.13).

The patient had his K-wires removed in the office at 4 weeks (Fig. 5.14), but the cast remained for an additional week. At 9 weeks postoperatively, radiographs confirmed the correction of the angular deformity (Fig. 5.15), and physical examination revealed restoration of elbow motion (−10–130°) (Fig. 5.16).

5.4.3 Case 3: Long-Standing Deformity Following Humerus Fracture in Childhood

A 51-year-old Asian female who had sustained a fracture of the left and right elbows when she was 3 years and 5 years old, respectively. The fracture on the left side healed with a mild varus deformity after conservative treatment. The fracture on her right side healed with a severe varus deformity despite initial surgical treatment at an outside hospital. Despite her deformity, she ultimately worked as a nurse for 30 years. When she started experiencing right elbow pain, she was referred for assessment and treatment. On examination, the patient was found to have severe varus deformity of her right elbow with elbow flexion of 1350° and elbow extension of −20°. Range of motion of her contralateral elbow was −10°/135° (Fig. 5.17). Plain radiographs of the right elbow demonstrated severe cubitus varus deformity with osteoarthritic changes of the ulnohumeral joint (Fig. 5.18).

A 3D deformity evaluation of the distal humerus was conducted using CT data. To obtain CT images, a low-radiation protocol (scan time, 0.5 s; scan pitch, 0.562:1; tube current, 20–150 mA; tube voltage, 120 kV) was employed. Bilateral 3D surface models of the humerus, radius, and ulna were then created from the CT data. Deformity was evaluated by comparing the affected side with the mirror image of the contralateral side. Based on the 3D deformity evaluation, a corrective osteotomy was simulated (Fig. 5.19) [48, 49].

A patient-specific guide (PSG) was designed and manufactured as a plastic model; it was made to fit exactly onto the surface of the humerus and assist in the creation of the osteotomy in accordance with the preoperative simulation (Fig. 5.20a). A correction guide, which maintained the correction of the osteotomy while internal fixation was being applied, was also manufactured (Fig. 5.20b). These plastic guides were created using a 3D printing machine (Eden250, Objet Geometries, Rehovot, Israel) with medical grade resin (RenShape™ SL Y-C 9300, Basel, Switzerland).

The osteotomy was created using the custom surgical cutting guide, followed by the use of the custom reduction guide restored the normal anatomy of the distal humerus. The distal humerus was exposed via the lateral approach, taking care to avoid the radial nerve, with the patient in the supine position if he/she has open physes, or via the posterior approach with the patient in the lateral decubitus position if he/she has closed physes. Once the posterolateral aspect of the humerus was exposed, the osteotomy guide was applied onto the posterolateral

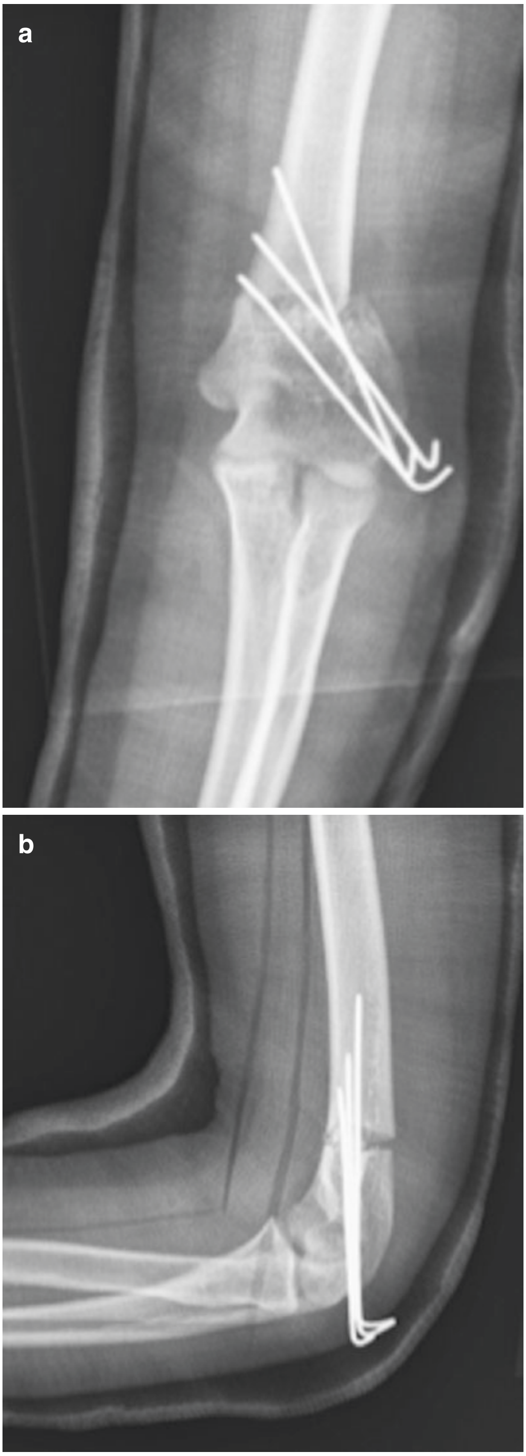


Fig. 5.13 Anteroposterior (**a**) and lateral radiographs (**b**) after a closing wedge osteotomy was performed and the osteotomy stabilized with three K-wires and the application of a long arm, univalved cast

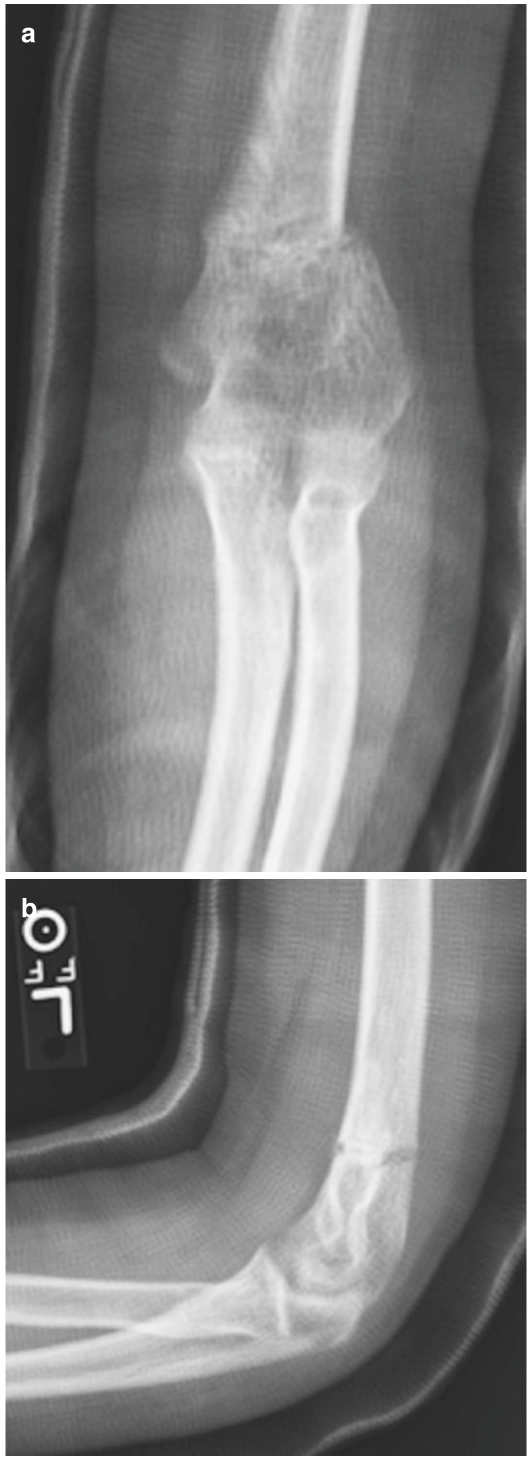


Fig. 5.14 Anteroposterior (**a**) and lateral radiographs (**b**) 4 weeks postoperatively of the left elbow following closing wedge osteotomy, pin removal, and re-application of a long arm cast

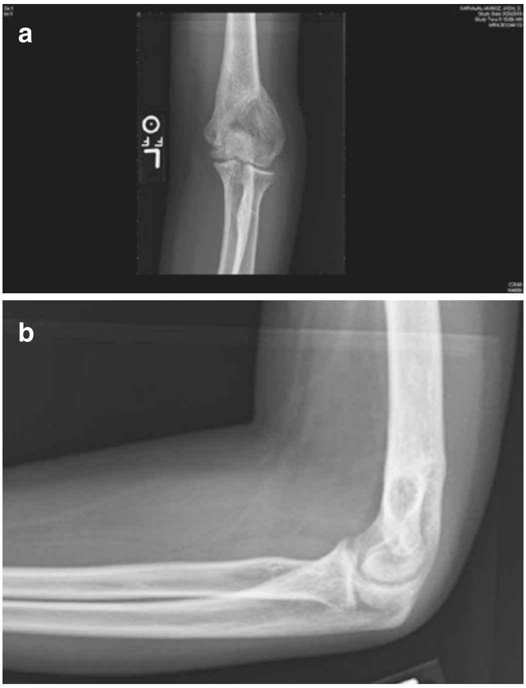


Fig. 5.15 Anteroposterior (**a**) and lateral radiographs (**b**) of the left elbow after complete healing of the osteotomy and correction of the alignment of the distal humerus

surface of the distal part of the humerus, where the lateral epicondyle and lateral half of the olecranon fossa serve as good landmarks. We verified that all edges of the guide were in exact contact with the bone surface. The guide was then fixed to the humerus with Kirschner wires (2.0 mm) inserted through the metal sleeves mounted on the guide. The osteotomy was created with a bone saw through the cutting slits on the guide, and the wedge-shaped bone segment was removed. The deformity correction was then achieved by bringing the Kirschner wires into a parallel position and held reduced with the aid of the reduction guide (Fig. 5.21). Stable internal fixation was accomplished with plates and screws, while the correction was maintained, per the preoperative plan (Fig. 5.22).

One year postoperatively, the osteotomy was healed, and the previous varus deformity was corrected (Fig. 5.23). Patient recovered her elbow range of motion, had improved appearance and decreased pain, and was very satisfied with her overall outcome (Fig. 5.24).

5.4.4 Case 4: Residual Deformity of Childhood Humerus Fracture Treated Nonoperatively

An 18-year-old Asian male who sustained a fracture of his left elbow at the age of 7 years. The fracture was treated nonoperatively and healed with a residual deformity. Patient had good function and little difficulty with ADLs until he started feeling pain after falling onto his left elbow while playing basketball 2 years prior to his presentation. Upon presentation, the patient reported elbow pain and a sense of instability of the elbow.

Physical examination revealed a cubitus varus deformity of the left elbow with a range of motion of 120° of flexion and full extension (Fig. 5.25a). Range of motion of his contralateral elbow was 135°/10°. Radiographs of the left elbow were consistent with a healed varus deformity and lateral collateral ligament instability (Fig. 5.25b, c). Range of motion of his left shoulder revealed increased internal rotation of 30° compared to his contralateral side, implying the presence of a considerable external rotation deformity of the distal humerus. Varus stress test and PLRI test of the left elbow were positive. It was determined that his instability resulted from his distal humerus malunion.

A 3D deformity evaluation was conducted using CT data. To obtain the CT images, a low-radiation protocol (scan time, 0.5 s; scan pitch, 0.562:1; tube current, 20–150 mA; tube voltage, 120 kV) was performed with the patient in the prone position and his arms elevated and extended overhead. Bilateral 3D surface models of each humerus, radius, and ulna were created. Deformity was evaluated by comparing the affected side with the mirror image of the contralateral side. Based on 3D deformity evaluation, corrective osteotomy was simulated (Fig. 5.26) [48, 50].

Fig. 5.16 Clinical photographs confirming the correction of the alignment of the patient's left elbow (**a**), with maintenance of the full range of motion of his left elbow (**b**,**c**)

Fig. 5.17 Clinical photos of a 51-year-old Asian female with a long-standing post-traumatic deformity of her right elbow following a right distal humerus fracture as a child. Patient has a varus deformity of her elbow (**a**) and a flexion contracture of approximately −35 degrees (**b**), with good elbow flexion (**c**)

A PSG was designed and manufactured to fit exactly on the posterolateral aspect of the distal humerus as a guide to creating the osteotomies according to the preoperative simulation (Fig. 5.27) [48, 49]. A custom-made plate was also designed and manufactured specifically for this patient (PSG and custom-made plates were provided by Teijin Nakashima Medical Co., Ltd., Okayama, Japan).

Intraoperatively, the osteotomy was carried out using a PMI and a custom-made plate, as per our preoperative CT reconstructions (Fig. 5.28a–c). The loose ulnar collateral ligament was reconstructed using palmaris longus tendon as a graft material (Fig. 5.28d).

At 1-year follow-up, the osteotomy has healed with complete correction of the deformity (Fig. 5.29a). At 1 year, the patient had regained normal limb alignment, and normal elbow range of motion, without further complaints of elbow instability (Fig. 5.29b–d).

5.4.5 Case 5: AO Type C3 Distal Humerus Fracture

A 59-year-old Asian woman injured her left, non-dominant arm, in a fall from a bicycle, sustaining an AO type C3 distal humerus fracture. She was treated with closed reduction and pinning with K-wires at an outside hospital (Fig. 5.30).

At 5 months after the initial injury, she was referred to our institution complaining of pain and restricted elbow motion. Her total range of elbow motion was 40°, flexion of −50° to flexion of 90° (Fig. 5.31). Plain radiograph and CT scan were consistent with an intra-articular malunion (Fig. 5.32).

Fig. 5.18 Anteroposterior radiograph of the malunited distal humerus demonstrating the ulnohumeral osteoarthritis

Three-dimensional computer models of both humeri were constructed from CT data and analyzed using commercially available software (BoneViewer™ and BoneSimulator™, Orthree, Osaka, Japan). Digitally, each fragment was manually segmented, and an intra-articular osteotomy was simulated using the mirrored model of the contralateral normal humerus. Repositioning of the lateral epicondyle by 8 mm proximally and the anterior part of the capitulum by 3 mm distally brought about a perfect reconstruction of the articular configuration in the simulation. In the digital images, the yellow and pink segments are the malunited anterior portions of the capitellum and lateral condyle, which are repositioned distally and proximally, respectively, in the post-correction model (Fig. 5.33).

For the surgical procedure, the patient was positioned supine with a tourniquet applied on the upper arm. An olecranon osteotomy was made in a chevron fashion through a midline posterior skin incision. The malunited lateral epicondyle was osteotomized and reflected distally, while the origins of the common extensor and lateral ligamentous structure were maintained. Despite the intra-articular step-off, most of the articular cartilage remained intact. The intra-articular osteotomy was performed through the original fracture line at the humeral capitulum with an osteotome (Fig. 5.34a). The fragments of the capitellum and the lateral epicondyle were reduced according to preoperative computer planning (Fig. 5.34b). The fragments of the capitellum were fixed with two double-threaded headless screws. The lateral epicondyle fragment and the olecranon were reduced to the humerus and stabilized with a tension band wiring technique. After closure, a posterior splint was maintained for 3 days before range-of-motion exercise started.

Eleven months later, the implants were removed from the olecranon and lateral epicondyle. Two years postoperatively, the patient reported no pain and showed almost normal range of elbow motion (5–140°) with good stability (Fig. 5.35).

Radiographs at 2 years showed no evidence of avascular necrosis or arthrosis, and a CT scan demonstrated anatomical reduction of the distal humerus articular surface (Fig. 5.36).

5.5 Summary

Supracondylar distal humerus fractures are one of the most common, if not the most common, fractures in children between the ages of 2 and

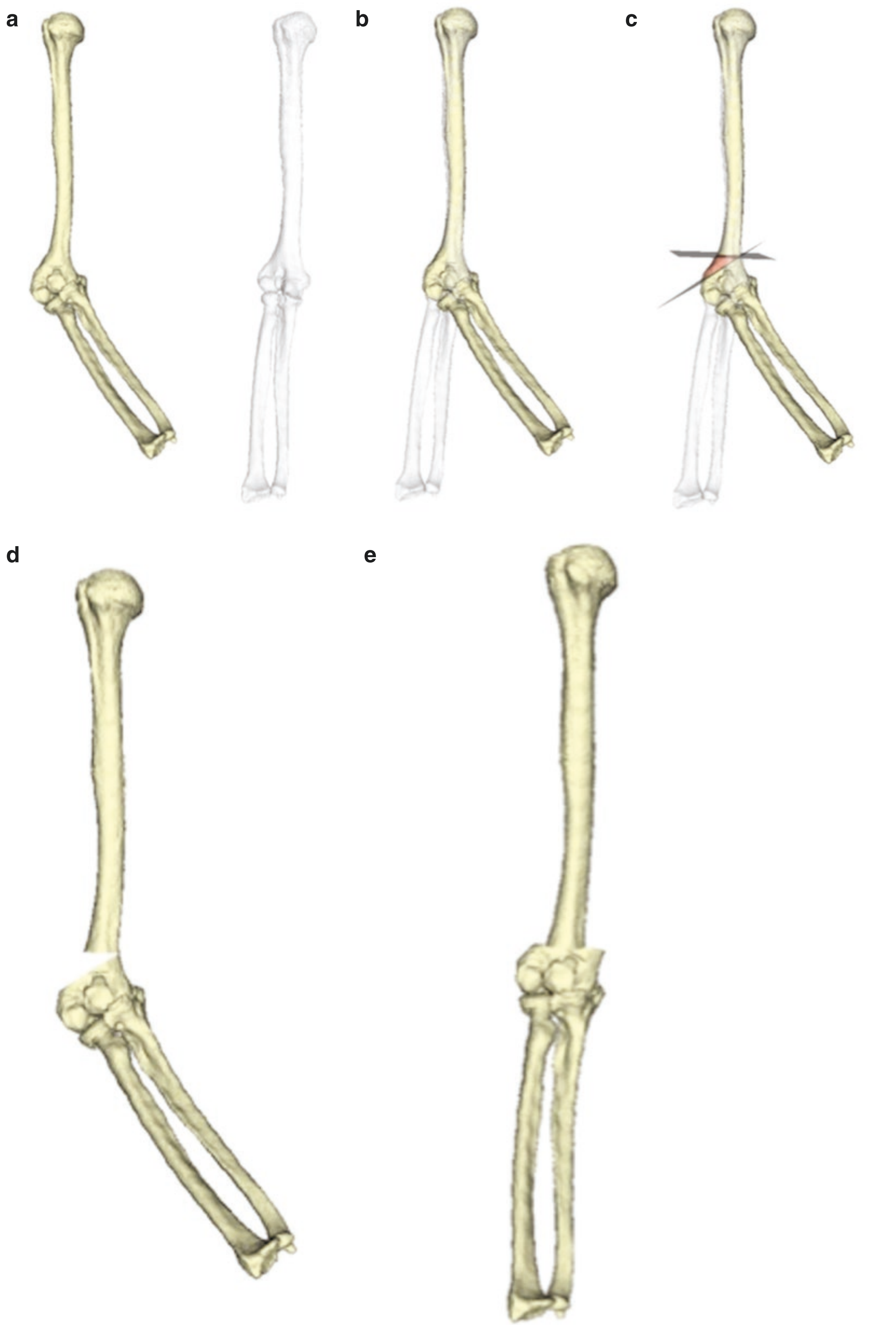


Fig. 5.19 CT reconstructed images of the right upper extremity is compared with the CT reconstructed image of the left upper extremity (**a**, **b**). The humeri are superimposed onto each other enabling 3D quantification of the deformity (**c**), the closing wedge osteotomy is designed (**d**), and the e-correction is simulated on a computer (**e**)

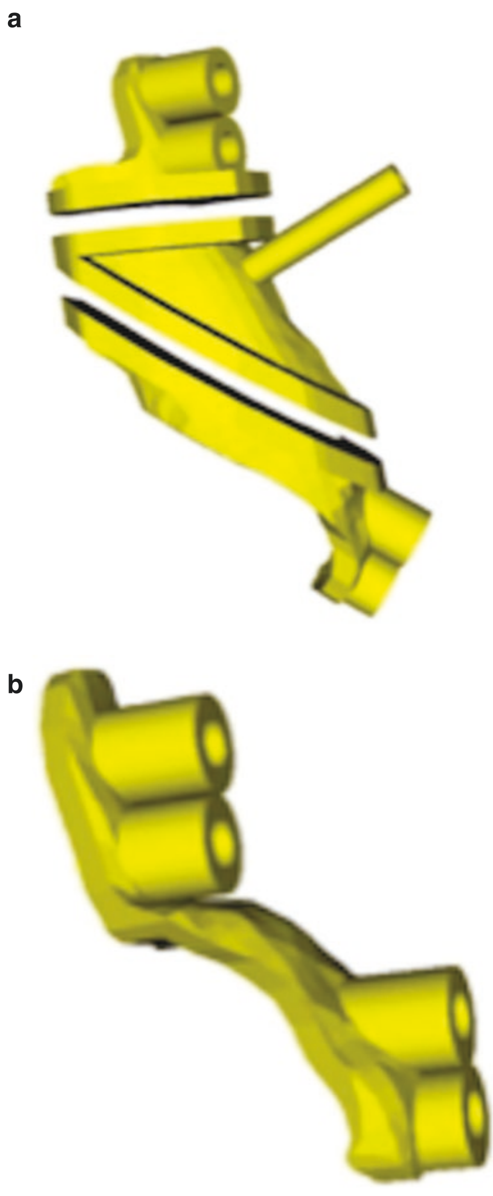


Fig. 5.20 The patient-specific guide (**a**) and correction guide (**b**) were designed and fabricated

12 years. These fractures most commonly occur as a result of a fall onto the outstretched hand while the child is playing on an elevated structure. The majority of the fractures are “extension” type although fractures of the “flexion” type are also known to occur generally as a result of a fall directly onto the point of the olecranon. The traditional classification of these fractures by Gartland delineates the direction of displacement of the distal fragment and the degree of its displacement. Acute treatment of these fractures generally includes either closed or open reduction and fixation often with laterally based K-wires and casting. Unfortunately, malunions of the distal humerus are still known to occur and when significant can result in a loss of elbow motion, cosmetic deformity, rotational instability of the elbow, and late ulnar nerve compromise. The operative treatment for distal humerus malunions generally includes an osteotomy of the distal humerus, restoration of normal alignment and rotation of the distal fragment, and stable internal fixation. The goals of treatment include restoration of elbow function, prevention and avoidance of complications, and improvement in the appearance of the elbow. This chapter reviews the development and treatment of supracondylar malunions and presents several case studies utilizing common and effective means for malunion corrections.

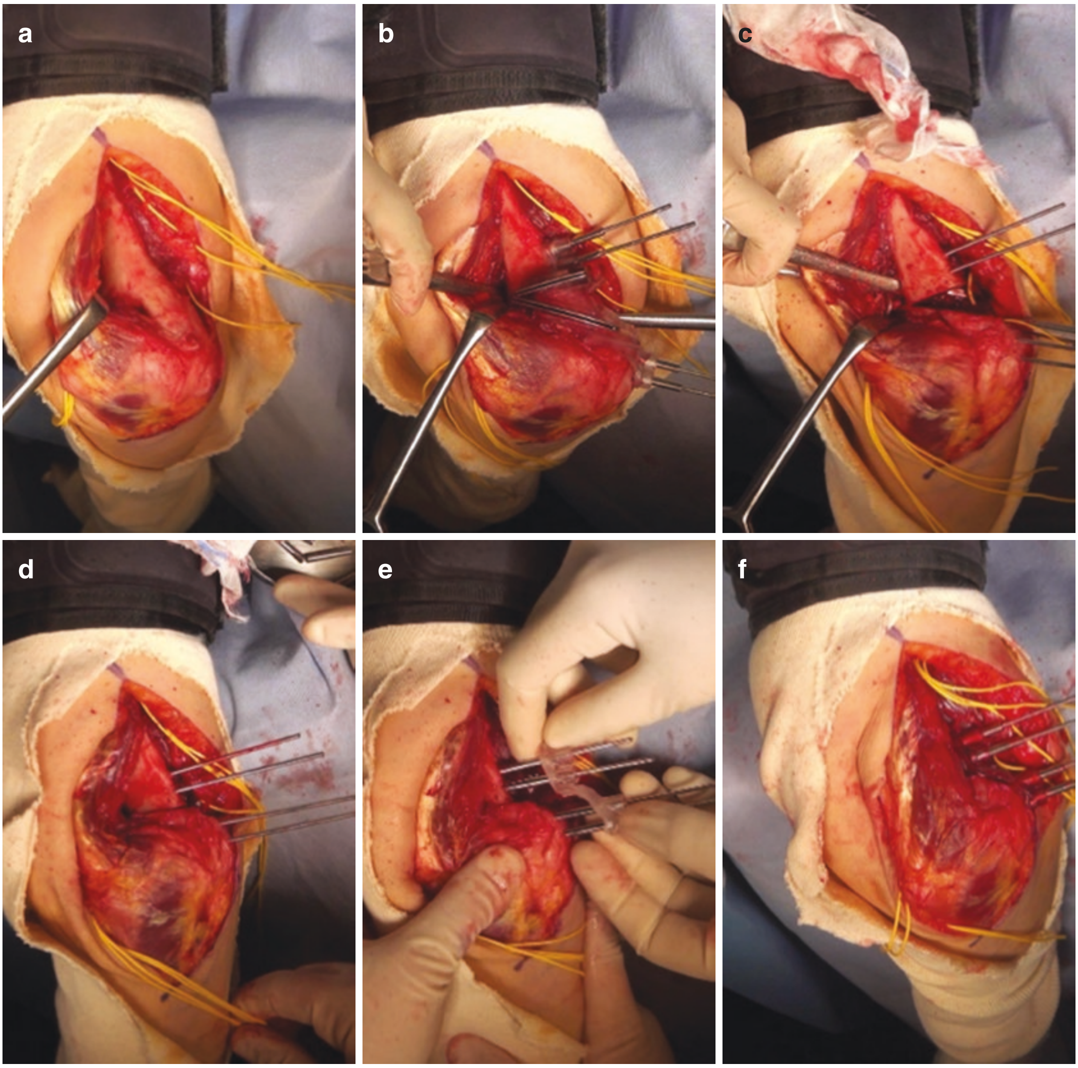


Fig. 5.21 *With the patient in a prone position*, a posterior incision and a lateral para-triceps exposure were performed to expose the posterolateral aspect of the distal humerus (**a**). The PSG is attached to the humerus with K-wires inserted through the guide holes (**b**), and the osteotomy is created by carefully sawing through the cutting guides and the bone wedge removed (**c**). The distal humerus is then reduced and the reduction maintained by positioning the correction guide over the originally placed K-wires (**d**–**f**)

Fig. 5.22 Fixation plates are pre-contoured to stabilize the distal humerus after the correction osteotomy has been carried out

Fig. 5.23 The pre-contoured plates are fitted and secured medially and posterolaterally to the distal humerus, to stabilize the osteotomy site, and the correction guide is removed

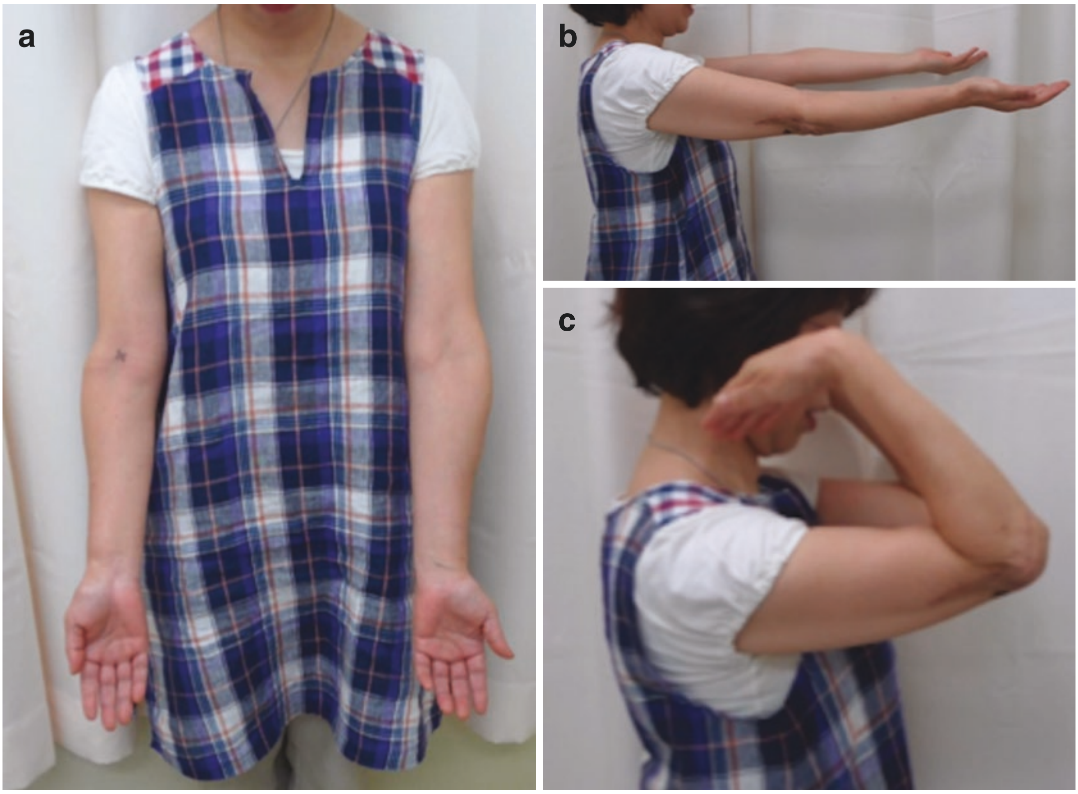


Fig. 5.24 One year postoperatively, the patient has a normally aligned right upper extremity with full extension and flexion of her right elbow (**a**–**c**)

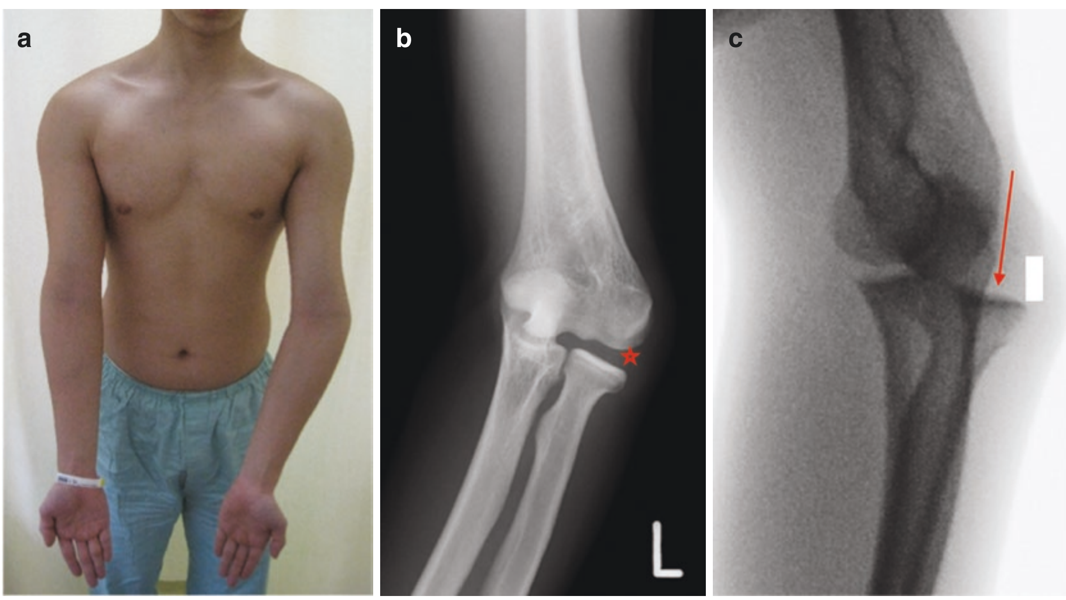


Fig. 5.25 Left cubitus varus deformity was apparent preoperatively (**a**). Anteroposterior radiograph also shows varus deformity with widening of the radiocapitellar joint (**b**, *star*). Intraoperative fluoroscopic images confirm his posterolateral rotatory instability (PLRI) with the radial head dislocating posteriorly (**c**, *red arrow*) when a valgus stress and external rotation force were applied to the elbow

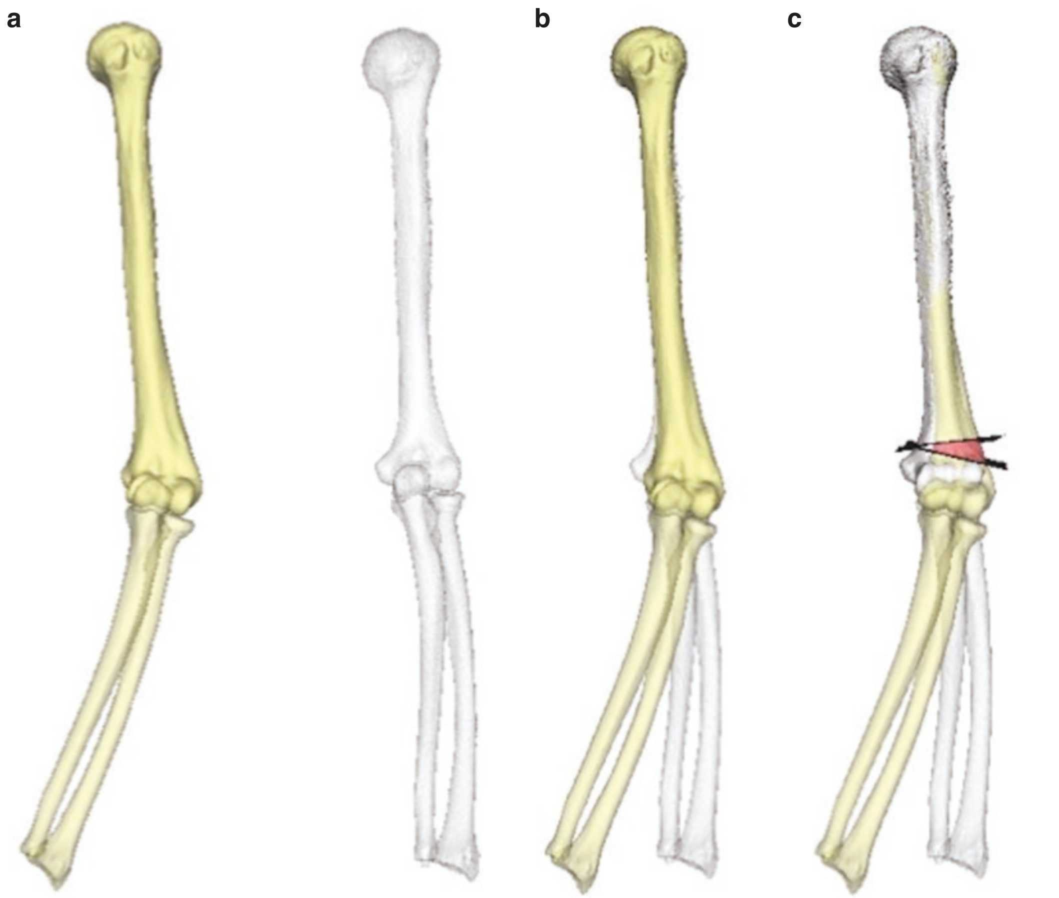


Fig. 5.26 The left upper extremity is compared with the mirror image of the contralateral side (**a**).The proximal portions of the humeri are superimposed enabling a 3D quantification of the deformity (**b**). A closing wedge osteotomy (**c**,**d**) and correction are simulated on a computer (**e**)

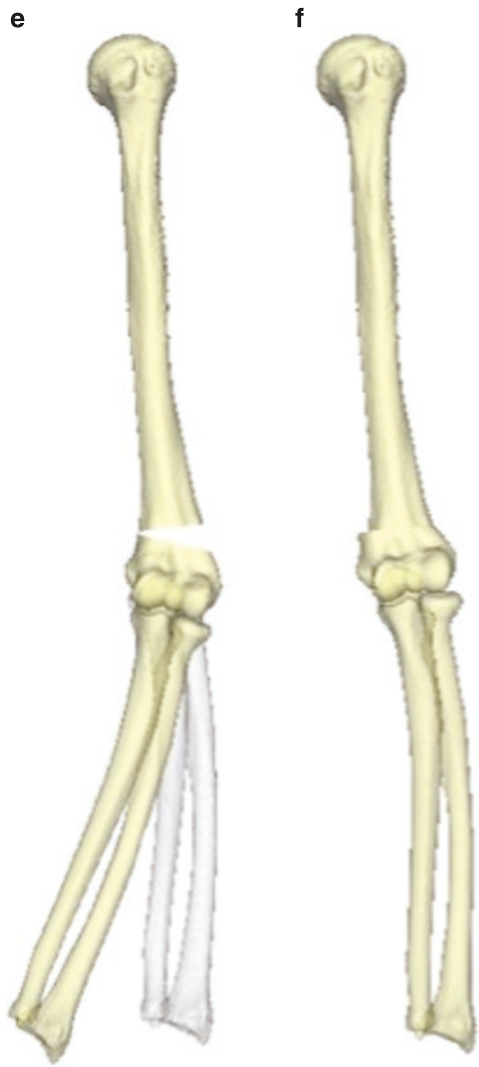


Fig. 5.26 (continued)

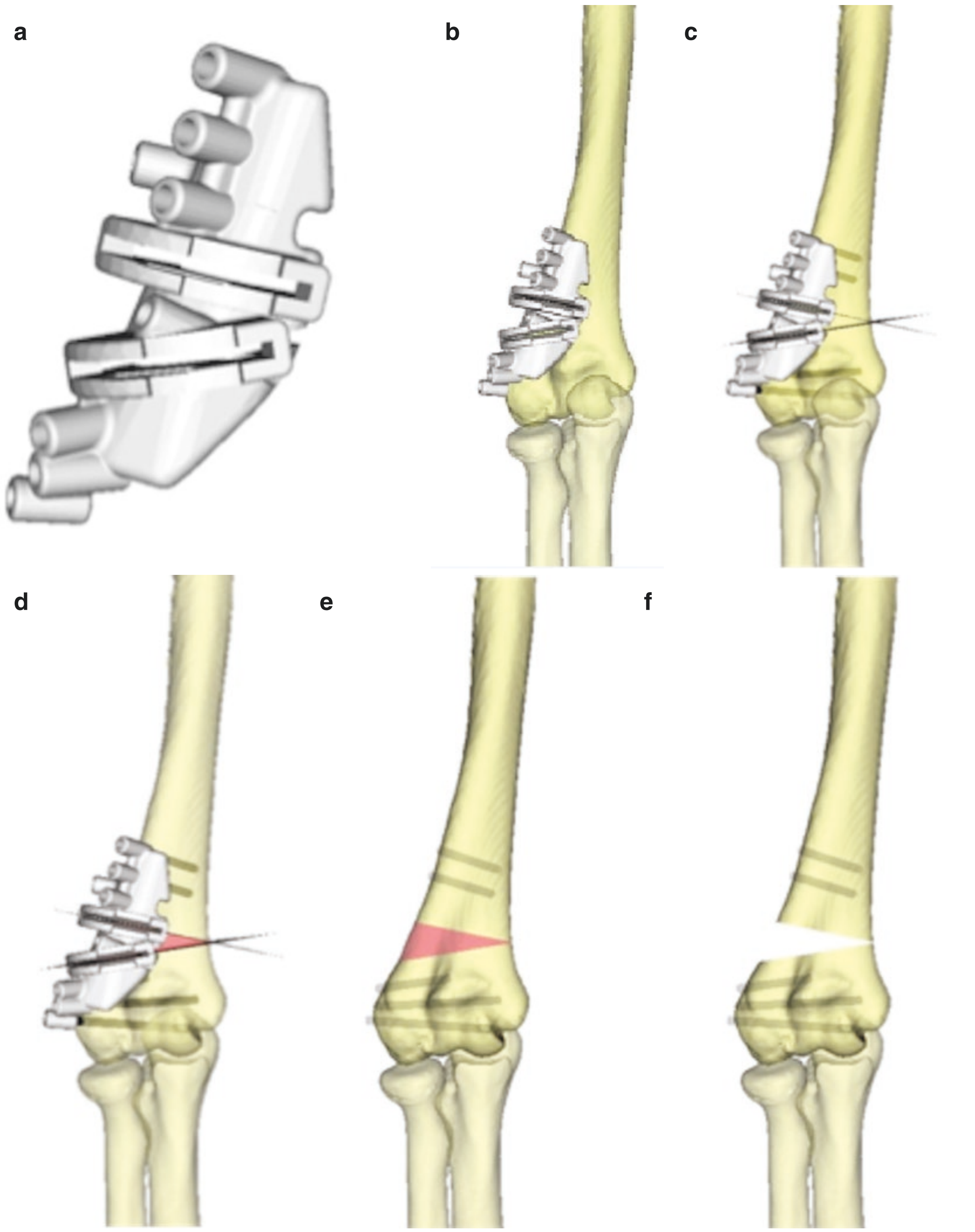
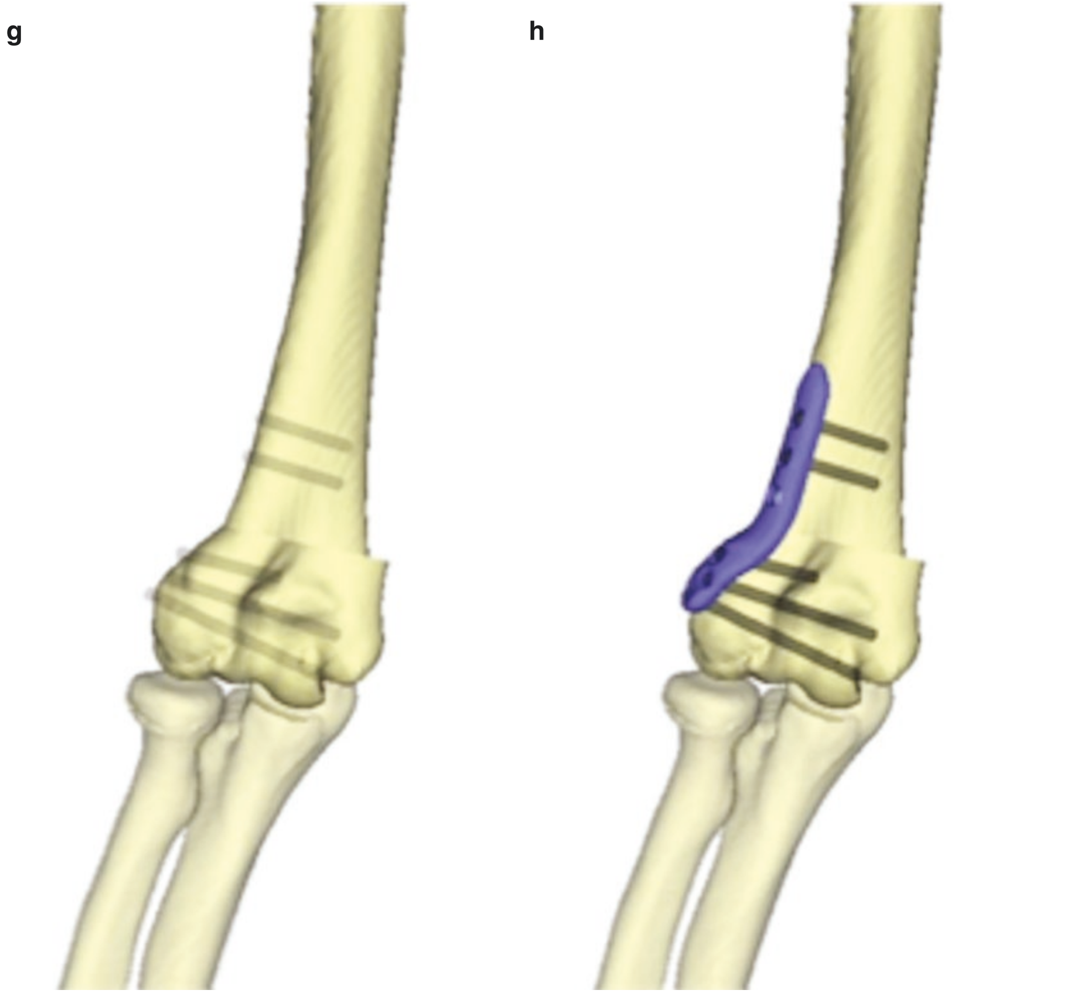


Fig. 5.27 *Based upon the CT reconstructions and the comparisons between the two sides*, a PSG is designed (**a**). The PSG is positioned along the posterolateral surface of the distal humerus (**b**). Predrilling for screws and the wedge osteotomy was conducted through the drill sleeves and cutting slits on the PSG (**c**,**d**). Varus deformity is corrected by closing the osteotomy site (**e**–**g**). A custom-made plate is applied on the lateral aspect of the distal humerus and stabilized with screws inserted through the predrilled holes (**h**)



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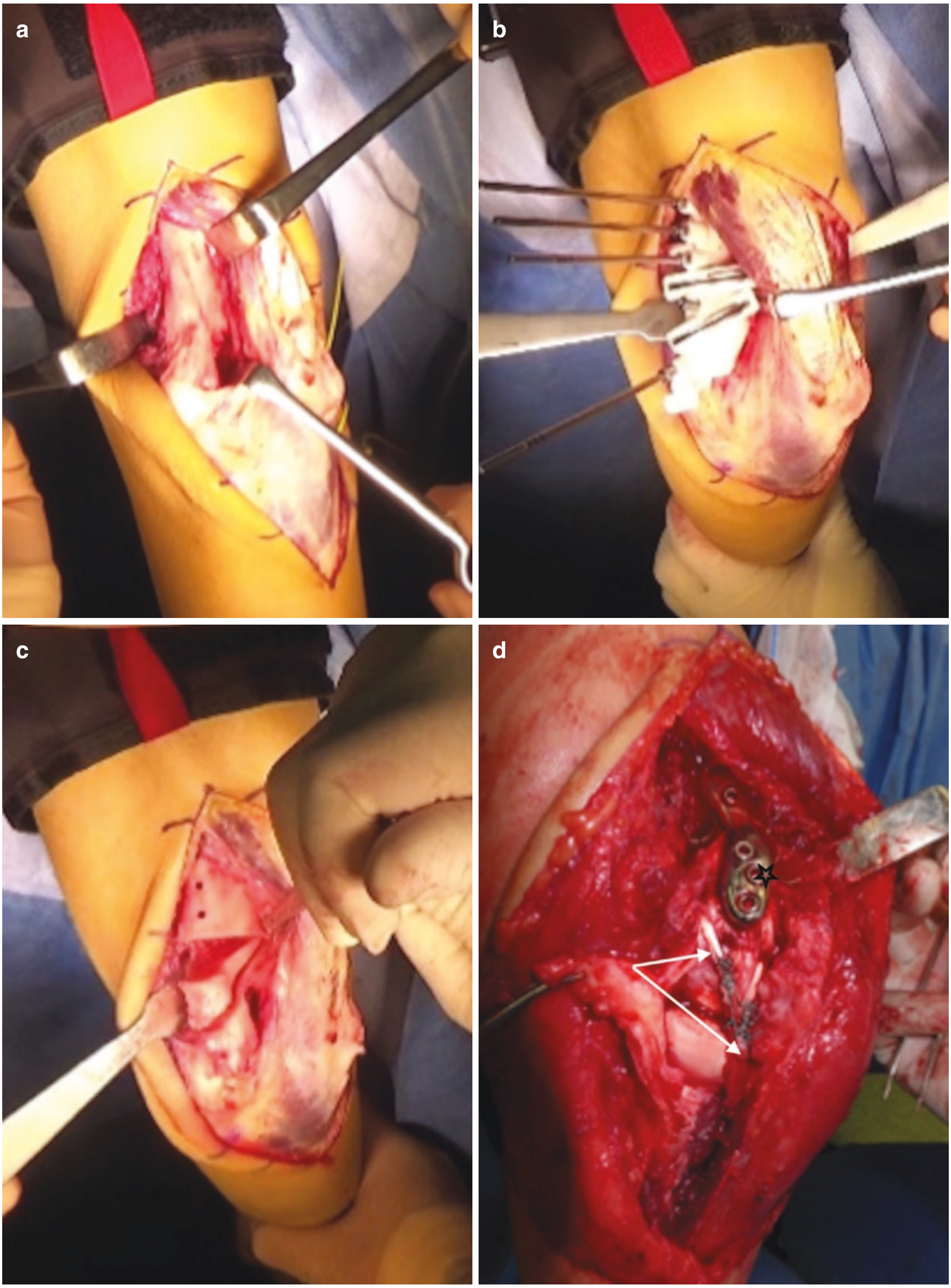

Fig. 5.28 The distal humerus was exposed and through a posterior approach as previously described (**a**). The PSG was placed on the lateral aspect of the exposed humerus and held in position with several K-wires (**b**). The osteotomy was conducted through the cutting slits of the PSG and the bone wedge removed (**c**). A custom-made plate was applied to the lateral side of the distal humerus (**d**, *black star*). The lateral ulnar collateral ligament was reconstructed (*white arrow*)

Fig. 5.29 Anteroposterior radiograph of the distal humerus 1 year following osteotomy and correction of deformity (**a**). Clinical photographs of the patient demonstrating excellent left upper extremity alignment and full range of flexion and extension of his left elbow (**b**–**d**)

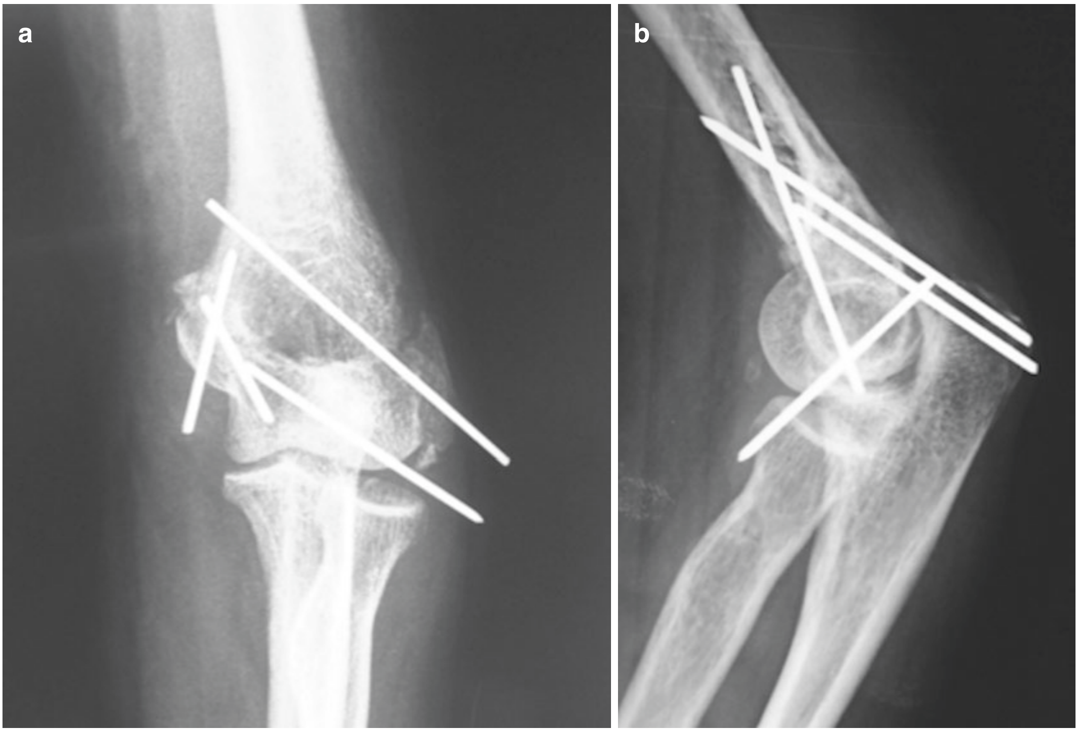

Fig. 5.30 Anteroposterior (**a**) and lateral (**b**) postoperative radiographs of an intra-articular distal humerus fracture with residual intra-articular displacement

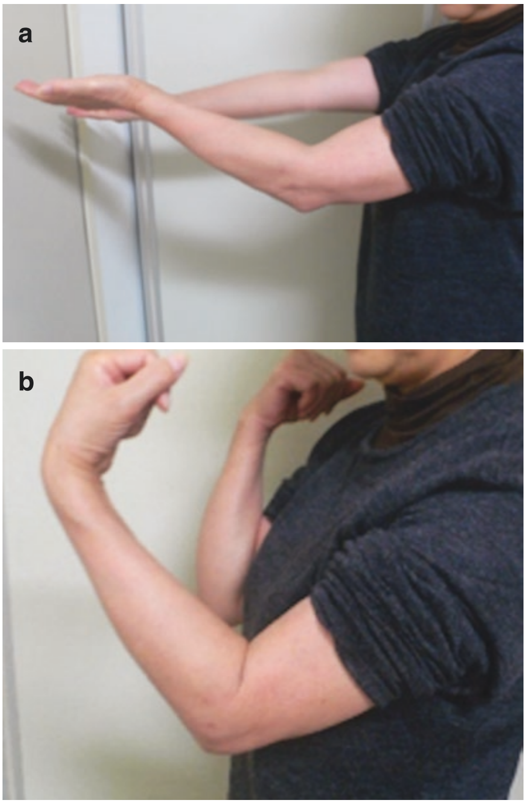

Fig. 5.31 Clinical photographs demonstrating the extension (**a**) and flexion (**b**) of the left elbow after healing of the original fracture and before corrective osteotomy and fixation

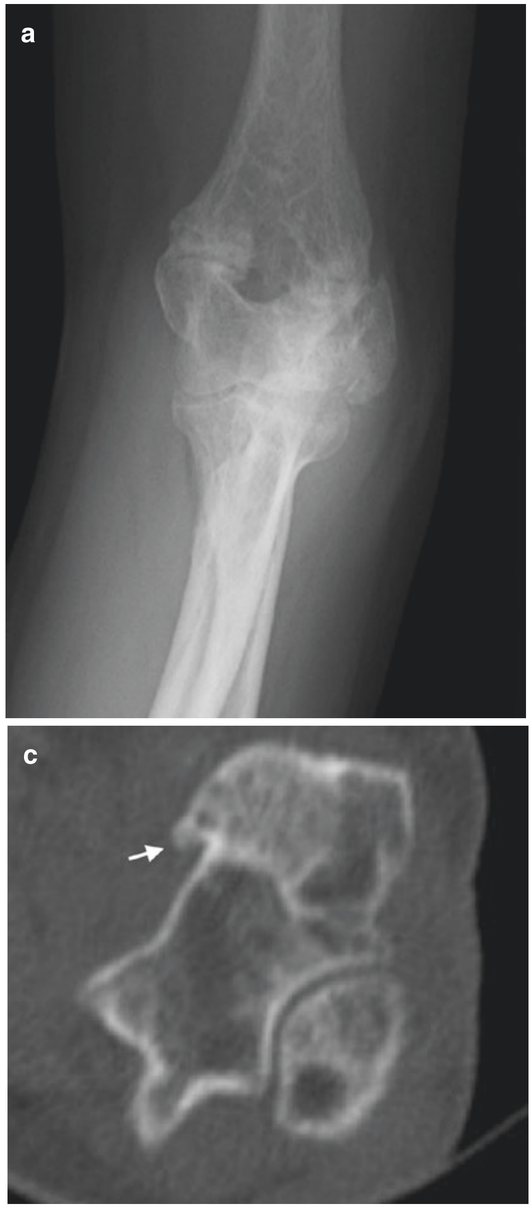

Fig. 5.32 Preoperative anteroposterior radiograph (**a**) demonstrates the intra-articular malunion of the distal humerus. A CT scan preoperatively further demonstrates the articular step-off of the capitulum (**b**, *arrow*)

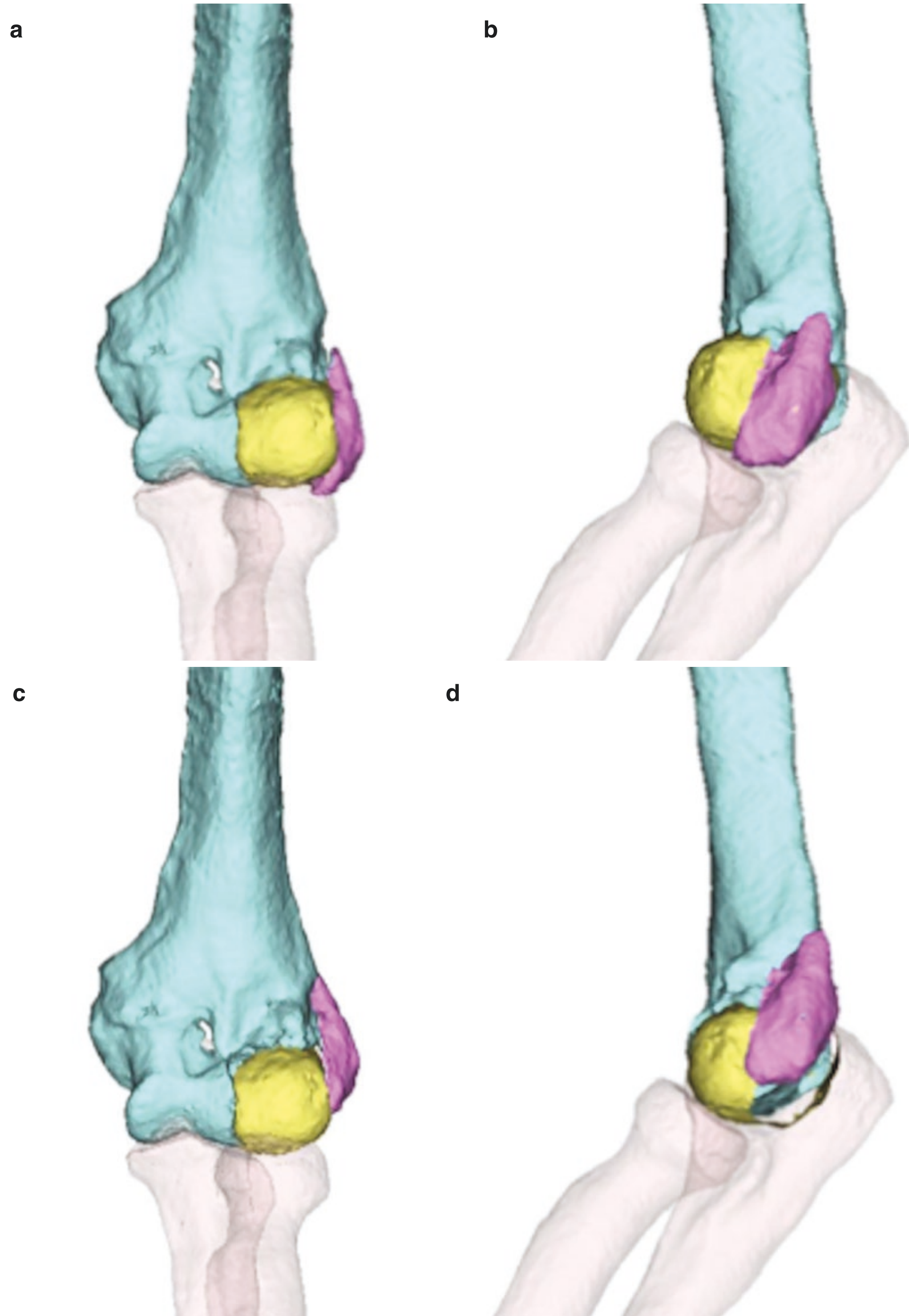

Fig. 5.33 Computer-reconstructed models including an anterior (**a**) and a lateral view (**b**) of the preoperative distal humerus. Computer-reconstructed models including an anterior (**c**) and a lateral view (**d**) of the osteotomized, reduced, and stabilized distal humerus

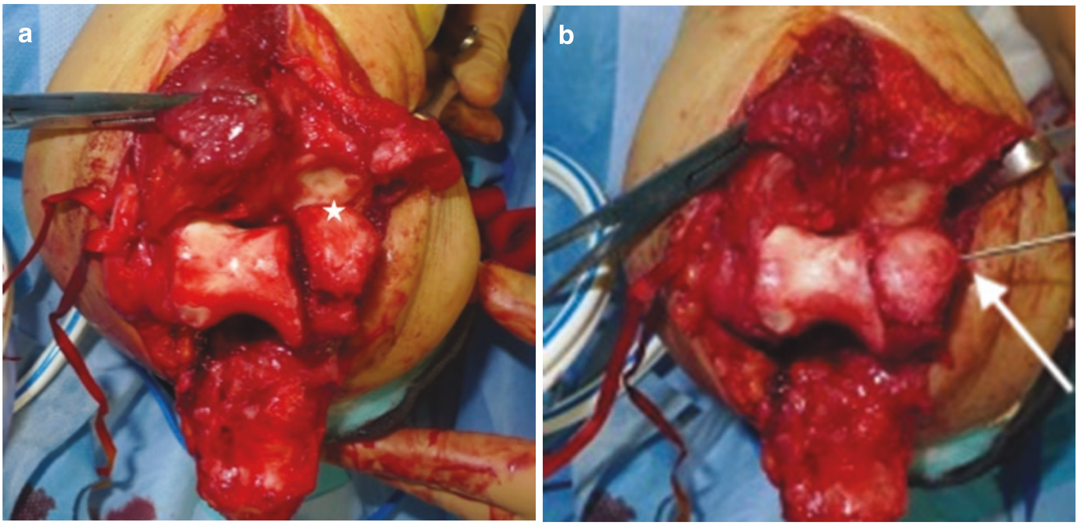

Fig. 5.34 Intraoperative photographs of the exposed distal humerus. The anterior portion of the capitulum was osteotomized through the original fracture line (**a**, *star*) and reduced, followed by temporary K-wire fixation (**b**, *white arrow*)

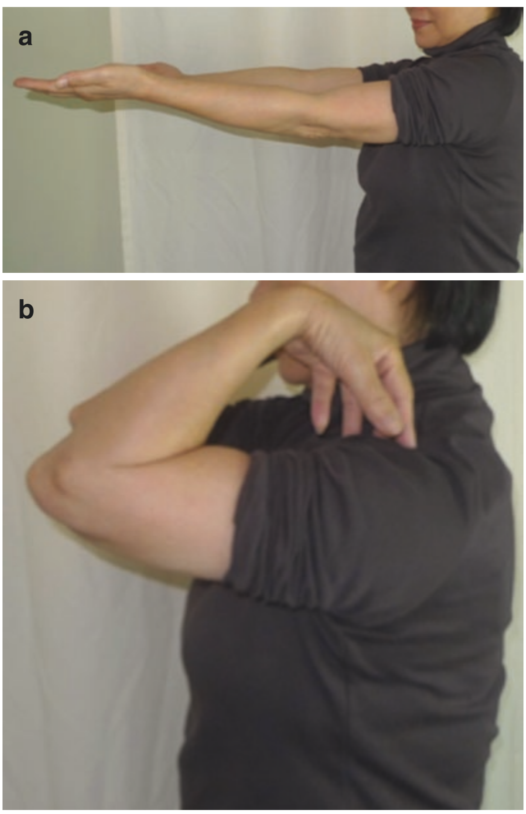

Fig. 5.35 Clinical photographs demonstrating full postoperative extension (**a**) and flexion (**b**) of the elbow

Fig. 5.36 Postoperative radiographs including an anteroposterior (**a**) and lateral (**b**) radiograph and CT scan (**c**) demonstrating excellent correction of the intra-articular malunion

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6 Malunions of the Forearm

Fred G. Corley and Ben S. Francisco

6.1 Introduction

The forearm is a distinctive anatomic structure in that it functions as a joint. Because of this unique quality, fractures of the radius and ulna should be approached as if they are articular fractures. Failure to restore minute perturbations of the angulation, length, or rotation of the radius or ulna ultimately impacts the function of the proximal radioulnar joint (PRUJ) and distal radioulnar joint (DRUJ). Consequently, forearm supination and pronation are altered. These effects, if severe enough, lead to impaired function as well as cosmetic deformity.

However, if the glenohumeral joint has normal function, some of the functional limitation can be compensated for [1]. In addition, Morrey et al. [2] assessed normal forearm rotation in 33 normal subjects. They determined that 50° of pronation-supination is necessary for most ADLs [2]. This is important to note, because even if patients have a malunion, they can get along satisfactorily, so long as they can perform the day-to-day tasks required of them.

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It should be noted however that the bone is not the only structure involved in the malunion. Significant soft tissue disruption, especially the interosseous membrane (IOM), can occur at the time of injury. As these structures heal, they too can contribute to the final malunion by healing in a contracted, non-anatomic position. This, in addition to the bony deformity, contributes to decreased forearm range of motion, pain, and disability.

Grace and Eversmann indicate, "Success in the treatment of fractures of one or both long bones of the forearm means that union of the fracture is achieved with minimum restriction of motion in the forearm, wrist, and elbow, and with restoration of good muscle strength without pain. The merits of any treatment regimen should be judged on these criteria because failure to achieve any one of them will compromise the functional result" [3]. This viewpoint was further validated by Schemitsch and Richards who maintained, "the recovery of function after a fracture of both bones of the forearm is dependent on the return of rotation of the forearm, the maintenance of a functional range of motion of the elbow and wrist, and the recovery of grip strength" [4].

6.2 Historical Perspective

Historically, closed reduction and conservative management of forearm fractures lead to unacceptable results [5–8]. However, Sarmiento et al.

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[9] report satisfactory results with closed reduction, above-elbow casting, and then transitioning to a functional brace. Failure can be multifactorial including, but not limited to, nonunion, angular or rotational malunion, distal or proximal radioulnar joint abnormalities, persistent pain and/or discomfort, and limitation of forearm supination and pronation. All of these factors can lead to impaired daily function.

For example, Knight and Purvis reported unsatisfactory outcomes in 71% of their 41 patients treated conservatively with longer times to union and angular and rotational deformities resulting in limitations in supination and pronation. In addition, they reported a 12% nonunion rate and 60% of the fractures had residual rotational deformities of 25–60° [5]. In their series of 92 patients treated with closed reduction and immobilization in a long arm cast, Bolton and Quinlan reported 38% of their patients suffered a clinical cosmetic deformity and 4% went on to nonunion. With regard to forearm rotation, 41% of cases resulted in impaired function, and 26% had a major loss of forearm range of motion. Perhaps most telling is that 11% of patients were unable to return to his or her previous employment but were able to find a lighter type of work or work that did not entail substantial financial loss. Twelve percent had significant disability and suffered substantial financial loss [7]. Hughston stated that of the 38 cases of Galeazzi fractures initially managed non-operatively, 92% resulted in failure or unsatisfactory results by his study group's standards. Fourteen percent went on to nonunion. The criteria for an unsatisfactory result are one or more of the following: nonunion, shortening, subluxation at the distal radioulnar joint (DRUJ), or dislocation of the DRUJ, and some degree of limitation of supination [6].

Given the high incidence of failure by closed conservative means, this led investigators to treat these fractures with internal fixation. Various operative methods were employed. Authors employed intramedullary pins or rods and differing types and plates and screws [5, 6, 8, 10–18]. These methods improved the overall outcome of fractures of the forearm. Union rates were improved, and disability from forearm rotation deficits was diminished.

Sage and Smith [10] reported on a case series of 555 fractures in 338 patients treated with various methods of intramedullary fixation and postoperative immobilization in a long arm cast. Satisfactory results of less than 20° elbow range of motion (ROM) limitation and less than 60° limitation of pronation and supination were produced in 82% of patients. When the open fractures were excluded, a 17% nonunion rate was found.

Hughston [6] presented 41 cases of Galeazzi fractures, 3 were operated on without a trial of conservative management, and the other 38 were initially managed non-operatively. As discussed previously, these 38 cases had unsatisfactory outcomes. Three had good results and required no further treatment. Seven of the 38, despite failure, refused surgical treatment. Twenty-eight subsequently submitted to operative fixation. Twenty-one of these cases were operated on within 4 weeks of fracture, while 7 were operated on after 4 weeks with average time to operation being 6 months.

In the early group, a variety of methods were employed, including intramedullary pins, screw fixation, four-hole plates and screws, double onlay bone graft and four screws, and transfixation pins, and one was treated with open reduction and no fixation. And the late group was treated with double onlay bone graft, intramedullary pins and bone graft, distal ulna resection, onlay bone graft and ulnar shortening, and Kirschner intramedullary wires, bone graft, and distal ulna resection.

The early operative group had 14 satisfactory outcomes, while the other 7 had unsatisfactory outcomes including nonunion, delayed union, and persistent angulation and ulnar subluxation. Eighty percent of those treated with plates and screws or onlay grafts and screws had a satisfactory result. The other methods did not produce such good results. In the late group, three had satisfactory outcomes with six having unsatisfactory outcomes of nonunion, delayed union, and malunion.

Sage [11] then reported on 82 fractures in 50 patients wherein he used intramedullary rods to stabilize the fracture and then immobilized them in a long arm cast postoperatively. Eighty-nine percent of these fracture united, 5% had a delayed union but subsequently united, and 6.2% experienced nonunion.

Jinkins et al. [12] reported on 65 cases of both-bone forearm fractures. Forty-nine were acute fractures, and 16 were nonunions at the time of presentation. These were treated with a variety of methods.

Of the 49 acute fractures, 33 were treated with open reduction and internal fixation using plates (contact splints), 28 with autogenous iliac crest bone graft, and 5 without autogenous bone graft. Four of the 28 with no bone grafting developed nonunions, whereas there were no nonunions in the 5 treated with initial bone grafting. Ten of the acute fractures were treated with plating of the ulna and an intramedullary rod in the radius. There were no nonunions in this group. Seven were treated with a plate on the radius only and no bone grafting, and one went on to develop a nonunion. One acute both-bone forearm fracture was treated with a plate on the radius and an intramedullary rod in the ulna with no bone graft, and this healed without problem.

Of the 16 fractures that presented as nonunions, 11 received plates to the radius and ulna, 2 without bone graft and 9 with bone graft. Two were treated with plating of the ulna and an intramedullary rod in the radius and bone graft, and these healed. One nonunion was treated with rods in both the radius and ulna, and this healed. Of the final two, one had a large amount of bone loss in the midshafts and was converted to a one-bone forearm with a rod from the proximal ulna to the distal radius and bone graft. This continued as a nonunion. The other was treated with a plate from the proximal ulna to the distal radius with a plate and bone graft and subsequently united.

Burwell and Charnley [8] reported on a series of 150 fractures of radial and/or ulnar shafts treated with plates and screws. They noted that if three screws were used on both sides of the fractures, 95% united. Of those fractures treated with two screws on both sides of the fractures, 64% united. Of the 38 failures they reported, 21% had osteoporotic bone, 34% had comminution, and 73% were treated with closed methods initially.

Sargent and Teipner [16] reported 100% union in a series of 29 diaphyseal forearm fractures treated with plating of both the radius and ulna. They divided their patients into three groups. In those patients without another associated extremity injury, they reported a less than 10-degree supination or pronation loss. In the three patients with an associated soft tissue or bony injury to the same, one patient developed a radioulnar synostosis, one regained near-complete forearm rotation, and one lost 10° of supination only. The other four patients had associated fractures or dislocations at the proximal forearm. The first patient developed a radioulnar synostosis, and the others had near-complete forearm range of motion.

Dodge and Cady [18] reported on a cohort of 119 fractures in 78 patients treated with open reduction and internal fixation using swiss society for fracture fixation (ASIF) compression plates. Forty-one patients sustained both-bone fractures, 28 of which were treated with fixation of both the radius and ulna and 13 were treated with plating of the radius only. Twenty-one patients had Galeazzi fractures, 14 patients had fractures of the radius in the middle or proximal thirds, and 2 had fractures of the ulna only. They reported the following complications: 5% loss of fixation, 13% implant corrosion, 13% infection, 1% refracture, 10% transient neuropathy of the superficial branch of radial nerve, and 22% loss of motion. Interestingly three of the four patients who had loss of fixation had a four-hole plate implanted, and they stated that they switched to the shortest plate being a five-hole plate.

Neglecting nonunion secondary to infection, the authors reported eight cases of delayed union and three cases of nonunion. Two of these had been treated with a four-hole plate and required bone grafting and eventually healed with limited forearm ROM, two experienced delayed union, and the other seven were in both-bone forearm fractures wherein the radius had been plated, but the ulna had not, and the ulna experienced delayed union.

As techniques continued to improve, a shift in treatment moved toward plating of both the radius and ulna with union rates above 96%, minimal complications, and overall satisfactory outcomes [4, 19–22]. However it should be noted that regardless of plate fixation, those with open fractures or those with both-bone forearm fractures tend to do worse with regard to forearm rotation [3].

6.3 Types of Malunion

Generally speaking, malunions of the forearm are due to angular or rotational deformities or a combination of both. Angular deformities are much easier to appreciate on standard radiographs. Rotational deformities can be much more subtle and often require more sophisticated methods for evaluation and even then can be difficult to identify.

It is vital to assess for rotational malunion, especially if the patient's decreased forearm ROM cannot be fully attributed to a marginal angular malunion. Otherwise, the patient may continue to have decreased forearm ROM even after surgical correction of the angular malunion.

Various authors [23–28] have looked at these aspects of malunion, either in isolation or in combination. Various methods have been employed, but unfortunately, much of the work has focused on cadaver specimens. Cadaver models cannot take into account the inevitable associated soft tissue injuries that occur at the time of fracture. Consequently, scarring and contracture of the IOM that occurs with forearm fractures cannot be assessed. This is reflected in the work of Sarmiento et al. whose cadaver model when compared to clinical results provided comparable but not exact results of forearm rotation. In addition, Sarmiento et al. point out that actual angulation of fractures sustained by patients are subtly different, "or out of plane," as compared to fractures created in the lab. For example, an actual fracture will likely have a component of dorsal or volar angulation, in addition to radial and ulnar deviation [25].

Tynan et al. [26] assessed rotational malunion in the midshaft of the ulna only using six fresh-frozen cadavers with intact soft tissues. After dissection was performed, a custom, adjustable, internal fixation plate was then applied to the osteotomy created in the midshaft of the ulna. A simulated rotational malunion of the ulna was then created in 0, 15, 30, and 45° of supination and pronation. Rotation was then simulated by applying torque in increasing increments through a cable attached to a wheel. As the degree of ulnar pronation malunion increased, pronation increased, and supination decreased and vice versa for a supination malunion. When the ulna was fixed in 45° of pronation malunion and the highest torque was applied, a mean loss of 20° of supination was noted. A simulated supination malunion of 45° leads to a mean loss of 18° of pronation. These findings support previously reported data that a malunion of the radius results in greater losses of forearm rotation [24]. Furthermore, if other studies [23–25] are accurate with regard to 20° loss of supination/pronation not interfering with ADLs, then rotational malunion of the ulna is clinically insignificant.

Dumont et al. [28] used five fresh-frozen cadavers to create simulated rotational malunions in mid-diaphysis of the ulna and radius leaving all of the soft tissues intact. The osteotomies were rotated by 10° increments if an isolated bone was being evaluated or 20° if both bones were being evaluated. The bones were then fixed in place with the use of a custom-made metal implant. Maximum rotational malunion was 80° for each isolated bone and 60° if both bones were rotated to a malunion spot simultaneously. When looked at in isolation, simulated malunion of the radius had the greatest effect on reducing forearm ROM, especially if the radius was malunited in supination, rather than pronation. The ulna had the least. When both bones were malunited, if they were malunited in the same direction, the results were similar to the isolated malunion results. If both bones were malunited in an opposite direction, then ROM was limited the most.

Matthews et al. [23] used ten fresh cadavers with the soft tissues around the osteotomy sites removed to create angular malunions of both the radius and ulna. Osteotomies were created in the mid-diaphysis of both the radius and ulna, and then custom-fabricated plates were applied to the osteotomy sites. The plates were fabricated at angles in the coronal and sagittal planes of 0°, 10°, and 20°, respectively. It was impossible to create 20-degree malunions of both bones toward the IOM. Nor did they test malunions of one or both bones away from the IOM, stating that this deformity is not frequently found in clinical situations and if it is seen implies gross damage to the soft tissues.

They reported that 10° angulation in any direction of a single bone in its middle third resulted in reduction of pronation or supination of less than 20°. In addition, this degree of angulation in some specimens produced an unacceptable cosmetic appearance. A simulated malunion of 20° in any plane produced a statistically and clinically significant loss of rotation due to the bones impinging on each other or by tension on the IOM. In addition, this degree of angulation produced a significantly deformed appearing limb. Supination or pronation or both decreased below the necessary 50° of rotation threshold as proposed by Morrey et al. [2] when the degree of angulation in any plane was 20°. As a cadaver study, factors such as grip strength, probability of and time to union, how these simulated malunions truly impact the patient's function, and how long the patient will be disabled by his or her injury are unable to be assessed.

Tarr et al. [24] simulated malunions created in middle and distal thirds of the radius and ulna in six fresh-frozen cadavers, with preservation of the soft tissues surrounding the osteotomy sites. They replicated malunions in 5-degree increments from 5° to 30° of angulation in radial and ulnar deviation and in volar and dorsal angulation. In general, their results correlated with results of Matthews et al. for angular deformities. They reported that angular deformities of the distal third, rather than the middle third, resulted in more of a loss of pronation than supination. Whereas, angular deformities of the middle third resulted in a drastic loss of supination as compared to distal third deformities. This built on the results of Matthews et al. [23] as they investigated malunions in the mid-diaphysis only.

Sarmiento et al. [25] simulated angular deformities of either the radius or ulna at 5°, 10°, or 15° of volar, dorsal, radial, or ulnar angulation in the proximal, middle, or distal third of the respective bones of 18 fresh cadavers. They noted that as the angulation of the radius increased, loss of motion increased. Pronation was more affected with increasing angulation of the distal third of the radius, and supination was most affected with increasing angulation of the middle third of the radius. They also determined that angulation of the middle third of the ulna produced a larger decrease in range of motion, than did angulation of the proximal third of the ulna.

The data from the cadavers were then compared to clinical and radiographic results of 105 patients treated conservatively. They also included results from their previous cadaver study of both-bone forearm malunions [24]. Their cadaver results demonstrated that angulation of the radius or ulna in the coronal or sagittal planes reduced pronation and supination by less than 24° and in most cases less than 20°. When the experimental cadaver results were compared to the patients' clinical findings, the study group was able to predict the clinical loss of pronation and supination to within 17% when the radius was fractured and within 8% when the ulna was fractured.

They reiterated that the level of the fracture, not just the degree of angulation, is important to take into account, as a fracture of the distal third of the radius limits forearm rotation differently than does a fracture of the middle third of the radius. The same is also true for the ulna.

McHenry et al. [27] assessed the effects of ulnar displacement on forearm rotation. Using seven fresh-frozen cadaver forearms, they created osteotomies at the junction of the proximal and middle thirds, in the mid-diaphysis, and at the junction of the middle and distal thirds of the ulna. These were then plated in 0, 50, and 100% in radial, ulnar, dorsal, and volar displacement at the above stated osteotomy sites. The forearms were then taken through a range of motion, and supination and pronation deficits were assessed.

The amount of supination lost was less than 15° regardless of which combination of displacement was assessed. Pronation loss was less than 10° at the distal osteotomy site, 19 and 20° with 100% radial and ulnar displacement at the middle osteotomy site, and, at the proximal osteotomy site, 19° with 50% radial displacement, 41° with 100% radial displacement, and 33° with 100% ulnar displacement. All other combinations of displacement resulted in less than 15° of loss of pronation. They concluded that forearm range of motion might be good with 100% displacement of a distal third ulna fracture and 50% displacement of a midshaft ulna fracture. A midshaft fracture with more than 50% displacement and a displaced proximal fracture should be treated operatively.

6.4 Anatomy of the Forearm

The forearm is composed of the radius and ulna, and the "forearm joint" is the result of the interplay between these two bones at their two distinct articulations proximally and distally, the proximal radioulnar joint (PRUJ) and the distal radioulnar joint (DRUJ). Interposed between these two joints and the two bones is the interosseous membrane (IOM), which provides stability to the forearm and transfers forces from the distal radius and ulna proximally, as well as stabilizing the PRUJ and DRUJ [29–32]. The coordinated action and stability provided by these three structures allow the forearm to function appropriately. The forearm axis of rotation passes from the center of the radial head through the fovea of the distal ulna [33], thereby allowing the mobile radius to rotate around the fixed ulna 150–180° as the forearm musculature moves the hand from pronation to supination. Working simultaneously with the carpus, this degree of freedom provides the forearm with the ability to position the hand intricately in space.

Varying authors have determined forearm range of motion with 68–70° pronation and 75–85° supination being average [2, 24, 34]. However, Morrey et al. noted that only 55° of supination and 50° of pronation are needed for most activities of daily living (ADLs), indicating that supination is needed more than pronation.

6.4.1 Bony Anatomy

The radius is a long bone with proximal and distal epiphyses. At the proximal end, the radial head is nearly round and articulates with the ulna in its radial fossa and the capitulum of the humerus. As the radius moves distal, it narrows to form the radial neck. On its ulnar side, there is a bony prominence called the radial or biceps tuberosity, where the biceps tendon inserts. In its midsubstance, the radius is triangular in shape. The ulnar border is the apex of the triangle and is the origin of the IOM.

In addition, the radius has three bows. At the distal one-fifth, the radius has a convex dorsal bow and at the proximal one-fifth a convex ventral bow. The middle three-fifths contains the most prominent radial bow. This bow corresponds to the insertion sites of the pronator teres and supinator muscles; hence, the radial bow is vital in ensuring correct forearm rotation. A fracture in this area leads to the most disability if the fracture is not anatomically aligned, as the lever arms of these respective muscles are shortened [12]. Interestingly, in Burwell and Charnley's series of 231 fractures in 150 adult patients, 93% of radius fractures occurred in the middle three-fifths of the radius [8], and Sage and Smith reported that three-fifths of their radius fractures were found in the middle third [10].

Therefore, in forearm fractures, the radial bow must be restored, or else loss of rotation will ensue. Schemitsch et al. [4] demonstrated the method by which the apex of the radial bow can be found. This is foundational in the treatment of forearm fractures and the prevention of anatomic and rotational malunion.

At its distal end, the radius flares to receive articulations with the ulna at the sigmoid notch and the lunate and the scaphoid at the lunate and scaphoid fossae and also forms the radial styloid on the radial side to receive the insertion of the brachioradialis. The radius rotates about the ulna 150–180°. This arc of rotation has a longitudinal axis that is centered in the radial head proximally and at its distal end passes through the center of the ulnar head and consequently the index finger. As the radius rotates around the ulna, the ulna moves in a varus-valgus direction about 9° at the elbow, thus allowing the ulna to move out of the way of the rotating radius distally [35].

The ulna is also a long bone. At its proximal end is the olecranon, which receives the insertion of the triceps. Anterior to this is the trochlear notch, which forms the stable articulation with the trochlea of the humerus. The trochlear notch terminates in the coronoid process. On its radial side is the radial notch or fossa, which together with the radial head forms the PRUJ. On the ulnar side of the trochlear notch is a small tuberosity, which receives the insertion of the brachialis. The diaphysis of the ulna is triangular in shape, with the apex pointed to the radius. This apex receives the insertions of the IOM. At its distal aspect, the ulna flares to form the ulnar head and ulnar styloid. On its radial side, the ulna articulates with the sigmoid notch of the radius to form the DRUJ. The ulnar styloid forms the origin for the triangular fibrocartilage complex (TFCC).

6.4.2 Muscle Anatomy

The volar forearm is comprised of 14 muscles, whereas the dorsal forearm has 13 involved muscles. As one moves from proximal to distal along the shaft of the radius, the following muscles are encountered: the insertion of brachioradialis, the origin of pronator quadratus, the origin of flexor pollicis longus, the origin of flexor digitorum superficialis, the insertion of pronator teres, the insertion of supinator, and the insertion of biceps.

As one moves distal to proximal along the dorsal radius, the following muscles are encountered: the insertion of brachioradialis, the origin of extensor pollicis brevis, the insertion of pronator teres, the insertion of abductor pollicis longus, and the insertion of supinator [36].

The musculature of the forearm is the driving force of forearm motion and plays vital roles in hand and wrist function. Their coordinated actions contribute to pronation, supination, flexion, and extension needed to perform the many gross and fine movements needed in the complex functions we are involved in in daily life.

It is also these muscles that can contribute to the formation of anatomic and rotational malunions. The muscles responsible for pronation are mainly the pronator teres and to a lesser extent the pronator quadratus, while the biceps brachii and supinator perform supination. It is these muscles that produce the majority of deformity in fractures of the forearm, causing the fracture ends to approach each other centrally toward the IOM. Furthermore, the proximal fragments tend to be flexed – the ulna by the brachialis and the radius by the biceps brachii [12].

The brachioradialis is also a major deforming force. Its action is best demonstrated in a Galeazzi fracture, where the distal 1/3 of the radius is pulled into valgus, as there is no opposing force. The pronator quadratus is also involved in this fracture wherein it pulls the distal fragment into pronation as a result of unopposed action.

6.4.3 Distal Radioulnar Joint Anatomy

Distally, the ulna articulates with the radius at the sigmoid notch to form the distal radioulnar joint (DRUJ). This joint is stabilized primarily by the triangular fibrocartilage complex (TFCC). The palmar radioulnar ligament (PRUL), dorsal radioulnar ligament (DRUL), articular disc, ulnocarpal ligaments, extensor carpi ulnaris subsheath, and meniscus homolog comprise the TFCC. The ligamentous complex is the primary stabilizer of the DRUJ, whereas the fibrocartilage component transmits force across the ulnocarpal joint. The differences in curvatures in the ulnar head and sigmoid notch allow for DRUJ incongruity and thus the ability of these two structures to rotate and translate relative to one another, thereby providing a portion of the rotation necessary for forearm movements [37].

6.4.4 Interosseous Membrane Anatomy

The IOM and its anatomy have been studied both anatomically and biomechanically by various authors [29, 38–43]. Biomechanically, the IOM serves as an origin for forearm musculature, stabilizes the DRUJ [30–32] and the longitudinal forearm, transmits loads from the radius to the ulna, and allows for smooth forearm rotation [1, 3, 4, 8–11]. Anatomically, the IOM can be divided into distal membranous, middle ligamentous, and proximal membranous portions [41]. Together, these structures average roughly 22 cm in length, with the radial origin being an average of 10.6 cm in length and ulnar insertion measuring 10.6 cm [42]. The width of the IOM is roughly 3.5 cm and 0.94 mm at its thickest point [38].

The distal membranous portion is composed of the distal oblique bundle. This portion of the IOM is found under the pronator quadratus and inserts on the inferior rim of the sigmoid notch and blends with the DRUJ, TFCC, and dorsal and palmar ligaments at its most distal aspect [41]. Working in concert, these structures serve to stabilize the DRUJ [30–32].

The proximal oblique cord and dorsal oblique accessory cord comprise the proximal membranous portion [41]. The dorsal oblique accessory cord has also been called the proximal ascending bundle [39], or the proximal interosseous band [42]. The proximal oblique cord is found between the origin of flexor digitorum profundus and supinator. It originates from the anterolateral aspect of the coronoid process and inserts just distal to the radial tuberosity. The dorsal oblique accessory cord is located below the origin of abductor pollicis longus [41].

The central ligamentous complex is composed of several distinct bands: the stout central band, one to five accessory bands, membranous portions, and the proximal interosseous band [41, 42]. The central ligamentous complex is divided into the central and accessory bands. The central band is the most robust portion of the IOM and is always present and, as such, is considered to be of prime importance. Furthermore, it comprises 40–60% of the total IOM [43]. Hotchkiss et al. reported that it provided 71% of the stiffness of the IOM [38]. The central band, which is 3.5 cm in width or 2.6 cm if measured perpendicular to its fibers, originates on the radius an average of 7.7 cm distal to the articular surface of the radial head. As the central band moves distally toward its ulnar insertion at a 21° angle relative to the longitudinal axis of the ulna, the fibers fan out and form an insertion 4.2 cm in length on the ulna. The average insertion point of the central band is 13.7 cm distal to the tip of the olecranon [42]. The accessory bands are distinct anatomic structures, separate from the central band, and vary in number. Furthermore they are less robust of structures [41, 42].

6.4.5 Proximal Radioulnar Joint Anatomy

Proximally, the radius articulates with the ulna at the PRUJ, which is composed of the radial head, the capitulum of the humerus, and the lesser sigmoid notch of the ulna. The PRUJ is constrained and stabilized by the annular ligament, the lateral ulnar collateral ligament (LUCL), the radial collateral ligament, and the surrounding elbow joint capsule and musculature. The intrinsic bony anatomy of the proximal ulna and its articulation with the distal humerus allows the ulna to be a fixed construct around which the radius can rotate.

6.5 Etiology of Forearm Malunion

As is true with all fractures, the mechanism of injury and vector of force transmission are the driving force behind the initial spatial orientation of the fracture fragments. The muscle and soft tissues further contribute to malalignment. As soon as the bones are fractured, the anatomic homeostasis of the muscle, bone, and other surrounding soft tissues is disrupted. Subsequently, these structures want to rotate or shorten to their own respective points of minimal tension. As this occurs, the fracture fragments are pulled along with the soft tissues. When these bony and soft tissue aspects of fractures are combined, not only is range of motion impaired, but muscle strength is affected, minimal to debilitating pain can be present, arthritis can develop at the PRUJ and/or DRUJ, PRUJ and/or DRUJ instability can be present, and cosmetic appearance can be disfiguring.

If the forces acting on the fracture fragments are not balanced and maintained, either by closed reduction methods or various operative techniques, then continued malalignment will ensue as the fracture fragments unite. As pointed out in the previous discussion, not all malunions result in significant deficits to patient function. However, malunions of the forearm can and do impair a patient's quality of life if severe enough.

6.6 Treatment of Forearm Malunions

In order for the clinician to appropriately treat forearm malunions, he or she must appreciate the radius and ulna's relationship, not only in a radiographic sense but also how the surrounding soft tissues and proximal and distal articulations function together to provide forearm function.

The goals of treatment for forearm malunion are much the same as with other fractures and are based on basic AO principles of fracture management. This implies, first, restoration of anatomy, which includes restoration of length, axial alignment, and rotation; second, stable fracture fixation; third, preservation of blood supply; and, fourth, early mobilization of the patient and their injured extremity [44]. Specifically, the proximal and radioulnar joints need to be realigned, the radial bow needs to be restored, and angular deformities need to be corrected [28, 45].

6.6.1 Initial Evaluation

6.6.1.1 Patient History and Physical

All patients who present with a forearm malunion need a detailed history and physical, as this information proves invaluable in the planning and execution of the treatment strategy.

Pertinent points in the history should include age at which injury was sustained, whether the fracture was open or closed, if an infection is or ever was present, and initial and subsequent treatments. If at all possible, operative notes should be acquired, as well as pertinent physician notes relating to the malunion of interest. In addition, original radiographs can prove invaluable in formulating a treatment plan.

If there is any suspicion for a current or previous infection, infectious laboratory studies should be obtained. Our initial laboratory evaluation includes a white blood cell count, an erythrocyte sedimentation rate, and a C-reactive protein. If these are within normal limits, we proceed as normal. However, if these are elevated, we initiate more advanced radiologic evaluation, which, in addition to standard radiographs, includes a triple-phase bone scan, followed by an indium scan and sulfur colloid scan if the bone scan indicates the presence of infection.

Regarding the physical, the skin needs to be assessed. Things to pay close attention to are the location of prior surgical scars, if any, and the quality of the skin, including areas of previous or current skin deficits. The muscles of the forearm and hand should be examined in a sequential manner, noting any deficits that may be present. The neurovascular status of the limb should be assessed as well. This would include an assessment of the anterior interosseous nerve, the posterior interosseous nerve, the superficial branch of radial nerve, the dorsal sensory branch of ulnar nerve, and the median and ulnar nerves proper. The quality of the radial and ulnar arteries should also be noted.

The DRUJ and PRUJ should be assessed. The PRUJ is assessed by palpating the radial head while taking the forearm through a range of motion. The DRUJ is assessed by applying a volar and dorsal directed force to the ulna while stabilizing the radius. If, while applying a minimal volar directed force, the ulna shifts volar and then rebounds dorsally, this is termed a positive piano key test. An ECU subluxation test can also be performed. If the ulnar head of the ECU subluxes during passive range of motion, this is deemed a positive test.

Shoulder range of motion should be evaluated as well, because a well-functioning glenohumeral joint can compensate for a portion of lost forearm rotation, especially pronation. Flexion and extension of the elbow should also be assessed, as there may be concomitant elbow pathology, such as in a Monteggia fracture. This is done with the shoulder at 30° of forward flexion. The presence or absence of elbow pain should also be noted.

Forearm range of motion needs to be carefully assessed and documented. The humerus is tucked in against the chest wall, and the elbow is held in 90° of flexion. The forearm is then taken through a passive and active range of motion. As with the elbow, presence or absence of pain should be noted. Wrist range of motion should also be assessed, including flexion, extension, and ulnar and radial deviation.

The malunion site should be evaluated as well by manual palpation. The presence of pain with palpation is an important sign to be noted.

6.6.1.2 Imaging and Other Diagnostic Studies

The initial method for evaluating forearm malunion is obtaining precisely orthogonal anterior to posterior and lateral radiographs of both the forearm of interest and the contralateral normal side. The radiograph should include the entire forearm on one plate. It is paramount that the radial styloid and biceps tuberosity be well visualized as these anatomic landmarks are used not only for clinical evaluation but also are of importance during radiographic evaluation in the operating room.

The forearm has unique features that are important to consider when approaching their treatment. These include, but are not limited to, the radial bow, the degree of ulnar variance, the spatial relationship of the biceps tuberosity and radial styloid, and the ulnar styloid and coronoid relationship. The biceps tuberosity should be 180° opposite the radial styloid in a standard anterior to posterior radiograph. The ulnar styloid and coronoid process should also be 180° opposite each other on the lateral radiograph.

A radiograph of the contralateral forearm, if normal, is also valuable as it can provide you with length of the patient's radius and ulna, as well as location of the radial bow. This can then be used for preoperative templating for location of corrective osteotomies, as well as to determine if surgical reduction is appropriate in the operating room.

Radiographic Evaluation Richards et al. [46] described a reliable way to obtain proper forearm radiographs. The patient sits with the shoulder abducted to 90°, and the elbow is flexed to 90°. The arm is then placed on the imaging table. The volar surface of the forearm is then placed against the X-ray cassette, and the beam is directed orthogonal to the forearm in a posterior to anterior direction. This positioning ensures that the forearm will be in a neutral position.

A series of tuberosity views of the normal side can also be obtained as described by Evans [47]. He initially described this technique to help with setting forearm rotation during closed reduction and cast application; however, these methods can still be used as a surgical aid. The tuberosity view can be helpful to determine rotation of the proximal fragment while in clinic and intraoperatively while establishing correct rotation of the proximal portion of the radius. The patient is set up for a standard anterior-posterior (AP) view of the elbow, with the humeral condyles being at the same level. The tip of the olecranon is placed forward one-third of the distance along the plate. The forearm occupies the remaining one-third of the plate. The X-ray tube is then angled 20° toward the patient. Successive images of the tuberosity are obtained as the normal forearm is rotated from full supination or 180° to full pronation 0° in 30-degree increments. The tuberosity profiles of the normal side can then be traced out and taken to the operating room. These will help in setting the rotation of the pathologic side. In addition, once the physician has a set of tracings of a normal tuberosity profile, he/she need not perform this radiographic evaluation for every patient. Rather he/she can save his/her tracing and then obtain a tuberosity view on any patient with a both-bone forearm fracture and simply compare the patient's tuberosity profile to his/her standard tracings to determine the rotation of the proximal fragment.

As discussed previously, the radial bow plays a prime role in forearm rotation. When the radius is fractured, the deforming forces, namely, supinator, pronator teres, pronator quadratus, and brachioradialis, shorten the fracture, pronate the distal fragment, and pull the fracture into valgus. If and when the fracture eventually unites, the axis of rotation that usually passes from the center of the radial head through the ulnar head is shifted, and anatomic forearm rotation no longer proceeds as normal. Thus, a vital part in the surgical treatment of forearm malunions is correction and restoration of the radial bow.

Schemitsch and Richards [4] followed 55 patients with varying severity of both-bone forearm fractures. All of the fractures were fixed with plating of both the radius and ulna. The plates used were either AO dynamic compression plates, semitubular plates, or one-third tubular plates. Seven fractures that had severe comminution received iliac crest bone grafting at the time of surgery.

In addition to the standard clinical evaluation, they described a method for evaluation of the maximum radial bow as well as the location of the maximum radial bow. These are found by drawing a line from the biceps tuberosity to the ulnar most aspect of the radius at the wrist. A perpendicular line is then drawn to this longitudinal line at the location of the maximum radial bow. The distance from the biceps tuberosity to the line marking the maximum radial bow is then recorded. This measurement is then divided by the overall length of the initial longitudinal line. This ratio gives the location of the maximum radial bow.

The mean maximum radial bow in the normal forearm of their patients was 15.3 +/− 0.3 millimeters. The restoration of this radial bow to within 1.5 +/− 0.2 millimeters had at least 80% forearm rotation as compared to the normal side. If the radial bow was restored to within 2.8 +/− 0.7 millimeters, these patients had less than 80% of forearm rotation as compared to the other side. The mean location of the maximum radial bow in the normal arm of their patients was 59.9 +/− 0.7 percent. Those patients who had at least 80 percent rotation as compared to the contralateral normal forearm had the location of the maximum radial bow that was 4.3 +/− 0.7 percent, whereas those patients who had less than 80% rotation as compared to the contralateral normal forearm had a location of maximum radial bow that was 8.9 +/− 1.8 percent. Grip strength also followed a similar pattern.

Determining the maximum radial bow and its location preoperatively using the contralateral normal forearm is a valuable tool, especially in comminuted fractures. Knowing these relationships and seeking to restore the fracture to as nearly anatomic as possible can help the surgeon be more confident that forearm rotation and grip strength will be restored to its maximal attainable level.

Rotational malunions and the degree to which they need to be de-rotated are evaluated by determining the relationship of the radial styloid and biceps tuberosity on the anterior to posterior radiograph and the ulnar styloid to the coronoid process on the lateral radiograph. As stated previously, these anatomic landmarks should be 180° apart in the anterior to posterior and lateral radiographs, respectively. The profile of the biceps tuberosity can further determine the degree of rotation of the proximal radial fragment and consequently the degree of correction needed [47].

Advanced Imaging Standard radiographs are often insufficient at providing a true assessment of the multi-planar characteristics of a forearm malunion, especially the often associated rotational component. For this reason, some authors have evaluated the forearm with advanced imaging in preoperative planning, such as computed tomography (CT) [48, 49], fluoroscopy with goniometer [28], magnetic resonance imaging (MRI) [28, 50], or CT with creation of a patient-specific osteotomy template [51, 52].

Fluoroscopy with goniometer is an extension of the technique described by Evans [47] using anatomic landmarks to determine forearm pronation and supination. Dumont et al. [28] determined that this method was adequate for determining the torsion profile of the ulna but was poor for the radius. Their results demonstrated a 0.90 interclass correlation coefficient for ulna, but less than 0.65 for the radius.

In the same study, Dumont et al. [28] assessed the effectiveness of MRI in determining torsion profiles of the radius and ulna. They discovered that, while the interclass correlation coefficient was higher for MRI than fluoroscopy with goniometer, 0.8 versus less than 0.65, it was only able to detect a rotational difference of 35° or more for the radius and 20° or more for the ulna. Thus, if a patient has a radial rotational malunion of less than 35° or an ulnar rotational malunion of less than 20°, MRI may not be able to adequately detect it.

Bindra et al. [49] employed conventional CT scans to assess radial rotational profiles in 39 pairs of dry cadaver forearms without bony forearm pathology and 4 cadaver forearm pairs with previous ipsilateral fracture of the distal radial metaphysis. They reported a high interclass correlation coefficient of 0.87–0.94 with a mean side-to-side variation in the uninjured forearm pairs of 4.9°, while the previously injured forearm pairs demonstrated a mean difference of 24.1°.

They concluded that conventional CT is an adequate method to determine the rotational profile in skeletally mature forearm malunions, wherein a contralateral normal forearm CT can be obtained and the malunion is not associated with a comminuted fracture at the distal radius. Furthermore, they recommend that the patient should be positioned prone on the scanner with both arms positioned overhead, the elbows extended, and forearms pronated.

6.7 Surgical Treatment of Forearm Malunions

6.7.1 Osteotomy Planning

A foundation of malunion surgery is the planning and execution of the corrective osteotomy. A transverse osteotomy can correct rotational or translational deformity, but does little to address an angular deformity, as this osteotomy cannot be used to restore length. An oblique osteotomy can help achieve moderate lengthening as well as correction of angular deformity. However, the oblique osteotomy has it limits. Forearm malunions are often a complex combination of angular, rotational, and length-deficient deformities, and thus more complex osteotomies are often required.

If a rotational component to the forearm malunion is not suspected based on clinical exam, standard radiographs may be sufficient to plan the surgical osteotomy. In this instance, obtain precise orthogonal anterior-posterior and lateral radiographs of the normal and pathologic forearms.

As stated previously, it is imperative that the proximal and distal radioulnar joints be included on the radiographs. Once again, the presence or absence of a suspected rotational malunion is assessed for using the radial styloid-bicipital tuberosity relationship on the AP radiograph and the coronoid process-ulnar styloid relationship on the lateral radiograph. If these relationships are not congruent with the contralateral normal side, then a rotational component must be suspected, and advanced imaging should be obtained.

Second, the outlines of the bones on the radiographs are then traced on standard tracing paper. This exercise facilitates identification of the area and magnitude of maximum deformity, with its resultant angle of deformity. The true angle of deformity can be determined with the use of pre-established tables defined by Nagy [53, 54]. In addition, the distance to the apex of maximum deformity from the proximal or distal end of the bone of interest should be notated as this will be valuable intraoperatively.

Anticipated osteotomies are then planned. The base of this angle, measured in millimeters, is the length that needs to be restored or removed by the opening or closing wedge osteotomy. An opening wedge is indicated if length needs to be restored. Comparing the ulnar variance of the malunited forearm to the normal forearm can also help assess the length discrepancy.

If a rotational component is suspected, a CT or MRI should be obtained. We prefer a CT scan, because it is less expensive and is easier for the patient to tolerate; in addition, it appears more able to accurately detect torsion [28, 49, 50]. However, it does expose the patient to radiation, which should be considered before ordering.

If resources are available, custom-made osteotomy templates can be manufactured using computer simulation techniques preoperatively [51, 52].

6.7.2 Surgical Approach: Authors' Preferred Treatment

6.7.2.1 Operating Room Setup

An adequate sized room should be obtained to allow for an arm table, C-arm, and back tables for bone graft. If an arm table is used, the C-arm is positioned to enter from the foot to obtain adequate views. The monitor is placed at the location most convenient and freely viewed by the surgeon.

The arm should be draped out at the shoulder and a sterile tourniquet is applied. The draping of the patient should also allow the forearm to be positioned across the chest. If needed, access to the opposite side of the table allows the arm to be positioned over the chest.

The surgeon should arrange for capable, interested assistants to be present and an anesthesiologist who is engaged in the procedure.

With regard to instruments that should be available, bone tools, rongeurs, osteotomes, burrs, curettes, screw removal and broken screw removal sets, saws, and/or burrs capable of cutting stainless steel and titanium should all be readily accessible in the OR suite.

There should also be a discussion with the patient about the type of anesthesia to be used. Will regional or general anesthesia be administered? If no autogenous iliac graft is needed, regional anesthesia is preferred.

In addition, the surgeon should discuss postop pain, bleeding, swelling, and compartment syndrome with the patient and the appropriate treatment and response to these postoperative conditions.

6.7.2.2 Surgical Approach and Exposure

For the ulna diaphysis, the approach should be just dorsal to the subcutaneous border. Choose the interval between the flexor carpi ulnaris and extensor carpi ulnaris. This is adequate for exposure of all the ulnar diaphysis. The skin incision should be over the muscle, not the bone [55].

For the radius, the distal two-thirds of the shaft can be approach through a Volar-Henry approach [55]:

1. The skin incision should follow a line drawn from the radial styloid distally to the biceps tendon proximally.
2. Sharply incise the skin and subcutaneous tissue to the forearm fascia.
3. Incise the fascia over the flexor carpi radialis tendon down to the tendon itself.
4. Use a moist lap sponge to dissect the subcutaneous tissue off the fascia, exposing the interval between the flexor carpi radialis and the radial artery.
5. The artery does not need to be dissected out completely unless the incision approaches the mid-forearm.
6. If the fracture requires exposure proximal to the mid-forearm, the radial artery needs to be dissected so that it can be mobilized and retracted either radially or ulnarly.
7. The deep interval between the flexor pollicis longus and the brachioradialis is developed proximally and distally.
8. The pronator quadratus is dissected and subperiosteally cleared off the distal radius, from its radial styloid attachment.
9. If proximal exposure is needed, the pronator teres is sharply incised and its tendinous insertion dissected off the bone.
10. Volar exposure can be extended proximal to the biceps tuberosity by ligating the radial recurrent vessels and subperiosteally dissecting the supinator off the radius, with protection of the posterior interosseous nerve.

11. The volar approach to the radius allows exposure of the entire diaphysis. One must be aware of and protect the radial artery, the superficial sensory branch of the radial nerve, and the posterior interosseous nerve proximally, as well as the brachial artery and median nerve.

The posterior Thompson approach [55] can be used for those nonunions that require exposure of the entire route of the posterior interosseous nerve:

1. The skin incision is made along a line with the forearm pronated starting at the lateral epicondyle of the elbow and ending over Lister's tubercle.
2. The skin is incised, and a moist lap sponge is used to dissect the subcutaneous tissue off the fascia.
3. The interval between the extensor digitorum communis and the extensor carpi radialis brevis is more easily found distally.
4. In large individuals, you can use the bovie to stimulate the muscle bellies proximally and easily separate the extensor digitorum communis from the extensor carpi radialis brevis.
5. The dissection through the muscle bellies is more easily done from distal to proximal.
6. The glistening fascia over the supinator is easily identified, and the distal border of the muscle is the anatomic point where the posterior interosseous nerve arborizes.
7. Prior to branching, the posterior interosseous nerve lies between the two muscle layers of the supinator accompanied by its artery and vein. It can be easily found and freed up to the radial head.
8. The supinator then can be easily elevated off the proximal radius.

Pitfalls occur when the proper interval is not recognized, and denervation of the extensor digitorum communis can occur. Vigorous retraction of the posterior interosseous nerve can result in a posterior interosseous nerve palsy.

6.7.2.3 Essentials of Exposure

1. Adequate draping to allow full exposure of the limb.
2. Appropriate functioning tourniquet and equipment.
3. Functioning C-arm and easily available screens.
4. Comfortable seating and height for the surgeon and assistant along with loupe magnification.
5. Draw incisions with a marker.
6. If two incisions are needed, allow at least a 6–8 cm interval between the incisions.
7. The secret to soft tissue dissection is adequate tension on the tissues in the correct vector.
8. Dissect from normal to abnormal tissue. Never seek to identify structures in scar tissue.
9. Dissect with the tips of your scissors.
10. Scissors work best in normal tissue, and a scalpel is needed in scar tissue.
11. Hemostasis can be obtained with clips, sutures, or the bovie. To avoid any intimal damage to the artery, bovie at least 1 cm away from the artery.
12. Most exposures in normal tissue can be done by dividing fascia and mesentery avoiding proximity to major nerves and vessels.
13. Place retractors appropriately; remember "the bone and periosteum are your friends."
14. Keep tissues moist.
15. If, after adequate exposure, there is concern about bleeding, let your tourniquet down to control it. It is often easier to ligate vessels that may be difficult to reach if the fracture is not stabilized with a plate. After hemostasis is obtained, you can reinflate the tourniquet and place the fixation.

6.7.2.4 Bone Preparation

The surgeon should avoid extensive subperiosteal stripping. The periosteal elevator should be used against the acute angle of the muscle attachments. Once the fracture site is exposed and the plate(s) removed, if any, use bone hooks to bring the bone to you. Meticulous attention should be placed upon preserving the soft tissues and blood supply.

If the malunion involves both the radius and ulna, we prefer to realign the ulna first and then approach the radius second. However, if the radius is significantly more malaligned than the ulna, we will osteotomize and correct it before the ulna. Using intraoperative fluoroscopy, the site of maximal deformity is identified, and a ruler can then be used to compare to the preoperative radiographs.

The status of the IOM is then inspected to assess if it has scarred significantly. If the malunion united with the fragments pointing toward each other, it is highly probable that the IOM will impede reduction, and it can be pre-emptively partially released.

Technique for Bone Preparation

1. If hardware is present, it should be removed.
2. Curette the screw holes.
3. Two Kirschner wires are then inserted proximal and distal to the planned osteotomy site to assess for rotational control once the osteotomy is made.
4. Using a rongeur, debride the bone ends back to bleeding bone at fracture site.
5. Reconstitute the medullary canal in both fragments to allow ingress of pluripotential cells.
6. Use an osteotome to "rose petal" the cortical bone for 1 inch on both sides of the malunion site [46].
7. Select a plate that has at least six cortices in non-violated bone on both sides of the malunion site. Do not use previous drill holes.
8. Contour the plate, planning for reestablishment of the radial bow, if indicated.
9. The planned osteotomy site is then marked.
10. Either the closing or opening wedge osteotomy is then carried out. If a closing wedge osteotomy is performed, a periosteal hinge is left in place. If an opening wedge osteotomy is performed, a compressive resistant corticocancellous bone graft is fashioned and then inserted into the osteotomy site.
11. The osteotomy site is closed, and then the pre-contoured plate is applied with at least three screws proximal and distal to the osteotomy.
12. Fluoroscopy is used to confirm that the angular and rotational deformities have been corrected.
13. With the elbow flexed to 90°, the forearm is taken through a range of motion to assess pronation and supination.
14. If the patient does not have at least 50° of supination and pronation, rotation and angulation of the malunion should be assessed with fluoroscopy again and corrections performed. Also the IOM can be released more if needed.
15. Perform a routine closure without drains, and apply a bulky sterile dressing with a sugar-tong splint.
16. Depending upon the stability of the fixation, active range of motion can be initiated at 10 days with a removable orthosis.

6.7.3 Technical Points

1. Preserve soft tissues as much as possible.
2. Begin dissection in normal tissue.
3. Keep tissues moist.
4. Achieve meticulous hemostasis.
5. The tourniquet should be released at 60 min and possibly reinflated if needed.
6. Antibiotics should be administered pre-op and post-op for 24 h.
7. Leave sutures in place for 2 weeks.
8. Obtain radiographs at 2 months unless otherwise indicated.
9. The expected healing time is 6–12 months.

6.8 Case Discussion

A 46-year-old left-hand dominant male sustained a crushing injury to his left forearm. He was evaluated at another institution and found to have a Galeazzi fracture. The patient elected to be treated non-operatively at that time, despite being told he needed surgery. He presented to our emergency department after he had an increase in his pain after moving some mattresses the day prior. He was only able to supinate his hand to neutral but had full pronation (Figs. 6.1 and 6.2). Radiographs demonstrated a malunited Galeazzi fracture (Figs. 6.3 and 6.4). Surgical versus non-operative treatment options, including risks, ben-

Fig. 6.1 Clinical photo showing neutral supination. (Courtesy of Animesh Agarwal)

Fig. 6.2 Clinical photo showing full pronation. (Courtesy of Animesh Agarwal)

Fig. 6.3 Anterior-posterior radiograph showing malunion of radial shaft. (Courtesy of Animesh Agarwal)

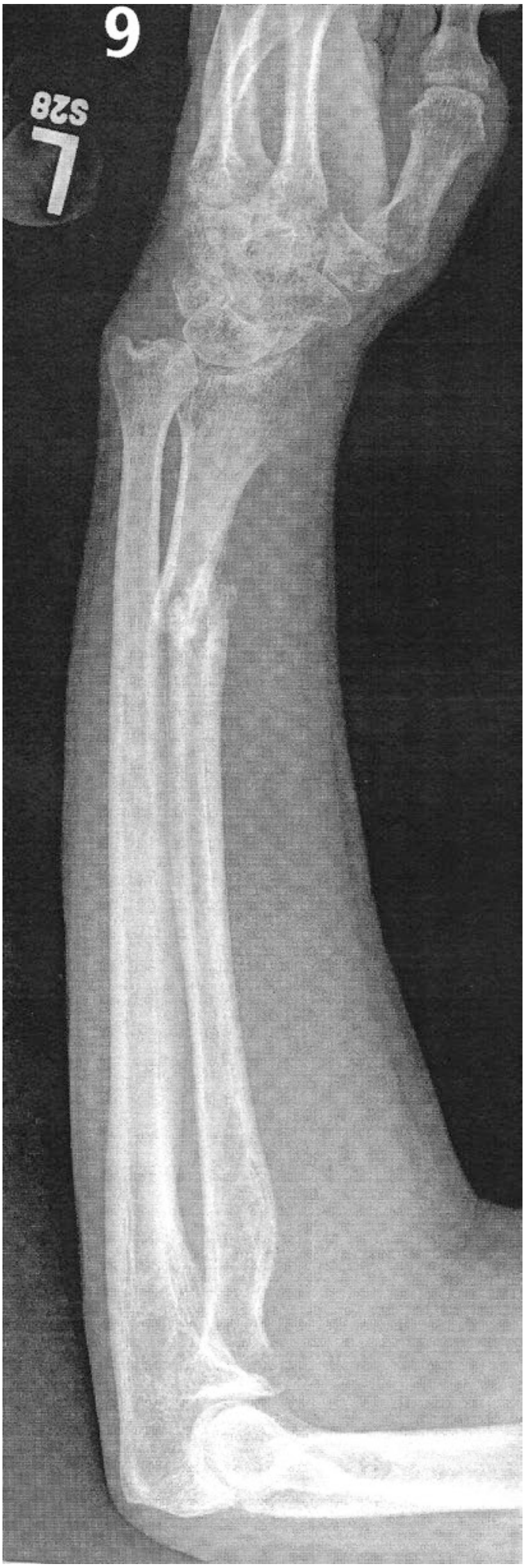

Fig. 6.4 Lateral radiograph showing malunion of radial shaft. (Courtesy of Animesh Agarwal)

efits, and alternatives, were discussed with the patient, and the patient elected to pursue surgical treatment.

The malunion was approached using a standard volar Henry approach with malunion correction and application of a 3.5 mm locking compression plate (Figs. 6.5 and 6.6).

Fig. 6.5 Anterior-posterior radiograph showing correction of radial shaft and stabilization with meta-diaphyseal plate and correction of radial bow. (Courtesy of Animesh Agarwal)

Fig. 6.6 Lateral radiograph showing correction of radial shaft and stabilization with meta-diaphyseal plate and correction flexion deformity. (Courtesy of Animesh Agarwal)

Fig. 6.7 Clinical photo showing full pronation at 2 weeks postoperative. (Courtesy of Animesh Agarwal)

Fig. 6.8 Clinical photo showing near full supination at 2 weeks postoperative. (Courtesy of Animesh Agarwal)

Intraoperatively, the patient had full restoration of pronation and supination. He was then placed in a well-padded volar splint. The patient returned to the clinic at 2 weeks for a wound check and staple removal. He had near-complete restoration of range of motion (Figs. 6.7 and 6.8) at this first postoperative visit.

6.9 Conclusion

Malunions of the forearm present a difficult challenge to the treating physician. The patients are often limited in their day-to-day activities, they may experience persistent pain and discomfort, and they may have a cosmetic deformity, which is also of concern to the patient.

There are many factors to consider when treating a forearm malunion, some of which include angular and rotational relationships of the bones, the length of time since the initial injury, the presumed status of the deep soft tissues, as well as the patient's desires and wishes.

For these reasons, we encourage a systematic approach to this problem through patient evaluation, careful preoperative planning, and meticulous operative execution.

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7 Malunions of the Hand and Wrist

Matthew Lyons, Ahmad Fashandi, and Aaron M. Freilich

7.1 Distal Radius

7.1.1 Background

Distal radius fractures are common injuries of the upper extremity, accounting for between 8 and 17% of all upper extremity fractures and representing the most common injury seen in the Emergency Department setting [1, 2]. Given the frequency of these injuries, numerous techniques have evolved for their management. Depending on the severity of the fracture, treatment ranges from closed reduction and casting to surgical interventions, including percutaneous pinning, external fixation, internal fixation with plate and screw constructs, and various combinations of these methods. Despite the substantial attention given to treatment of these injuries, malunion remains the most common complication of distal radius fractures, occurring in up to 17% of cases [2]. Numerous studies have detailed the biomechanical effects of a malunited fracture and the resulting negative impact on patient function [3–10]. Distal radius fractures occur in a bimodal distribution in society and malunion has a significant impact on both. In young, active patients, there is a potential for lost wages and increased medical costs if a patient is unable to return or has a delayed return to work. These injuries are typically classified as fragility fractures in the elderly population and portend a negative impact on quality of life, work potential and recreational activities. Given that the percentage of persons age 65 or older in the United States is predicted to nearly double in the next 25 years, the magnitude of this problem is likely to increase [11–13].

Techniques for treatment of distal radius malunions have existed in the literature since the 1930s, consisting initially of biplanar osteotomies with use of the distal ulna for bone grafting [14, 15]. With improving surgical techniques and greater understanding of the anatomy and biomechanical principles of the distal radius, a stepwise approach to malunited fractures is now possible.

7.1.2 Anatomy

The distal radius forms an articular platform on which the carpus rests. The stability provided by the radiocarpal articulation and its surrounding ligaments allows the complex functions performed by the carpus and hand. The distal radius has three concave surfaces, which form the foundations of this articulation, the scaphoid fossa, lunate fossa, and sigmoid notch. The scaphoid and lunate fossas are divided by a sagittal plane ridge. The radiocarpal articulation is further stabilized by the strong radial ligamentous structures, including the radioscaphocapitate (RSC), radiolunotriquetral (RLT), radioscapholunate

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(RSL), and dorsal radiotriquetral (RT) ligaments. The sigmoid notch acts an articulation for the distal ulna, allowing forearm motion through rotation of the radius around the ulna. It has well-defined dorsal, volar, and distal walls, with further stability provided by the components of the TFCC, including deep and superficial volar and dorsal radioulnar ligaments [13].

The radiographic anatomy of the distal radius and distal radial ulnar joint (DRUJ) articulation can best be described in four key parameters: radial height, radial inclination, radial tilt, and ulnar variance. These measurements, along the articular congruity and DRUJ stability, play a central role in management of distal radius malunions. Radial height is measured on the PA radiograph by drawing two lines tangential to the radial styloid and ulnar head articular surface and perpendicular to their shaft axes. The distance between the lines is measured. The average normal value is 11 mm with an acceptable limit of 4 mm. Radial inclination, also measured on a PA radiograph, is the angle formed by one line perpendicular to the longitudinal axis of the radial shaft and a second line along the distal radius articular surface. The normal value for this angle is 22° with an acceptable change of 15° in either direction. Measured on the lateral radiograph, radial tilt is the angle between the distal radius articular surface and a line perpendicular to the longitudinal axis of the radial shaft. It has a normal value of 11° of volar tilt with an acceptable limit of 15° of dorsal or 20° of volar tilt. Finally, the ulnar variance is calculated on the PA radiograph by the axial difference in length from lines drawn parallel to the ulnar head articular surface and ulnar most edge of articular distal radius. It averages neutral to 1 mm of ulnar negative variance with an acceptable limit of +/−4 mm [13, 16].

7.1.3 Biomechanics

Changes in the above anatomic parameters result in significant alterations to biomechanics of the radiocarpal and distal radioulnar articulations and can exert a profound effect on patient function. Malunion most commonly results in a combination of wrist pain, decreased range of motion, and radiocarpal or midcarpal instability.

In particular, increased dorsal tilt will result in a change in axial load orientation to a more dorsal position on the radiocarpal joint and with increased load across the distal ulna [4]. In neutral radial angulation, the distal radius bears 82% of the compressive load across the wrist. With 45° of dorsal angulation, the load shifts to 65% across the distal ulna. Additionally, grip strength decreases when dorsal angulation is greater than 20°. With dorsal angulation, there is commonly a loss of wrist flexion and supination. In contrast, patients with increased volar angulation will experience a loss of wrist extension and pronation [17].

Carpal instability is another effect of increased dorsal tilt and will typically follow one of two patterns. In the first, patients will develop isolated radiocarpal instability with dorsal subluxation of the carpus relative to the distal radius. The second pattern is believed to occur more commonly in patients with underlying ligamentous laxity and involves an adaptive dorsal intercalated segment instability (DISI) midcarpal instability pattern. The resulting DISI pattern can be described as either reducible or fixed, depending on its ability to be corrected by a radial osteotomy. On lateral radiographs, the lunate assumes an extended position with the capitate lying in relative flexion. Both are no longer in line with the longitudinal axis of the radius. Reducible instability patterns are characterized radiographically by the presence of a mobile lunate on flexion and extension lateral radiographs. While both instability patterns can exhibit significant detrimental effects on patient function, it is believed the DISI pattern is more likely to be symptomatic [7, 18, 19].

Additional parameters that negatively affect wrist biomechanics include radial height, inclination, and ulnar variance. Dorsal angulation and loss of radial height in combination result in tensioning of the interosseus membrane and a resulting loss of forearm pronation-supination [17]. Even in isolation, radial shortening leads to an increase in radiolunate contact with axial load and decreased wrist and forearm range of motion. This can be compounded by a loss of radial inclination, which further shifts axial load bearing from the scaphoid fossa to the lunate fossa of the distal radius [4]. Additionally, the relative increase in ulnar positive variance from radial shortening can result in ulnocarpal impaction syndrome, manifested by ulnar-sided wrist pain and chondromalacia of the ulnar carpal bones.

Given that each parameter exerts its own effect on wrist biomechanics, it is difficult to determine which parameter is of the greatest clinical importance. Either in isolation or in combination, excessive loss of radial height, radial inclination, and radial tilt can result in alteration of the stability, motion, and load-bearing relationships of the radiocarpal, ulnocarpal, midcarpal, and distal radioulnar articulations. Over time, these changes can both cause and accelerate degenerative disease of each of the individual articulations or the wrist as a whole [4, 7, 18, 19].

7.1.4 Clinical Evaluation

Patients will most commonly present with a combination of wrist and grip strength weakness, pain, decreased wrist motion and forearm rotation, instability, numbness, and cosmetic concerns. Pain can involve radiocarpal, radioulnar, or ulnocarpal joints, but ulnar-sided wrist pain is most common [20].

As with any initial assessment, it should begin with a detailed history of the patient's injury mechanism and attempted treatment. Any previous surgical treatment may play a role in perioperative planning, although it should be noted that the majority of malunions result from failed nonoperative management [3, 9, 10, 21]. The location, quality, severity, and frequency of the pain should be obtained, as the goal of the history and physical examination is to localize the pain to the radiocarpal, midcarpal, ulnocarpal, and distal radioulnar articulations whenever possible. Any factors that alleviate or aggravate symptoms, along with a history of instability, should be noted. All previous radiographs should be obtained and reviewed, including, whenever possible, initial injury films. A complete medical history should be elicited, with particular attention given to the patient's occupational demands, recreational activities, and goals for treatment. Comorbidities that may preclude surgical intervention should be appropriately managed and any history of tobacco use should be discouraged.

The physical examination should focus on the strength, range of motion, and stability of the upper extremity from the shoulder to the digits utilizing the unaffected side as a comparison when possible. Grip strength and wrist range of motion, including flexion, extension, pronation, and supination, should be tested. A complete motor and sensory exam should be performed. When combined with provocative tests for carpal tunnel syndrome, they can expose an underlying median nerve compression or injury. Skin inspection should be performed for any previous surgical incisions, which may have an effect on the choice for later surgical approach. Also, given the association of distal radius fractures with complex regional pain syndrome, special attention should be given to disproportionate pain, finger stiffness, swelling, allodynia, or paresthesias. When the patient describes a history of instability, the stress tests should seek to localize it to the radiocarpal, midcarpal, or distal radioulnar joints. In the adaptive DISI instability pattern that occurs with increased dorsal tilt, laxity of volar wrist ligaments allows patients to experience provocative instability with wrist ulnar deviation and forearm pronation [22]. Increased anterior to posterior translation of the ulna on the radius compared to the contralateral side can be indicative of DRUJ instability. Finally, an Allen's test should be performed to assess the specific vascular supply crossing the zone of injury [2].

Radiographic examination constitutes the second core component of the clinical examination. A current series of wrist radiographs should be obtained, including PA, lateral, and oblique views. High-quality, appropriately aligned radiographs allow measurement of the key parameters outlined earlier: radial, height, radial inclination, radial tilt, ulnar variance, articular congruity, and distal radial ulnar joint stability [13, 16]. Small changes in forearm position can have an effect on measurement, so all radiographs should be taken with the forearm in a neutral position [23]. Pronated PA views may be useful when searching for a dynamic component of ulnar positive variance in a patient with symptoms of ulnocarpal impaction. Also, comparison views of the contralateral can aid with preoperative planning. While the radiographic parameters serve as a useful benchmark in treatment, they should not be used as absolute indications. In a biomechanical study by Park et al., dorsal tilt frequently exceeded what was measured on radiographs [7]. Each patient's symptoms and function should be taken in account when determining a treatment course.

The role of advanced imaging is also difficult to define and can be considered on a case-by-case basis. Rotational deformity and articular congruity are often difficult to assess on plain radiographs and computed tomography (CT) can be a useful adjunct. Three-dimensional reconstruction images allow consideration of axial plane deformities in addition to the coronal and sagittal planes provided by standard radiographs. They also provide the ability to evaluate subtle deformities within the DRUJ or carpus. Some authors advocate obtaining a CT scan of the contralateral limb for if a comparison is needed [5, 21, 23, 24].

As mentioned previously, the radiographic presence of a malunited distal radius fracture is not an automatic indication for surgery, as each patient should be considered on an individual basis. Patients who are experiencing pain, weakness, loss of motion, and instability or mechanical symptoms that limit their work or recreational activities should be considered strong candidates for surgery if they have failed an adequate trial of rest and dedicated hand therapy. While there are no strict contraindications to surgery, certain factors are against a successful outcome. These include advanced age with low physical demands, complex regional pain syndrome, a medical diagnosis or mental illness that would interfere with postoperative rehabilitation or patient compliance and advanced degenerative arthritis within the radiocarpal or midcarpal joints [2, 13]. In this setting, a salvage procedure should be considered. Motion-preserving procedures may be utilized in young, high-demand patients, such as proximal row carpectomy and radioscaphoid or radioscapholunate fusion. In older, lower demand patients with adequate bone stock, total wrist arthroplasty is a consideration [25]. Wrist arthrodesis is used as a final salvage procedure, but in the setting of extensive radiocarpal and midcarpal degenerative changes, it may be the only option [13]. In contrast, degenerative findings within the DRUJ are not a contraindication to surgery but require a procedure to address the problem and will be covered later in this chapter [2].

7.1.5 Treatment

Preoperative planning is a key component of treatment and should be conducted prior to proceeding with surgery. Key considerations to be made by the surgeon include timing of procedure, surgical approach, type of osteotomy to be performed, need for and source of bone graft, mode of fixation, and management of the DRUJ.

Many authors have advocated and we agree with preoperative templating of the planned osteotomy. Printed radiographs and tracing paper can be used. More advanced computer-assisted techniques that created a three-dimensional preoperative template for deformity correction utilizing CT images have also been developed. The use of templating software has been expanded to the intraoperative setting. Using three-dimensional models, cutting guides are created, which are then sterilized and used to perform the surgical osteotomy. While clinical trials have shown positive outcomes, these consist of only small case series and single-case reports. Excellent outcomes have been consistently demonstrated with conventional techniques and there is increased cost associated with computer-assisted systems. Jupiter et al. have proposed a multicenter randomized control trial comparing conventional planning to computer-assisted planning for surgical correction of distal radius malunions. This has yet to be published but may be useful in determining if improved outcomes are associated with use of computer-assisted intraoperative techniques and in what settings they may be of greatest benefit (https://clinicaltrials.gov/ct2/show/NCT01193010) [21, 26–29].

Timing of surgical intervention represents the next key component of surgical planning. Ring and Jupiter have characterized malunion as nascent or mature. Nascent malunions occur between 4 and 12 weeks from injury, in which fracture lines are still identified on radiographs. In contrast, mature malunions are characterized by complete fracture consolidation. Consideration for treatment of mature injuries is considerably easier, as they will require a surgical osteotomy for deformity correction. Nascent malunions propose the questions of whether to perform early intervention or allow fracture healing prior to surgical treatment. In strictly adhering to the acceptable radiographic parameters as the only guide to when to perform surgery, it is possible that a significant number of unnecessary procedures could be performed on asymptomatic patients. In comparing a group of nascent patients treated on average 8 weeks post injury and mature patients treated at 40 weeks, Ring and Jupiter found no difference in clinical outcomes. However, they noted that treatment of nascent injuries lessened the period of disability and proved technically easier, given the identifiable fracture lines and lack of soft tissue and capsular contracture [12, 30]. It is most reasonable to consider each patient individually, taking into account symptoms, functional demands, limitations in motion, and severity of radiographic deformity in deciding which course of action to pursue. Bushnell and Bynum also proposed the concept of "intentional delay" in the treatment of nascent malunions [2]. This idea involves purposely allowing a late presenting, highly comminuted fracture to heal in a malunited position with the intention of performing a technically easier osteotomy once the fracture fragments have consolidated.

The next consideration in the treatment of malunions is surgical approach. The choice of surgical approach is dependent on a combination of the location of the deformity and surgeon preference. Most commonly, the location of the planned osteotomy determines the approach. Historically, volarly angulated malunions were treated with a volar approach, and dorsal nonunions were treated with a dorsal one. However, with multiple osteotomy options, this is not always the case. The standard volar approach is centered over the FCR tendon and is a distal continuation of the Henry approach to the forearm. The dorsal approach is performed between the second and fourth extensor compartments with the EPL mobilized radially and left transposed with final closure of the extensor retinaculum. While multiple studies have shown similar union and complication rates between the two approaches, there are some advantages and disadvantages to each [13, 31]. In patients with preoperative median nerve compression symptoms or who require extensive deformity correction that may place the median nerve at risk, a volar approach is recommended. The FCR approach can be extended into the palm, or the hybrid volar approach proposed by Chhabra et al. can be utilized to release the carpal tunnel [32]. Additionally, the dorsal approach is useful for intra-articular deformity correction, as a dorsal capsulotomy allows excellent visualization without violating the stouter volar wrist ligaments.

Meticulous and careful handling of soft tissues is of paramount importance with any surgical approach and can result in decreased postoperative complications related to tendon adhesions and wound healing. Long-standing malunions are also often associated with soft tissue contracture, which must be addressed to facilitate complete deformity correction and hardware placement [2]. This may require release or lengthening of the pronator quadratus and flexor tendons from the volar side, first dorsal compartment, and other extensor tendons from the dorsal side and brachioradialis from either approach [2, 13].

The choice of surgical osteotomy is the next step in the treatment algorithm and varies depending on the nature of the deformity. In treatment of extra-articular malunions, the categories of available osteotomies can roughly be divided between opening and closing wedge techniques.

Opening wedge osteotomies are the most commonly used technique for treatment of distal radius malunions and have an excellent success rate [6, 9, 10, 33–38]. The osteotomy is designed to generate radial length and correct ulnar variance. Given that the distal fragment is free from the proximal one, a correctly designed osteotomy can correct deformity if in the coronal, sagittal, and axial planes. The alignment can be further manipulated alignment by the position of the plate used for fixation and graft size and position [25]. A single cortical cut, in which the distal cortex is intentionally left intact can be used for angular correction alone, whereas a bicortical cut allows both angular correction and lengthening. Graham proposed a useful technique utilizing K-wires in opening wedge osteotomies to correct both radial inclination and sagittal tilt. An initial K-wire is placed proximal to the planned osteotomy site perpendicular to the radial shaft. For correct radial inclination, a second wire is placed distal to the osteotomy and perpendicular to the radial shaft. The angle of separation between the wires after deformity correction corresponds with the change in radial inclination. To correct sagittal tilt, the second wire is placed distal to the osteotomy and parallel to the joint surface of the radius. During correction, parallel alignment of the wires corresponds to neutral tilt and anything beyond will result in increased volar tilt [13]. Given the separate fracture fragments, the potential for instability represents the major disadvantage of an open compared to a closing wedge technique. This raises the theoretical risk of delayed healing or nonunion related to hardware failure but has not been reported as a common complication in the literature [2, 6, 9, 33–38].

Closing wedge techniques have some inherent advantages, namely, increased stability and the lack of need for bone graft due to direct apposition of the cut bone ends. This is especially effective in the setting of single-plane deformities. Wada et al. have published a technique utilizing a volar closing wedge osteotomy to correct dorsal tilt, while Fernandez et al. have successfully employed a lateral closing wedge to resolve increased radial inclination [23, 39]. Similar to opening wedge osteotomies, closing wedge techniques also allow correction of multiplanar deformities. Posner and Ambrose have described a biplanar osteotomy for correction of radial inclination and sagittal tilt. They were able to successfully restore alignment in all patients treated with this technique, including resolution of adaptive midcarpal instability when it was present [18]. The major disadvantage is shortening of the radius relative to the ulna and the risk of ulnocarpal impingement, which may necessitate an ulnar-sided procedure [2]. In fact, descriptions of the techniques of Wada and Posner and Ambrose include either ulnar shortening osteotomy or ulnar head resection for correction of ulnar positive variance.

There are a number of variations on the common closing and opening wedge techniques. The trapezoidal osteotomy technique developed by Watson and Castle involves harvesting a wedge that is long in the longitudinal plane and shorter in the transverse plane from the dorsal, metaphyseal distal radius. The wedge is then rotated 90° into the distal edge of the defect to correct dorsal tilt [19]. The sliding osteotomy created by Thivaios and McKee requires an oblique saw cut in the distal radius from proximal volar to distal dorsal. The distal fragment can then be slid dorsally and/or tilted dorsally on the proximal, effectively correcting volar tilt and radial height [40]. Finally, Arslan et al. described a distraction osteotomy using an Ilizarov-type technique for restoration of radial height. The care of the Ilizarov frame would require significant patient education and compliance [41].

Distal radius fracture malunions with significant intra-articular incongruity represent a more technically challenging surgical procedure in comparison to extra-articular deformity correction. Most authors recommend addressing deformity when the articular displacement is greater than or equal to 2 mm on the PA radiograph [13, 16]. While radiographs are excellent at allowing visualization of incongruity of 2 mm or greater, a CT scan with three-dimensional reconstruction images may be useful in accurate preoperative planning [16]. Ring et al. have published a technique for treating intra-articular malalignment based on the location of the deformity. Whenever possible, they recommend utilizing a dorsal approach to avoid violation of the volar wrist ligaments and capsule. Through a standard dorsal approach and capsulotomy, a longitudinal osteotomy cut is made at the location of the articular step-off with a transverse cut performed more proximally. The articular surface is realigned utilizing fluoroscopic imaging and fragment-specific fixation is used to stabilize the osteotomy. A volar approach is typically reserved for isolated volar step-off on the axial CT and cases of volar carpal subluxation, such as seen with a volar ulnar corner fragment. The volar capsuloligamentous complex is left intact and fluoroscopy and fragment specific fixation are again used to reduce and stabilize the fragment. Similar results have been reported for treatment of intra-articular and extra-articular osteotomies [16, 30]. However, intra-articular deformities are easier to correct and may yield improved results when performed in the nascent period [30]. Graham has described treatment of isolated malunions of the anterior or posterior rim of the radius with bone resection and of the lunate facet with radial styloidectomy.

The next step in the treatment algorithm for distal radius malunions requires filling the void created by opening wedge osteotomy techniques. There are numerous options for both bone grafts and bone graft substitutes, including structural cortical graft, cancellous bone, hydroxyapatite, calcium phosphate cement, and porous tantalum implants. The correct choice of graft is still open for debate. Historically, studies have supported use of structural cortical graft, which can be harvested from the iliac crest, olecranon, or distal ulna if resection is required for realignment and local graft from the radius is insufficient [5, 9, 18, 25, 34, 36, 37, 42]. Structural graft provides increased stability to the fracture construct, allowing increased load bearing potential. In fact, early technique descriptions, prior to the common use of internal fixation, recommended using the graft alone [14, 15]. Iliac crest cortical graft is probably the most common used structural graft. A tricortical or outer table alone graft is harvested in a trapezoidal shape from the superior iliac crest. It is then contoured to match the size and angle needed to fill the defect and correct malalignment. The graft is rotated so the superior iliac crest becomes the radial cortex of the distal radius. Laminar spreaders are useful to over distract the void and allow graft placement. They are then removed, resulting in compression and stabilization of the graft [13].

More recent studies have compared cortical graft to alternative graft sources and found similar results. Ring et al. examined functional and radiographic healing in patients treated with either structural cortical graft or cancellous autograft, reporting similar outcomes [34]. Using hydroxyapatite as a bone graft substitute in extra-articular opening wedge osteotomies, Luchetti reported a 100% healing rate with clinically significant improvements in range of motion and patient outcome scores [33]. In a case report, Yasuda et al. used calcium phosphate bone cement as a substitute for graft, reporting complete fracture healing and clinical improvement [43]. Finally, a canine model proposed by Adams et al. described the use of osteoconductive tantalum-coated wedges to act as structural grafts. While successful in demonstrating bony ingrowth as early as 4 weeks from surgery, these implants likely require further clinical trials before their use can be recommended [44].

Stabilization of the osteotomy is the next step in treatment and a variety of techniques have been described. Internal fixation with a plate remains the most commonly used method, with implant options including volar locking plates, dual dorsal plates, T plates, and fragment-specific fixation. As mentioned previously, malunions were historically stabilized at the site of the osteotomy, with volar T plates used for volar osteotomies and dorsal T plates used for dorsal ones. The advent of locking fixed angle devices has challenged that concept. Gesenway et al. initially demonstrated increased strength and rigidity of a dorsally placed locking plate compared to a standard T plate [45]. This is clinically relevant given the higher incidence of dorsally angulated malunions and the need to provide correction through a dorsal opening wedge osteotomy. Unfortunately, dorsal plating is associated with a number of potential soft tissue complications. The most concerning complication is tendon irritation and risk of rupture, which can necessitate a secondary operation for plate removal [19, 25, 37, 45–47].

The development of volar locking plates negated many of the risks and challenges associated with dorsal plating. Their enhanced biomechanical stability allows volar fixation of both volar and dorsal osteotomies. The modular and fixed angle locking design of the distal screws allows for rigid stability to sustain alignment after deformity correction. According to studies by Orbey, the risk of tendon irritation and eventual rupture is reduced by a combination of low-profile design of the screw heads, increased between the plate, and the ability to cover the plate with the pronator quadratus [31, 46]. However it should also be noted that a risk of flexor tendon rupture still exists with volar plates and increases significantly with distal placement of the plate beyond the watershed area of the volar distal radius. In a model that is easily applicable to deformity correction, multiple studies have demonstrated excellent healing and low complication rates in both volar and dorsal angulated distal radius fractures. The stability of the construct also permits early postoperative range of motion [31, 46–49]. Despite the stability afforded by volar locking plates, osteotomies, which create a large, dorsal defect, may require a dual dorsal approach for adequate placement of the graft [2]. As mentioned previously, graft placement by laminar spreader distraction of the osteotomy site can help facilitate graft compression and stability and negate the need for dorsal plate stabilization of the graft [13]. Cancellous autograft can often be placed through the defect or around the plate from the volar side.

The standard sequence of steps for surgical correction of distal radius malunions is as described in this chapter with approach and soft tissue release followed by osteotomy, graft placement, and plate fixation. Bushnell and Bynum have advocated for distal fixation of a volar plate prior to osteotomy. They argue that this allows more accurate placement of the distal screws and facilitates the "lift maneuver" described by Smith and Henry, in which the initial distal fixation of the fracture fragments allows correction of dorsal tilt through reduction of the proximal end of the plate to the diaphyseal distal radius [2, 48].

Other options for osteotomy stabilization include external fixation and wire or screw fixation without plates. External fixation has been well studied with variable levels of success [36, 41, 42, 50]. McQueen reported high healing rates in the use of external fixation for the treatment of distal radius fractures [50]. In a study by Pennig et al., all 14 osteotomies treated with an external fixator successfully healed with acceptable alignment [36]. However, in the previously referenced study using Ilizarov style fixation for distraction osteotomies, Arlsan et al. reported a 67% rate of unacceptable loss of alignment [41]. Another potential use for external fixation is as an adjunct for achieving or maintaining alignment prior with graft placement and plate fixation [9, 34, 51]. Case reports and small case series detailing the use of Kirschner wires or screws for fixation also exist within the literature. Given the decreased stability afforded to these constructs and the low complication rates associated with volar plating, their use is largely limited to secondary stabilization to plate and screw constructs [18, 19, 25, 42]. Whenever possible, it is useful to place the distal external fixator pin either through the distal radius plate or in a position where it can be filled with a screw upon plate placement.

Assessment and treatment of deformity of the ulnar side of the wrist marks the final step in treatment of distal radius fracture malunions. Correction of ulnar-sided deformity should be performed as a final step, as corrective osteotomy of the radius may be the cause of the deformity. An excellently performed realignment of the distal radius can lead to clinically poor results if the proper attention is not given to ulnar-sided deformity. This can be manifested as DRUJ incongruity, instability or contracture, ulnocarpal impaction, and ulnar styloid nonunion and resulting risk for stylocarpal impaction [2, 20].

Incongruency of the DRUJ can be caused by intra and extra-articular malalignment in isolation or in combination [20]. Extra-articular malalignment refers to mismatch in orientation of the distal radius and ulna that lead to incongruency of the sigmoid notch and can be corrected with the distal radius osteotomy. Fracture displacement that extends into the sigmoid notch or ulnar head is the standard cause of intra-articular incongruence and is more difficult to treat. When posttraumatic arthritis is present on preoperative radiographs, treatment is guided by patient age, occupational and functional demands, and degree of degenerative changes. In young, active patients with early DRUJ degenerative changes, an ulnar shortening osteotomy has proven effective in treatment of symptoms [52].

In the setting of advanced arthritic findings, procedures are designed to eliminate the articulation between the distal radius and ulna. These include the Sauve-Kapandji, Darrach, and Bowers hemiresection arthroplasty and ulnar head arthroplasty procedures [2]. Sauve-Kapandji procedure relieves pain by creating a pseudarthrosis through the ulnar neck and performing arthrodesis of the distal radioulnar joint. Due to the potential complication of proximal stump instability, most authors recommend stabilization of the stump with slips of the ECU or FCU tendons alone or in combination [53, 54]. It has been suggested as a treatment of choice in young persons with advanced degenerative changes, to provide stability and preserve forearm rotation. The Darrach and Bower's hemiresection arthroplasty procedures both seek to resect the distal ulna while preserving ligamentous attachments to the distal radius. In the Darrach procedure, the distal ulna which articulates with the sigmoid notch is resected at the ulnar neck. The ulnar styloid and its soft tissue attachments can be left in place. Instability of the ulnar stump is also a potential complication and most authors recommend stabilization with a slip of the ECU or FCU. The procedure is typically reserved for older, lower demand patients. In his description of the hemiresection-interposition technique, Bowers sought to avoid instability by only resecting the articular portion of the ulnar head and preserving the ulnar attachments of the TFCC. A flap of the extensor retinaculum or dorsal capsule is then interposed within the DRUJ and anchored to the distal ulna [55]. While theoretically able to be performed on younger patients, the procedure requires an intact TFCC and may not withstand high-demand activities over the long term, leading to loss of ulnar support of the carpus. Ulnar positive variance is another contraindication, as ulnocarpal impaction symptoms would be unaffected by the procedure [20]. Finally, distal ulnar head arthroplasty is another option for advanced degenerative changes within the DRUJ. It is typically reserved for instability after distal ulnar resection in lower demand patients. Intact dorsal and volar rims of the sigmoid notch are required or instability will persist after surgery. Both partial and complete ulnar head arthroplasty implants are available. While limited long-term follow-up data is available, most studies have shown excellent pain relief, return of range of motion, improved grip strength from preoperative levels at 5 years of follow-up. Biomechanical testing has demonstrated complete restoration of DRUJ kinematics. Although patients are frequently restricted to low-demand activities following the procedure, Scheker et al. have reported no implant failures at 5 years allowing activities as tolerated [56–59].

Delayed treatment of residual DRUJ instability most frequently requires a soft tissue stabilization procedure, as the TFCC ligaments are often irreparable. If an ulnar styloid base fracture is present in the setting of chronic instability, fracture fixation alone is usually insufficient, due to attenuation of the radioulnar ligaments and surrounding soft tissues [56]. Most current techniques focus on anatomic reconstruction of the radioulnar ligaments. Scheker et al. published a technique using a tendon allograft to reconstruct the dorsal radioulnar ligament with a weave through drill holes in the radius and ulna [60]. Separate techniques by Adams and Berger, as well as Jones and Sanders, each describe reconstruction of both the volar and dorsal radioulnar ligaments using a palmaris longus autograft [61, 62]. The technique by Adams and Berger creates an anatomic reconstruction through drill holes placed at the ulnar corner of the distal radius and fovea of the distal ulna.

DRUJ capsular contracture can limit forearm rotation following trauma and should be addressed at the same time as malunion. Other conditions which limit forearm following trauma should be ruled out. These include radioulnar synostosis, DRUJ synchondrosis, interosseus membrane contracture, and proximal radial head fracture or dislocation [20]. Contracture of the pronator quadratus can lead to a fixed pronation of the DRUJ. Volar capsulectomy is performed for loss of supination, and dorsal capsulectomy is done for loss of pronation, with dual approaches reserved for bidirectional loss of motion [20, 62].

As described earlier, acquired ulnar positive variance from malunion is a risk factor for ulnocarpal impaction syndrome. In a cadaveric study, 2.5 mm of ulnar positive variance increased axial loading of the ulnocarpal joint by 42% [63]. Over time, repetitive abutment of the ulnar head against the carpus leads to chondromalacia of the articular ulna, lunate and triquetrum, tearing of the TFCC, and attenuation of lunotriquetral ligament [56]. If left untreated, end-stage findings include DRUJ instability from TFCC ligament attenuation, carpal instability, and cystic degenerative changes within the carpus and ulnar head. Treatment should aim to reduce ulnar variance to between neutral and 1 mm of negative ulnar variance [13]. Techniques include arthroscopic wafer resection of the distal ulna and ulnar shortening osteotomy. Ulnar shortening osteotomy is preferred in the setting of malunion surgery as it preserves the TFCC ligaments and joint capsule and exerts a positive effect on DRUJ stability [20, 64]. Stylocarpal impaction, which results from painful impingement from the tip of an ulnar styloid nonunion on the carpus can be treated by excision of the fragment [20].

7.1.6 Postoperative Management

Given that one of the primary indications for surgical intervention is loss of motion, the goal of any fixation construct should be to allow early range of motion. Patients are immobilized in a postoperative splint for a total of 10–14 days. Following this, a removable splint can be placed and rehabilitation is initiated, focusing on early progressive range of motion. Forearm rotation, especially supination, can be difficult to recover. Strengthening exercises are initiated once there is radiographic evidence of healing, usually between 8 and 12 weeks from surgery. Resumption of all activities typically occurs between 3 and 4 months from the index procedure [2].

7.1.7 Distal Radius Malunion: Case 1

A 45-year-old female s/p closed treatment of a closed distal radius fracture. Figure 7.1a, b demonstrates the malunion with dorsal angulation and shortening. The patient had pain and stiffness with a loss of wrist flexion and forearm rotation. Figure 7.1c, d demonstrates the correction with volar plate and osteotomy. The resulting improvement in volar tilt and ulnar variance can be seen in these fluoroscopic images. Allograft was then used to fill the osteotomy defect with progressive healing at 2 months (Fig. 7.1e, f). Note that the plate is somewhat prominent volarly due to the difficulty in getting full correction of the original deformity. This may necessitate hardware removal and should be monitored for tendon irritation.

7.1.8 Distal Radius Fracture: Case 2

A 40-year-old female s/p closed treatment of a distal radius fracture. Figure 7.2a, b demonstrates the malunion with ulnar positive variance, increased scapholunate angle in compensation for loss of normal volar tilt. She had continued pain and stiffness despite conservative treatment. Figure 7.2c, d shows postoperative images after osteotomy and correction of the deformity. Volar tilt is restored as is carpal alignment and ulnar variance. The correction was in a single plane with minimal volar gap so no bone graft was used. The osteotomy is healed (Fig. 7.2e, f).

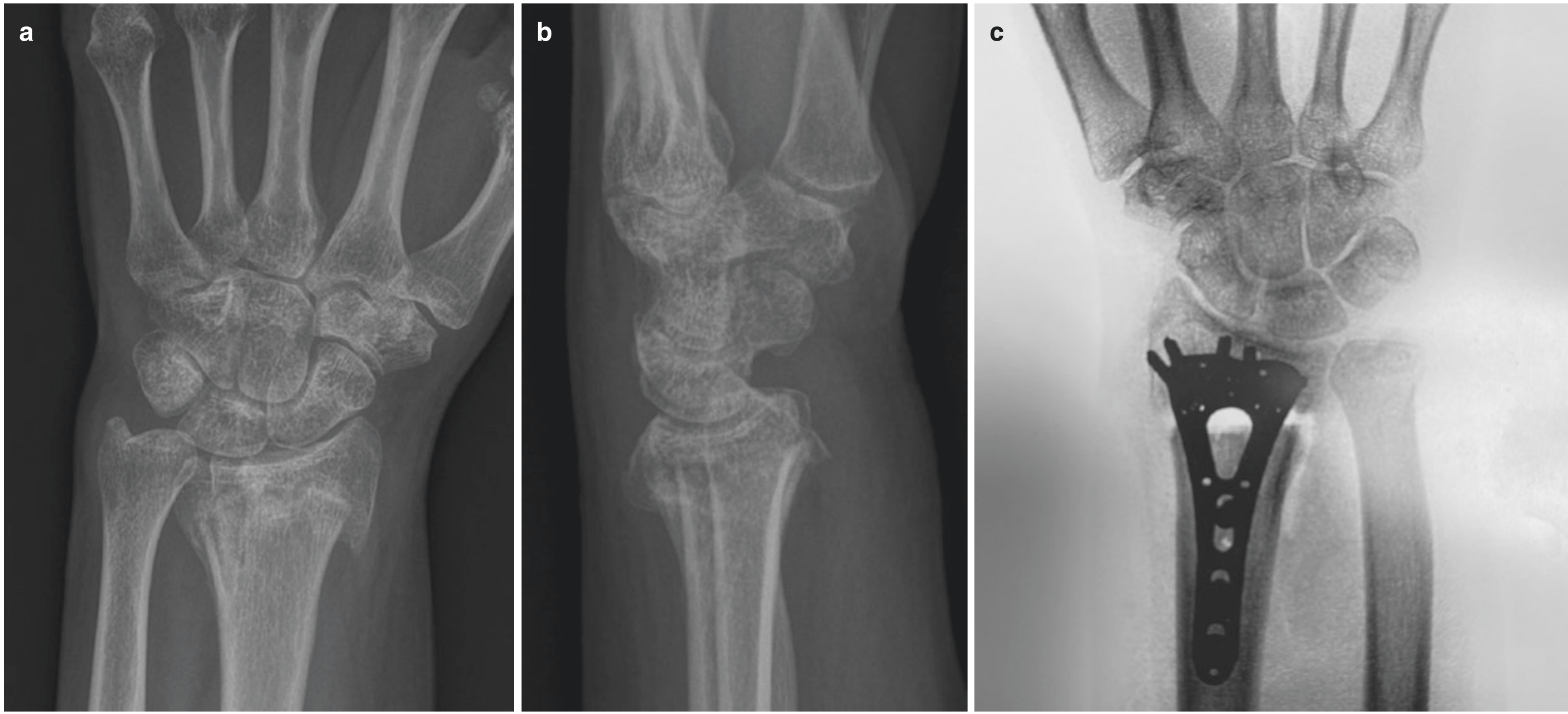

Fig. 7.1 Distal radius malunion. Case 1. (**a**, **b**) Malunion with dorsal angulation and shortening resulting from earlier closed treatment of a distal radius fracture. A 45-year-old female patient had pain and stiffness with a loss of wrist flexion and forearm rotation. (**c**, **d**) Fluoroscopic images of the correction with volar plate and osteotomy of the malunion, showing improvement in volar tilt and ulnar variance. (**e**, **f**) Allograft was used to fill the osteotomy defect, with progressive healing at 2 months. The plate is somewhat prominent volarly due to the difficulty in getting full correction of the original deformity

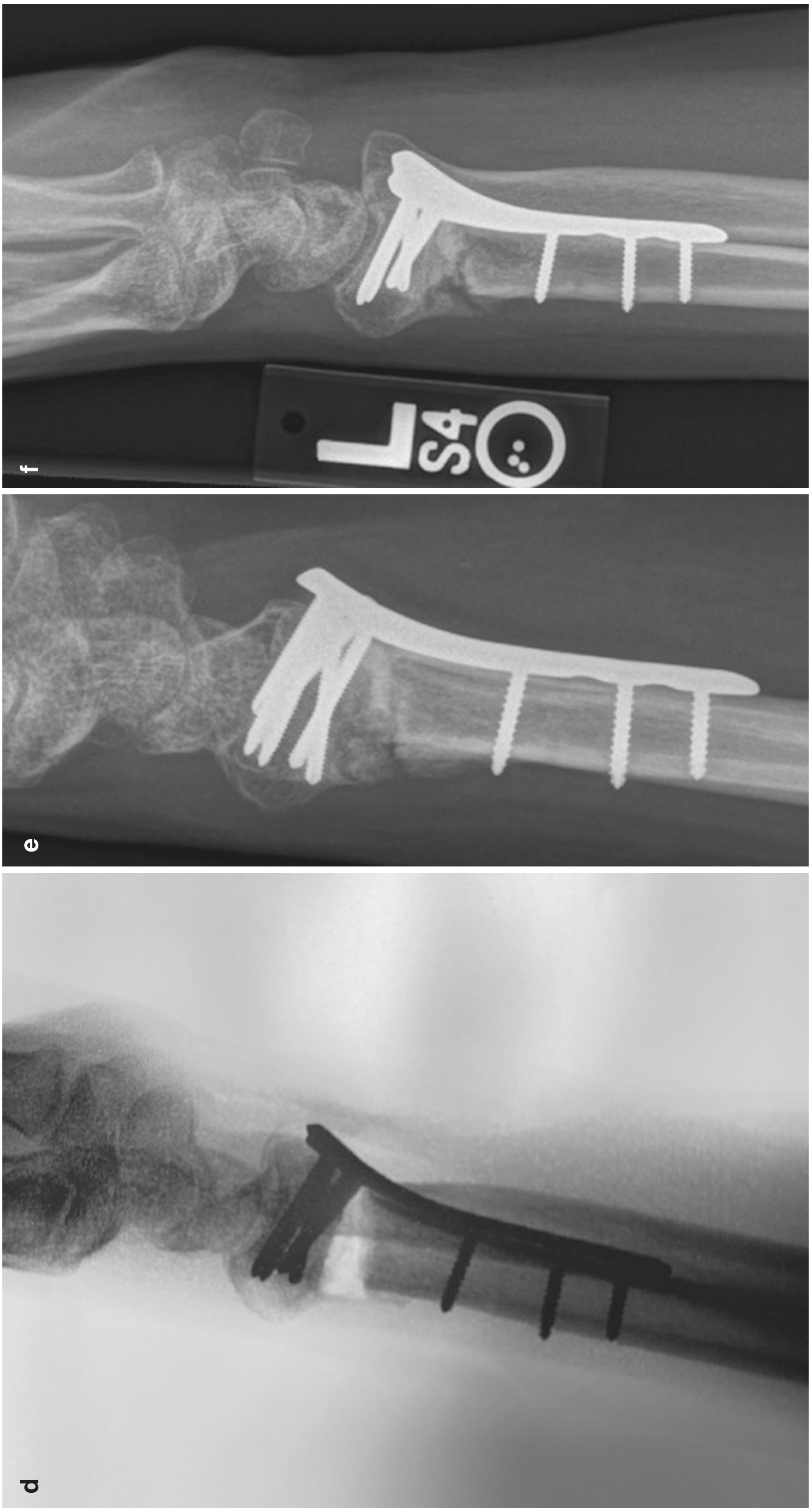

Fig. 7.1 (continued)

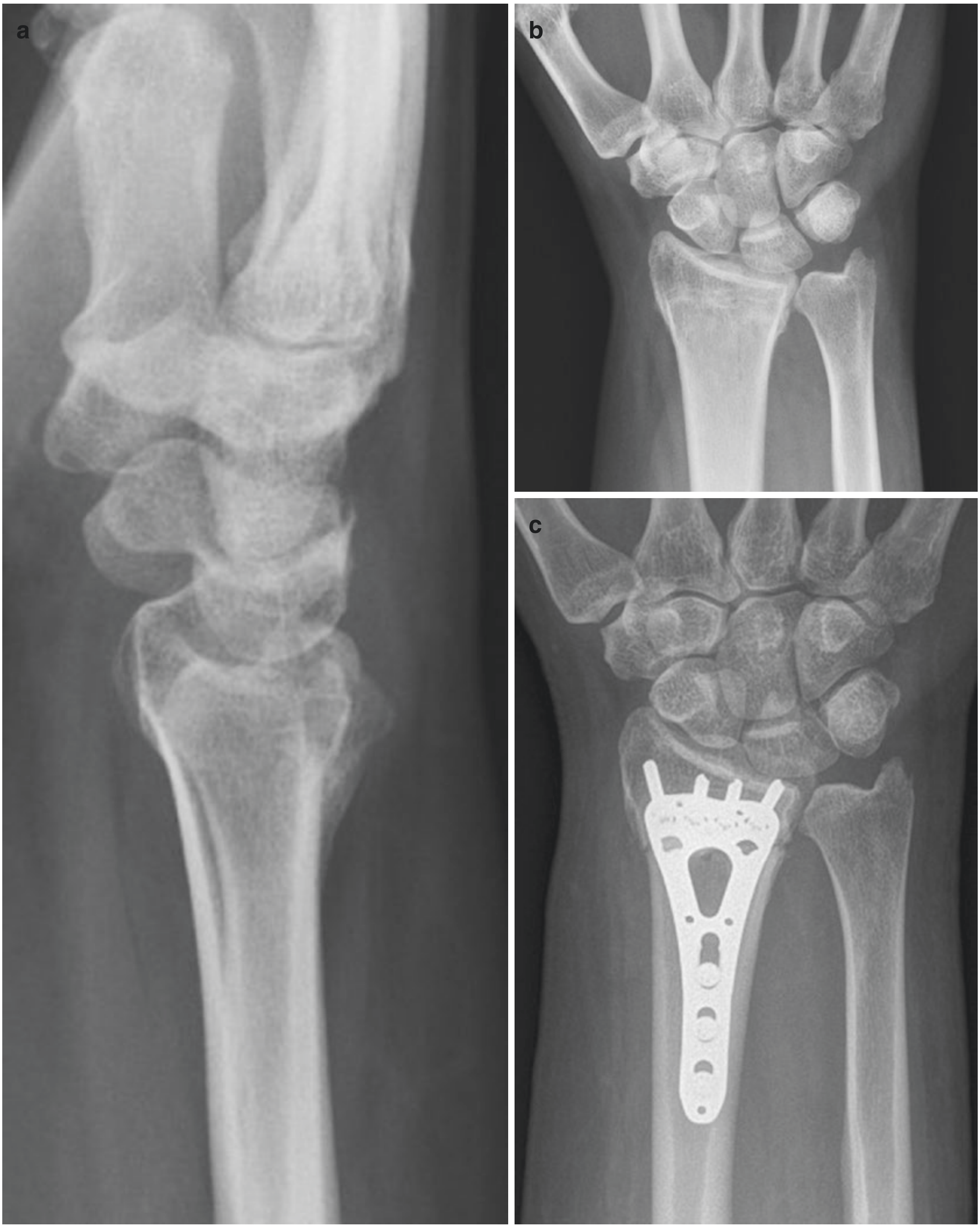

Fig. 7.2 Distal radius malunion. Case 2. Malunion in a 40-year-old female after closed treatment of a distal radius fracture. (**a**, **b**) Malunion with ulnar positive variance, increased scapholunate angle in compensation for loss of normal volar tilt. She had continued pain and stiffness despite conservative treatment. (**c**, **d**) Postoperative images after osteotomy and correction of the deformity. Volar tilt is restored as is carpal alignment and ulnar variance. The correction was in a single plane with minimal volar gap so no bone graft was used. (**e**, **f**) The osteotomy is healed

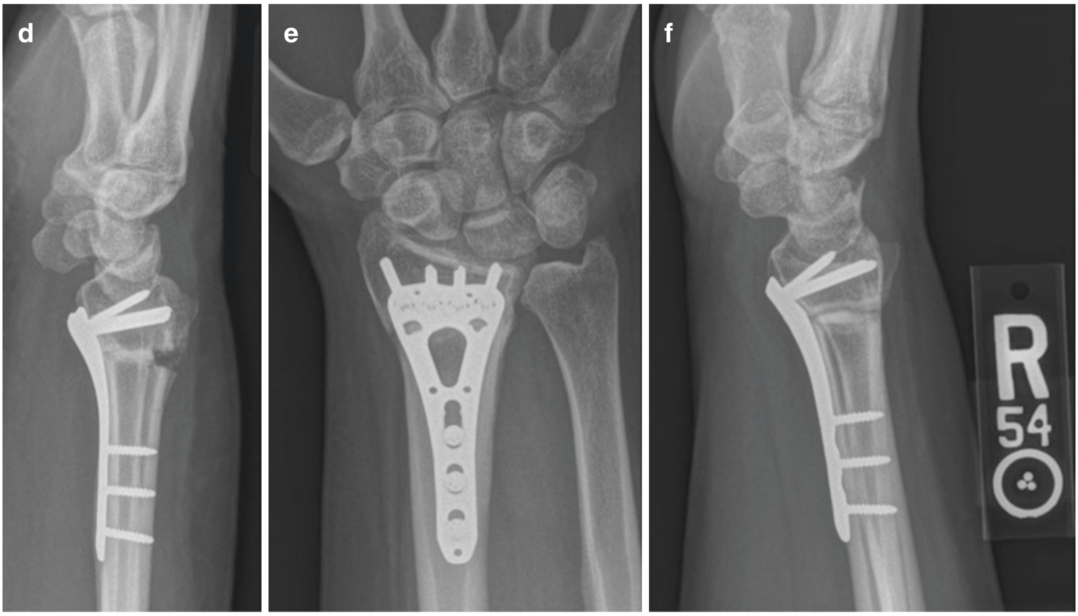

Fig. 7.2 (continued)

7.2 Scaphoid

7.2.1 Background and Pathoanatomy

The scaphoid is the most commonly fractured bone of the carpus, accounting for 60–70% of all fractures [65]. Due to its position in the carpus and ligamentous, the healing scaphoid is subjected to numerous complex forces. Without adequate initial management, a combination of bending, shearing, and translational forces can lead to fracture displacement [65]. Unstable fractures additionally almost always exhibit some degree of perilunate ligamentous injury [66]. In scaphoid waist fractures, the combination of displacing forces and ligamentous attachments results in flexion of the distal pole of the scaphoid and extension of the proximal scaphoid pole through its attachment to the lunate. Volar bone reabsorption prior to fracture healing or inadequate surgical reduction lead to the characteristic "humpback deformity" [65]. Shortening of scaphoid length associated with humpback deformity is believed to cause an alteration in carpal mechanics. The resulting carpal instability pattern appears to most closely resemble dorsal intercalated segmental instability (DISI) seen in scapholunate advanced collapse (SLAC) and scaphoid nonunion advanced collapse (SNAC), both of which lead to a predictable pattern of progressive degenerative changes [67]. Clinically, this can manifest as pain, loss of motion, decrease in grip strength and has also been postulated to result in an increased risk in the onset and progression of degenerative arthritis [68]. Amadio et al. reported on 46 scaphoids evaluated with computed tomography at least 6 months after scaphoid union. They defined malunion as a lateral scaphoid angle greater than 35°. In patients with satisfactory alignment, they reported satisfactory outcomes in 83% of patients, with only 22% of patients demonstrating degenerative changes. In contrast, when imaging displayed a lateral scaphoid angle greater than 45°, only 27% of patients reported satisfactory clinical outcomes and 54% had evidence of degenerative arthritis [69]. Despite the correlation between scaphoid malalignment and degenerative changes, little attention has been placed on its management in the literature.

7.2.2 Clinical Assessment

As with any clinical assessment, a detailed history of the patient's injury and any treatment should be obtained. If symptomatic, patients most commonly report pain, decreased range of motion, and inability to perform activities of daily living [68, 70]. The physical examination should test the strength, range of motion, and stability of the wrist, utilizing the unaffected side as a comparison. Decreased wrist extension, supination, and radial deviation are more common than flexion, pronation, and ulnar deviation [68]. Grip strength of both hands should be obtained, as a majority of symptomatic patients will demonstrate a decrease in grip correlating with limitations in hand and wrist function. Tenderness will most commonly present over the anatomic snuff box and scaphoid tubercle. Patients may also demonstrate symptoms indicative of extensor tenosynovitis, with dorsal swelling and pain with digit extension [68].

Both radiographs and advanced imaging are useful in establishing the diagnosis and planning treatment. Initial radiographs should include standard posteroanterior, lateral, 45-degree pronated oblique and navicular (PA in wrist ulnar deviation) views. Views of the contralateral wrist are useful for comparison, and any previous radiographs should be obtained and evaluated. Radiographs will most commonly reveal a deformed scaphoid with shortening and flexion on the lateral radiograph, and ulnar deviation of the distal pole on the PA radiograph. In the navicular view, the scaphoid may overlap the radial border of the capitate. The distal fragment is also commonly axially rotated and pronated [68]. Radiographs should also be examined for evidence of early degenerative changes, which most commonly begin at the radioscaphoid articulation.

Three-dimensional computed tomography (CT) scans provide the most detailed images of the osseous anatomy and can be useful in determining the true nature of the deformity. CT has demonstrated high intra-observer reliability in determining displacement and fracture union [71]. CT images are used to determine angulation of the scaphoid with the lateral intrascaphoid angle or height to length ratio on sagittal images [71]. For accuracy, the CT should be oriented perpendicular to the long axis of the scaphoid, rather than the wrist [72]. The normal lateral intrascaphoid angle is 24°, while an angle greater than 45° is predictive of an increased risk of arthritis, even in healed fractures [69]. Scaphoid collapse is considered significant with a height-to-length ratio greater than 0.65 [73, 74]. CT can also evaluate for technical errors, such as inadequate fracture reduction. Current CT protocols with metal suppression are useful in minimizing hardware artifacts. CT can provide a more precise examination for early degenerative changes than plain radiographs.

7.2.3 Treatment

As mentioned previously, despite the apparent correlation between scaphoid malalignment and early degenerative changes, there is a lack of consensus within the literature on the definitive management of these injuries. As a result, treatment should encompass a collaborative effort between the surgeon and patient and be based on each individual's symptoms, activity limitations, and functional goals, rather than malalignment alone. The first step should be to precisely determine the degree of malalignment through radiographic and CT examination as discussed above. In the setting of a nascent malunion, or a fracture encountered up to 3 months from initial injury, which has yet to completely consolidate, our recommendation is for early surgical management to correct the deformity and hopefully prevent any further negative sequelae.

The treatment of established scaphoid malunion is more controversial. Three earlier studies established symptomatic scaphoid malunion as a risk factor for wrist progressive degenerative arthritis [69, 75, 76]. This must be balanced against potential iatrogenic risk factors associated with treating a previously united scaphoid fracture, including osteonecrosis and nonunion [68]. In symptomatic patients, studies have consistently demonstrated improvement in pain, range of motion, and grip strength [68, 70, 77, 78]. Decision-making becomes significantly more complicated in the setting of asymptomatic patients, as surgery is aimed at preventing conditions that may not become symptomatic for years into the future. Forward et al. reported no difference in pain, range of motion, or grip strength at 1-year follow-up between patients with malunited and normally aligned scaphoid fractures [79]. At an average of 11 years follow-up, Jiranek et al. compared patients with either malunion or normal alignment after Matti-Russe bone grafting. They found that while there was a significant difference in objective findings, including degenerative changes, range of motion, and grip strength, there was no difference in subjective patient satisfaction [80].

Surgical management requires a volar approach to the scaphoid, as described by Russe and described in detail in the chapter on scaphoid nonunion, to accurately correct the humpback deformity. Depending on the severity of the deformity and degree of volar bone reabsorption, structural bone graft may be required for stabilization. Fernandez et al. were the first to describe the use of wedge-shaped corticocancellous graft from the iliac crest to correct humpback deformity [77]. They reported on three patients treated with this technique to correct the standard flexion, pronation, and ulnar deviation humpback deformity. At a minimum 4 years of follow-up, all patients were pain-free, satisfied with their treatment, and demonstrated improved range of motion and grip strength [77]. In the largest series in the literature to date, El Karif reported on 13 symptomatic patients treated with the tricortical iliac crest graft technique [68]. At an average of 42 months follow-up, they reported excellent results in seven patients, good in four patients, and fair in two patients. Compared to the contralateral side, grip strength and range of motion improved from 48% and 47% to 82% and 79% at the final follow-up. Nakamura et al. treated ten patients with symptomatic scaphoid malunions, seven required a volarly placed wedge graft. They reported a correlation between the degree of deformity and decreased range of motion and grip strength. All patients reported satisfactory results [70]. Finally, Lynch and Linscheid reported on five patients treated with corrective osteotomy for symptomatic malunion at an average of 9 years post-operatively. Using CT imaging, they found that all osteotomies healed and scaphoid and carpal alignment was well maintained. All patients demonstrated an improvement in grip strength and range of motion [78].

The presence of degenerative changes represents the final consideration in treatment of these patients. Imaging should be carefully reviewed for early arthritic changes. The goal of surgical deformity correction is the prevention of premature arthritis in the young patient with high functional demands. With significant radiocarpal or midcarpal degenerative changes, surgical treatment of scaphoid malunion is unlikely to produce a meaningful outcome. As mentioned earlier in the chapter, scaphoid collapse can lead to a DISI pattern of carpal instability, with degenerative changes progressing in a pattern resembling scaphoid nonunion advanced collapse (SNAC). Management of this condition consists of salvage procedures based on patient symptoms and discussed in detail in the chapter on scaphoid nonunion.

7.3 Thumb Trapeziometacarpal Joint

Although relatively rare injuries, fractures involving the thumb carpometacarpal joint have the potential to significantly impact thumb function. They tend to occur in a bimodal distribution, most commonly involving children and the elderly [81]. When occurring in young, high-demand patients, malunited fractures of the base of the first metacarpal and, less commonly, the trapezium can have a detrimental effect on thumb range of motion and strength [82, 83]. The trapezium forms a saddle-shaped articulation for the base of the first metacarpal, allowing a complex array of movement, including flexion and extension, palmar abduction and adduction, and rotation. The articulation is stabilized by ligamentous structures, which can also be involved, depending on the injury pattern. Initial radiographic assessment should include a thumb series with standard PA, as well as true thumb AP and lateral views. Known as Robert's view, the true thumb anteroposterior view requires the hand to be pronated so the dorsum of the thumb lies against the radiographic plate. To obtain the true lateral or Bett's view, the palm is placed flat on the cassette, the hand is pronated between 15 and 35° and the beam is directed 15° distal to proximal. This allows visualization of the trapeziometacarpal joint, as well as the three other articulations of the trapezium, with the scaphoid, trapezoid, and first metacarpal [81]. Enhanced imaging with three-dimensional computed tomography can be beneficial to definitively determining the deformity and evaluate for degenerative changes.

7.4 Thumb Metacarpal

Intra-articular fractures of the base of the first metacarpal can be divided into simple and complex fracture pattern types. First described by an Irish surgeon in 1882, Bennett's fracture refers to a single intra-articular split of volar-ulnar base of the metacarpal from the remaining bone. It most commonly occurs from axial load of a partially flexed metacarpal [81]. The injury is really a fracture-subluxation, with the volar-ulnar fragment remaining reduced to the carpometacarpal joint by the attachment of the anterior oblique or beak ligament to the trapezium. Meanwhile, the distal metacarpal shaft displaces in a dorsal, proximal, and radial direction, as a result of the attachments of the abductor pollicis brevis, adductor pollicis, and flexor pollicis brevis [82]. Silvio Rolando initially termed Rolando fracture for a three-part fracture of the base of the first metacarpal in 1910. It is now applied to any comminuted fracture of the first metacarpal base [81]. Historically, acute treatment of these injuries consisted of closed reduction and cast immobilization [82]. While current treatment favors operative realignment and stabilization, there is conflicting literature to support anatomic reduction and the literature concerning the management of malunion is nonexistent. Cannon et al. and Demir et al. examined long-term results following closed and open treatment of these fractures, finding no correlation between the quality of reduction and radiographic or subjective outcomes [84, 85]. Further, a biomechanical study by Cullen et al. demonstrated a significant increase in trapeziometacarpal joint contact pressure only with articular displacement greater than 2 mm, resulting in dorsal shift in contact pressure. They concluded that up 2 mm of articular step-off was acceptable [86]. In contrast, Kjaer-Petersen et al. noted an increase in symptomatic, radiographic arthritis at an average follow-up of 7.3 year when post reduction joint incongruity was greater than 1 mm [87]. Livesley et al. reported diminished strength and range of motion and the presence of degenerative arthritis in all of 17 patients followed for an average of 26 years after closed reduction with persistent displacement or joint subluxation [83]. Other studies have also demonstrated improved subjective and radiographic outcomes from anatomic reduction [88–90].

Treatment of a malunited, intra-articular fracture is complicated and should be dependent on the patient's individual function, symptoms, and expectations. It is helpful to try to determine whether the patient's functional limitations stem from more decreased range of motion or pain. In patients with range of motion limitations and without intra-articular incongruity or pain, an extra-articular osteotomy can be performed to restore alignment. The thumb can be approached through the standard Wagner incision, with a longitudinal limb over the dorsal metacarpal between the thenar musculature and abductor pollicis longus tendon, which is extended at the base of the trapeziometacarpal joint proximally and ulnarly to the radial edge of the flexor carpi radialis [80]. The osteotomy is performed either at the site of deformity or distal to it, using a compensatory deformity to restore overall length and alignment. Given the complexity of the standard deformity, which includes flexion, adduction, and rotation, a compensatory distal osteotomy can represent a less technically demanding procedure. Additionally, contracture of the first webspace may occur from the initial deformity or immobilization and require soft tissue techniques such as Z-plasty or webspace release and skin grafting to fully restore thumb range of motion.

Management of the articular deformity is more technically demanding and involves sound preoperative planning. Nascent malunions with significant articular incongruity encountered in the first 6–8 weeks following injury before fracture consolidation may be amenable to open fracture reduction and stabilization if the native fracture lines remain visible and the fragment large enough. Correction of chronic injuries is only recommended in the setting of a young, high-demand patient with significant symptomatic incongruity greater than 2 mm and no evidence of radiographic degenerative changes. The joint can again be approached through the Wagner incision, with a longitudinal osteotomy made at the site of deformity and transverse cut made more distally. The articular surface is reduced and the fragment is stabilized. We recommend the use of small 2.0 of 1.5 mm screws or K-wires.

7.5 Trapezium

Fractures of the trapezium are less common than the first metacarpal, representing only 1–5% of all carpal fractures and rarely occurring in isolation. Trapezial fractures are associated with fractures of the first metacarpal and distal radius, as well as carpal tunnel syndrome, tendonitis, and rupture of the flexor carpi radialis tendon as it passes by the trapezium [65]. Fractures most commonly involve the body or longitudinal ridge, which extends in a volar direction and serves as the attachment point for the transverse carpal ligament. The FCR then passes through a groove formed by the longitudinal ridge. Overall, fractures of the body are more common and occur from a direct blow, in which the base of the thumb metacarpal is driven axially into the trapezium [65]. With an intra-articular split, the dorsal and radial body of the trapezium displaces proximally along with the first metacarpal base, resulting in trapeziometacarpal subluxation.

As with fractures of the base of the first metacarpal, literature on the treatment of these injuries is lacking. Given the joint subluxation associated with an intra-articular split, most authors recommend acute anatomic reduction and fixation with either Kirschner wires or, more commonly, compression screws [91]. The presence of frank joint subluxation or mechanically restricted range of motion in the nascent period should be an indication for reduction and stabilization. Additionally, fracture displacement is associated with a high incidence of delayed or nonunion if fracture lines persist beyond the expected time to healing [65]. Due to the compressive nature of the injury, bone impaction is common and bone graft may be required to support the articular surface [65]. Similar to the above treatment for thumb metacarpal malunion, once a malunited fracture has completely healed, treatment should be based on a combination of patient age, functional demands, and symptoms, in addition to deformity. In young, high-demand, symptomatic patients, an intra-articular osteotomy can be performed through the Wagner approach. The goal of treatment should be to reestablish both articular congruity and trapeziometacarpal joint realignment. For malunited and nonunited fractures of the trapezial ridge, the FCR tendon may be at risk and fragment excision can be performed through a volar approach if symptomatic [65].

7.6 Salvage

Care of patients with trapeziometacarpal malunion should include close radiographic evaluation for degenerative changes, which are a contraindication to a joint leveling procedure. Often early symptomatic arthritis can be managed conservatively with a combination of therapy, corticosteroid injections, and bracing. If conservative management fails, salvage procedures are used as a last result. The procedure chosen depends on the functional demands of the patient. For young, active patients or patients with heavy labor occupations, trapeziometacarpal arthrodesis is the best surgical option [92, 93]. The procedure is contraindicated in patients with arthritis in the scaphotrapeziotrapezoid joint. For older, lower demand patients, trapeziometacarpal joint arthroplasty is indicated.

7.7 2nd–5th Carpometacarpal Joints

Intra-articular fractures involving the 2nd–5th CMC joints are relatively rare injuries but may be underreported due to the difficulty associated with their imaging [94]. Typically, these fractures are imparted with relative stability due the strong attachments of the palmar and dorsal carpometacarpal ligaments and interosseus ligaments [94]. Ligamentous mobility increases in a radial to ulnar direction, resulting in significant more motion in the 4th and 5th CMC joints than the 2nd and 3rd. As a result, fractures of the 4th and 5th CMC joints are inherently less stable than their more radial counterparts. Additionally, the tendinous insertions of the extensor carpi radialis longus (2nd metacarpal), extensor carpi radialis brevis (3rd metacarpal), and extensor carpi ulnaris (5th metacarpal) can produce avulsion fractures of the base of the metacarpals on which they attach and provide a deforming force in fracture displacement [94].

Given the rarity of these injuries, there is no consensus regarding their treatment. Initial management of a suspected malunion should include a detailed history of injury and previous treatment. The most frequent mechanism is an axial force applied through the wrist. With loss of alignment and resulting malunion, the most common complaint is loss of grip strength. Patients can also experience loss of wrist extension, decreased range of motion, and pain [94]. A complete neuromuscular exam should also be performed. The deep branch of the ulnar nerve lies in close proximity to the bases of the 4th and 5th metacarpals and is at risk for injury with fracture displacement. As mentioned previously, obtaining adequate imaging can be challenging. Initial standard anteroposterior, lateral, and oblique radiographs of the hand and wrist should be obtained. While one should look closely for dorsal displacement of subluxation of the CMC joints on the lateral radiographs, the trapezium, trapezoid, and hamate bones can obscure visualization [95]; 30-degree partially supinated and pronated lateral views can help to demonstrate metacarpal subluxation [96]. Additional advanced imaging with three-dimensional computed tomography can give a more detailed picture of joint subluxation, fracture pattern, and intra-articular incongruity.

As a rule, intra-articular malunions of the carpometacarpal joints are rarely amenable to corrective osteotomy. In the setting of a nascent malunion, with visible fractures lines, osteotomy may be able to restore articular congruity. Fractures of the second and third carpometacarpal joints have increased stability compared to the 4th and 5th. While the 4th and 5th joints possess some radio-ulnar and pronation-supination motion, the 2nd and 3rd move in only flexion and extension. There is a lack of consensus in the literature regarding treatment of fracture displacement. Acute treatment of the radial CMC joints in the literature consists of small case series or case reports totaling 15 cases of 2nd CMC joint fractures and 7 cases of 3rd CMC fractures. The only near consensus for surgical management is in the setting of loss of wrist extension from ECRL or ECRB avulsion and fracture fragment displacement resulting in tendon irritation and risk of tendon rupture [94]. There are no studies detailing long-term function or risk of early degenerative arthritis. Similar to management of nascent malunions, corrective osteotomy can be considered in young, active patients if fracture fragments are visible and restoration of wrist extension may be accomplished by reduction of the wrist extensor tendon attachments.

The 4th and 5th metacarpal bases form an articulation with the hamate bone of the carpus. The 4th metacarpal can form a secondary articulation with the capitate through a radial facet. Unlike the other metacarpal bones, the 4th metacarpal is free of tendinous attachments and its stability is augmented by an articulation with the 3rd and 5th metacarpal bases. As a result, fractures of the 4th metacarpal rarely occur in isolation. Fractures of the 5th metacarpal base have been termed "baby Bennett" and "reverse Bennett" injuries due to the displacing force of the extensor carpi ulnaris attachment, which results in proximal and dorsal subluxation of the metacarpal base [82]. Fractures of the intra-articular hamate, as well as the 4th and 5th metacarpal bases, can affect joint congruency. As with fracture of the radial CMC joints, there remains a lack of consensus regarding acute treatment of 4th and 5th CMC fracture-subluxations. Petrie and Lamb reviewed outcomes of 14 fifth CMC fracture-dislocations at an average of 4.5 years. Despite persistent radiographic abnormalities, including metacarpal shortening, articular incongruity, and joint widening, only one patient described significant enough pain to affect work [97]. Kjaer-Petersen et al. compared closed reduction versus operative fixation in a total of 50 patients with 64 fifth metacarpal fracture-dislocations at an average of 4.3 years follow-up. They discovered that although surgical treatment resulted in a lower incidence of joint incongruity and early degenerative findings, it had no impact on the presence of pain at follow-up. Thirty-eight percent of patients (19 of 50) reported significant pain at the time of follow-up [98].

As a result, it is difficult to support a role for corrective osteotomy in treatment of malunited fractures of the 4th and 5th CMC joints. As with fractures of the 2nd and 3rd metacarpals, nascent malunions with clear fracture lines may be amenable to surgical correction in the symptomatic, young, active patient. Similar patients with simple articular splits in the hamate with resulting 4th or 5th CMC incongruity may also be amenable to corrective osteotomy stabilized with small compression screws through a dorsal approach prior to the onset of degenerative changes. For patients with activity-limiting symptoms and findings of degenerative arthritis, CMC arthrodesis with iliac crest bone autograft is a reasonable procedure and has been reported to successfully relieve symptoms [99].

A final consideration is in patients with intra-articular metacarpal base fracture malunions and resulting rotational abnormalities of the finger. Scissoring over an adjacent finger can produce a significant cosmetic deformity and impair grip strength. Ignoring any intra-articular incongruity, an extra-articular rotational osteotomy can be performed at the base of the metacarpal through a dorsal approach and fixed with either provisional Kirschner wires or plates [81]. Limited by the transverse metacarpal ligament, the maximum correction is typically between 18° and 19° for the index, long and ring fingers, and 20–30° for the small finger [100]. Correction is determined by a combination of inspecting the plane of the fingernails, confirming that all digits point to the scaphoid tubercle, and observing the tenodesis effect with passive wrist flexion and extension [81].

7.8 Metacarpal Fracture Malunion

Malunion of metacarpal fractures is one of the most common complications after injury. The nature of the initial injury often directs the resultant deformity and guides future treatment. Metacarpal fractures may be subdivided into those involving the shaft, neck, head, or intra-articular portion of the bone. The patient's specific needs and degree of function as well as the location of the fracture and the specific digit involved dictate the amount of acceptable angulation, shortening, and rotation which can be tolerated and defines what is within reasonable limits versus a malunion. Occupational and vocational demands of the patient in addition to other patient-specific factors must be taken into account when evaluating this complication and determining an appropriate and individualized treatment plan.

The normal anatomy of the metacarpals and their role in defining the form and function of the hand are important to understand when evaluating deformity after injury. The metacarpals are key in forming the three arches of the hand: the longitudinal arch and two transverse arches. The metacarpal base at the carpometacarpal joint defines the proximal transverse arch and the metacarpal neck at the level of the metacarpophalangeal joint defines the distal transverse arch. The longitudinal arch is formed by the dorsal surface of the metacarpals. Adjacent metacarpals are held to each other at their bases by the interosseous ligaments and deep transverse intermetacarpal ligaments distally [101]. These strong fibrous attachments help in maintaining the arches of the hand but can be disrupted by severe crush injury or multiple fractures. Furthermore, these attachments limit the overall shortening that is possible after fracture.

Fractures of the metacarpals angulate in a predictable pattern as a result of the muscle attachments along the ray. Though several muscles attach to the bases of the metacarpals, it is the actions of the interossei that is most important in creating deformity. Both the dorsal and palmar interossei take origins from the metacarpals and insert on the extensor hood and lateral bands [101]. As a result, transverse or short oblique fractures of the head and shaft of the metacarpal displace in a characteristic apex dorsal pattern given the deforming forces applied to each fragment. Primarily, the unopposed pull of the interossei results in a flexion deformity of the distal fragment of these fractures. As a result, malunions tend to occur in this fixed position.

Fractures of the metacarpal can be broken down into those involving the shaft, neck, or the articular surfaces (head and base). Slight variation exists in the literature regarding acceptable amounts of deformity, but in general, 10° of angulation through the metacarpal shaft of the index and long finger, 20° of the ring, and 30° of the small finger are acceptable and treated nonoperatively [1]. This variable amount of acceptable deformity is a function of compensatory motion imparted at the carpometacarpal joints, which is greater for the more ulnar digits. The index and long finger metacarpals are more rigid and part of the longitudinal arch of the hand [82]. Fractures of the metacarpal neck may tolerate an even greater amount of angulation before significant deficit is noted. Angulation of 10–20° of the index and long finger, 30–40° of the ring, and up to 70° of the small finger can be considered acceptable when the deformity is apex dorsal [102–105]. Fractures of the articular surfaces of the metacarpal are treated primarily when an incongruent joint results, in order to limit the risk of accelerated arthrosis. When there is less than 1 mm of articular step-off or 25% joint surface involvement, the fracture may be treated nonoperatively [82]. Further, fractures of the metacarpal base are often associated with an acute dislocation of avulsion injury which both warrant reduction or fixation [97].

Shortening of a metacarpal after fracture is often a result of relative loss in length as a function of angulation rather than true axial shortening. Nonetheless, decreasing the functional length of a metacarpal can alter the balance of the intrinsic and extrinsic systems working in concert to coordinate digital motion. The common finger extensors undergo a relative lengthening in this scenario resulting in extensor lag at the metacarpophalangeal joint which has been calculated to be 7° of lag and 8% loss in grip strength per 2 mm of shortening [106, 107]. However, the capacity of the MCP joint to hyperextend (on average 20°) provides a mechanism to compensate for this lag, and thus clinically significant deficits in function are not noted until greater than 6 mm of shortening is present.

Rotational deformity, unlike angulation and shortening, is poorly tolerated at the level of the metacarpals, and anatomic reduction in this plane is required. Relatively small amounts of malrotation at the level of the metacarpal are magnified at the fingertip. Each degree of metacarpal malrotation may result in as great as 5° of malrotation at the fingertip and 1 cm of symptomatic fingertip overlap [108]. This is best evaluated with the patient making a fist and noting any overlap of the digits, or more precisely, any variance from the normal cascade of fingers pointing toward the tuberosity of the scaphoid. This can be a functionally debilitating issue leading to loss of dexterity and deficits in grip strength.

7.9 Phalangeal Fracture Malunion

Phalangeal fractures result in predictable deformity due to the ligamentous attachments along each phalanx and the relative location of the fracture lines. Short, simple fractures of the phalanges exhibit characteristic patterns of angulation and subsequent deformity depending on the location of the initial fracture and the deforming forces on each fragment. Those involving the shaft of the proximal phalanx typically result in apex volar angulation due to the forces exerted by the lumbricals to flex the proximal fragment and the central slip to the middle phalanx to extend the distal fragment. It is in this position that most malunions of the proximal phalanx will occur.

Similar fractures at the middle phalanx may result in apex dorsal or apex volar deformity contingent on the location of the fracture relative to tendon insertions on this bone. Specifically, the relative location of the fracture compared to the flexor digitorum superficialis (FDS) is key. Those fractures proximal to the FDS insertion result in an apex dorsal deformity as a result of the flexed distal fragment secondary to the unbalanced pull of the FDS tendon and an extended proximal fragment due to the pull of the central slip. Conversely, fractures distal to the flexor digitorum superficialis will angulate volarly as a result of the flexion force on the proximal fragment by the FDS and extension force on the distal fragment by the terminal extensor. Again, it is in these characteristic positions that malunions will typically occur.

More complex fractures of the phalanges often result in variable amounts of deformity and do not fit within the simple rules presented above. Long oblique or spiral fractures may display varying amounts of angulation and shortening and often result in multidirectional deformity.

7.9.1 Phalangeal Fracture Malunion: Case 1

A 41-year-old female s/p attempted fixation of a 5th proximal phalanx fracture. The fracture healed but with an extension deformity as well as rotation, resulting in digit overlap and functional impairment (Fig. 7.3a, b). Fluoroscopic images (Fig. 7.3c, d) demonstrate plate fixation after osteotomy and correction of multiplane deformity, including both flexion and rotation. Subsequent radiographs demonstrate some early healing (Fig. 7.3e, f). The mismatch between edges of the osteotomy is due to correction of the rotational deformity. Also noted is her clinodac-

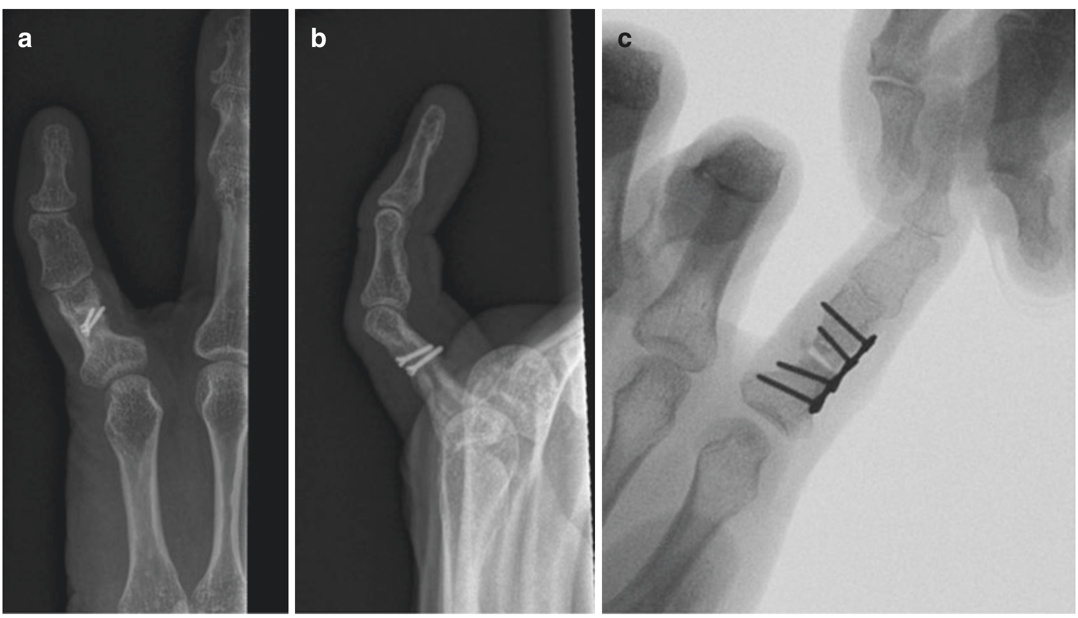

Fig. 7.3 Phalangeal fracture malunion. Case 1. (**a**, **b**) Malunion in a 41-year-old female patient after an earlier attempted fixation of a 5th proximal phalanx fracture. The fracture healed but with an extension deformity as well as rotation, resulting in digit overlap and functional impairment. (**c**, **d**) Fluoroscopic images of this malunion demonstrate plate fixation after osteotomy and correction of multiplane deformity, including both flexion and rotation. (**e**, **f**) Subsequent radiograph of correction of this malunion. The mismatch between edges of the osteotomy is due to correction of the rotational deformity. Note clinodactyly at the distal phalanx, which is symmetric to the contralateral side

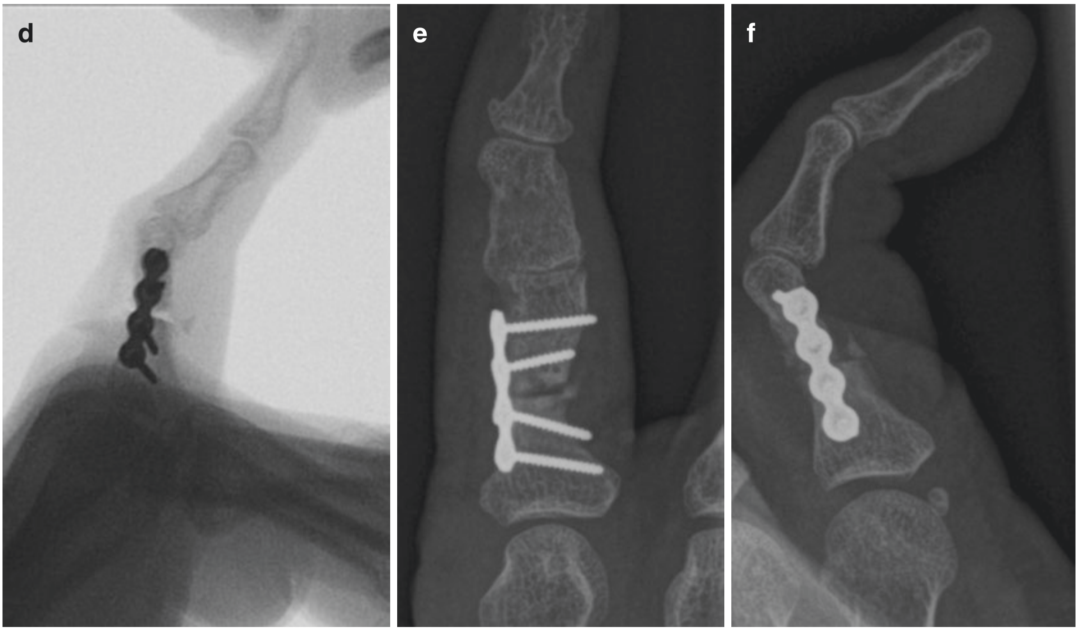

Fig. 7.3 (continued)

tyly at the distal phalanx, which is symmetric to the contralateral side.

7.9.2 Phalangeal Fracture Malunion: Case 2

A 7-year-old female with a growth abnormality and subsequent malunion-like deformity after correction of a thumb polydactyly at an earlier age (Fig. 7.4a, b). In this case the osteotomy was made remote to the physis, and smooth wires were used for fixation allowing for correction of the functional deformity (Fig. 7.4c–e). X-rays demonstrate progressive healing after removal of the first wires.

7.10 Nonoperative Management

Treatment for malunion of metacarpal and phalangeal fractures is highly successful with relatively low complication rates when performed correctly but should not be undertaken without steadfast indications [109]. Each patient and individual case should be scrutinized to determine the amount of functional deficit caused by the deformity being considered. Though radiographic evidence of malunion may exist, operative correction should not be considered for asymptomatic malunions, especially those that are clinically stable and late presenting (greater than 10 weeks from injury) with signs of bridging callus. Correction of malunion for purely cosmetic reasons is not indicated. Patient-specific factors that define the amount of functionality and demand the patient has of their hand are important to consider. Young patients, athletes, and those who work in manual labor or require high functionality of their hands to perform job-related activities are all good candidates for operative fixation in order to optimize their outcome. Appropriate hand therapy for strength and conditioning is a critical factor in management of all patients with malunion of the metacarpals of phalanges, even when considering surgical intervention. Long-term results are improved even after surgery when adequate physical therapy is performed before operation [109]. Appropriately counseling patients prior to surgery is key in setting realistic expectations and providing true patient-specific care.

Fig. 7.4 Phalangeal fracture malunion. Case 2. (**a**, **b**) A 7-year-old female with a growth abnormality and subsequent malunion-like deformity after earlier correction of a thumb polydactyly. (**c**, **d**) Anteroposterior (AP) and lateral views showing steotomy was made remote to the physis and smooth wires were used for fixation, allowing for correction of the functional deformity. (**e**) Final AP after pin removal showing healed osteotomy

7.11 Operative Management

When indicated in cases of significant deformity or disability, malunion is typically treated with corrective osteotomy. Performed correctly, this is quite a successful procedure with desirable outcomes [109]. The procedure is not without risk however and patients should be well educated of the expectations and limitations associated with each individual case. Common risks associated with corrective osteotomy are infection (0.01%), increased stiffness (10%), implant failure (8%), and delayed bone healing (15%) requiring prolonged therapy and protected motion [110]. Additional difficulty in perfectly restoring function and cosmesis may result from coexisting tendon or joint contractures, factors that are exacerbated by increasing chronicity of the injury. It is for these reasons that careful patient selection and preoperative planning are the keys to success.

In approaching operative management, one of the first considerations is whether to place the osteotomy at the site of deformity or to use a compensatory osteotomy to impart a reciprocal deformity on the bone resulting in overall correction. In principle, corrective osteotomy at the site of injury is ideal and will allow for full correction of the malunion in all planes. However, consideration should be given to other important factors such as soft tissue or tendon complication secondary to its potential proximity to hardware. Additionally, malunited fractures at the diaphysis have decreased healing potential after osteotomy than in metaphyseal bone due to periosteal stripping when approaching the bone and increased cortical to cancellous bone ratio [111, 112].

In general, symptomatic malunion of the metacarpals is a function of rotational deformity and less commonly of shortening or angulation. This is not only because rotation is poorly tolerated as mentioned previously, but also a result of the support provided by the deep intermetacarpal ligaments in preventing shortening greater than 3–4 mm and angulation [113]. When correcting rotational malalignment alone, consideration must be given to performing a transverse osteotomy at the proximal metacarpal metaphysis or metadiaphyseal junction instead of utilizing the site of malunion. Up to 20° of pure rotational deformity can be corrected with proximal metacarpal metaphyseal osteotomy that is subsequently fixed with Kirschner wires or a plate-and-screw construct [100]. Bone healing is enhanced by this technique and thus is ideal for malunions where the angular component of deformity is minimal. In contrast, when the deformity is multidirectional or has significant angulation, the site of malunion should be utilized for corrective osteotomy.

Similar concepts apply to the phalanges when planning for corrective osteotomy. Rotational deformity with minimal amounts of angulation can be corrected by osteotomy outside the site of malunion providing benefits to fracture healing and local tissue biology. Both subcondylar and phalangeal base osteotomies can be utilized to correct the deformity. In the case of proximal phalanx osteotomies, the phalangeal base is preferred because of the increased risk of stiffness of the proximal interphalangeal joint relative to the metacarpophalangeal joint when a subcondylar osteotomy is used [114]. Multiplane deformity (sagittal plane deformity in addition to malrotation) often requires osteotomy at the site of deformity for adequate correction.

Intra-articular fractures of the metacarpals and phalanges are treated with the same core principles guiding treatment of all intra-articular fractures. Anatomic restoration of the joint surface and fixation with absolute stability to promote primary bone healing are the tenets of appropriate care and critical to preventing arthrosis. Early presenting malunions (less than 10 weeks) can potentially be corrected through the fracture site after debriding any soft callus or intervening soft tissue from the fracture fragments and fixed with miniscrews. With later presenting intra-articular malunions, intercondylar wedge resection and sliding osteotomy can help recreate the articular surface [115]. Bone graft can be used in addition to condylar miniplates to secure fixation. Importantly, however, the techniques required to correct intra-articular malunions require expertise and should not be undertaken lightly. Even in the hands of the experienced surgeon, equipment should be available for arthroplasty or arthrodesis should fragmentation of the condyles or difficulty arises. With small intra-articular fracture fragments, excessive manipulation and fixation through these fragments may increase the risk of avascular necrosis and subsequent accelerated arthrosis.

In cases of malunion of the metacarpals and phalanges, bony deformity is often accompanied by significant stiffness which is only exacerbated by the rigid fixation and postoperative immobilization. As a result, the surgeon should consider tenocapsulolysis at the time of fixation to improve motion and allow for early guided therapy regimens. Flexor or extensor tenolysis and capsulotomy can successfully alleviate tendon adhesions or joint contracture in the acute period following corrective fixation [116, 117]. This must be followed postoperatively by appropriate splinting in order to avoid contracture, edema control, and adequate analgesia to facilitate early motion guided by a specialized hand therapist.

7.12 Surgical Approaches/ Osteotomy Techniques

Recognizing the geometry of deformity in a malunion of the metacarpals or phalanges can guide the treatment approach and technique. Other factors such as amount of bone loss, soft tissue and neurovascular compromise, and location of the deformity are important considerations in surgical planning. In regard to location, both the digit involved and the portion of bone implicated (base, midshaft, neck, intra-articular) factor into the choice of approach.

Angulation of the metacarpal is often in the sagittal plane with an apex dorsal direction of displacement due to the deforming force of the lumbricals. Malunion in this plane, or less frequently in the coronal plane, can be corrected with a simple opening or closing wedge osteotomy at the site of deformity. A closing wedge osteotomy risks a relative amount of shortening of the metacarpal, which could lead to extensor lag if significant shortening were to occur. As a benefit however, this treatment approach only requires a single bone interface to heal after fixation. An opening wedge osteotomy on the other hand avoids loss of length but is not without its own inherent risks. Two bony interfaces are required to heal after fixation and an interposition graft is required. There is subsequent donor site morbidity and a slightly higher risk of failed union [118, 119]. After performing the chosen osteotomy, fixation is required for adequate healing. This can be achieved through the use of K-wires, interosseous wires, or most frequently a rigid plate and screw construct. Use of a T-plate or mini fragment plate allows for early postoperative mobilization and helps minimize stiffness and loss of range of motion.

Rotational deformity is very poorly tolerated at the level of the metacarpals and can result in significant functional impairment. Deformity in this plane can be corrected at the base of the metacarpal or through the malunited fracture site. Alternatively, a z-shaped step-cut osteotomy can be used to correct the deformity [120, 121]. Using this technique, a wedge of bone is removed longitudinally to allow for varying amounts of derotation and the fragments are then fixed with lag screws or cerclage wires. However, given the constraints of deep intermetacarpal ligaments, only up to 18° of correction can be achieved in the index, middle, and ringers and up to 30° in the small finger [100].

When there is bone loss secondary to crush, blast injuries, or soft tissue stripping resulting in devitalized bone, significant shortening may result if not addressed at the time of presentation. Temporizing these types of injuries allows for a relatively simpler reconstruction when soft tissues are amenable. Initial thorough debridement and damage control in the form of external fixation, bridge plating, or K-wire fixation into adjacent metatarsals is often indicated [122]. Delayed primary bone grafting with a corticocancellous graft sized to the defect and rigid plate and screw fixation is used for definitive treatment.

Intra-articular malunions may involve the head or the base of the metacarpal. In addition to having the potential to cause disability through angulation or rotational malalignment that limits range of motion, accelerated joint degeneration and posttraumatic arthritis may result from these fractures if the articular surface is not congruently reduced. The former may be treated with an extra-articular opening or closing wedge osteotomies as malunions of the shaft are treated. Articular step-offs or incongruity should be corrected as soon as possible however in order to limit joint degeneration and irreversible arthrosis [123]. When intra-articular fractures result in a condylar split or have simple fracture lines with relatively sizeable fracture fragments, reduction and interfragmentary fixation is possible. However, more complex fractures with comminution or impaction of the articular surface cannot be treated this way. In these scenarios an osteotomy may be advanced into the metacarpal shaft in order to create a large fragment for advancement and fixation. The advancement osteotomy is then back filled with bone graft for support. The entire construct is then fixed with a minicondylar plate or T plate [115]. With intra-articular malunions involving the metacarpal base, advancement osteotomy is not indicated however. These deformities are best treated with arthrodesis of the carpometacarpal joint to alleviate painful arthrosis with little functional deficit through the ray [94].

The most common deformity in the proximal phalanx resulting from phalangeal shaft fractures is apex volar angulation. This is due to the imbalanced pull of the lumbricals and the extensor tendons, which typically counteract each other. Beyond 15° of angulation, relative shortening of the extensor mechanism may result in extensor lag, and beyond 25° can result in pseudoclawing and proximal interphalangeal joint contractures [124]. Malunion may also less commonly result from lateral angulation or shortening. Treatment of each of these deformities is ideally achieved at the site of malunion prior to the onset of the deleterious effects of soft tissue attenuation. Closing wedge osteotomies at the fracture site are ideally used and secured with a straight plate or T plate though interosseous wiring is also an option [118, 119]. If there is concern for excessive shortening should a closing wedge osteotomy be used, an opening wedge osteotomy with interposed bone graft is also an option.

The deformity needing to be addressed in the middle phalanx is often dependent on the location of the fracture lines relative to the insertion of the flexor digitorum superficialis tendon. Those fractures proximal to the insertion of the tendon tend to result in an apex dorsal deformity, while those distal to the tendon insertion result in a characteristic apex volar deformity. Again, lateral angulation or shortening may also occur though less commonly. As with the proximal phalanx, treatment of each deformity is ideally achieved through the site of the original fracture with a closing wedge osteotomy and held in place with a rigid plate. Opening wedge osteotomies may also be used if additional shortening cannot be tolerated [118, 119].

Long oblique or spiral fractures of both the proximal and middle phalanges more commonly result in malrotation than simple angulation deformity [116]. These deformities may be quite functionally debilitating and often require correction. Derotation osteotomies can be used through the metacarpal base although this is a more dated approach to treating this type of malunion [116]. With the advent of lower profile plates and screws, the correction of a malrotated malunion of the proximal and middle phalanx is more effectively achieved at the level of the phalanx itself with a transverse osteotomy, derotation, and fixation with a 1.3 mm or 1.5 mm plate [118].

Malunion at the distal phalanx rarely results in functional deficit [125]. Deformity may be angular or rotational but when healed is infrequently limiting to the function of the hand. Cosmetic deformity at this level of the digit is generally not an indication for treatment of a healed malunion without pain. When there is a functional deficit as a result of distal phalanx malunion, osteotomy and fixation with K-wires or headless screws is the treatment of choice [118]. Articular malunion that results in impaired grip through instability or a painful joint should be treated. The treatment of choice is a formal arthrodesis through the distal interphalangeal joint [125].

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8 Malunions of the Acetabulum and Pelvis

Kyle F. Dickson

8.1 Introduction

Malunions and nonunions of the pelvis present challenging problems for both the patient and the surgeon. Though optimal initial care can potentially prevent these complications, nonunions and malunions still occur [1–10]. Tile estimated a 5% incidence of residual severe deformity in major disruptions of the pelvic ring [11]. However, nonoperative management of vertically unstable pelvises can lead to malunions and nonunions in 55–75% of cases [3, 6, 12, 13]. In the case of acetabular fractures, nonunions are only seen in 0.7% of operatively treated acetabular fractures [14]. Deteriorating results are seen if operative treatment is delayed [15].Though optimal initial care can potentially prevent these complications, in some clinical scenarios, other patient factors such as soft tissue injuries prevent surgical intervention causing a malunion or a nonunion (Fig. 8.1a). If early surgical intervention can be performed, anatomical reduction can in most cases prevent malunions and nonunions.

When evaluating a patient with a pelvic malunion or nonunion, a thorough workup is required to identify the cause of the patient's pain, define the deformity of the pelvis, review the expectations of the patient, and plan treatment. In nonunions, associated medical morbidities need to be diagnosed and corrected before surgery (i.e., malabsorption, vitamin D deficiency, diabetes, etc.). The amount of peer-reviewed literature on the subject is very small. Data from our publications [1, 5, 10, 13] are used to highlight points of assessment (i.e., physical exam, radiology, definition of deformity) and management of these difficult and potentially disabling problems. The key to surgical treatment is to define the deformity and perform an adequate release of the soft tissue/bone so anatomical reduction can be achieved.

Malunions and nonunions of the acetabulum present an order of magnitude more difficult problem than malunions of the pelvis due to the need for perfect reductions of the acetabular cartilage. In the case of acetabular fractures, deteriorating results are seen if operative treatment is delayed [15]. The acetabulum portion of this chapter could also be titled, "delayed treatment of acetabular fractures using the extended iliofemoral (EIF) approach" due to the fact that most of the time the EIF is chosen because there is a delay in treatment. An ilioinguinal (II) or Kocher-Langenbeck (KL) may not allow the opposite or indirect column to be anatomically reduced due to callous formation. Simultaneous II and KL approaches could be an alternative to the EIF. However, in the established acetabular approach, simultaneous II and KL will not give adequate release to achieve anatomical reduction. Sequential approach will be effective if the second approach is an EIF (Figs. 8.1 and 8.2). Because a continuum exists, the actual definition

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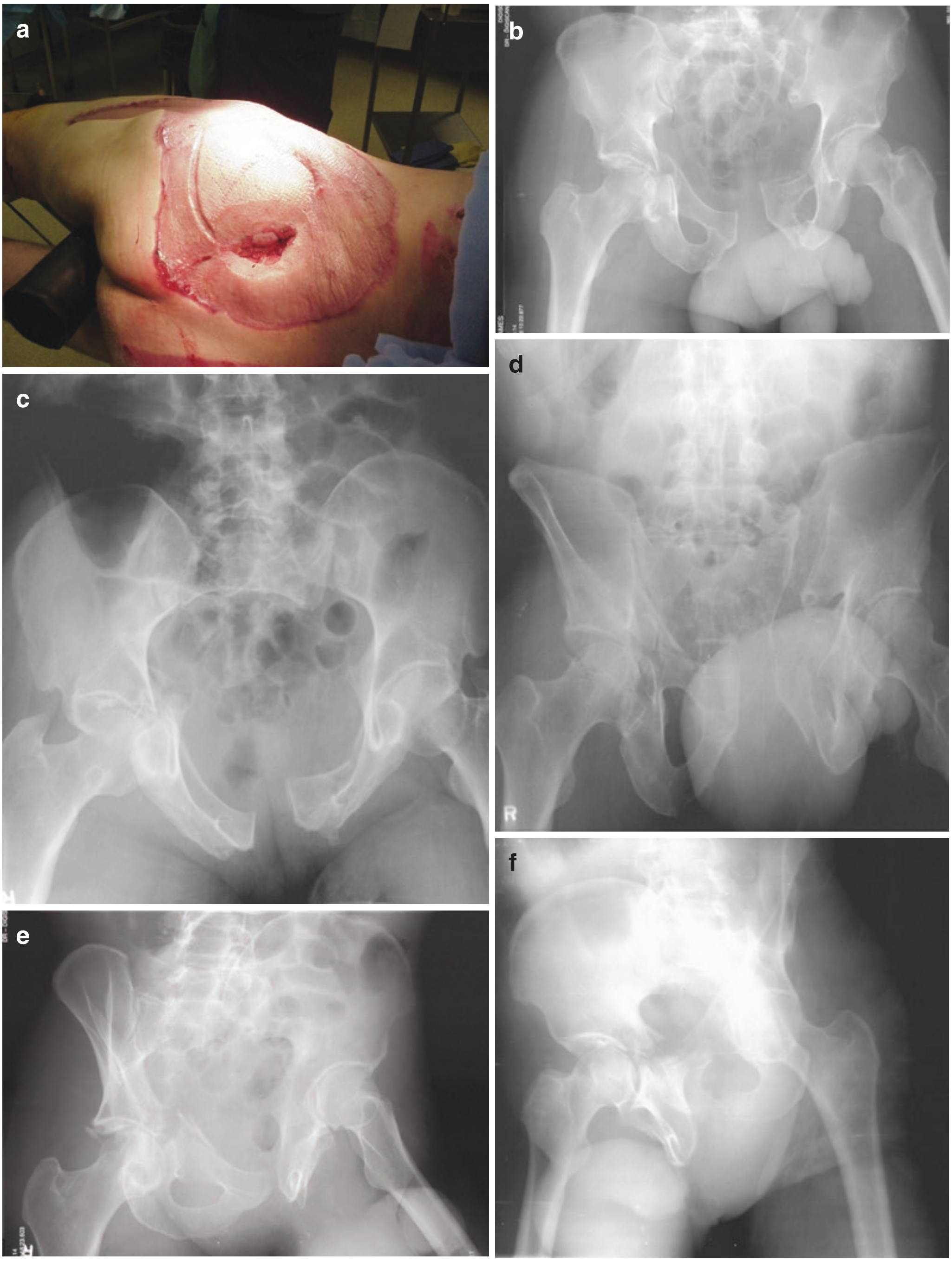


Fig. 8.1 Patient with combined left pelvic ring disruption and right "T-"type acetabular fracture. Treatment was delayed 3 months secondary to a fungal infected Morel-Lavallee lesion. (**a**) Clinical photograph of fungal infection at surgical site. (**b–f**) AP, inlet, outlet, obturator oblique, and iliac oblique X-rays of the pelvis at the time of injury. (**g**) Axial CT scan image demonstrating left SI joint injury. (**h**) Axial CT scan image demonstrating a right T type with posterior wall acetabular fracture. (**i**) Postoperative AP X-ray of the pelvis following anterior release of both the anterior SI joint and the anterior column of the T-type acetabulum fracture (Stage 1) and posterior release with reduction and fixation of the SI joint (Stage 2). (**j–l**) AP, obturator oblique, and iliac oblique X-rays of the pelvis after posterior release of the posterior wall and column of the T type and ORIF of the acetabulum using an extended iliofemoral approach (Stage 3) and ORIF of the anterior pelvic ring (Stage 4)

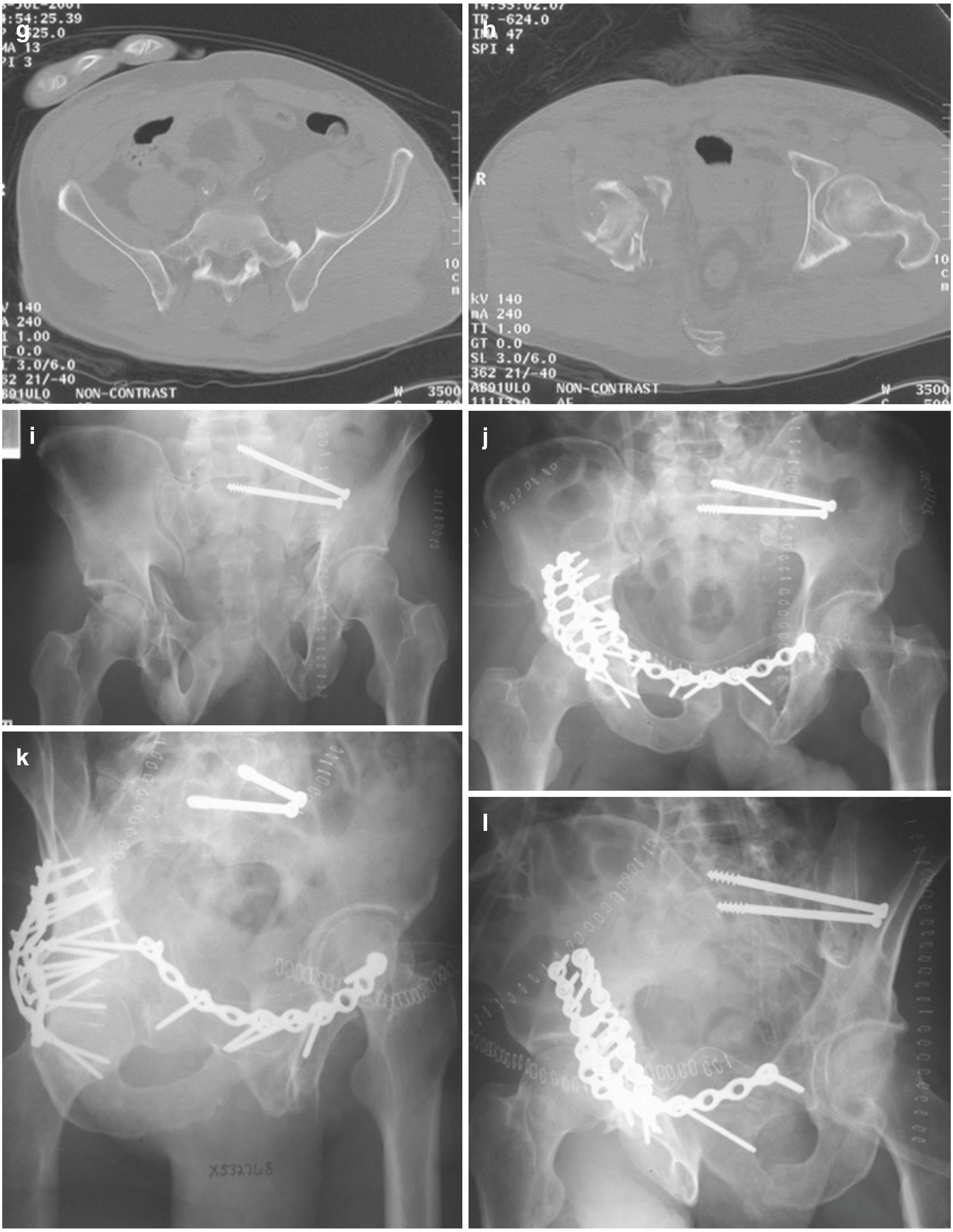


Fig. 8.1 (continued)

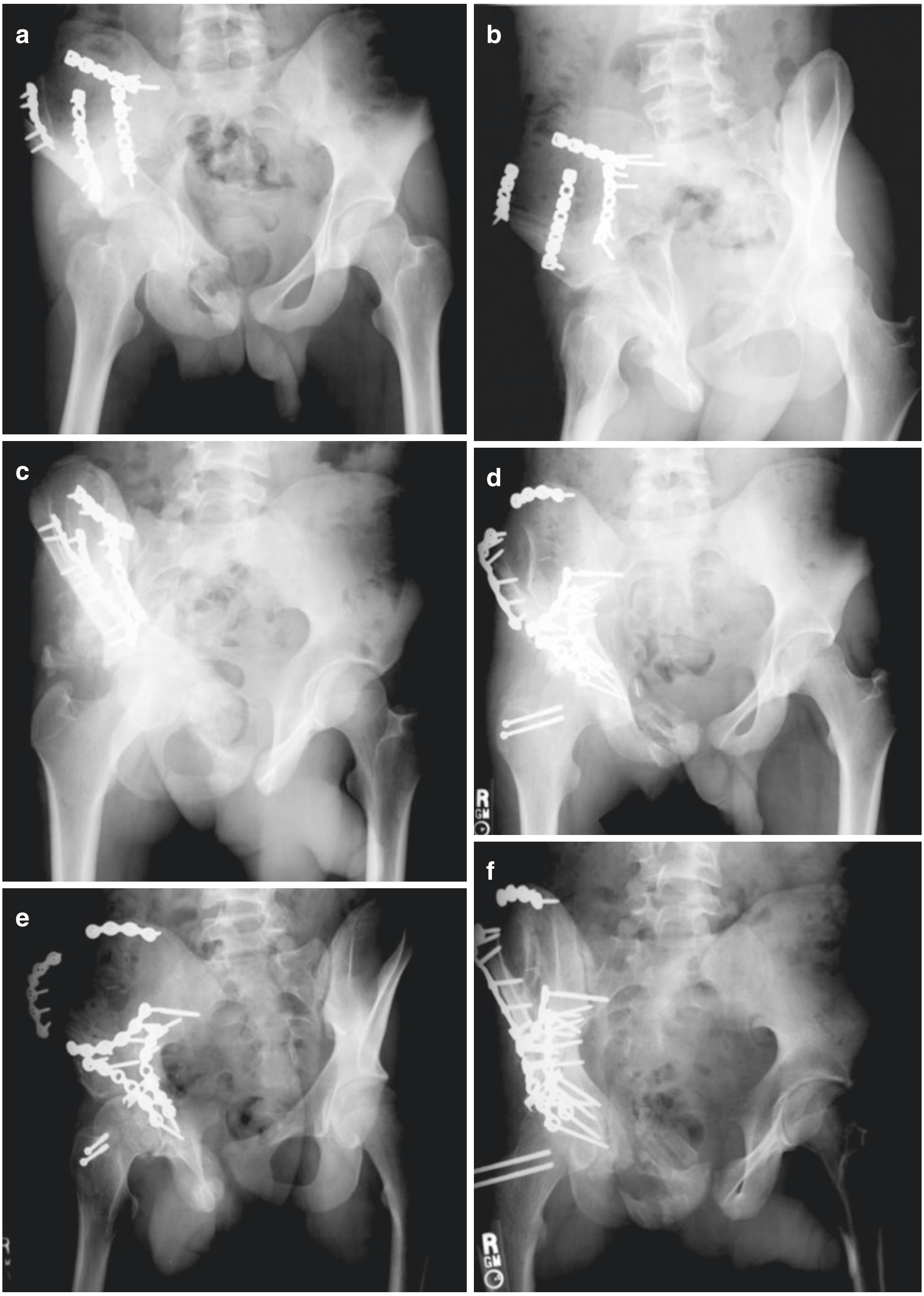


Fig. 8.2 Patient with an associated both-column acetabular fracture who presented >3 months post injury after initially being treated at another institution. (**a–c**) AP, iliac oblique, and obturator oblique X-rays of the pelvis on presentation showing a malunion of both the anterior and posterior column. (**d–f**) Postoperative AP, iliac oblique, and obturator oblique X-rays of the pelvis following a two-stage reconstruction. Hardware and callous were removed through an ilioinguinal approach with an osteotomy of the anterior column (Stage 1) followed by ORIF of the acetabulum and pelvis through and extended iliofemoral approach (Stage 2). (**g–i**) AP, iliac oblique, and obturator oblique X-rays of the pelvis at 3 years postoperative. Patient ambulating without pain

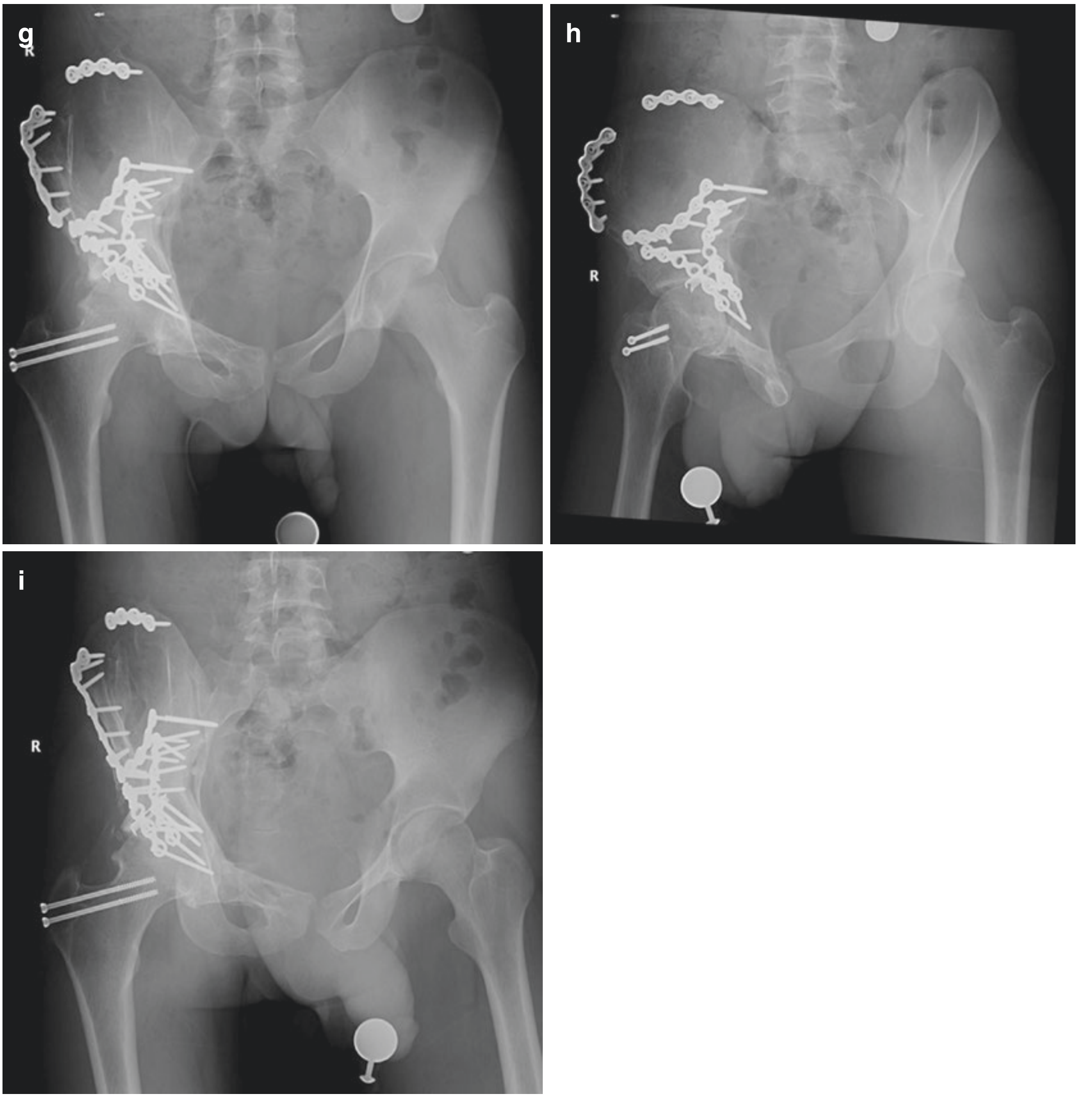
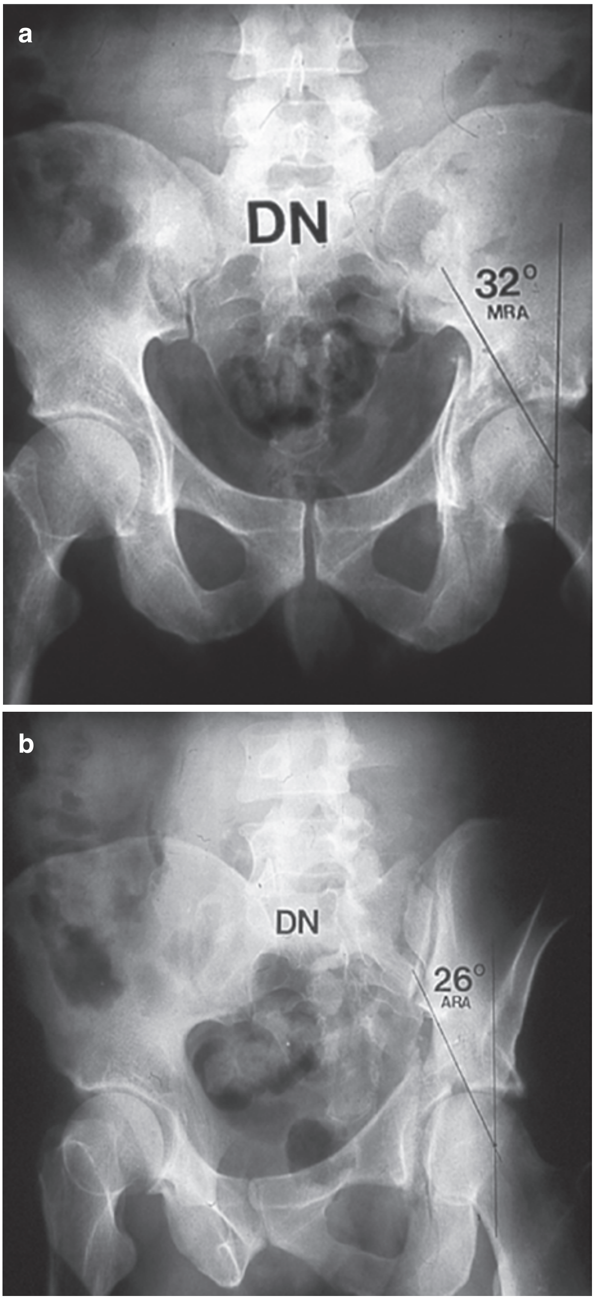


Fig. 8.2 (continued)

of delayed fixation is difficult. For transtectal transverse (Tr) and "T" fractures, a delay of more than 5 days can make the opposite column anatomical reduction impossible, that is, the anterior column through the KL approach or the posterior column through the II approach (Figs. 8.3 and 8.4). Most other acetabulum fractures can be operated on within 2 weeks without added problems. Letournel felt there was a significant increase in difficulty operating on the acetabulum after 3 weeks [14]. When evaluating a patient with a malunion of an acetabular fracture, a workup is required to define the deformity of the acetabulum, review the expectations of the patient, and determine whether the patient has a salvageable hip or whether the patient would be better served with a total hip arthroplasty (THA). If a THA is indicated, the surgeon must decide whether an in situ THA can be performed with adequate bone stock (typically a nonunion exists that requires stabilization prior to a THA) or osteotomies and soft tissue releases are required to reduce the columns



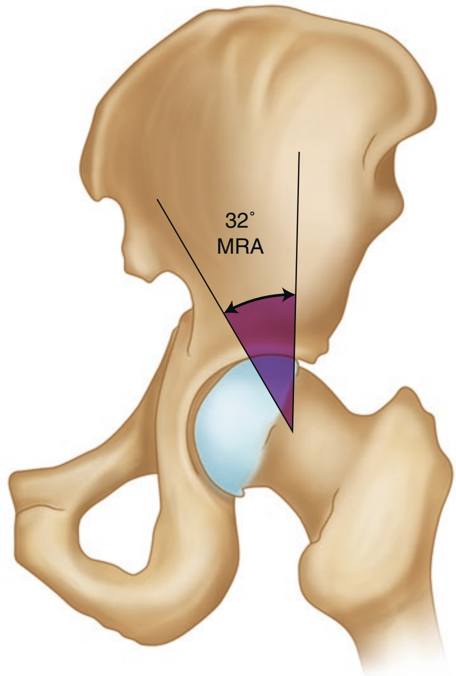


Fig. 8.3 Delayed reduction of a T-type (posterior column anterior hemitransverse) acetabular fracture. (**a**) AP radiograph of a T-shaped (technically a posterior column anterior hemitransverse classified in the T-shape category by Letournel) 4 weeks after the injury showing a medial roof arc of 32 degree. (**b**) Obturator oblique radiograph showing an anterior roof arc of 26°. (**c**) An iliac oblique radiograph showing a posterior roof arc of 40°. (**d**) CT scan showing the extensive callous already present and immediate postoperative AP after an extended iliofemoral approach (without a greater trochanteric osteotomy)

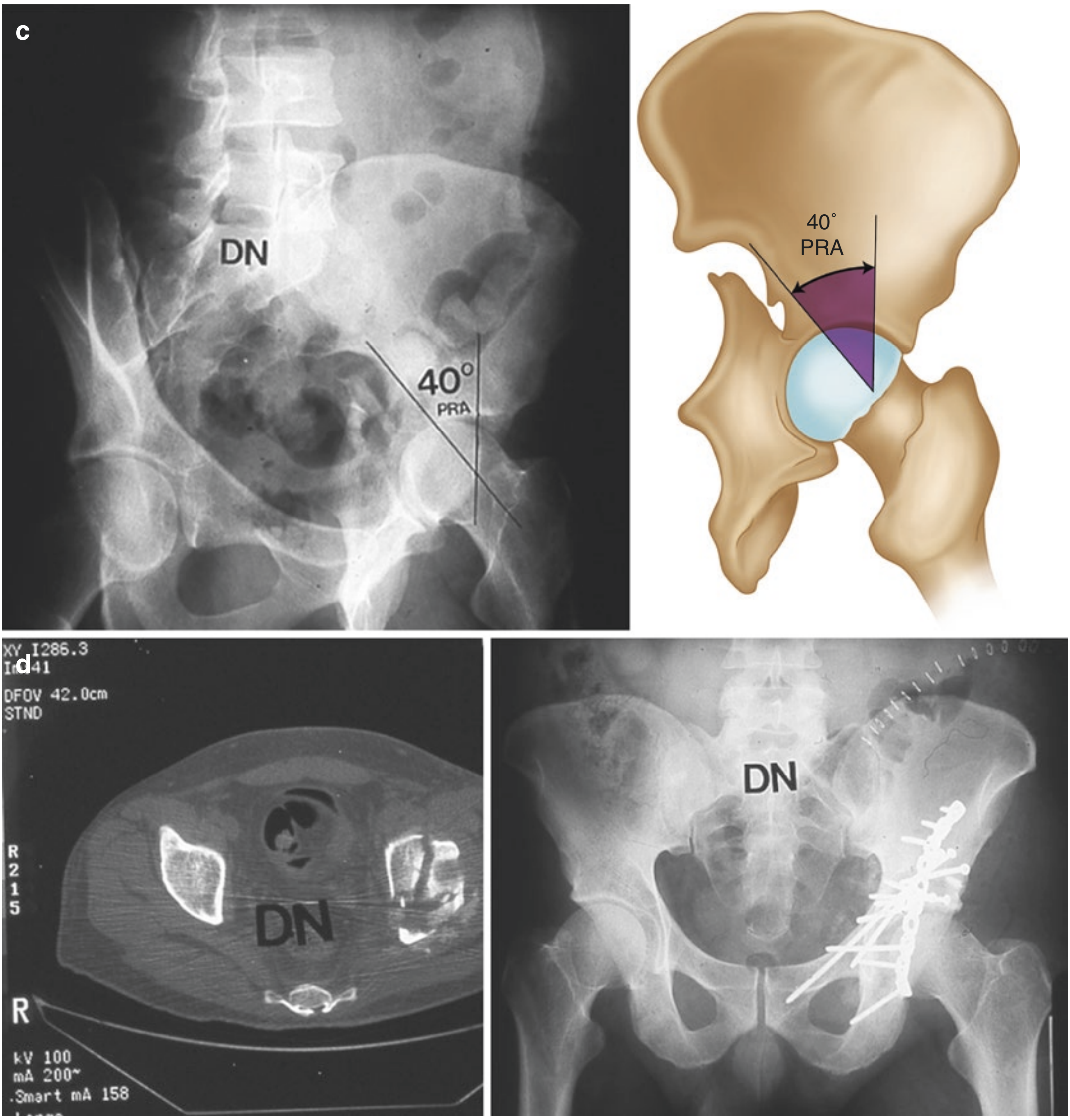


Fig. 8.3 (continued)

(i.e., a severe protrusio to lateralize the hip) prior to doing a THA. This chapter will focus on the salvageable hips. The amount of peer-reviewed literature on the subject is very small but with detailed cases that will highlight the points of assessment (i.e., physical exam, radiology, definition of deformity) and management of these difficult and potentially disabling problems [4, 7, 9, 10]. The mindset of the surgeon who is going to undertake these difficult surgeries on the acetabulum is not to make them better but to make them anatomical. Otherwise the complications are too high and conservative treatment is indicated.

8.2 Clinical Assessment Pelvis

Indications for surgery include pain, pelvic ring instability, and clinical problems relating to the pelvic deformity (gait abnormalities, sitting problems, lying problems, limb shortening, genitourinary symptoms, vaginal wall impingement, etc.).

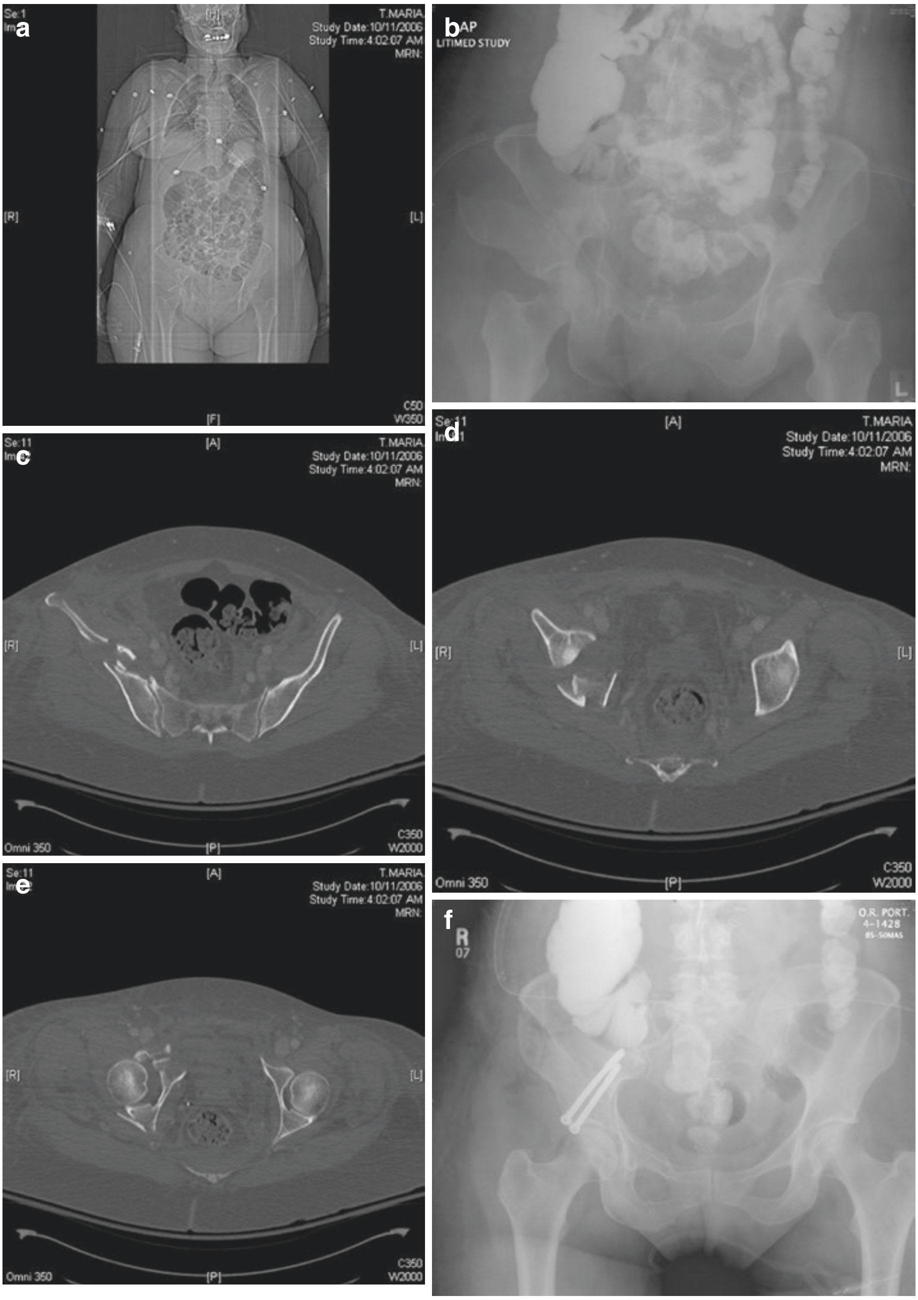


Fig. 8.4 Patient failed percutaneous fixation of a both-column posterior wall acetabular fracture. A 52-year-old with a history of obesity, hypertension, and fibromyalgia who suffered an MVA that included a crush foot. (**a**) CT scout film showing the size of the patient; (**b**) AP radiograph showing a both-column fracture with displacement of both the anterior and posterior column and some femoral head protrusion; (**c**) 2D CT showing the comminuted fracture of the wing; (**d**) 2D CT showing the anterior and posterior column with the intact portion of the iliac wing ("spur sign"); (**e**) 2D CT showing the anterior wall comminution and the long posterior spike of intact iliac wing with proximal displacement of the posterior column; (**f**) initial AP radiograph postoperative showing significant displacement of the crest and the separation of the iliopectineal and ilioischial line confirming a unacceptable intra-articular reduction. (**g**) AP radiograph verifying further loss of an already poor reduction with protrusion of the femoral head; (**h**) the preoperative drawing for revision of the both-column fracture; (**i–k**) AP, iliac oblique, and obturator oblique radiographs post extended iliofemoral approach, anatomical reduction of the joint, and fixation; (**l**) AP radiograph 3 years postoperative. The patient is 5 years postoperative without hip pain but with some pain in the opposite foot after the crushing injury

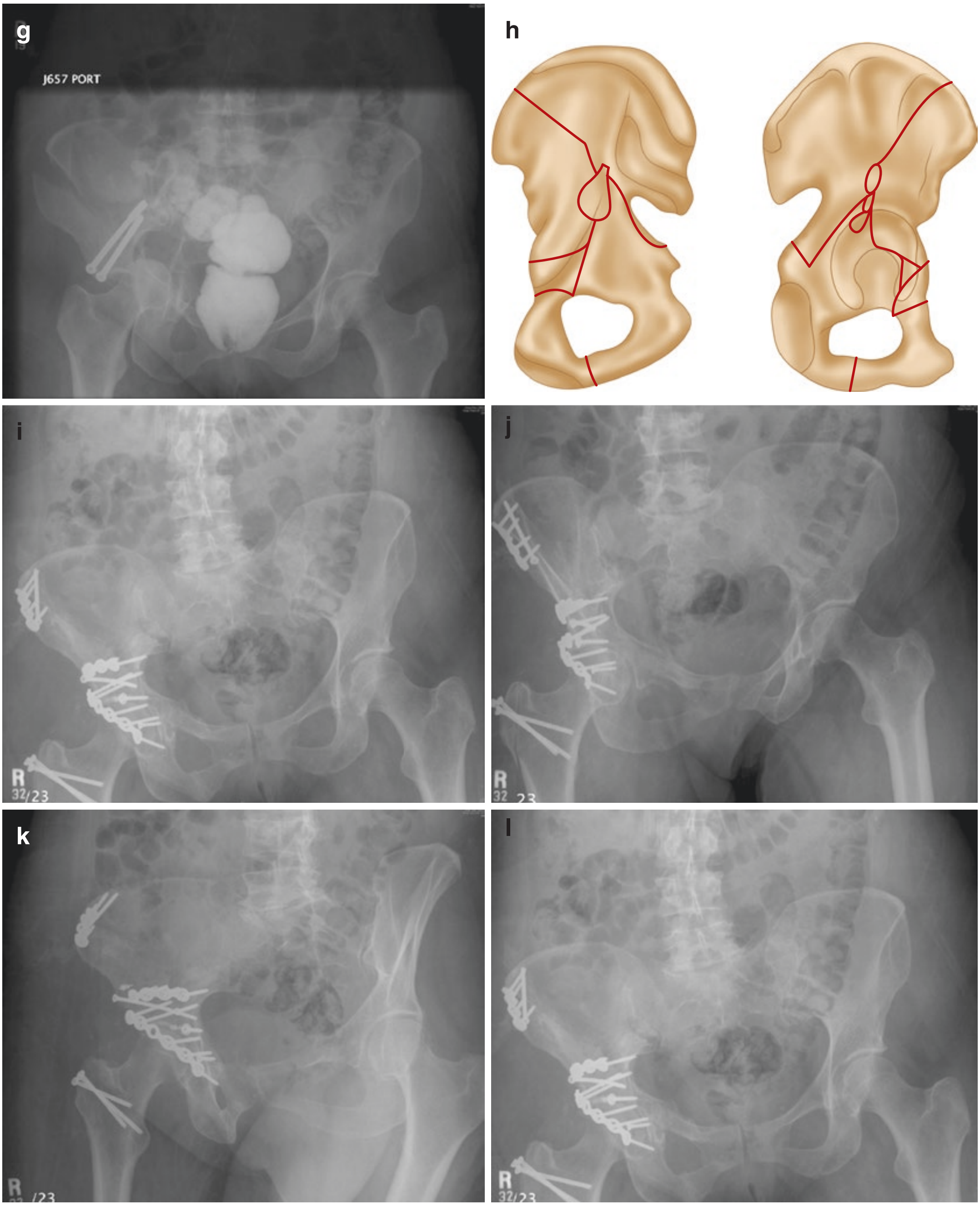


Fig. 8.4 (continued)

8.2.1 Pain

Although pain is not always present in malunions and nonunions, it is often the primary reason for a patient to seek medical consultation. The pain is commonly secondary to instability of the pelvis, or malreduction, and is most frequently located posteriorly in the sacroiliac (SI) region [4]. Posterior pelvic pain associated with malunion often improves after correction of the malunion, although the reason for this is less apparent than with correction of nonunions [1, 2, 8, 13]. Direct compression/irritation of the lumbosacral trunk or lumbar roots can be so intense that ambulation is not possible due to the pain (Figs. 8.5a–d). Some residual chronic pain often occurs even after anatomical reduction of malunion. In an acute injury, instability is readily apparent on physical examination of the pelvis. This is more difficult to appreciate in chronic malunions and nonunions. In these situations, the physician's hands are placed on each of the anterior superior iliac spine (ASIS) and the pelvis is rocked from side to side. Subtle motion and/or posterior pain of the pelvis can be detected in this manner. In these chronic cases, radiographic single-leg stance anteroposterior (AP) views are usually more helpful as will be reviewed later.

Pain secondary to malunion or nonunion of the pelvis is often present during weight-bearing and improves with rest. Because weight is transmitted posteriorly through the pelvis, pain is more commonly associated with sacroiliac joint (SI) malunions and nonunions. Malunions and nonunions of the anterior pelvic ring are rarely painful because less than 10% of the body's weight is transmitted through the anterior part of the pelvis [11]. When the rare case of a painful malunion or nonunion of the anterior pelvic ring does present, it is often following a protracted course and multiple consultations with medical specialists (gynecologists, general surgeons, urologists, rheumatologists, etc.; see the chapter in the 2018 companion book on nonunions [16]). The patient may also experience low back pain secondary to the pelvic deformity or neurogenic pain that radiates to the ankle secondary to compression, injury, or distraction of the nerves at the level of the roots or the lumbosacral plexus. Scarring within the nerve is a common cause of chronic pain.

Patients may also complain of pain while sitting or lying (Fig. 8.6a–e). The pain can be caused by either partial motion at the nonunion site (i.e., a nonunion of the ischium) or a fixed malunion (i.e., a vertically elevated ischium). The sitting imbalance is caused by different heights of the ischial tuberosity (Fig. 8.8h and see Fig. 8.6h). AP radiographs are often used to determine these height differences. Lying imbalance often occurs when there is an internal rotation and/or a vertical migration of one of the hemi-pelvis, and this makes the posterior superior iliac spine (PSIS) prominent on that side (Fig. 8.8a–d and see Fig. 8.7a, b). However, posterior or anterior displacement of the hemi-pelvis can also occur either with or without vertical translation of the hemi-pelvis causing prominence of the PSIS.

8.2.2 Deformity

Pelvic deformity is responsible for complaints in many clinical areas, that is, pain, gait abnormalities, genitourinary system, etc. The most common deformities include cephalad and posterior translation and internal rotation of the hemi-pelvis [1, 2, 5, 13]. One can often appreciate the deformity by physical exam. With significant cranial displacement of the hemi-pelvis, a constant cosmetic deformity is observed. As the patient stands and faces either toward or away from the examiner, the shortened side appears flattened with the trochanteric area medialized. Conversely, the normal (opposite) side has the appearance of an exaggerated outward curvature of the hip. Nonobese, female patients will have typically identified this deformity and complained about it. This deformity will be exaggerated by further innominate bone displacement – such as adduction or internal rotation (see Fig. 8.6a–c).

Other patients complain of posterior prominence. The patients notice this when lying supine due to lying imbalance. This deformity can be seen by comparing the posterior superior iliac spines (PSISs) while the patient lies prone. The main cause of posterior prominence of the PSIS is from an internal rotation deformity of the innominate bone which causes PSIS to become more prominent (see Figs. 8.6a–c and 8.8a–d). However, this condition can also occur from posterior translation of the innominate bone. Furthermore, cranial displacement of the hemi-pelvis results in the sacrum and coccyx becoming

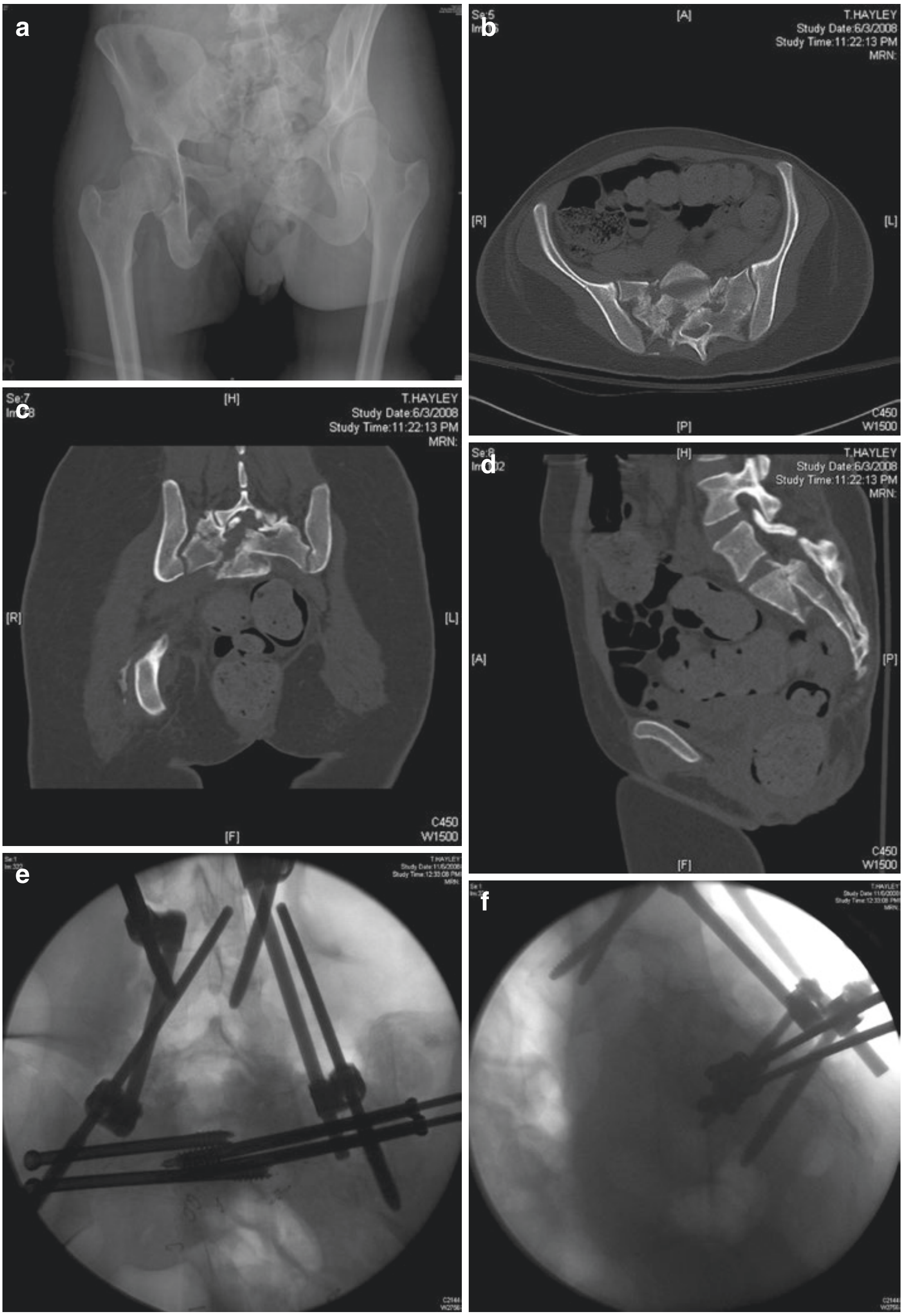


Fig. 8.5 Patient with H-type fracture pattern of the sacrum. She presented 6 months post-injury with pain and inability to walk. (**a**) Initial 6-month post-injury AP radiograph. (**b**) Axial CT scan image. (**c**) Coronal CT scan image. (**d**) Sagittal CT scan image. (**e**,**f**) AP and LAT intra-operative fluoroscopy images demonstrating use of lumbar-pelvic fixation for reduction. After anterior bilateral sacral osteotomies and posterior completion of the sacral osteotomies and release of ligaments, reduction is performed by hyperextension of bilateral lower extremities, spinopelvic distraction along bent rods that reduce the kyphotic deformity and levering the top of S2 under S1 with a cobb between the nerve roots posteriorly. Two iliosacral screws are placed bilaterally and the reduction spinopelvic fixation is removed during the surgery. (**g**) Postoperative sagittal CT scan image illustrating reduction of the sacral fracture. (**h**) Postoperative AP radiograph. Patient now >5 year postoperative and walking with minimal posterior pain (no narcotic or NSAIA use)

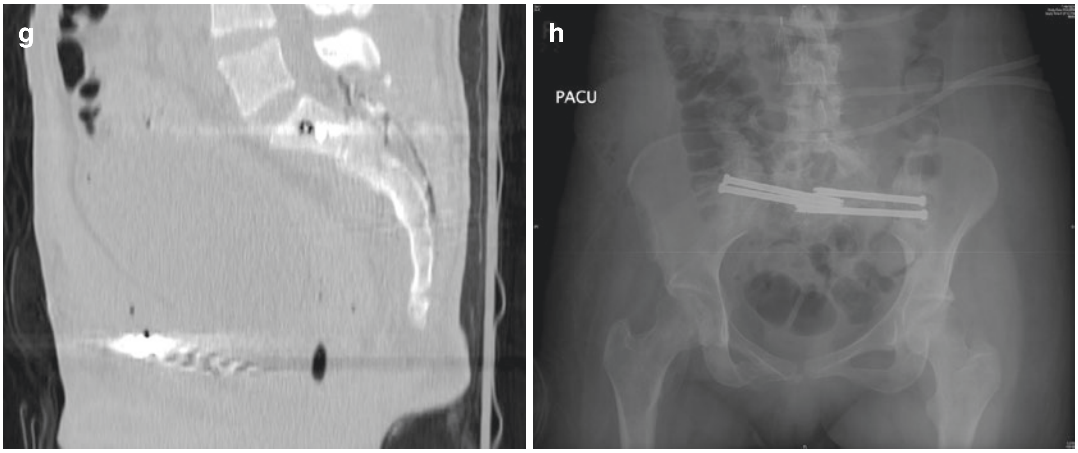


Fig. 8.5 (continued)

relatively more prominent, and this bony prominence can be symptomatic (see Fig. 8.6a–c). Sacral prominence can become particularly severe with bilateral hemi-pelvis displacement (“U” or “H” patterns) (see Fig. 8.5a–d). We have seen numerous cases where this sacral prominence causes skin breakdown.

This cranial displacement also creates sitting problems and is especially noticeable when sitting in hard chairs (see Fig. 8.7a, b). The sitting imbalance is due to the ischium being at different heights. In addition to vertical migration of the hemi-pelvis, this condition may be caused by a flexion/extension deformity of the hemi-pelvis (see Fig. 8.6a–c). The patient is often observed leaning toward one side while sitting, though the direction he/she leans is not always consistent. The patient will lean toward the short side when attempting to sit on each buttock equally. Some patients with severe deformity will sit only on the uninjured side and lean away from the cranial displaced hemi-pelvis. Other patients are observed to shift their position frequently or place their hand under the cranially displaced side for support.

Gait abnormalities can also be caused by malunions. Cranial displacement causes shortening of the ipsilateral extremity. In our study of pelvic malunions resulting from unstable vertical fractures, the average leg-length discrepancy was greater than 3 cm with a range of up to 6 cm [1, 5]. The malunited pelvis may also cause an internal or external deformity of the lower extremity that alters the patient’s gait. For instance, in Fig. 8.6b, the patient has a windswept pelvis, where one side is internally rotated and the other side is externally rotated, and the patient feels that they are “walking crooked.”

8.2.3 Genitourinary System

With significant internal rotation of the hemipelvis or a rotated and displaced rami fracture, impingement of the bladder/vagina can occur. This is usually caused by the superior rami which can heal in a malrotated position causing impingement. Symptoms of impingement include frequency, urgency, and hesitancy. The workup should include a retrograde urethrogram and cystometrogram.

In very unusual cases, the ischium may displace so far medially that it causes impingement on the wall of the vagina and subsequent dyspareunia. Clitoral stimulation with weight-bearing secondary to an unstable pubic symphysis has also been described [11]. In addition, herniation of bowel through the rectus abdominis, or herniation of the bladder through the symphysis pubis is possible.

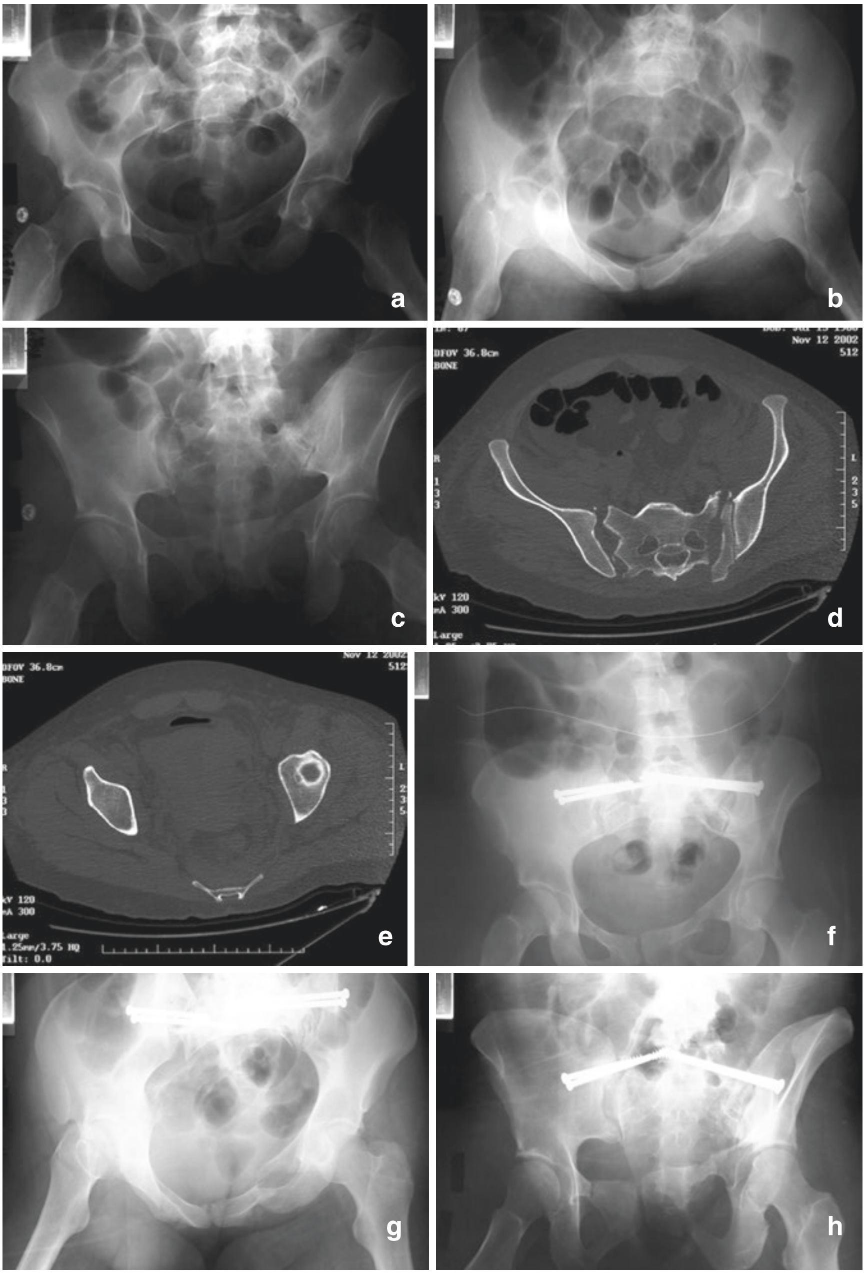


Fig. 8.6 Patient with windswept pelvic malunion presented 1-year post injury with pain, deformity, and feeling as if they were "walking crooked. " (**a**–**c**) AP, inlet, and outlet X-rays of pelvis from the time of injury. (**d**) Axial CT-scan image demonstrating bilateral sacral injuries. (**e**) Axial CT-scan image demonstrating initial rotational deformity. (**f**–**h**) AP, inlet, and outlet X-rays of pelvis following initial fixation with sacroiliac screws that did not address the deformity. (**i**) Intraoperative photos illustrate the application of femoral distractors to create the necessary force vectors for correction of the deformity. This was the second part of a two-stage procedure. The first stage involved removal of the SI screws. In the second stage, bilateral sacral osteotomies were performed in conjunction with anterior and posterior pelvic fixation. A wedge of bone was removed from the osteotomy site on the right side and used to graft the opposite left side. (**j**–**l**) AP, inlet, and outlet X-rays of pelvis 18 months postoperative. The patient was back to work walking normal without pain. (**m**) Patient prone with right pelvis and femur fixed to the bed (half pins are placed into the PSIS and trochanter) so the left side can have skeletal traction to reduce vertical translation

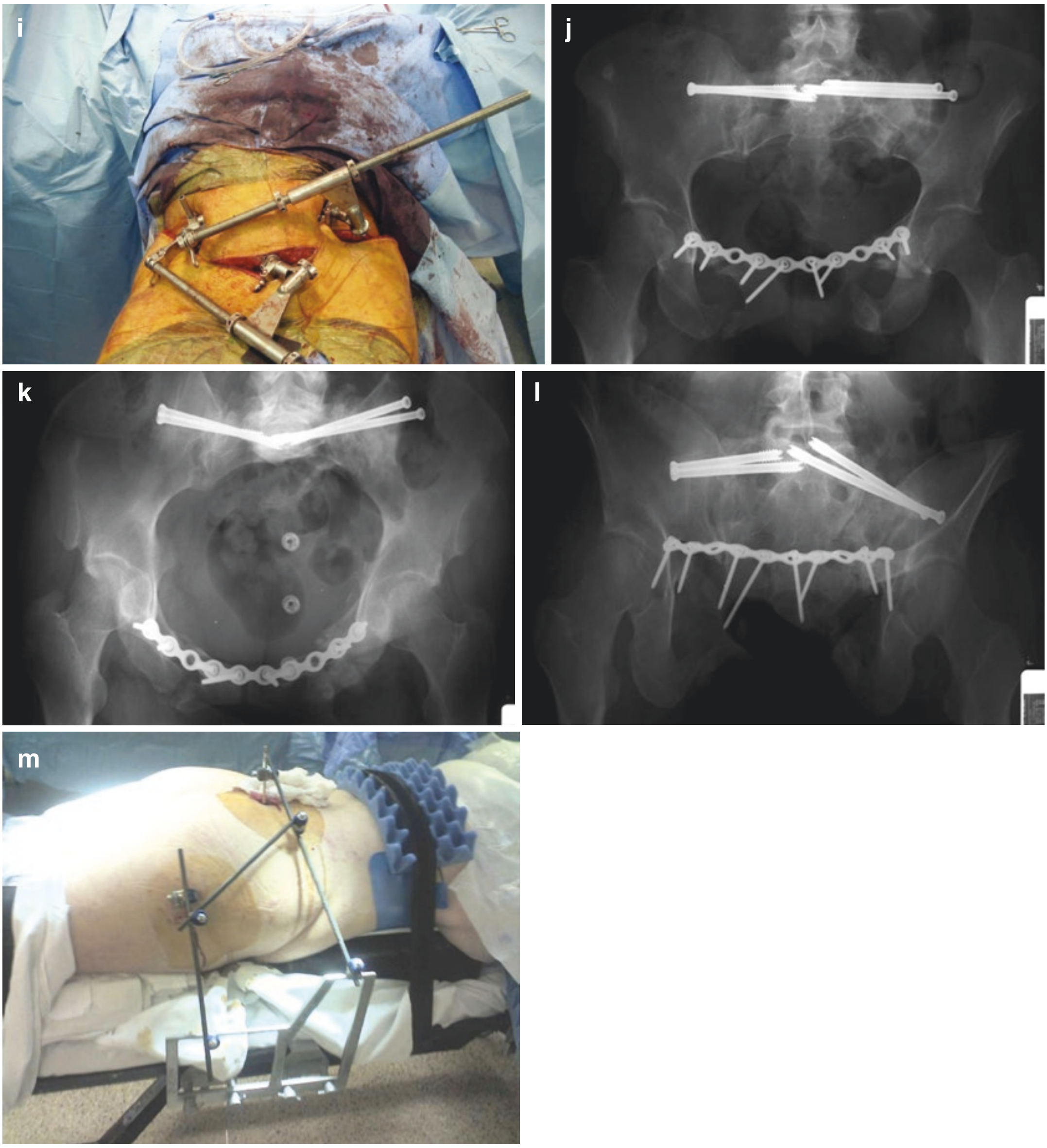


Fig. 8.6 (continued)

8.2.4 Neurologic Injuries

Permanent nerve damage is a common cause of disability following pelvic injuries. A nerve injury occurs in 46% of the patients with an unstable vertical pelvis [15]. The most commonly affected nerve roots are L5 and S1, but any root from L2 to S4 may be damaged. In Huittinen's study of 40 nerve injuries, 21 (52.5%) were traction injuries, 15 (37.5%) were complete disruptions, and 4 (10%) were compression injuries [15]. Interestingly, the lumbosacral trunk and superior gluteal nerve sustained traction injuries while most of the disruptions occurred in the roots of the cauda equina. Compression injuries occurred in the upper three sacral nerve foramina in patients with fractures of the sacrum (see Fig. 8.5a–d). Furthermore, the traction and nerve

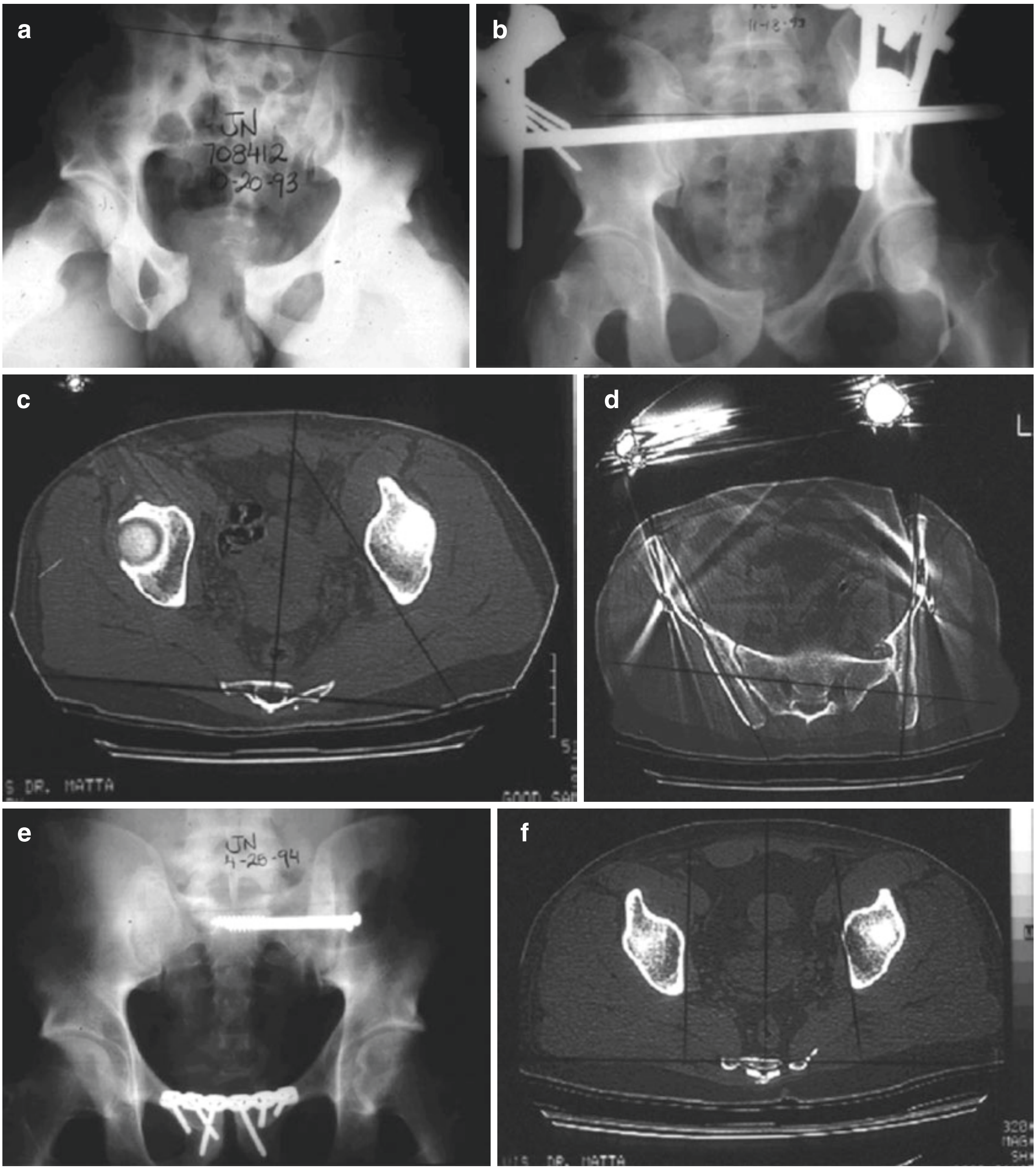


Fig. 8.7 Worsening pelvic reduction with an external fixator placed in an emergent situation for hemodynamic instability. (**a**) Initial AP view of pelvis after a pedestrian versus motor vehicle showing what looks like an open book pelvis. (**b**) Patient was hemodynamically unstable at an outside hospital and an anterior external fixator was placed reducing the pelvis anteriorly but widening the posterior SI joint. (**c**) Axial CT showing an internal rotation deformity of the hemi-pelvis with the anterior external fixator in place. (**d**) Axial CT showing the displacement at the SI joint. (**e**) Postoperative AP view after ORIF through a posterior approach followed by an anterior symphyseal plating. (**f**) Axial CT showing rotational alignment postoperatively. (**g**) Drawing of an axial CT scan cut through the quadrilateral surface, illustrating the technique for measurement of rotational malalignment (normal rotation approximately 7° of internal rotation off the vertical)

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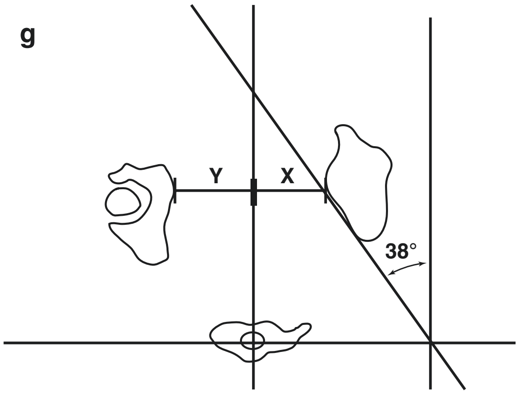


Fig. 8.7 (continued)

disruption injuries occurred in the vertically unstable pelvic injuries, while the compressive nerve injuries occurred following lateral compression of the pelvis. Lateral compression injuries of the pelvis often impact portions of the sacral bone into the foramen resulting in compression of the nerve and may require decompression if neurologic exam worsens.

A thorough neurologic examination is necessary to determine any preoperative deficits and for intraoperative as well as postoperative nerve monitoring. Disruption of peripheral nerves should be evaluated by nerve conduction/EMG tests. Peripheral disruptions may be repaired with some salvage of function or return of protective sensation. Myelograms and magnetic resonance imaging (MRI) are used to rule out spinal nerve avulsions.

Our studies on malunions and nonunions show that 57% of the patients had a preoperative nerve injury and only 16% were resolving postoperatively [1, 5]. Only one patient in our studies would not have the nonunion/malunion surgery again, and this was due to a postoperative nerve complication. The patient underwent two operations on a 16-year-old nonunion that was extremely mobile. An L5 nerve root injury occurred from the vertical reduction or the posterior fixation. The patient required reoperation for persistent nonunion. At the time of the second operation, the posterior fixation was changed. The complaints of deformity were completely resolved, but the patient still suffered from pain in the L5 nerve distribution, despite having a stable pelvis.

8.2.5 Patient's Expectations

An important aspect of the preoperative assessment is to discover a patient's understanding and expectations regarding their clinical problem. Significant discussion is necessary prior to making a decision for surgery. The patient must make the final decision based upon realistic goals and an understanding of the risk of complications. Specific symptoms of deformity such as limb shortening, sitting imbalance, vaginal impingement, and cosmetic deformity are expected to be reliably addressed by surgery. The patient must be cautioned however that while the majority of the deformity can be corrected, the actual anatomical result is usually less than perfect. In our series of pelvic malunions, only 76% of our reductions had less than 1 cm of residual deformity [1, 5].

Posterior pelvic pain in the absence of a demonstrable nonunion or instability is often difficult to explain and may not completely or reliably improve with correction of the pelvic deformity. Ninety-five percent of patients with malunion of the pelvis report improvement of their pain; however, only 21% have complete relief of their posterior pain [1, 5]. Radiographic evidence of sacroiliac joint arthrosis is not a reliable indication of the cause of posterior pelvic pain. However, in patients with a pelvic nonunion, a significant reduction in pain is seen [8].

8.3 Pelvis Radiographic Assessment

Radiographic assessment includes five standard pelvis X-ray views (AP, 45-degree obliques, 40-degree caudad, and 40-degree cephalad), a weight-bearing AP X-ray, CT scan, and a 3D CT. The CT scan can be used to make a three-dimensional pelvic model. This model helps the surgeon to understand the deformity and plan preoperatively. The displacement and the rotation of all fragments needs to be understood so appropriate release and reduction of fragments can be obtained. An obturator oblique clearly shows the sacroiliac joint on the ipsilateral side, while a single-leg weight-bearing AP determines stabil-

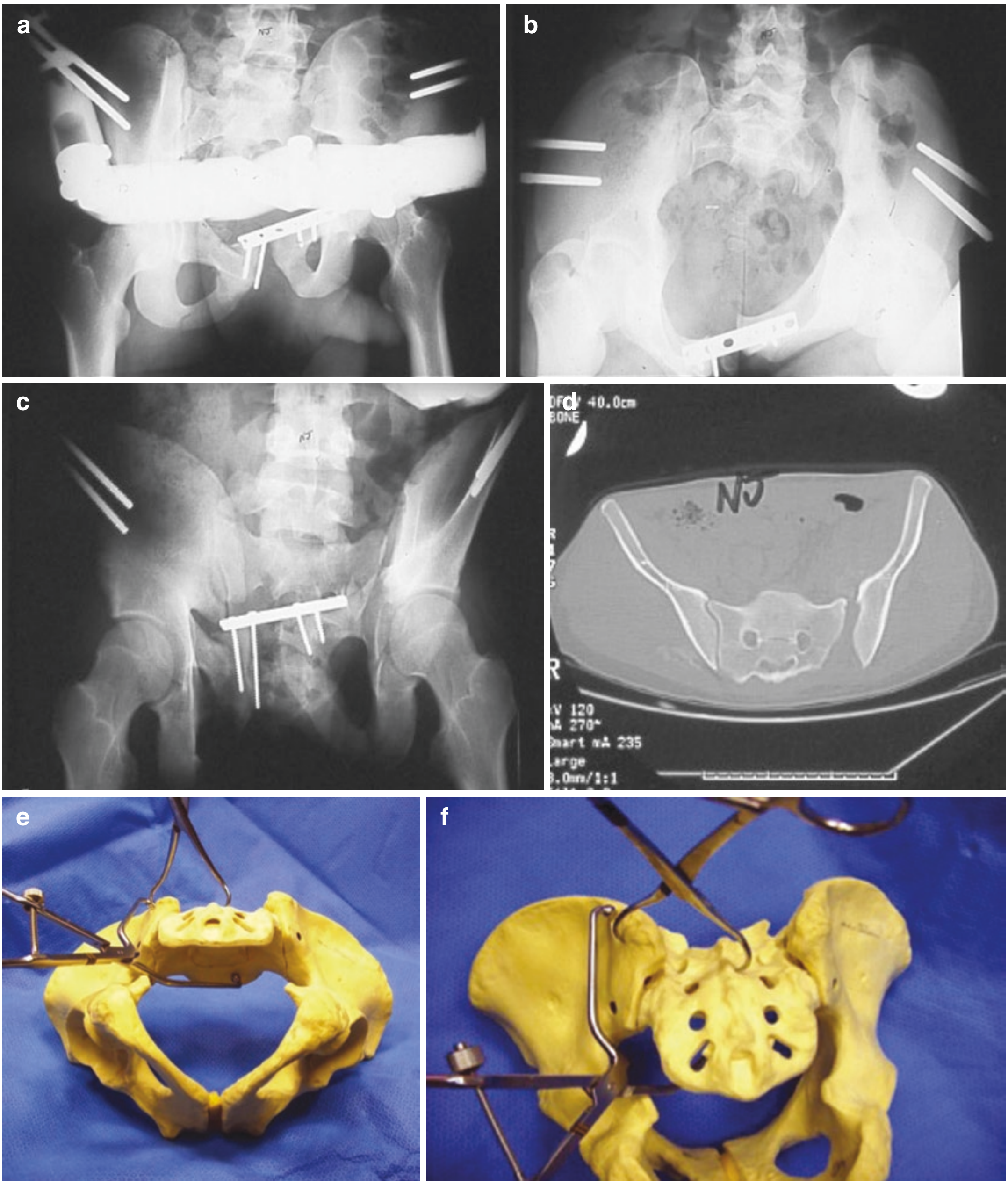


Fig. 8.8 Poor treatment initially of a vertically unstable pelvis. College football player with a vertically unstable pelvic ring injury initially treated at another hospital. (**a**–**c**) AP, inlet, and outlet X-rays of the pelvis >3 months post initial surgery. Fixation is insufficient and pelvis remains malreduced. (**d**) Axial CT scan image demonstrating dislocation of SI joint with some sacral impaction. (**e**,**f**) Images illustrating positioning of clamps for reduction of the SI joint from the posterior approach (Stage 2). (**g**–**i**) AP, inlet, and outlet X-rays of the pelvis following three-stage (anterior/posterior/anterior) revision ORIF of pelvic ring. Patient returned to play football and is without pain >10 years postoperatively

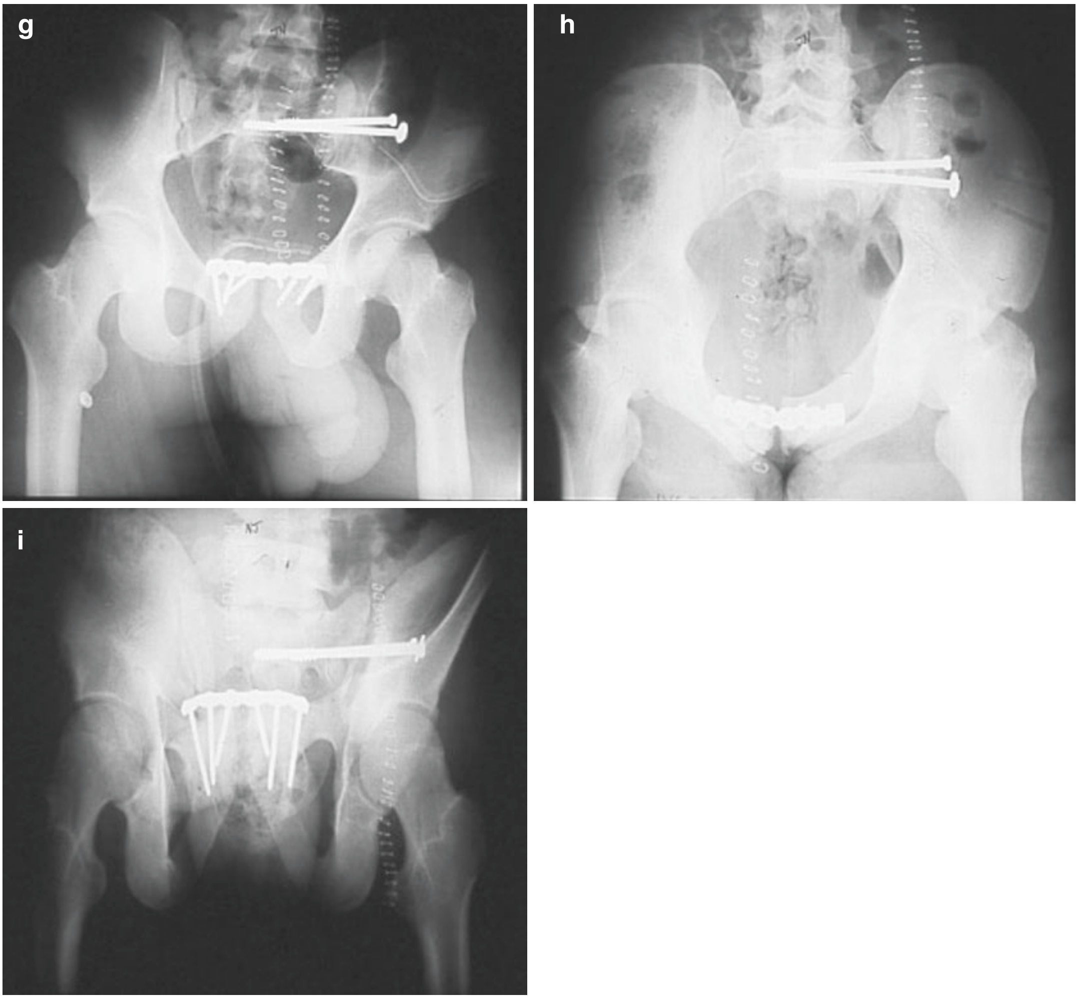


Fig. 8.8 (continued)

ity of the nonunions. Technetium bone scans may be helpful in identifying the activity of the nonunion (atrophic or hypertrophic) but are not routinely ordered. Together, these multiple plain films and CT scans are used to assess nonunions and deformities of the pelvis. The displacements are often complex and include rotational and translational displacements. A three-ordinate axis can be used to create a vector of displacement. Although there is no point where all rotational displacements occur, comparison with the normal hemi-pelvis allows the deformity to be classified (Fig. 8.9) [13]. The most common

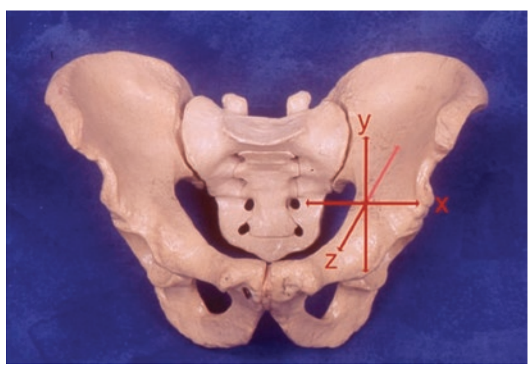


Fig. 8.9 Illustration of the three ordinate axes for assessment of rotational and translational displacements

deformities seen are posterior and cephalad translation and internal rotation and flexion of the hemi-pelvis [5, 13].

Translation of the pelvis from the normal anatomically positioned pelvis can be described using a three-vector axis system. The translational deformities are as follows:

1. Impaction/diastasis (*x*-axis)
2. Cephalad/caudad (*y*-axis)
3. Anterior/posterior (*z*-axis)

Measuring cephalad translation on the AP X-ray is easily performed by measuring the difference in height between two fixed points on the pelvis – often the ischium, acetabular sourcil, or iliac crest. Classically, the posterior displacement is defined using the caudad (inlet) view. However, direct cephalad translation of the hemi-pelvis will cause an apparent posterior translation on the caudad (inlet) view and the apparent posterior lying imbalance because the PSIS becomes more prominent. Therefore, the posterior translation is best measured on the CT scan. The actual cephalad translation is measured on the AP pelvis X-ray from a line in the plane of the sacrum. A perpendicular distance from this line to the ischium, top of the iliac wing, or the acetabular dome demonstrates the amount of vertical translation. This distance is compared to the other hemi-pelvis. The difference between the measurements of the ischia correlates with sitting imbalance. The differences in acetabular dome measurements give the leg length discrepancy. The symptoms of sitting imbalance and leg length discrepancies are the deformity complaints caused by severely displaced pelvic malunions. These values measuring vertical translation may differ between ischial height and dome height, for instance, because of different degrees of flexion or extension between the two hemi-pelvises.

Each axis also has a rotational component. Flexion/extension of the hemi-pelvis is defined as the rotation of the hemi-pelvis around the x-axis. Various anatomic relationships are used to define flexion/extension of the hemi-pelvis. They are as follows:

1. Obturator acetabular line to the tear drop (the more cephalad the line crosses the tear drop, the more flexion of the hemi-pelvis)
2. The shape of the obturator foramen on the cephalad (outlet) or the AP view (the foramen becomes more elongated and elliptical with flexion)
3. The position of the ischial spine within the obturator foramen on the outlet view (the more caudad the ischial spine is in relation to the foramen, the more flexion)

The best measurement of flexion is obtained from the three-dimensional CT. The normal hemi-pelvis and sacrum are removed from the anatomically positioned pelvis. The angle is measured from a line between the ASIS to the symphysis and a line perpendicular to the floor (normally this is 90°).

Internal and external rotation of the hemi-pelvis is defined around the y-axis. Defining internal rotation on plain films is performed by the following:

1. Comparison of the widths of the ischia (increased width shows internal rotation)
2. Width of the iliac wing (greater with external rotation)
3. The relationship of the ilioischial line to the tear drop (the more lateral the line, the more internal the rotation)

A CT scan can precisely define the degree of rotation (Fig. 8.7c, d, f, g). Drawing a line parallel to the constant quadrilateral surface (2–5 mm above the dome) and the angle this forms with the horizontal line in the plane of the sacrum measures rotation solely (Fig. 8.7g). Sponseller used the line from the ASIS to the PSIS to measure the deformity of the hemi-pelvis in children with congenital pelvic deformity [17]. However, this measurement is a combination of internal/external rotation and abduction/adduction.

Abduction/adduction deformity is defined as the rotation of the hemi-pelvis around the z-axis. This axis passes anterior to posterior. The true rotation axis is likely closer to the posterior sacroiliac joint, but the axis can be defined in any anatomical position. What is important is the rotational deformity as compared to a normally positioned hemi-pelvis. Therefore, pure abduction and adduction will not affect the internal/external rotation measurements. Pure abduction/

adduction deformities however are rare and are usually associated with other rotational deformities. One can also define the abduction/adduction deformities in degrees of rotation on the caudad (inlet) view if no internal/external rotation exists. The angle formed by a line from the PSIS to the symphysis pubis and a line in the plane of the sacrum estimates the abduction/adduction deformity. A CT scan can be used to estimate the amount of abduction/adduction by comparing the distance from the center of the quadrilateral surface to the midline on the injured side to that of the non-injured side; however, this does not give an actual degree of rotation.

8.4 Pelvis Malunion Treatment

As mentioned earlier, the best treatment is prevention [1, 2, 5]. The problem of malunions and nonunions appears most commonly after inadequate initial treatment of displaced fractures and unstable pelvic ring injuries (see Figs. 8.5a–d, 8.6a–e, and 8.8a–d) [1, 5]. From the technical standpoint, late correction is very difficult because the anatomy is altered and less recognizable and the potential complications are increased. Nerves are scarred down and difficult to mobilize to allow reduction. Osteotomies can easily damage the structures that lie on the opposite side of the bone.

Indications for surgery include pain, pelvic ring instability, and clinical problems relating to the pelvic deformity (gait abnormalities, sitting and lying problems, limb shortening, genitourinary symptoms, vaginal wall impingement, etc.). A thorough knowledge of pelvic anatomy is required to understand the three-dimensional deformity and the anatomical structures blocking the necessary releases to obtain a reduction. Furthermore, extensive preoperative planning is needed to determine the proper order of exposures for release, reduction, and fixation. Because each patient is different, it behooves the surgeon to individualize the treatment.

Previous literature focused on simple nonunions. These patients often do not require extensive anterior and posterior ring releases and reduction and respond to in situ fusion only (see the chapter in the 2018 companion book on nonunions [16]). Pennal [8] showed that patients treated with surgery are significantly better than those treated conservatively. In his study, 11 out of 18 surgery patients returned to pre-injury occupation versus 5 out of 24 conservatively treated patients. In nonunion cases with significant displacement, in situ fusions are unrewarding and leave the patient with complaints related to deformity as well as significant pain.

The surgical technique often involves a three-stage procedure (Fig. 8.8e–i). The three-stage reconstruction as described by Letournel [4] allows maximal degree of deformity correction as well as secure fixation. The three stages are performed with the patient supine–prone–supine or prone–supine–prone. After each stage, the wound is closed, and the patient turned to the opposite position. The first stage mobilizes anterior or posterior injuries by an osteotomy of the malunion or release of the nonunion. The second stage involves release and mobilization of the opposite side. The most important part of the second stage is the reduction of the pelvic ring. However, this stage also includes an osteotomy, mobilization, or both, of that side of the ring. Following reduction, the second stage is completed by fixation of that particular side of the pelvic ring. The third stage completes the reduction and fixation of the opposite side (relative to the second stage) of the pelvic ring.

For correction of cranial displacement of the hemi-pelvis, it is necessary to cut the sacrotuberous and sacrospinous ligaments at their attachment to the sacrum. It is preferable to perform osteotomies at the old injury site, but most posterior releases are through a lateral sacral osteotomy (see Figs. 8.5 and 8.6). With advances in technology of the operating room table and the ability to fix the patients normal hemi-pelvis to the table [18] (see Fig. 8.6m), some deformities can be corrected in one or two stages (see Fig. 8.5) [2]. This is especially true in rotational malunions (see Fig. 8.6). Vertical malunions require at least two stages to adequately release the hemi-pelvis. For example, an initial posterior osteotomy and release of the hemi-pelvis in the prone position followed by anterior release and reduction of the vertical and rotational displacement and combined anterior/posterior fixation with the patient in the supine position.

A radiolucent table with image intensification is commonly used for the three-stage procedure. The Judet table is also useful. Somatosensory evoked potentials (SSEPs) and motor evoked potentials have been used on some patients that require significant correction of vertical displacement but are not routinely used.

8.4.1 Simple Pelvic Nonunions and Approaches

Simple nonunions are covered in the 2018 companion book on nonunions [16]. Painful nonunions without deformity can be treated with stabilization, bone and soft tissue preparation, and bone graft.

During an anterior approach to the symphysis and brim, a Foley catheter is always placed preoperatively. A Pfannenstiel incision is made 2 cm cephalad from the symphysis. The decussation of the fascia fibers of the rectus abdominis marks the division between the two heads of the rectus. The two heads are split with extreme care being taken to avoid entering the bladder. The surgeon then inspects the bladder to detect any perforations. The Foley should be palpated to ensure the urethra is intact. A malleable retractor or a lap sponge is then used to hold the bladder away from the symphysis pubis. Two Hohmann retractors are used to retract the two heads of the rectus from the superior surface of the symphysis pubis. The superior surface of the superior rami is cleaned for the plate, but the anterior insertion of the rectus remains intact. A large Weber clamp or pelvic reduction clamp can be used anteriorly to hold the symphysis together or rami fracture together. Depending on the area that requires stabilization, a six- to twenty-four-hole 3.5 reconstruction plate is then implanted (see Figs. 8.6, 8.7, and 8.8). Clinical research supports the implantation of this device [19]. When a fusion of the symphysis is needed, an additional four-hole plate is used anterior to the symphysis. Additionally, when fusion of the symphysis is indicated, an eight- to ten-hole plate may be used rather than a six-hole plate superiorly. Through the Pfannenstiel approach, the SI joints can be visualized, and the quadrilateral surface exposed via the modified Stoppa approach [20]. Therefore, a plate can be placed from the symphysis to the SI joint along the brim superiorly bilaterally. Furthermore, a plate can be placed within the pelvis from the symphysis along the quadrilateral plate to the SI joint.

For SI joint arthrodesis, iliac wing nonunions, or sacral osteotomies, the lateral window of the ilioinguinal approach is performed (see Figs. 8.5 and 8.6). The L5 nerve runs 2 cm medial to the SI joint, has a slight medial to lateral orientation (almost touching the SI joint caudad), and must be protected. If vertical translation has occurred, mobilization of the nerve is required to reduce the hemi-pelvis without causing a nerve palsy. For SI joint arthrodesis (which are rarely indicated) from the anterior approach, after curetting the joint (starting on the better bone of the iliac side of the SI joint first), creating a trough in the anterior SI joint, and packing with cancellous graft from the gluteus tubercle, place two three-hole plates at approximately 70° to each other. Place the first plate as caudad as possible with one screw in the sacrum and two in the ilium. Due to the anatomy of the sacrum, this caudad position allows placement of the longest screws possible into the best bone. Angle the screw in the sacrum slightly medially to parallel the SI joint. Bicortical 3.5 mm screws are used. The use of a long oscillating drill is recommended because of its flexibility and safety because the cortical bone is able to be felt while drilling. The second plate is placed just cephalad to the first forming a 70° angle. Alternatively, percutaneous iliosacral screws can be placed. Iliac wing nonunions usually require plate fixation only without involvement of the SI joint.

Sacral nonunions, due to limited visualization, almost always are operated on through a posterior approach [21]. A longitudinal approach 2 centimeters lateral to the PSIS is made. The gluteus maximus is raised off of the iliac crest, lumbodorsal fascia, and paraspinal muscles exposing the posterior SI joint and ligaments. For arthrodesis of the SI joint through the posterior approach, fibrous and cartilaginous tissue is removed from the joint and posterior superior iliac spine cancellous bone is used to fuse the joint. An osteotome is used to remove the articular cartilage from the iliac side first, and then a curette is used to remove cartilage from the sacrum all the way to the anterior brim. Fixation is usually obtained with two 6.5 mm, 16 mm thread length iliosacral screws. Again, the use of an oscillating drill is recommended for safety and so that three cortices are entered but not the fourth. Additional stability can be achieved by placing one or two posterior reconstruction plates from one iliac wing to the other iliac wing. These plates act as a tension band and are less prominent if placed caudal to the PSIS. Iliosacral bars are also an option; however, they are usually prominent and were not used in our series [1, 5]. More recently, trans-sacral screw fixation has been described [22] to combat a fairly significant failure or loss of reduction of sacral fractures [23]. However, with anatomical reduction, two well-placed iliosacral screws into the S1 endplate even in segmentally comminuted sacral fractures, reduction can be maintained with simpler iliosacral screws [21].

Patients are touchdown weight-bearing for 12 weeks postoperatively. In cases of fusion or when poor bone is present, bilateral lower extremities are non-weight-bearing with wheelchair transfers only for 12 weeks. After adequate healing, range of motion and strengthening exercises are instigated.

8.4.2 Malunions and Displaced Nonunions of the Pelvis

To treat symptoms related to deformity of the pelvis, a reduction of the pelvis is required because a simple in situ fusion will be unrewarding and not completely relieve the pain (see the chapter in the 2018 companion book on nonunions [16]). As mentioned earlier, this often involves a three-stage, two-stage, or one-stage procedure [1, 2, 5]. If combined with an acetabular malunion, four stages may be required (see Fig. 8.1). The key with combination pelvic and acetabular malunions and nonunions is after release of all the associated pieces, reduction and fixation of the pieces proceeds from the posterior pelvis to the anterior pelvis (i.e., posterior SI joint, acetabulum, and then the symphysis and/or rami osteotomy; see Fig. 8.1).

The first stage includes release of one side of the ring (i.e., posterior osteotomy through an old iliac wing/SI joint injury, sacrum and transverse processes, and release of all the ligaments and scar tissue including the sacrospinous, sacrotuberous, iliolumbar ligaments etc.). The second stage includes the release of the other side of the ring (i.e., bilateral superior and inferior rami osteotomies, and further release of anterior interosseous SI joint, sacrospinous, and sacrotuberous ligaments as well as a sacral osteotomy), reduction of the pelvic deformity, and stabilization of that side of the pelvis (i.e., 10-hole reconstruction plate across the symphysis pubis). The third stage is used for additional reduction and fixation of the first-stage side of the pelvis (i.e., two 6.5 mm iliosacral screws). Obviously, if the pelvis is well reduced and opposite side fixation can be performed, a third stage is not required (i.e., fixation of the posterior ring during the second stage using percutaneous iliosacral screws in the supine position). The order of stages depends on the pelvic deformity, where the initial injury occurred, and which side (anterior or posterior) will allow the best reduction during the second stage after complete release of the deformity both anteriorly and posteriorly. Often, rotational deformities are best reduced with the patient supine (see Fig. 8.6). With the ability to stabilize the normal hemipelvis to the bed, vertical translation can now be corrected using either anterior or posterior approaches (see Fig. 8.7). However, bilateral vertical translations (“H” or “U” sacral fractures) are best reduced from a posterior approach after adequate release anteriorly (bilateral anterior sacrum osteotomies) using pedicle screws and fixation into the PSIS (see Fig. 8.5).

Depending on the particular deformity, different reduction techniques are used. With the patient prone, posterior reduction techniques include table traction (Judet table) or skeletal traction with fixation of the opposite side of the pelvis to the table (see Fig. 8.6), pelvic "C" clamp (to help reduce diastasis), pointed reduction forceps (Weber clamp between the spinous process and iliac wing, see Fig. 8.8) [21], pedicle screws attached to PSIS in distraction (see Fig. 8.5), femoral distractor between the two PSISs, and an angled Matta clamp through the notch (one tong on the sacrum anteriorly and the other tong on the outer cortex of the iliac wing). With the patient supine, various anterior maneuvers include the Weber clamp, large Jungbluth pelvic reduction clamp across the symphysis pubis, pelvic "C" clamp, external fixation compression distraction devices (depending on the deformity), table traction, and use of a femoral distractor between two iliac wings just lateral to the SI joint and between the iliac wing and the contralateral quadrilateral surface to external rotate the pelvis (see Fig. 8.6). The key to reduction is to recognize the deformity, adequately release the deformity, and create a force vector to reduce the deformity.

Surgical approaches also vary with particular deformities of the pelvis. Anterior approaches include bilateral ilioinguinal, unilateral ilioinguinal, Pfannenstiel (modified Stoppa) incision, or lateral window of the ilioinguinal. Posterior surgical approaches include the posterior longitudinal incision [21] (sometimes bilaterally), extended iliofemoral (EIF) incision (if combined with an acetabular malunion, see Fig. 8.1), a posterior midline incision (for an "H" or "U" type of sacral fracture; see Fig. 8.5), or a lateral approach from the PSIS to the ASIS.

A typical surgical plan for a vertical malunion of the pelvis would be the following:

- Stage 1. Patient is positioned supine. Bilateral superior and inferior rami osteotomies are performed along with release of the soft tissue around the osteotomies, an anterior sacral osteotomy just medial to the sacroiliac joint with release of the soft tissue associated with the L5 nerve root, and release of the sacrospinous and sacrotuberous ligaments. This is done through a Pfannenstiel incision and the lateral window of the ilioinguinal approach.
- Stage 2. The patient is placed prone and a posterior approach to the sacral osteotomy is performed. Further release of the sacral osteotomy is performed, along with release of the sacrotuberous and sacrospinous ligaments and the soft tissue around the iliac wing (including the iliolumbar ligament). Reduction of the vertical migration of the hemi-pelvis is performed using table traction through an ipsilateral femoral traction pin with the contralateral pelvis fixed to the table, and with a Weber clamp and angled Matta clamp as mentioned previously. Fixation is with two iliosacral screws.
- Stage 3. The patient is again positioned supine and additional reduction of the rotational deformity is performed along with plating of the bilateral superior rami osteotomies (see Fig. 8.6). Alternatively, if the vertical deformity is minor (i.e., a posterior release is not required to get a minor correction with table traction) and the deformity is more rotational, the release, reduction, and fixation can be done in a single stage anteriorly [2] (see Fig. 8.6).

Stabilization of the pelvis also varies depending on the location of the deformity and the amount of release required for proper reduction. Standard fixation anteriorly includes curved 3.5 reconstruction plates of various sizes anteriorly along the brim and symphysis.

Posteriorly, 6.5 cancellous iliosacral screws 16 mm thread length, 3.5 mm and 4.5 mm osteotomy lag screws, and large reconstruction plates from PSIS to PSIS are used. In each case, however, the actual type of fixation is determined only after the reduction is performed. Due to the extensive releases required to reduce pelvic malunions, postoperatively, patients are instructed to limit weight-bearing for 3 months before aggressive physical therapy and advancement to weight-bearing as tolerated.

8.4.3 Results

The time frame from injury to operation in our series averaged 42 months (range from 4 months to 14 years) [1, 5]. Operative time averaged 7 h (range 1.5–10.4 h). Operative blood loss averaged 1977 cc (range 200–7200 cc).

At follow-up, (average 3 years, 11 months; range −9 months to 11 years), all but one patient had a stable union of their pelvic ring. Ninety-five percent of the patients were satisfied with the operation and 100% of the patients were satisfied with the improvement of their preoperative deformity. As mentioned earlier, the unsatisfied patient continues to have an L5 nerve palsy. Now with over a hundred pelvic nonunion and malunion patients, prevention is still the key. Furthermore, given the potential blood loss with the osteotomies and soft tissue releases, the final 1 or 2 stages may be delayed 5–7 days if a blood volume loss (cell saver) occurs; 76% of the patients had less than 1 cm of displacement on postoperative radiographs [24].

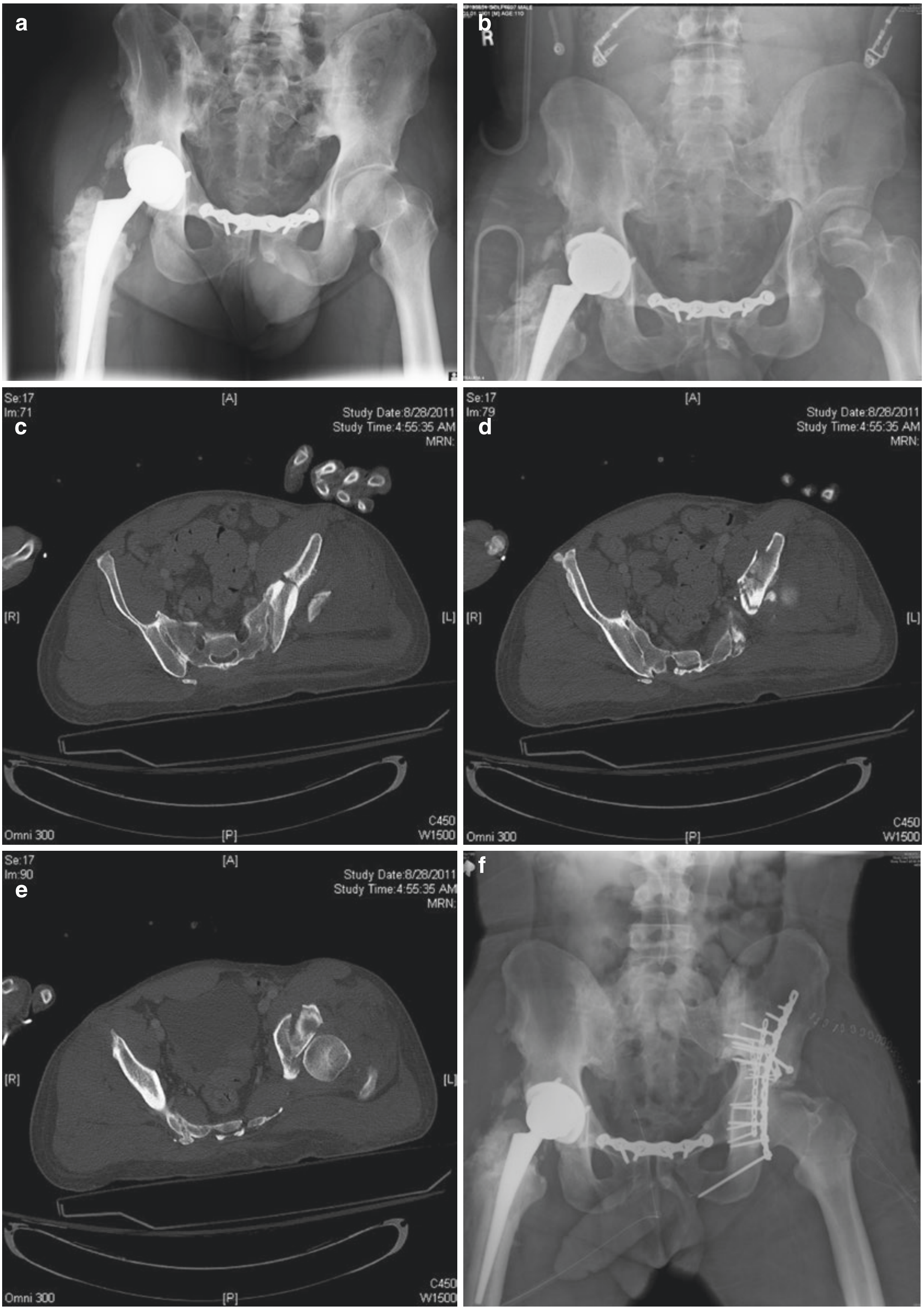
Complications included loss of reduction, neurologic injury, and vascular injury (external iliac vein). There were no surgical infections. Although residual low back pain was present in most of the patients preoperatively, 95% reported less pain following surgery however; only 21% reported no pain postoperatively.

8.5 Acetabulum Clinical Assessment

8.5.1 Pain

Pain associated with malunions of acetabular fractures generally decrease initially after the acute fracture prior to increasing due to arthrosis of the hip. This occurs whether there is a delay in reduction or when the acetabulum was malreduced (see Figs. 8.1, 8.2, and 8.4). A displaced acetabular fracture is painful because of increased intra-articular pressure during weight-bearing due to articular incongruity reducing the contact area between the head and the acetabulum, wear of the head rolling over a malreduced fracture line, avascular necrosis, small motion at the fracture site, or osteoarthritis of the acetabulum. Symptoms include increasing severity of pain with hip motion, limp, and restriction of hip motion. Radiographic studies are used (as described later) to determine the fracture type, whether there is bridging bone, and the extent and location of the damage in the hip. Critical to the preoperative assessment is the condition of the femoral head (Fig. 8.10 and see Figs. 8.1, 8.2, 8.3, and 8.4) (see the chapter in the 2018 companion book on nonunions [16]). Evaluation of the hip joint is also important to determine how much cartilage remains. Attempts to compensate

Fig. 8.10 Malreduced both-column posterior wall (anterior column posterior hemitransverse and posterior wall type pattern) in a 35-year-old that was not salvageable. Patient suffered a previous MVA associated with bilateral unstable sacroiliac joints and femoral neck fracture. The femoral neck initially was treated with ORIF that subsequently failed and required a right THA. The next MVA caused a right L5 S1 instability and a left hip dislocation with a both-column posterior wall fracture. (**a**) AP radiograph of the pelvis prior to second MVA. (**b**) AP plain radiograph showing the left acetabulum fracture. (**c**) Axial CT of showing the anterior column iliac wing fracture. (**d**) Axial CT showing the posterior hemitransverse fracture. (**e**) Axial CT showing left hip dislocation and posterior wall. (f-h) Postoperative AP, iliac oblique, and obturator oblique radiographs from an outside institution show after ORIF via a KL approach showing the malreduced anterior column, posterior column, and posterior wall. (**i**) Axial CT showing the malreduced anterior column. (**j**) Axial CT showing the malreduced posterior wall. (**k**) Axial CT showing the malreduced dome. (**l**) Axial CT showing the malreduced hemitransverse and posterior wall fracture. (**m**) Sagittal reconstructed CT scan showing unacceptable gap between anterior column and posterior hemitransverse. (**n**) AP radiograph after second attempt at ORIF at an outside institution with additional plates and screws but still malreduced anterior and posterior column. (**o**) AP radiograph 3 months postoperative when presented to the author's institution with an unsalvageable hip with elevation of the femoral head <3 cm. (**p**) AP radiograph in another patient who had >7 cm of hip elevation treated with a ring fixator to bring the hip down to the normal position prior to a THA. (**q**) AP radiograph after removal of the fixator and THA in the patient in (**p**). (**r**) Postoperative AP radiograph after staged removal of hardware and THA with bulk allograft of the superior and posterior wall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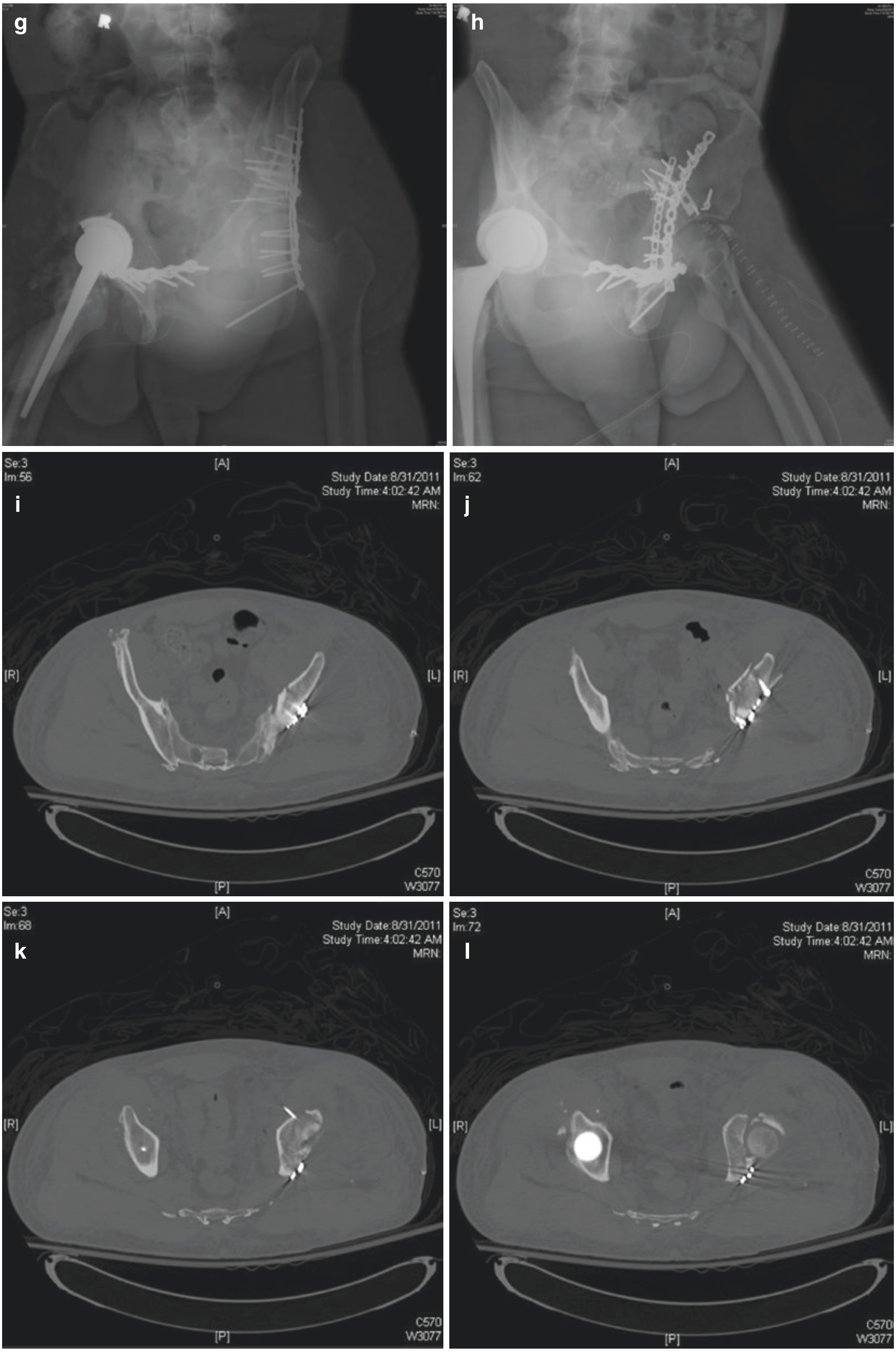

Fig. 8.10 (continued)

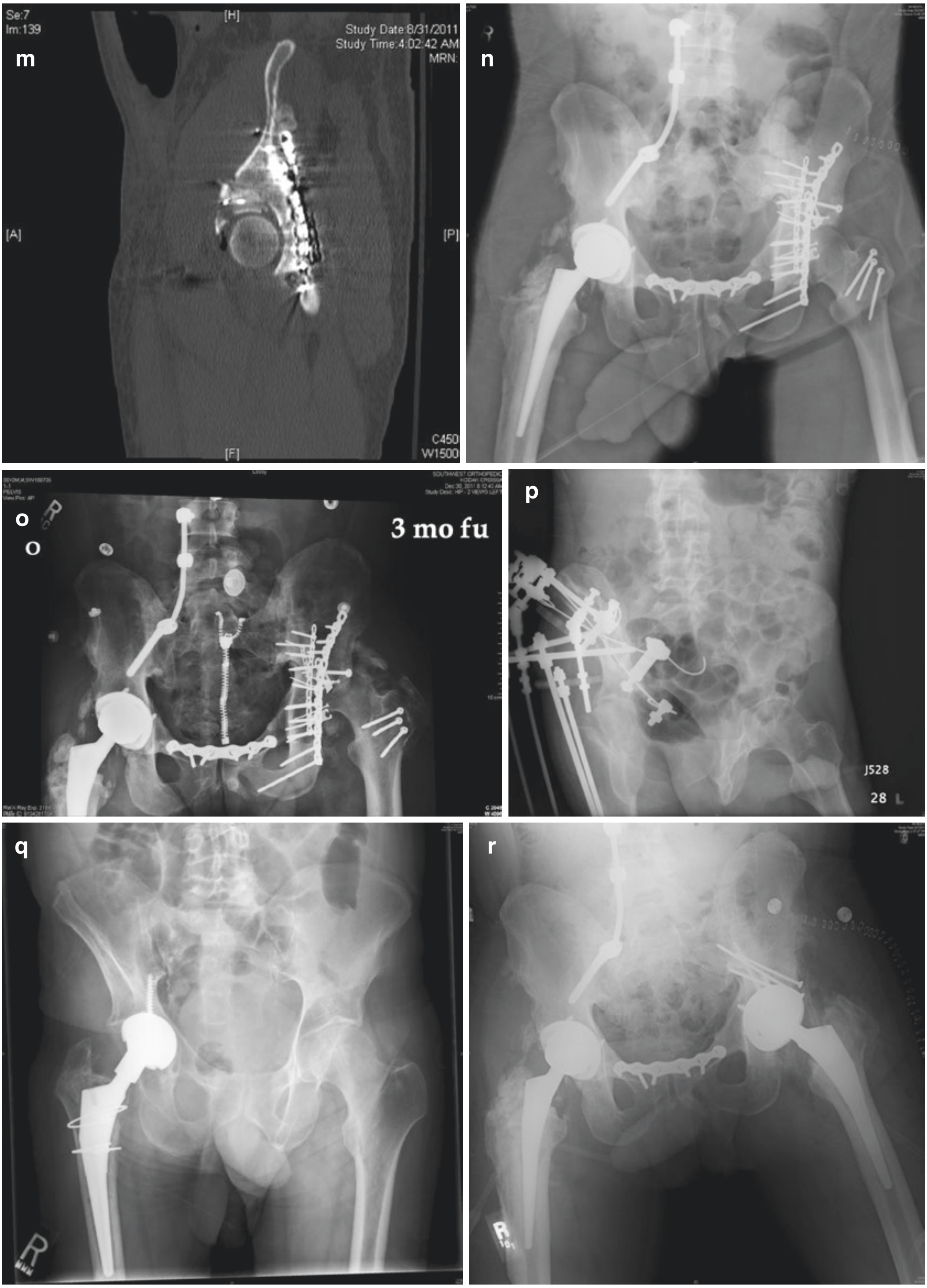

Fig. 8.10 (continued)

for loss of substance of the femoral head or the cartilage have not been successful. The osteoarthritis rarely improves, and at best the deterioration is halted. Before attempting reconstruction of an acetabular malunion fracture, the following must be understood:

1. The location and condition of the different articular fragments and the bony columns supporting them
2. The extent and location of wear on the femoral head
3. The presence, location, and extent of osteoarthritis
4. The presence, location, and extent of avascular necrosis [4]

In all cases, a total hip arthroplasty (THA) is considered an option (see Fig. 8.10). If there is complete cartilage loss involving more than 50% of the dome, a THA is probably required. Depending on the deformity, the total hip arthroplasty may need to be performed in conjunction with an osteotomy and reduction of the columns.

8.5.2 Deformity

Acetabular deformity and/or hip protrusio cause symptoms of gait abnormalities, sitting imbalance, and limb length discrepancy (i.e., shortening of a transverse fracture). Furthermore, protrusion of the femoral head centrally will cause a significant decrease in motion. Malunion of acetabular fractures requires early diagnosis to prevent the development of severe arthritis after which the hip will no longer be salvageable (see Fig. 8.10 and the chapter in the 2018 companion book on nonunions [16]). Radiographic analysis is critical (see radiographic analysis) to determine the type of the fracture present and the amount and direction of displacement.

8.5.3 Genitourinary System

Genitourinary symptoms in acetabular malunions occur secondary to the deformity of the pelvis, that is, a rami fracture pushing on or perforating the bladder. This will give symptoms of urgency, frequency, and hesitancy. Vaginal impingement or perforation can cause dyspareunia.

8.5.4 Neurologic Injuries

The neurologic injuries associated with acetabular fractures are predominantly a nerve injury to the common peroneal tract of the sciatic nerve causing a foot drop. Additional nerve injuries include the superior gluteal nerve (abductor weakness) and obturator nerve (adductor weakness and numbness of the inner thigh). Rarely, the femoral nerve may be injured. A preoperative exam will often identify partial or complete muscle weakness. In acetabular malunions reduction, a complete knowledge of the anatomy is required to free the affected nerves and allow for anatomic reduction of the acetabulum without causing additional traction injuries to the nerves. Mayo et al. described postoperative nerve palsies following correction of acetabular malunion in 6 percent of their cases (3 percent superior gluteal and 3 percent sciatic) [10].

8.5.5 Patient Expectations

In acetabular malunion patients, the results are poorer, and the degree of difficulty and the need for precise anatomic reduction an order of magnitude greater than in pelvic malunions. Nothing less than a perfect reduction of the acetabulum is acceptable, and even in experienced hands, 58% of the patients go on to develop arthritis [10]. Timing is also an important factor, with 57% good to excellent results if operated on within 3 weeks of the injury and 29% good to excellent results if the delay exceeded 12 weeks from the time of injury. Once again, significant discussion is necessary prior to making a decision for surgery. The patient must have realistic goals and an understanding of the risks and benefits of surgery. The patient needs to understand preoperatively that success is limited and total hip arthroplasty is likely in the intermediate or long term.

8.6 Acetabular Radiographic Assessment

The radiographic analysis of acetabular malunions is similar to the acute injury (five views of the pelvis and 3 mm CT without contrast with sagittal and coronal reconstructions) with the addition of an MRI to look for cartilage damage and avascular necrosis. Often these injuries have areas of bony bridging and non-healing in the same fracture line; that is, in a transverse fracture, the fracture heals supero-medially and has a nonunion postero-inferiorly. Fracture lines close to the joint are the last to heal. The patterns of displacement of certain fracture types have been determined. The way a both-column (see Figs. 8.2, 8.4, and 8.10) or T-type (see Figs. 8.1 and 8.3) fracture displaces is somewhat consistent. The anterior and posterior columns open up like “saloon doors” as the head pushes medially. Drawing the fracture on a model is mandatory to determine the rotation of the broken pieces that either needs to be released (nonunions) or osteomized and released (malunions) in order to obtain anatomic reduction. For instance, transverse fractures have two axes of deformity. The inferior piece rotates around an axis that travels down the symphysis pubis with greater displacement posterior versus anterior. The inferior transverse fracture segment rotates around a second axis from the symphysis pubis to the fracture site through the posterior column as the femoral head pushes medially.

Release of the fracture fragments allows derotation of the fractured pieces and anatomic reduction at the articular surface. Often, segmental bone removal is required to allow enough rotation of the fragments to restore anatomic reduction of the articular surface. The edges of nonunions are typically seen radiographically as hypertrophied bone. Narrowing of greater than 50% of the articular surface dome is an indication for total hip arthroplasty. Wear in other areas of the joint may be well tolerated. Interestingly, some both-column fractures detach the whole articular surface. The femoral head remains congruent with the dome despite widening medially between the two columns and medial translation of the entire joint. Medial widening up to 1 cm may be well tolerated; therefore, treating these acetabular malunion cases conservatively may be the best option.

8.7 Acetabular Malunion Treatment

The indications for surgery are similar to acute acetabular fractures (i.e., incongruence at the femoral head or >1 mm step off in the weight-bearing dome). If there is already complete loss of dome articular cartilage, the surgeon must decide whether a successful total hip can be performed with or without an osteotomy of the acetabulum (i.e., severe protrusion). If a nonunion exits, the fracture has to be stabilized first and then at the same setting a total hip arthroplasty can be done (see the chapter in the 2018 companion book on nonunions [16]). If the hip is out of the socket either medially or laterally or if weight-bearing has been delayed, usually the cartilage is preserved, and the joint can be salvaged despite a long delay in surgery (6 months).

Adequate release and mobility of the fracture fragments is a requirement for successful anatomical reduction. Generally, a two-stage reconstruction is required. An anterior Pfannenstiel, modified Stoppa, or full ilioinguinal approach is performed depending on the fracture pattern. For instance, in a both-column acetabular fracture, the ilioinguinal approach is used to release and osteotomize the superior and inferior rami (through the previous fracture lines) and separate the two columns along the quadrilateral surface at the anterior column. Importantly, all callous or healed bone that is preventing anatomic reduction is removed. This is followed by an extended iliofemoral approach to anatomically reduce the acetabulum (see Fig. 8.2).

8.7.1 Simple Acetabular Delayed Union

Unfortunately, the more common scenario is that by the time a diagnosis of acetabular malunion is made, the patient already has complete loss of the articular surface. It then becomes imperative to reduce and fix the delayed union prior to doing a total hip arthroplasty. If a THA is performed without stabilization of the delayed union, >80% of these cases will have loosening of the acetabular component.

If arthrosis is not present, the choice of approach in delayed unions is similar to the acute setting: the Kocher-Langenbeck (KL) for delayed unions of the posterior column and wall, the ilioinguinal (II) for the anterior wall and columns, and the EIF for all other fractures. In all cases the fibrous tissue is removed from the fracture site including intra-articularly through a capsulotomy. The edges of the delayed union can be sclerotic and need to be freshened up so that there is bleeding from both ends. Cancellous or cortical graft can be used if compression would cause an acetabular malunion acting as a spacer into the gap. Intraoperative traction with subluxation/dislocation of the hip allows the intra-articular delayed union to be reduced anatomically, and stabilization is performed with standard compression plate techniques [7]. Displaced delayed unions require mobilization of the fragments with direct intra-articular visualization. If greater than 50% of the dome has osteoarthritis, a total hip arthroplasty is performed usually without mobilizing the fractured fragments (see Fig. 8.10) unless there exists a protrusion of the head that needs to be stabilized with reduction of the two columns medially prior to doing a THA.

8.7.2 Malunions of the Acetabulum

In acetabular malunions, the surgeon must have a thorough knowledge of the displacement pattern of the fracture fragments and be able to draw it on a model preoperatively. Complete release of the bone and associated soft tissue is required for anatomic reduction of the joint. Interestingly, bone healing is much more rapid than cartilage healing, so osteotomies through malunions can be visualized intra-articularly more easily than extra-articularly. Also, reduction can be visualized intra-articularly to ensure congruence.

In many malunions of the acetabulum, osteotomies require a wedge resection to restore congruency of the acetabulum. This depends on the time to injury and the individual healing that occurs. In T-type malunions, a wedge of bone may need to be removed from the quadrilateral surface (see Fig. 8.1). This is in addition to superior and inferior rami osteotomies and soft tissue releases to allow the anterior and posterior columns to be rotated and reduced anatomically.

Isolated column or wall malunions can usually be corrected in one stage with release, reduction, and fixation all being performed through a single approach (i.e., anterior wall and column malunions and displaced nonunions can be corrected using the ilioinguinal approach or a portion of it, and posterior column or wall fractures can be corrected through a Kocher-Langenbeck approach). Two-column fractures (transverse, transverse posterior wall, anterior column/wall posterior hemi-transverse, T-type, and associated both columns) often require an extended iliofemoral approach (see Figs. 8.3 and 8.4) and possibly two stages (i.e., release of the anterior column through an ilioinguinal approach with additional release and anatomic reduction through an EIF approach) (see Figs. 8.1 and 8.2). Transverse and transverse posterior wall malunions/nonunions can often be adequately released, reduced, and fixed through a single extended iliofemoral approach as long as there is no associated symphysis, rami or posterior pelvis malunion. Typically, T-type, anterior wall/column posterior hemitransverse, and associated both-column fractures require two stages to achieve adequate release, mobilization, and anatomic reduction of the articular surface (i.e., anterior ilioinguinal followed by EIF with both-column malunions because the entire joint is separated from the intact iliac wing (see Fig. 8.2)). With two-column fractures, the inferior rami and the quadrilateral fracture lines need to allow rotation and anatomical reduction of the hip joint. Occasionally the joint can be reduced anatomically even though the entire joint is medialized (i.e., secondary congruence). The EIF is rarely used in acute fractures (see the next section on specific fracture types) but is quite common in the delayed cases.

Fixation is similar to acute fractures, and postoperatively, patients are touchdown weight-bearing for a longer period of time compared to the acute fractures (12 weeks vs. 8 weeks).

If there is loss of articular cartilage involving >50% of the dome, a THA is performed after stabilization of the acetabular (see Fig. 8.10). In severe cases of protrusio or dislocations, osteotomies (with release, reduction, and stabilization with lateralization of the head) are required prior to THA. The THA can be performed at the same setting or 5–7 days later.

8.7.3 The Treatment of Specific Fractures

8.7.3.1 Associated Both-Column Fractures

An EIF approach is preferred over the ilioinguinal approach for both-column fractures when there is a separate displaced segmental posterior column or notch piece, or a displaced posterior wall fragment that one cannot indirectly reduce through the ilioinguinal approach. If there is a complex posterior wall fracture in combination with a displaced brim fracture, potentially we need to treat that with two approaches, that is, an ilioinguinal followed by a Kocher-Langenbeck (KL). A locked posterior column fragment that cannot be disimpacted through the ilioinguinal approach or contralateral rami fractures (posterior column may be very difficult to reduce through the II) may be an indication for the EIF approach. A separate displaced piece of the SI joint and notch cannot be reduced through either a KL or an ilioinguinal approach. When there is more than 5 days delay to surgery, an EIF approach may allow easier release and anatomic reduction of the anterior column and the displaced posterior column fractures, as callous formation makes indirect reduction techniques difficult. A high posterior column fracture that enters the SI joint or a low posterior column fracture (close to the ischial spine) is sometimes difficult to reduce through an ilioinguinal approach and may require a sequential Kocher-Langenbeck approach. Instead of a sequential approach, an EIF approach can be chosen.

Twenty-three percent of Letournel's [14] both-column and 44% of our both-column acetabular fractures were operated on through an EIF approach. Eighty-eight percent of our patients had an associated posterior wall fracture that we believed was not reducible through an ilioinguinal approach, 25% of the fractures were more than 3 weeks old, and 25% had contralateral rami fractures and/or contra- or ipsilateral posterior pelvic ring injuries.

Treatment of the both-column fracture through an EIF approach usually begins with reduction of the iliac crest which often includes the anterior column and restoration of the convexity of the iliac wing (the mistake is to flatten the iliac wing from the outer table causing an external rotation malunion of the iliac crest or anterior column). The II can cause an internal rotation malunion (Fig. 8.2). Prior to tentatively fixing the iliac wing, one should make sure that the anterior column is not blocking the posterior column reduction and that the posterior column can be reduced using traction and placement of a bone hook through the notch. This confirms that the posterior column is somewhat mobile and that it will not be blocked by the reduction of the anterior column. Typically, both-column fractures have rotation of the fragments or the columns around the femoral head as the head displaces medially. Therefore, the reduction technique involves derotating both fragments and verifying the reduction of the anterior and posterior columns along the quadrilateral surface. Lateralizing the femoral head in its anatomical position aids the reduction of the columns.

One of the pathognomonic radiographic signs of both columns is a "spur sign." This is the intact part of the ilium. Therefore, besides the rotation of the fragments, the two columns need to be brought out laterally. A moveable lateral peroneal post can bring the femoral head out of the pelvis correcting the medial translation of both columns and greatly aid in anatomical reduction. Furthermore, varying degrees of longitudinal traction through a table also can aid in anatomical reduction.

Prior to reducing each of the columns, a thorough debridement of the fracture site must be done to ensure that both columns are mobile and that reduction is possible. The fracture lines are cleared about two millimeters of soft tissue, and the crest is reduced anatomically. Often there is a butterfly fragment in the crest, and therefore it requires two reductions. This is often performed with a Weber clamp and/or a Farabeuf clamp that uses screws to hold the fragments together. Provisional fixation can be obtained with a lag screw between the two cortical wings of the ilium, but often the reduction requires a plate along the crest to keep it from displacing. It is necessary to understand the fracture pattern to determine where lag screws can be placed, taking into account the curvature of the iliac wing. When compressing the anterior column to the intact portion of the iliac wing, the tendency is to overcompress, creating a flattened iliac crest as opposed to the appropriate convexity of the external table. This causes a common external rotation malunion of the anterior column and makes reduction of the posterior column more difficult. Simultaneous reduction of the anterior column may also need to be performed at the level of the joint with a large Jungbluth clamp. When using screws with the Jungbluth reduction clamp, the screws can be angled slightly toward the fracture plane to help with the reduction of the opposite cortex from the clamp. Reducing the iliac wing allows the roof of the acetabulum to be reduced, and therefore the femoral head can be reduced to the dome. It is critical to get the anterior column rotated correctly; otherwise anatomic reduction to the posterior column is impossible.

When there is a separate U-type fracture of the SI joint and greater sciatic notch, this is reduced prior to reducing the anterior column. This "U" fracture is not always seen on plain X-rays and needs to be diagnosed if present. The reason it sometimes does not show up as a radiographic "U" is because it lacks the rotation. However, this fragment can be seen on the CT scan.

In both-column acetabular fractures, it is helpful to imagine the two columns closing medially like a "saloon door" rotating back together. Rotation of the wing of the anterior column can be assessed by palpating the anterior cortex fracture line after detaching either the rectus or the sartorius and by visualizing the reduction posteriorly. Again, either the sartorius or the rectus is left attached to the anterior column so that its blood supply can be maintained. Besides the plate along the crest, another plate is placed in the supra-acetabular region to provide greater stability (Figs. 8.2 and 8.4). Often a Jungbluth is applied above the acetabulum to rotate and reduce the anterior column to the intact iliac wing. Additionally, an angled reduction clamp or a King tong can be placed across the fracture, with one tine on the anterior column anteriorly and one tine on the intact part of the iliac wing posteriorly. Posterior or superior wall acetabular fractures can be reduced similarly with one of the tongs applied to the inner table and the other to the outer table. The anterior column can be stabilized with two screws from the AIIS to the intact iliac wing and/or a plate in a similar position. Secondary fracture lines in the anterior column below the dome (the superior 12 mm of articular cartilage) can be ignored (i.e., they need to be freed up to obtain the reduction, but they do not need to be anatomically reduced) (Fig. 8.2).

Next, the posterior column is reduced to the anterior column and the intact part of the iliac wing and/or the posterior superior posterior wall fragment. This is generally done using a Jungbluth clamp with one screw placed in the supra-acetabular portion of the anterior column, and the second crew placed around the ischial spine. The latter is positioned as far posterior as possible, so that a plate can be placed more anteriorly. The direction of the reduction screws is critical and can be positioned so that the fractured piece is derotated and reduced with the attachment to the Jungbluth. Alternatively, the posterior column can be reduced to the intact iliac wing with screws in each fragment and the Farabeuf clamp. If there is a free segmental posterior column piece, it is provisionally reduced with a combination of a Weber clamp and K-wires. A Schantz pin can be used in the ischium to help rotate the posterior column. The Schantz pin is rotated posteriorly and inferiorly to correct the rotation of the posterior column and hopefully close down the quadrilateral surface. Palpation along the quadrilateral surface can ensure that the rotation of the column is correct. Intra-articular reduction can be visualized directly through a capsular incision or through a posterior wall fracture site. Fixation of the posterior column can involve lag screws and/or plates. Initial lag screw fixation can be achieved with a screw from the gluteus medius tubercle down the posterior column to the ischium. If possible, a lag screw is also placed from the anterior column (AIIS) to the notch of the posterior column. This compresses the anterior and posterior column through good supra-acetabular bone. A compression or neutralization plate can be applied along the posterior border of the posterior column onto the intact part of the ischium and/or anterior column (Figs. 8.2 and 8.4). Occasionally, a second plate is required over the posterior wall, closer to the joint if a posterior wall fracture exists (Fig. 8.2).

Most of the time, there is a segmental piece of the anterior column, but this can usually be ignored unless it is within 12 mm of the dome. If fixation is necessary, a column screw can be placed after an anatomic reduction has been obtained. More commonly this screw is necessary in T-type fractures.

Occasionally the posterior column is reduced first, especially if it can easily be reduced to an intact part of the ilium with the proper rotation. At that point the anterior column can be reduced to the posterior column as well as the intact portion of the iliac wing. Difficulty with reduction often means that there is an incarcerated fragment that needs to be removed.

Only in both-column acetabular fractures can you get secondary congruence. This is where the joint is accepted to be medially translated but the articular surface is well reduced. This means that the fragments are rotated properly; however, the entire joint is medial to the original position.

In some older fractures, that is, greater than 3 weeks, it is necessary to first debride and mobilize the anterior column fracture and rami through an ilioinguinal approach. Otherwise anatomic reduction of the anterior column through an extended iliofemoral cannot be performed (Fig. 8.2). In these situations, release of the anterior column through a full or partial ilioinguinal approach, that is, Pfannenstiel, modified Stoppa, and/or iliac portion of the ilioinguinal followed by an extended iliofemoral approach is indicated.

As mentioned earlier, in fractures that have comminution of the brim and indications for an EIF, a sequential approach is chosen (II followed by a KL). This assumes that a complex posterior column and/or posterior wall exists that cannot be reduced by an ilioinguinal approach. An ilioinguinal approach is followed by a Kocher-Langenbeck if there is a posterior wall or a posterior column fracture that cannot be anatomically reduced through the ilioinguinal approach.

After reduction and fixation, the c-arm is used to ensure that all the screws are outside the joint. Through an EIF approach, the surgeon can palpate completely around the superior acetabular region ensuring that the fracture is anatomically reduced.

8.7.3.2 T-Type Fractures

The T-type fractures and transverse fractures are ideally suited for the EIF approach. This is because the psoas groove, the area between the anterior inferior iliac spine and the pectineal eminence, is routinely where the anterior column fracture occurs. The cases where the benefit of the extended iliofemoral approach outweighs the benefits of the less invasive Kocher-Langenbeck approach for T-type fractures are as follows:

1. If there is a separate and displaced greater sciatic notch fragment. These are often difficult to reduce through a Kocher-Langenbeck approach.
2. A displaced transtectal T-type fracture can be difficult to anatomically reduce due to limited supra-acetabular exposure and difficulty rotating the anterior column through the Kocher-Langenbeck approach.
3. A posterior wall fragment that has comminution extending into the iliac fossa and anterior to the AIIS is difficult to visualize and fix through a Kocher-Langenbeck approach.
4. Often T-type fractures have an intact anterior labrum that allows the anterior column to be indirectly reduced. However, when there is

significant rotation and displacement of the anterior column, the anterior labrum is disrupted, preventing indirect reduction of the anterior column through the Kocher-Langenbeck approach. Similarly, these T-type fractures are not fixed very well through an ilioinguinal approach because the posterior labrum is often disrupted. Furthermore associated pelvic injuries including ipsi- or contralateral superior and inferior rami fractures or symphyseal injuries make the anatomic indirect reduction of the anterior column impossible through a KL approach.

5. A delay longer than 5 days especially in a transtectal fracture can make anatomical reduction through a simpler approach impossible (Figs. 8.1 and 8.3).

Twenty-nine percent of Letournel's [14] T-type fractures were operated through an EIF approach, compared with 52% of our T-type fractures. This increase is likely due to our referral patterns. Letournel's indication for using an EIF includes transtectal T-type fractures. Many of our transtectal T-type fractures are still treated through a Kocher-Langenbeck approach. However, a number of our cases have a delay of >3 weeks (even 5 days can make the indirect reduction of the opposite column difficult) with significant displacement of the anterior and posterior column. Sixty percent of these T-type fractures had a displaced anterior transtectal fracture line. Forty percent were juxtatectal. Fifty percent of T-type fractures had an associated posterior wall fracture. Thirty percent were operated on greater than 3 weeks post injury (Figs. 8.1 and 8.3), and 50% had contralateral rami fractures and/or displaced posterior pelvic ring injuries. Twenty percent had segmental posterior columns.

When the EIF approach is chosen for these types of fractures, the rectus is routinely taken down from the anterior interior iliac spine (leaving the sartorius to the ASIS), and the anterior fracture line is exposed all the way to the brim and onto the quadrilateral surface. After debriding the fracture, a smaller (3.5 mm) Jungbluth or Farabeuf clamp can be placed anteriorly with one screw above and one screw below the fracture line parallel to the articular surface. It is important when placing these screws that they are parallel to the fracture line and do not cross the fracture line. Furthermore, these screws must be close to the articular surface to allow two 3.5 mm anterior column screws. This allows manipulation of the anterior column and reduction of a portion of the transverse fracture. Depending on the obliquity of the transverse fracture, from anterior, a Weber or angled Matta clamp can be placed with one tine on the pectineal eminence and one tine on the posterior surface just above the dome on the gluteus medius tubercle to achieve anatomical reduction. Fixation can be obtained with two anterior column screws placed from the gluteus medius tubercle posteriorly down the anterior column to the superior rami (Fig. 8.3).

The order of the fixation of T-type fractures is often the reverse of both-column acetabular fractures, but the need to address the rotation of the columns around the head as it pushes medially is similar. The goal again is to reduce the "saloon doors." Initially reduction of the posterior column is performed using a large Jungbluth clamp with 4.5 mm screws. Again, these are placed close to the sciatic notch leaving adequate room for visualization of reduction as well as placement of a plate and lag screws. One screw is placed at the ischial spine, and the second above the superior border of the sciatic notch. This allows a wide spread of the Jungbluth clamp so that an angled clamp can be placed between the two arms of the Jungbluth to help with rotation of the fracture fragments. The Jungbluth clamp can often correct translation but has difficulty rotating the posterior column. An angled clamp placed between the Jungbluth with one tine on the posterior supra-acetabular region and the other on the quadrilateral surface/brim can derotate the posterior column, compress the fracture line, and can markedly improve the reduction. The direction of the reduction screws and placement of a Schantz pin in the ischium can also help with correction of the rotation of the posterior column. The Schantz pin is placed in the ischium close to the femur and the direction of pull is posterior and inferior rotating and anatomically reducing the posterior column. Once a reduction is obtained, the Jungbluth clamp is tightened. Due to the obliquity of the transverse fracture, the Jungbluth can be overtightened causing a shear and loss of reduction. Often reducing the posterior column and the anterior column sequentially will allow a more precise reduction of each column, going from one to the other and back again. In older fractures, that is, greater than 5 days, the fracture line along the quadrilateral plate between the anterior and posterior column has to be cleared of debris; otherwise derotation of the column may not be possible. Furthermore, release of the inferior rami may also be required to free up each of the columns (Fig. 8.1). The critical difference between a T-type fracture and a both-column fracture is that part of the articular surface still remains attached to the intact portion of the iliac wing; therefore, the anterior and posterior columns have to be perfectly reduced to that fragment.

Fixation with lag screws between the posterior column and the anterior column in the supra-acetabular bone and long anterior column screws from the gluteus medius tubercle into the superior rami are backed up with a posterior column plate with lag screws into the anterior column and posterior wall plate if a posterior wall is present (Figs. 8.1 and 8.3).

8.7.3.3 Transverse and Transverse Posterior Wall Fractures

Most of these acute fractures are treated using a Kocher-Langenbeck approach. However, if there is a transtectal transverse or transverse posterior wall acetabular fracture, Letournel [14] preferred an extended iliofemoral on these fractures. The authors generally will try to fix these through a Kocher-Langenbeck approach, but if any of the following conditions exist, an EIF approach for transtectal fractures may be chosen. These include the following:

1. A contralateral rami fracture or symphyseal injury (makes reduction of the anterior column of the transverse fracture harder to reduce).
2. An associated posterior sacrum, iliac wing, or SI joint injury.
3. A separate greater sciatic notch fragment.
4. Significant displacement of a juxtatectal or transtectal anterior column, that is, greater than 5 mm.
5. The transtectal transverse fracture is more than 7 days post injury, or there is significant callous secondary to a head injury (a little longer than the 5 days with a T- type due to the anterior and posterior column being together in a transverse fracture).

Twenty-one percent of Letournel's [14] transverse and transverse posterior wall were operated on through an EIF approach. Twenty-four percent of our transverse and transverse posterior wall fractures were operated on through an EIF approach. One hundred percent of these were transtectal. Forty-three percent of them had associated rami and/or displaced posterior pelvic ring injuries. Forty-three percent were greater than 3 weeks post injury. The isolated transtectal fractures without associated pelvic injuries and those that were less than 3 weeks from injury all had significantly displaced anterior columns (>1 cm) and were greater than 7 days from the injury. Some of these could have been managed through a Kocher-Langenbeck approach if treated earlier—within a few days of injury.

The rotational displacement of transverse fractures occurs in two planes. One axis of rotation is a line that goes along the symphysis pubis displacing the posterior column greater than the anterior column as the inferior portion rotates around the symphysis pubis. The second axis of rotation is around an axis from a point at the symphysis to the point where the fracture exits the posterior column. As the head pushes medially the transverse fracture widens. Reducing both of these rotational deformities is critical for anatomic reduction. This explains why transverse fractures with disruption at the symphysis or contralateral rami are more difficult to reduce through a standard Kocher-Langenbeck approach—they have lost part of their stability (the "hinge") that allows for indirect reductions.

Similar to a T-type fracture, these fractures have a fracture line through the anterior column in the psoas groove between the anterior-inferior iliac spine and the iliopectineal imminence.

Simultaneous reduction as mentioned in the T-type section can be performed with anatomic reduction of the transverse component. Use of a Schantz pin in the ischium close to the femur and rotated posteriorly away from the femur and inferiorly will help rotate the inferior transverse segment to its anatomical position similar to "T-"type fracture. Additionally, during an EIF approach, an angled clamp or a King Tong clamp with one tine placed on the brim piece and the other posteriorly on the intact part of the ilium can be used to reduce the fracture. Lag screws from lateral to medial will often be perpendicular to this fracture line and provide good fixation. The lag screw fixation and plate placement are very similar to the T-type fracture or both-column fracture, whether there is a transverse fracture or a transverse posterior wall fracture (refer to Sects. 8.7.3.1 and 8.7.3.2).

8.7.3.4 Associated Anterior Column Posterior Hemi-transverse Fracture

Most of these fractures are adequately reduced through an ilioinguinal approach. Occasionally, a significantly displaced posterior column, especially when associated with a delay in surgery or malunion, may require the surgeon to perform an extended iliofemoral approach. Although the anterior column is more easily reduced through an ilioinguinal approach, being able to reduce both the anterior column and the posterior hemitransverse through a single incision is beneficial. Alternatively, if the posterior column cannot be reduced anatomically through the ilioinguinal approach, a sequential Kocher-Langenbeck approach can be used to reduce the posterior column. The reduction of the anterior column is very similar to that described in the section on both-column fractures, and the posterior column is reduced as described in the section on T-type fractures.

Only 4 percent of the associated anterior column posterior hemi-transverse fractures are fixed through an EIF approach. All of our cases were the result of a delay in treatment of the fracture.

8.8 Conclusion

Stabilization of nondisplaced pelvic nonunions, especially posteriorly, has been proven to be successful in returning patients to their pre-injury status [8]. The one-, two-, or three-stage pelvic reconstruction has also benefited most patients with a pelvic malunion or displaced nonunion [1, 5]. The results of surgery on malunions or nonunions are not as good as those of acute treatment of pelvic ring injuries. Once the deformity has established itself and chronic symptoms develop, the probability of surgical reconstruction returning the patient to their pre-injury status is decreased. Also, the rate of complications is higher for late surgical treatment [5]. Prevention by anatomical reduction and internal fixation of unstable pelvic injuries is the best treatment for pelvic malunions and nonunions.

Operative correction of malunions and displaced nonunions of the acetabulum can give excellent results if the joint does not already have significant damage [10]. The results of surgery on malunions or nonunions are not as good as those of acute treatment of acetabular fractures. Once the deformity has established itself and chronic symptoms develop, the probability of surgical reconstruction returning the patient to their pre-injury status is decreased. In the acetabular malunion, determination of the status of the articular surface is required to separate those patients who have a salvageable hip versus those that require a THA. Also, the rate of complications is higher for late surgical treatment [10]. Prevention by acute open anatomical reduction and internal fixation of acetabular fractures is the best treatment for acetabular malunions and nonunions.

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9 Malunions of the Proximal Femur

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9.1 Introduction

Proximal femur fractures are among the most frequently encountered injuries by orthopaedic surgeons worldwide. Orthopaedic surgeons in both the community and at tertiary level referral trauma centers regularly treat these fractures, which include the femoral head, femoral neck, intertrochanteric, and subtrochanteric regions. Nearly all fractures in this region receive surgical treatment secondary to their debilitating effects on mobility.

Injuries to this area occur from a myriad of mechanisms ranging from low energy falls from standing to high energy motor vehicle accidents. Although the mechanism, in conjunction with patient-specific factors, can significantly alter the fracture pattern and treatment approach, the fundamental principles in the treatment of these fractures remain the bedrock upon which providers should approach these fractures. A systematic approach to these fractures helps maximize the chance of union and restoration of function, but as with fractures elsewhere, nonunions and malunions can and do occur in the proximal femur as well. While nonunions have been extensively described in the literature, particularly for femoral neck fractures, malunions of the proximal femur have received less attention to date.

Malunions occur when bone heals in a non-anatomic position. Malalignment includes angular deformities in the coronal, sagittal, and axial planes or a combination of these planes as well as rotational, translational, or length differences. In the proximal femur, malunions can occur following fractures treated nonoperatively. They also occur with fractures treated operatively with incomplete surgical reduction or inadequate fixation stability. Additionally, noncompliant patients who do not allow for osseous union prior to stressing fractures and the fixation construct can result in loss of fixation and potentially increase the risk of a malunion. Malunions in the proximal femur can lead to functional limitations, pain, and destructive joint changes. Most commonly, patients do not tolerate varus and rotational malunions in the proximal femur, whereas valgus and length-related malunions are better tolerated to a degree.

9.1.1 Proximal Femur Fracture Epidemiology

Estimates for the frequency with which orthopaedic surgeons encounter proximal femur fractures vary. Proximal femur fractures account for nearly 12% of all fractures encountered in trauma centers. These injuries are the third most common

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location for all fractures according to an epidemiological study by Court-Brown and Caesar [1]. The Danish Fracture Database revealed proximal femur fractures constituted one in three surgically treated fractures in adults [2]. Proximal femur fractures also are the third most common location for osteoporosis-related fractures per estimates by Burge et al., and these fractures account for nearly three-quarters of all costs associated with treating osteoporosis-related fractures [3]. Despite their frequency, proximal femur fractures account for less than 0.05% of all open fractures [4], likely secondary to the increased soft tissue surrounding the hip as well as the mechanism of injury for these types of fractures, which skews toward low-energy falls. With an aging population though, the incidence of these fractures seems to be increasing [5, 6].

Historically, the incidence of proximal femur fractures was lower. A landmark epidemiological study from Oxford, England, in 1959 revealed proximal femur fractures constituted about 5% of all treated fractures. Buhr and Cooke also noted men and women over 80 years old had a 30-fold and 300-fold, respectively, greater risk of a femoral neck fracture than those younger than 40 years old [7].

Studies over the past half century have confirmed that proximal femur fracture incidence multiplies with age. Increased lifespan and the corresponding escalation of osteoporosis worldwide fuels the increasing number of fractures and consequently the cost and burden on health systems. In 1992, Cooper et al. estimated approximately 1.66 million people worldwide sustained a hip fracture in 1990 and predicted that by 2050 6.26 million would suffer a hip fracture annually [8]. In 2005 alone, more than 2 million osteoporotic-related fractures occurred in the United States with about 15% of those involving the proximal femur. By 2025, osteoporotic fractures alone are projected to occur over 3 million times a year [9]. Unlike distal radius fractures, which increase linearly with age, proximal femur fractures increase exponentially as hip fractures are strongly associated with low bone mineral density [10, 11]. Bouyer et al. used the national health data system in France to demonstrate this exponential rise in incidence for femoral neck and proximal femur fractures among elderly patients. Femoral neck and proximal lower limb fractures had mean respective ages of 82 and 77.6 years and accounted for 14% and 3%, respectively, of all fractures in France in 2016 [12]. Although most fractures of the proximal femur occur in the pertrochanteric region, osteoporosis has increased the frequency with which people sustain subtrochanteric fractures as well.

In South Korea, the incidence of femoral neck, intertrochanteric, and subtrochanteric femur fractures were 29.3, 26.8, and 2.0 per 100,000 persons, respectively. People over 60 years old also had significantly higher chances of having a hip fracture, which included femoral neck or intertrochanteric fractures, and as has been shown in other studies, women more commonly sustained hip fractures than men with approximately 527.0 and 260.0 per 100,000 persons, respectively. However, people over 60 years old had a lower incidence of subtrochanteric femur fractures with 13.2 and 7.2 per 100,000 persons in women and men, respectively. In over 28,000 proximal femur fractures, Yoon et al. found the female-to-male ratio for all ages to be 2.534 for femoral neck fractures, 2.165 for intertrochanteric fractures, and 1.435 for subtrochanteric fractures, which constituted only 3.4% of all proximal femur fractures [13].

In keeping with higher rates of osteoporosis among Europeans and North Americans, the incidence of hip fractures among those in the United States is even higher than those found in South Korea. In patients 65 years and older, Brauer et al. found 77.2% of hip fractures occurred in women from 1986 to 2005. The calculated mean number of annual hip fractures was 957.3 and 414.4 per 100,000 persons for women and men, respectively. Despite comorbidities increasing in their patient population from 1995 to 2005, the overall incidence of hip fractures declined from 1995 to 2005 [14]. A number of other studies also have shown that hip fracture incidence and mortality rate have decreased in the past few decades after peaking in the 1990s [15–17].

Reasons for this decline are multifactorial. Some authors postulate that formerly high-risk populations are now healthier with increasing knowledge about, prevention of, and treatment for osteoporosis. These measures include, but are not limited to, more frequent physical activity, increased consumption of vitamin D and calcium, and the prescribing of bisphosphonates. Increasing body habitus may play a role as well. The number of obese patients has increased markedly over the past half century with the number of obese people worldwide tripling since 1975. According to the WHO, 39% of adults worldwide are overweight, and more than 2.8 million people per year die secondary to being overweight or obese [18]. Obese people tend to have a higher bone mineral density, which minimizes their fracture risk, whereas people underweight with lower bone mineral densities face a higher fracture incidence. A number of studies have revealed a decreased incidence of hip fractures in obese patients [19–22]. Consequently, the relationship between obesity and proximal femur fractures is inversely related in both men and women as demonstrated by Court Brown et al. [23].

Underweight postmenopausal females are particularly susceptible to proximal femur fractures. The differences between men and women emerge in the later stages of life after menopause with declining levels of estrogen, the most important sex steroid to achieve and maintain peak bone mass. Estrogen inhibits bone resorption, and as a result, women generally maintain their bone mineral density from late adolescence until menopause after which they sharply decline, thereby increasing the fracture risk [24]. Around menopause, the incidence of hip fractures is twice as high in postmenopausal women compared to premenopausal women, but among postmenopausal women, age becomes the most important determinant for the incidence of proximal femur fractures [25]. Underweight patients start at a disadvantage as they generally have a lower peak bone mass, which typically occurs in females in their early 20s and in males in their late 20s. Without the protective effects of estrogen after menopause, older female patients with lower peak bone mass have less reserve before developing osteopenia and osteoporosis placing them at greater risk for fractures. As patients of both sexes age, many of them also develop sarcopenia and become more susceptible to falls, which coupled with the weaker bone quality later in life increases the risk of fracture [26].

9.1.2 Proximal Femur Malunion Incidence

Despite the frequency with which orthopaedic surgeons treat fractures in the proximal femur, little is known about the incidence of malunions in this area. As aforementioned, most of these fractures are treated surgically, particularly in the developed world, and consequently, malunions from nonoperative management of these fractures are uncommon. Given the functional limitations associated with proximal femur fractures, proximal femur malunions most commonly occur secondary to inaccurate fracture reduction and suboptimal choice and placement of implants. Osteoporosis and noncompliance of patients can exacerbate the problem by requiring too much from the implant construct chosen leading to a loss of reduction and subsequent malunion.

Loss of fixation in proximal femur fractures plagued orthopaedic surgeons for decades. In 1975, Hunter concluded operative treatment of trochanteric fractures offered no benefit relative to conservative management as he had about a 14% rate of hardware complication and 7% nonunion rate [27]. Davis et al. then showed a mechanical failure rate of 16.5% in intertrochanteric fractures in 1990 [28]. Later in the 1990s, Baumgaertner et al. published a landmark study about the value of the tip-apex distance in predicting fixation failure of sliding hip screws for pertrochanteric fractures that helped significantly minimize screw cutout. They noted a 10% fixation failure rate which has subsequently decreased after the authors emphasized the importance of the screw being centered in the femoral head and having a tip-apex distance of less than 25 millimeters [29]. As knowledge has improved surrounding operative fixation of proximal femur fractures, the incidence of hardware failure has decreased. Unfortunately, both nonunions and malunions in the proximal femur remain relatively common though despite improvements in implants and knowledge regarding fracture reduction.

To date, the malunion incidence is poorly established for proximal femur fractures and varies widely based on the region of the proximal femur. A handful of case reports describe femoral head malunions as outlined below. A number of studies have demonstrated femoral neck malunions with an incidence ranging from about 6% to 40% [30–38], but these figures may underestimate the overall incidence of femoral neck malunions following fracture given femoral neck shortening, valgus impaction, slipped capital femoral epiphysis, and cam-type impingement lesions are all common. Unlike the femoral neck, intertrochanteric and subtrochanteric femur fracture malunions have less well-established incidence rates. One study reported a subtrochanteric malunion rate of 16.7% [39] while another noted a 20% rate of malreduction at the time of surgery [40]. Malunions in both the intertrochanteric and subtrochanteric regions typically occur as a result of nonoperative management, malreduction, or loss of fixation.

9.1.3 Proximal Femur Malunion Risk Factors

Proximal femur malunions occur for a myriad of reasons. Fractures of the proximal femur are unique relative to fractures elsewhere in the body in that they almost routinely are treated surgically given their debilitating effects on mobility. Consequently, proximal femur malunions rarely result in the developed world from nonoperative management or neglected fractures. Instead, malunions in the proximal femur generally arise from one or a combination of various factors. First, poor or inadequate fracture reduction at the time of fixation can lead to a malunion. Malreduction also can increase the stress placed on the hardware, thereby leading to another risk factor, hardware failure. Implants themselves can fatigue and fail if excessively stressed. Host factors, such as a patient's poor bone quality, also can cause implants to cut out and fail as can poorly positioned hardware. If neglected thereafter, union can occur with the implants no longer holding the reduction. Finally, noncompliance is an additional risk factor, one that is difficult for surgeons to control, as it also can place undue stress on the hardware.

Optimal reduction and correct intraoperative fluoroscopic views are intimately interrelated. Without the desired radiographic view intraoperatively, probabilities increase for an insufficient reduction. Optimal implant placement often requires a correct reduction since many implants are designed anatomically to fit a reduced bone [41]. Regardless of imaging issues or implants, surgeon error can still occur. Ramanoudjame et al. reported a 40% incidence of malreduction of more than 15° internal rotation when treating pertrochanteric femur fractures with closed cephalomedullary nailing [42]. Malpositioned implants due to residual malreduction results in a higher number of mechanical failures as well [43–45]. Making this potential pitfall more challenging, surgeons disagree on what is an adequate fracture reduction. Heetveld et al. demonstrated that although there is agreement on adequate reductions of displaced intracapsular femoral neck fractures on radiographs in the coronal plane, considerable variability existed among surgeons as to an acceptable fracture reduction on the lateral radiographs [46].

Given this variability, surgeon experience seemingly could contribute to better reductions and thereby minimize complications including loss of fixation and consequent malunions. Browne et al. concluded surgeon volume is associated with decreased mortality in the treatment of hip fractures [47], and Kukla et al. demonstrated a reduction in intraoperative and early postoperative complication rates for intertrochanteric fractures with increasing departmental experience [48]. Authen et al. also reviewed over 30,000 hip fracture procedures and concluded surgeons with less than 3 years of experience had increased risks of reoperation indicating experienced surgeons likely should manage displaced femoral neck fractures [49]. Data revealing no increase in complications when delaying surgery for displaced intracapsular femoral neck fractures more than 48 hours makes waiting for experienced surgeons more plausible as well [50]. Conversely, a systematic review of hip fracture morbidity and mortality by Malik et al. found hospital volume rather than surgeon volume was more predictive of postoperative complications [51]. In hip hemiarthroplasty for femoral neck fractures, Spaans et al. demonstrated surgeon volume does not influence early outcome or complication rates [52]. Additionally, Wieggers et al. concluded neither hospital nor surgeon volume has an effect on outcomes in a systematic review and meta-analysis of over two million hip fractures [53]. Despite the challenges associated with proximal femur fracture treatment, the literature has not yet demonstrated a clear association between surgeon volume and risk of complications.

There are a number of patient-specific risk factors that can contribute to proximal femur fracture malunions. For example, obesity presents a myriad of challenges for providers. Significant soft tissue can increase the difficulty of patient positioning, visualization and reduction of the fracture, and intraoperative imaging. Struggling while treating proximal femur fractures in turn can contribute to malreductions, poor implant positioning, and subsequent complications. Obesity also is a risk factor for increased morbidity in orthopaedic trauma patients with increased surgical site complications, longer hospital stays, increased costs, and delays to fixation [54, 55]. Specifically with intertrochanteric femur fractures, Kempegowda et al. determined obese patients are more likely than nonobese patients to have both wound infections and systemic complications [56]. Orthopaedic literature across multiple subspecialties has shown increased operative time and blood loss for obese patients as well [57–59]. Patients under body mass index (BMI) 18.5 also have increased odds of perioperative complications, and as a result, orthopaedic trauma patients have increased complication rates at each extreme of the BMI spectrum [60]. This bimodal complication profile relative to BMI is associated with the malnutrition prevalent in both underweight and obese patients [61]. Malnutrition is closely intertwined with wound healing and bone quality, which can impact loss of fixation and malunion formation.

The bone quality and vascular anatomy also contribute to the ability of the bone to heal. As trabecular bone loss occurs in osteoporosis, it predisposes the proximal femur to fracture in part because of the compensatory shift of loading forces to the medial cortex at the base of the femoral neck. The blood supply to the proximal femur also can be tenuous, which can play a key role in determining the optimal treatment modality as well as the likelihood of vascular compromise and possible nonunion or avascular necrosis (AVN). Intracapsular fractures often compromise the femoral head blood supply increasing the risk of AVN and nonunion. Most commonly, the lateral epiphyseal vessels penetrate the lateral margin of the femoral head-neck junction putting fractures in this area at high risk of vascular injury. This risk generally decreases as fractures occur further distally along the femoral neck though, and basicervical femoral neck fractures as well as extracapsular intertrochanteric and subtrochanteric fractures have significantly less risk for femoral head blood supply disruption [62]. Although a compromised vascular supply is typically thought to be a higher risk for a nonunion, it can precipitate a malunion by prolonging the time to union during which the implant may be stressed to the point of fatigue and failure causing loss of reduction and subsequent union in a nonanatomical position.

In proximal femur fractures, failure of fixation is a common cause of malunions, nonunions, and other complications. This complication is multifactorial and affected by the patient's age, bone quality, fracture pattern, quality of reduction, screw positioning in the femoral head, and implant design and choice. Each fracture pattern also has varying degrees of risk associated with implant cutout and failure of fixation as well. For example, more vertical femoral neck, unstable intertrochanteric, and complex fracture patterns all have higher risks of implant failure. Although surgeons cannot change the fracture pattern or the host factors, they can control the quality of reduction and positioning of the implant in the femoral head, which significantly affect the cutout rate [28, 29]. Nonanatomical reduction and nonoptimal lag screw positioning are interdependent factors given the implant designs, and complex fractures with tough reductions can create difficulties with correct implant positioning [63].

Implant cutout is the most commonly reported complication with proximal femur fracture fixation. Baumgartner et al. described the sequelae of implant cutout in the proximal femur as the collapse of the neck-shaft angle into varus and extrusion of the screw(s) in the femoral head [29]. Incidence of cutout in studies has varied for compression hip screws and intramedullary devices from 0 to 16.5% [28, 64, 65]. For sliding hip screws, authors have reported failure rates of up to 10% in stable trochanteric fractures and 15% in unstable trochanteric fractures. Most commonly, these failures occurred as the lag screw cuts through the femoral head secondary to poor positioning in osteoporotic bone, articular penetration of the lag screw due to its failure to slide, shortening and varus collapse with medialization of the femoral shaft secondary to collapse at the fracture site and sliding of the lag screw, and lateral cortical failure. Although they have less blood loss and fluoroscopy time, cephalomedullary devices also have had similar postoperative complication rates [65]. Bartoníček et al. highlighted the numerous complications associated with proximal femur cephalomedullary nails that can lead to hardware failure and malreduction, which most commonly causes healing in varus. As a result, the authors recommended reducing proximal femur fractures in slight valgus when using cephalomedullary nails to minimize hardware complications [66]. Because proximal femur fractures fixed with both intramedullary and extramedullary implants have high rates of complications, a systematic review of implant selection in proximal femur fractures by Nyholm et al. concluded that the use of specific implants for proximal femur fractures lacked quality systematic-level clinical evidence. The authors recommended the establishment of large implant-specific registries to help monitor and qualitatively assess clinical results [67]. Nonetheless, most authors contend most complications are related to technical errors with insufficient reduction or incorrectly placed implants, which can lead to loss of fixation and malunions in the proximal femur.

9.2 Patient Evaluation

9.2.1 Clinical Examination

The clinical evaluation of patients with suspected proximal femur malunions begins with a history. Most patients will recall a fracture to the proximal femur and the vast majority will have had surgery to correct this injury. Providers should assess whether patients continue to have pain, functional limitations, a perceived leg length discrepancy, or rotational deficits. Many patients with malunions of the proximal femur may deny any notable deficits though, and the history of an injury and surgery to the area is the clue to providers to obtain imaging on which malunions may be diagnosed. Patients with a malunion may not have debilitating pain as seen in nonunions given union has occurred but in an abnormal position. Patients also may not have notable functional deficits as many proximal femur malunions are subtle, so much so that authors frequently do not report malunions as adverse outcomes in the literature in the treatment of proximal femur fractures as nonunions and hardware failure tend to lead to much more severe sequelae for patients. Obtaining a patient's history should not be limited to just a history of injury though. The patient's medical and metabolic history also are important pieces of information that help guide management. A history of osteopenia or osteoporosis can significantly increase the risk of loss of fixation and subsequent malunion. Similarly, medical conditions such as osteogenesis imperfecta, Paget's disease, malnutrition, and cancer can weaken bone, which can prolong the time to union and place increased demands on implants already in place.

Once completed with a thorough clinical history, providers should conduct a complete physical exam. This exam should assess patients' gait taking care to note any limp, rotational differences between the lower extremity, and leg length discrepancies by assessing the height of the patient's greater trochanters and iliac crests bilaterally. Range of motion of the hip and knee also can provide important data points as can pain with range of motion as the proximal femur malunion may lead to or exacerbate arthritic changes of the hip. Any palpable deformities or hardware along the lateral hip may also provide clues that over time the fracture reduction was lost or that hardware failed. Examining patients' previous scars can help surgeons not only ascertain what approach and implants may have been used prior to seeing radiographs but also develop surgical plans for treating the malunion. Additionally, a neurovascular exam distally in the bilateral lower extremities is important to help detect risks for future falls, such as neuropathy, which can place the patient at greater risk for refracture, hardware failure, or recurrent malunion after surgical treatment.

Some patients with proximal femur malunions may present with decreased functional mobility. If severe, the altered morphology of bone in malunions can alter the soft tissue kinematics. Consequently, the muscles, particularly the hip abductors, and tendons around the proximal femur may fatigue quickly given the abnormal nonanatomic tension. If present for a long period of time, the malunion may lead to visible atrophy of the musculature around the hip relative to the contralateral side. Although patients with proximal femur malunions can have pain, the pain is often activity related secondary to the soft tissue strain and fatigue unlike nonunion pain, which frequently is more constant and exacerbated by weight-bearing.

Patients with proximal femur malunions also may have soft tissue contractures that restrict not only the range of motion of the hip but also more distal joints in the lower extremity. The severity of the contractures is related to the period of immobility. These can develop as sequelae of long periods of immobility, which can occur intentionally if a fracture is treated nonoperatively. The vast majority of proximal femur fractures are treated operatively to avoid complications associated with prolonged periods of immobility, but patients with life-threatening injuries too unstable for operative fixation of the proximal femur may be treated nonoperatively. Likewise, fractures neglected in areas of the world with poor access to medical and orthopaedic care also may be treated nonoperatively. Additionally, patients with proximal femur fractures treated with operative fixation may lose fixation and subsequently reduction secondary to another accident such as a fall, poor bone quality, or hardware failure. If not identified early, these patients are at risk of developing a malunion and contractures.

9.2.2 Radiographic Imaging

When ordering studies, providers should think about how the information obtained from each study will affect both the diagnosis and subsequent treatment. Cost and radiation exposure are factors to consider. Radiographic evaluation of a proximal femur malunion begins with a standard anteroposterior (AP) pelvis along with AP and lateral views of the affected hip. A common mistake with AP radiographs is to leave the lower extremity, and therefore the hip, externally rotated. Consequently, care should be taken to keep both patellae at a 90° angle to the patient's coronal plane when taking the AP radiographs. Alternatively, internally rotating the lower extremity about 15–20° to match the femoral anteversion on the AP X-ray will provide a true anteroposterior profile of the proximal femur perpendicular to the plane of the radiograph. Flexion contractures though may alter image magnification and distort providers' ability to scrutinize femoral orientation. In such situations, the AP radiographs may need to be obtained in an oblique fashion to ensure they are perpendicular to the coronal plane of the femur in the contracted position. A number of imaging techniques for lateral radiographs of the proximal femur exist including the frog-leg lateral, 45° or 90° Dunn view, cross-table lateral, and false profile view. These each have their own advantages and disadvantages. The frog-leg lateral usually profiles the head-neck junction, but the greater trochanter can obscure the anatomy in this area. Frequently insufficient internal rotation of the limb is achieved with the cross-table lateral, a notable problem if the lesser trochanter is visible. Patients' body habitus also can obscure osseous landmarks in the cross-table lateral as soft tissue radiodensities can interfere with osseous landmarks [68, 69]. In patients with femoral head fractures, Judet pelvis radiographs also should be assessed for possible concomitant acetabular wall fractures.

Similarly, AP and lateral radiographs of the femur are also helpful given the incidence of femoral neck and femoral shaft fractures. Additionally, full-length femur X-rays allow providers to better assess mechanical alignment in both the coronal and sagittal planes, which can be particularly important for subtrochanteric femur fractures. These images will help guide treatment by informing providers if there is a significant femoral bow, which could increase the risk of anterior cortical perforation in antegrade femoral cephalomedullary nail treatment for basicervical femoral neck, intertrochanteric, or subtrochanteric fractures. It can affect the length of the construct desired by the surgeon as well if, for instance, the patient has hardware distally in the knee whether from a distal femur fracture or total knee arthroplasty in which case the surgeon may desire to bridge fixation constructs to minimize the risk of a stress riser.

Advanced imaging often is unnecessary in the diagnosis of a malunion, which typically is readily apparent on plain radiographs. Many proximal femur malunions are apparent in a single plane, and a sizable number occur after hardware failure. For example, a neglected cephalomedullary screw cutout from the femoral head as a result of technical error with an imperfect reduction or malpositioned implant, poor bone quality, or combination of the two can result in a malunion, which is readily apparent on plain radiographs. Likewise, radiographs also easily allow providers to diagnose a malunion in a subtrochanteric femur fracture treated nonoperatively with significant varus and procurvatum deformities.

Rotational deformities, however, can also occur in proximal femur malunions. In the operating room, surgeons frequently utilize the lesser trochanteric profile to assess femoral version relative to the uninjured contralateral side by utilizing fluoroscopy to assess the position of the patella or the tibia-fibular overlap distally at the knee and comparing it the lesser trochanter profile. Marchand et al. concluded that despite some natural variability in patients' contralateral lower extremity rotation, this method reestablishes native rotation intraoperatively [70]. While standing full-length AP radiographs of the bilateral lower extremities provide some comparative data about rotation in the ambulatory clinical setting, it often is inaccurate relative to the intraoperative fluoroscopic technique and provides only a very rough estimate of femoral malrotation. Consequently, a computed tomography scanogram enables providers to measure the angle of rotation of the femoral necks relative to the femoral condyles bilaterally allowing for a more precise measure of the proximal femur malrotation. Standing AP radiographs of the bilateral lower extremities should be the initial study for evaluating patients with a leg length discrepancy though [71], which can occur in proximal femur malunions. These full-length films of the lower extremities also are crucial to evaluate the mechanical axis. Standing AP radiographs of the bilateral lower extremities allow providers to measure and assess how deformity has affected the mechanical lateral proximal femoral angle (mLPFA = 90° +/− 5°) and the anatomic medial proximal femoral angle (aMPFA = 84° +/− 4°).

Computed tomography (CT) can be used for a variety of reasons in the setting of a suspected proximal femur malunion. Because assessment of union in the clinical setting remains an imperfect practice [72], a CT scan can be used to delineate whether a fracture has united or whether it is to a nonunion. If the scan detects a nonunion instead, providers should begin workup for possible infection and metabolic disorders with laboratory tests or additional advanced imaging such as gallium scans or radiolabeled white blood cell scans. Additionally, a CT scan with two- and three-dimensional reconstruction may allow for more complete evaluation of malunions of the trochanters, femoral head cavitation, trabecular bone loss, rotational malalignment, and arthritic changes in the hip joint. All of these variables may change the chosen management of the proximal femur malunion.

9.3 Femoral Head

9.3.1 Femoral Head Fractures

Femoral head fractures are uncommon injuries that frequently result from high energy trauma to the hip or lower extremity, and hip dislocations often accompany these injuries. Most femoral head fractures occur following motor vehicle accidents with a posterior hip dislocation, and less commonly these injuries occur from an anterior hip dislocation or in isolation without dislocation. The hip position at the time of the accident in flexion, abduction or adduction, and rotation coupled with the direction and amount of force determines the pattern and severity of the fracture. Approximately 6–16% of posterior hip dislocations have an associated femoral head fracture, and given delayed reduction increases femoral head osteonecrosis, reductions of hip dislocations are emergencies [73]. A femoral head fragment incarcerated in the joint can prevent reduction of a hip dislocation, increases the instability of the joint, and can cause damage to the articular surfaces. Considering the infrequency of these fractures though, numerous studies of large patient populations have been lacking. As a result, there is sparse literature about femoral head malunions.

Giannoudis et al. published a systematic literature review of 29 articles reporting a total of 453 femoral head fractures. Among papers included in the review, most authors utilized the Pipkin femoral head fracture classification scheme. Over 85% of these fractures occurred as a result of an automobile accident, and as is often the case in high energy traumatic incidents, the majority of patients were younger with a mean age of 38.9 years. The younger age of these patients presents a treatment challenge for surgeons as arthroplasty is generally a viable treatment for elderly patients who have a lower chance of needing revision arthroplasty in the future. In younger patients though, attempts to avoid bone loss must be balanced with the need to preserve the tenuous blood supply to the femoral head. As such, debate existed over the treatment modalities, surgical approach, and fixation techniques. Currently, recommendations for these injuries include urgent closed reduction and definitive operative management for the majority of the cases with fragment excision as a justifiable option for Pipkin I cases and open reduction internal fixation for larger fragments. Nonoperative management should be reserved for femoral head fractures in appropriate alignment with close attention paid, using advanced imaging, to the articular congruency and to the joint space to ensure no loose fragments remain interposed. The authors also noted that 11.8% of the cases developed AVN, which although not statistically significant, tended to be more likely when surgeons utilized a posterior approach rather than either a trochanteric flip osteotomy approach or anterior approach. Additionally, they found anterior and posterior approaches lead to 20 and 30 times higher incidence, respectively, of post-traumatic arthritis when compared to a trochanteric flip osteotomy. Consequently, the authors concluded a trochanteric flip osteotomy is the best choice for operative fixation of femoral head fractures [74].

Scolaro et al. described the management and outcomes of femoral head fractures with the largest cohort of patients treated with open reduction internal fixation in the literature. In their paper, the authors noted 53.1% of femoral head fractures underwent open reduction internal fixation, 25.1% received only fragment excision, and 19% were treated nonoperatively. With a minimum follow-up of 6 months, 90% of the fractures proceeded to union, whereas a number of patients sustained hardware failure and 8.7% developed femoral head AVN. The majority of their fractures treated operatively received a Smith-Peterson anterior approach, yet they concluded

Pipkin III fractures may not be amenable to operative fixation as they had high rates of fixation failure and AVN necessitating conversion to arthroplasty [75].

9.3.2 Femoral Head Malunions

Given the scarcity of femoral head fractures, femoral head malunions are even more rare and constitute intra-articular malunions. Literature review and cohort studies such as those aforementioned do not describe the incidence of malunion among femoral head fractures, but when present, malunions of the femoral head can be devastating to the hip joint. By altering the joint reactive forces, cartilaginous and labral damage can lead to pain, arthritic changes, and a limp. Malunions of the femoral head also can cause impingement and limited range of motion as well. Consequently, a femoral head malunion should remain on a differential in a patient with a history of a femoral head fracture and continued pain and limited range of motion. If a femoral head malunion occurs and is identified on a clinical and radiographic exam, a number of treatment options exist. With severe arthritic changes, a total hip arthroplasty is the best salvage procedure, particularly in an elderly patient (Fig. 9.1). In younger patients without arthritic changes though, a few authors have provided case reports to describe their preferred treatment methods.

Matsuda described an arthroscopic osteosynthesis for a femoral head fracture treated with open reduction internal fixation that progressed to a malunion in a noncompliant patient who had broken hardware in place. The patient, who had no radiographic evidence of osteonecrosis preoperatively, presented with painful decreased range of motion and perceived leg length discrepancy with a clinical exam picture consistent with femoroacetabular impingement (FAI). After removing a screw percutaneously, the author used a small osteotome through an arthroscopic portal to perform an osteotomy through the malunion after which he obtained reduction with direct visualization arthroscopically before placing bone graft and percutaneous screws. Osteophytes also were removed using an arthroscopic burr [76]. Although not performed by the average general or trauma orthopaedic surgeon, hip arthroscopy can be a valuable tool for the surgeon adept in its use in the treatment of femoral head malunions and assessment of femoral head reductions if not performing an open reduction. Of note, arthroscopy also can be used in extraction of incarcerated fragments or to aid in the fixation of femoral head fractures [77].

Most orthopaedic surgeons are likely more skilled with surgical hip dislocations rather than

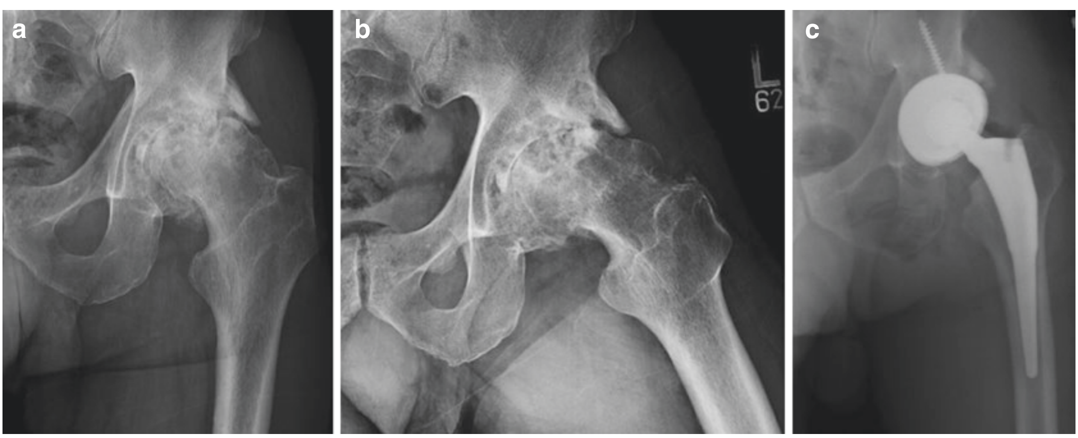

Fig. 9.1 (**a**) Anteroposterior and (**b**) lateral radiographs in a 58-year-old male who over 20 years ago had sustained a femoral head fracture dislocation treated initially nonoperatively. He subsequently developed an intra-articular femoral head malunion and severe arthritic changes for which he underwent a total hip arthroplasty (**c**)

hip arthroscopy. Ross et al. reported a case of FAI in a young, active male who developed a femoral head malunion after a femoral head fracture. This particular patient had a Pipkin II injury treated nonoperatively at the time of injury. After fracture union occurred and the patient resumed bearing weight, he continued to have pain with hip flexion. Clinical exam revealed painful and limited range of motion of the hip, and advanced imaging demonstrated a labral tear and chondral disease along with a femoral head malunion. The authors treated the patient with a Ganz trochanteric osteotomy and surgical hip dislocation preserving the medial femoral circumflex artery. They repaired the labral tear, freed the malunited femoral head piece using osteotomes, prepared the femoral head cancellous bed, and anatomically reduced the femoral head piece using headless compression screws. Prior to completion of the procedure, they utilized a burr to remove the cam-type deformity to improve anterolateral femoral head and neck impingement on the acetabulum as well as protect the labral repair. The patient reportedly did well postoperatively [78]. Yoon et al. also reported three Pipkin I femoral head malunions treated with partial ostectomy. The patients initially received nonoperative treatment in traction for 6 to 8 weeks for the inferomedial femoral head fractures after which they presented to the authors with pain and limited hip motion. Utilizing an anterior Smith-Peterson approach, the authors noted excellent results with ostectomies of the malunions and immediate weight-bearing and range of motion exercises [79]. Not only can malunions occur on the femoral head, but they also can occur on the acetabulum as reported by Sontich et al. Their patient sustained a Pipkin I femoral head fracture treated nonoperatively that went on to a malunion with the femoral head fragment uniting with the acetabulum causing functional deficits for which the patient underwent surgical debridement with excellent results [80].

Consequently, femoral head malunion presentation and treatment varies widely among providers. With a dearth of reports, no surgical approach or treatment method has proven to have superior outcomes. As aforementioned, arthroplasty remains a viable option for a femoral head malunion with significant arthritic changes secondary to either the malunion causing increased joint destruction or avascular necrosis. In patients in whom joint and bone preservation is possible though, preserving the blood supply is important regardless of the surgical approach taken to correct the malunion. The femoral neck and head blood supply has three distinct components with an extracapsular arterial ring arising from the lateral circumflex femoral artery anterior and the medial circumflex femoral artery posteriorly, ascending intracapsular cervical branches of the extracapsular retinacular arteries, and the artery of the ligamentum teres. While the medial circumflex artery generally provides the largest contribution of blood supply to the femoral head, particularly the superolateral weight-bearing portion, via the lateral epiphyseal artery complex, the lateral circumflex femoral artery supplies the anteroinferior femoral head via the inferior metaphyseal artery [62]. Given the importance of the blood supply in trying to avoid AVN postoperatively, it stands to reason that approaches to treat femoral head malunion should be guided by the literature available for femoral head fractures. Ganz et al. first described the surgical dislocation of the hip utilizing a trochanteric flip osteotomy in 2001, which provides a 360° view of the femoral head [81]. A number of authors have demonstrated good results and low rates of AVN with this approach in fixing femoral head fractures as well as osteochondral transplantation for femoral head osteochondral defects [74, 82–86]. Other authors also have advocated for a direct anterior approach to fix femoral head fractures [75, 87–89]. Given the conflicting data, surgeons at this time likely should choose whichever approach at which they are most adept and feel will provide the best access to the malunion when treating femoral head malunions.

9.4 Hip

Hip fractures constitute the vast majority of proximal femur fractures. Hip fractures can be divided into four types of fractures: (1) nondisplaced or impacted femoral neck, (2) displaced femoral neck, (3) stable intertrochanteric, and (4) unstable intertrochanteric. As these fractures have a preponderance to affect older patients, the goal of treatment for these injuries is to quickly maximize post-injury function by allowing for weight-bearing as soon as possible. Consequently, differentiating hip fractures into these four subtypes helps dictate the preferred method of treatment. While numerous studies have evaluated hip fracture outcomes and morbidity rates, Cornwall et al. subdivided their analysis based on the four types of hip fractures. They found preinjury function was the best independent predictor of mortality, and nondisplaced femoral neck fractures had the lowest 6-month mortality rate [90].

Patients can suffer significant declines in post-injury function after hip fractures as well, particularly if a malunion ensues. Before modern surgical techniques and implants when fears of infection and surgical complications outweighed potential benefits of operative intervention, most proximal femur fractures were treated nonoperatively with traction. During the treatment course, which included prolonged periods of bed rest and non-weight-bearing, many patients developed decubitus ulcers, venous thromboembolism, pulmonary complications, and significant muscle atrophy. For those patients that survived, their fractures usually united but in a varus, shortened, and often rotated position [91]. The resultant proximal femur malunions from nonoperative treatment lead to hip abductor weakness and a limp. With innovations in both surgical techniques and implants for hip fractures, the benefits of operative management eclipsed the risks, and consequently, most proximal femur fractures are treated with either surgical fixation or arthroplasty to reduce the morbidity and mortality associated with conservative management. Malreduction intraoperatively and implant failure postoperatively though both can lead to symptomatic malunions in which the proximal femur shortens and develops a varus deformity. Additionally, some implants for hip fractures are designed to allow for shortening to minimize nonunion rates, which can result in coxa vara.

The arthroplasty literature has demonstrated a strong correlation between femoral offset, abductor lever arm, and hip abductor strength. In particular, the hip abductors' lever arm strongly correlates with the gluteus medius activation angle. Maximizing offset during a total hip arthroplasty to match the normal contralateral side decreases joint reactive forces and improves abductor strength by increasing the lever arm, which also reduces the incidence of a Trendelenburg gait postoperatively. Ford et al. postulated femoral offset is the most important factor in decreasing postoperative total hip arthroplasty dislocations, more so than leg-length equality and acetabular component position. Younger patient ages and smaller prosthetic head size also increased the dislocation risk [92]. In total hip arthroplasty, impingement is often the cause of dislocation, and it is well established that larger diameter femoral head components increase range of motion before the femoral head or neck impinge on the acetabulum or prominent anterior inferior iliac spine, thereby increasing stability of the implant [93–97]. Range of motion improves as well with increased femoral offset by decreasing bony impingement of the greater trochanter on the acetabulum during flexion, abduction, and internal and external rotation [98–107]. While increasing femoral offset does not increase pain, it does preserve function and longevity of the total hip arthroplasty, and conversely, patients left with decreased femoral offset have diminished function [108, 109].

As illustrated in the arthroplasty literature, decreased femoral offset and limb shortening, such as in a malunion leading to a shortened femoral neck, can have debilitating effects. Slobogean et al. published a study on young femoral neck fractures in which patients from 18 to 55 years treated with femoral neck fixation had a 13% chance of having severe shortening, which they defined as 10mm or more. These patients all had significantly worse functional outcomes [30]. The recent Fixation Using Alternative Implants for the Treatment of Hip Fractures (FAITH) trial also revealed a greater amount of femoral neck shortening was associated with poorer hip function [110]. Not only will the femoral neck shortening affect femoral offset, thereby changing the lever arm of the hip abductors, but it also can alter leg lengths relative to the contralateral side leading to a perceived or real leg length discrepancy. Patients note leg length discrepancies of only 5 to 7 millimeters after total hip arthroplasty, which can alter gait mechanics and cause dissatisfaction [111–114]. This dissatisfaction makes postoperative leg length discrepancy one of the most common claims in medical malpractice lawsuits following total joint arthroplasty [115].

9.4.1 Femoral Neck

Femoral neck fractures are among the most common for proximal femur fractures. While typically an injury in the elderly after a low energy mechanism fall, young adults can sustain high energy femoral neck fractures as well. In the elderly, displaced femoral neck fractures frequently are treated with a hemiarthroplasty or total hip arthroplasty to allow for immediate weight-bearing and minimize risks associated with remaining immobilized. Providers generally elect to treat femoral neck fractures in younger patients with internal fixation. These patients are often more capable than elderly patients of withstanding and recovering from the insult of non-weight-bearing restrictions to the affected extremity during the recovery process. Younger patients also are more likely to need a revision arthroplasty later in life if treated immediately with an arthroplasty, and consequently, maintenance of bone stock can minimize arthroplasty-related complications and possibly avoid the need for arthroplasty altogether.

Young patients with femoral neck fractures often have injuries elsewhere, especially if the injury occurs as a result of a high energy mechanism. In patients with injuries to the lower extremity, it is essential to evaluate the patient and carefully scrutinize imaging for femoral neck fractures, particularly if the patient is experiencing groin pain or pain with attempted weight-bearing or has an ipsilateral femoral shaft fracture. Up to about 8% of femoral shaft fractures also have a concomitant femoral neck fracture, yet providers historically missed up to 30% of the femoral neck fractures [116]. Missing the diagnosis of femoral neck fractures though can lead to fracture displacement, femoral head osteonecrosis, and femoral neck nonunion or malunion [117]. Consequently, various protocols have emerged to try to better identify these injuries as prevention of a femoral nonunion or malunion and femoral head osteonecrosis is far easier than the treatment of those. These protocols include using dedicated preoperative internal rotation hip radiographs and fine-cut computed tomography [118], intraoperative fluoroscopic imaging and postoperative radiographs [119], and rapid-sequence magnetic resonance imaging [120].

9.4.1.1 Femoral Neck Malunions

While femoral neck fractures have had a complicated history with nonunions, femoral head osteonecrosis, and hardware failure frequently cited as complications, malunions of the femoral neck have received far less attention to date. Historically, femoral neck nonunion rates were close to 60% [121], but with technological improvements and better fracture care, these rates have dropped to between 0 and 30% in young patients [122–124]. Recent meta-analyses have calculated complication rates following femoral neck fractures to be about 20–30%. Damany et al. reviewed 18 studies with 564 femoral neck fractures looking for reported incidences of nonunion and avascular necrosis (AVN) of the femoral head, which they found were 8.9% and 23%, respectively. Of the 13 of the studies in the analysis that reported the type of fracture as well as the type of reduction, over 75% were treated with closed reduction, and this closed reduction cohort had a 4.7% nonunion and 28% AVN rate, respectively. The open reduction cohort had a higher nonunion rate at 11.2% and lower AVN rate at 10.1%. This meta-analysis demonstrated not only that open reduction may be associated with a higher incidence of nonunion but also that time to surgery did not significantly affect the rate of AVN [125].

Slobogean et al. published another meta-analysis assessing complications following young femoral neck fractures, which provides the most comprehensive analysis to date of the incidence of femoral neck complications, including malunions. They included 41 studies with over 1500 fractures and looked at a number of additional outcomes as well. The authors found isolated femoral neck fractures had an 18% reoperation rate, and although all nondisplaced femoral neck fractures had lower reoperation rates at 6.9% than displaced fractures at 17.8%, it did not reach statistical significance. Displaced fractures, on the other hand, had significantly higher AVN rates than nondisplaced fractures with a total incidence of 14.3%. This meta-analysis also revealed a nonunion rate of 9.3%. Interestingly, concomitant femoral shaft and neck fracture complication rates mirrored isolated, nondisplaced femoral neck fractures. Implant failure, infection, and malunion were not as widely reported in the studies included. Implant failure had an incidence of 9.7% while surgical site infections occurred in 5.1% of cases. Finally, femoral neck malunions occurred in 6.4% of all femoral neck fractures, 7.1% of isolated femoral neck fractures, and 5.6% of combined femoral shaft and neck fractures [32].

Malunions of the femoral neck though are undercounted in the literature. Given the severe problems associated with them, nonunions, avascular necrosis, and hardware failure tend to be primary outcome measures in many studies while malunions are evaluated more infrequently in studies on femoral necks. Many femoral neck malunions are asymptomatic. For example, patients rarely have issues with valgus malunions as exemplified by the acceptability of treated valgus impacted femoral neck fractures with percutaneous screws without a reduction. Unless they have AVN or implant failure, these patients tend not to have problems, yet their femoral neck fracture was not anatomically reduced (Fig. 9.2). Similarly, a valgus closing wedge osteotomy in the proximal femur often is the treatment for a femoral neck nonunion as it redirects the high shearing forces associated with more vertically oriented fractures to compressive forces. When performed for nonunions, these valgus trochanteric osteotomies intentionally generate malunions, but they are rarely described in the literature as malunions as they remain asymptomatic, particularly when compared to debilitating nonunions. Additionally, a number of femoral neck fixation constructs are designed to allow for compression and shortening, which in itself is a

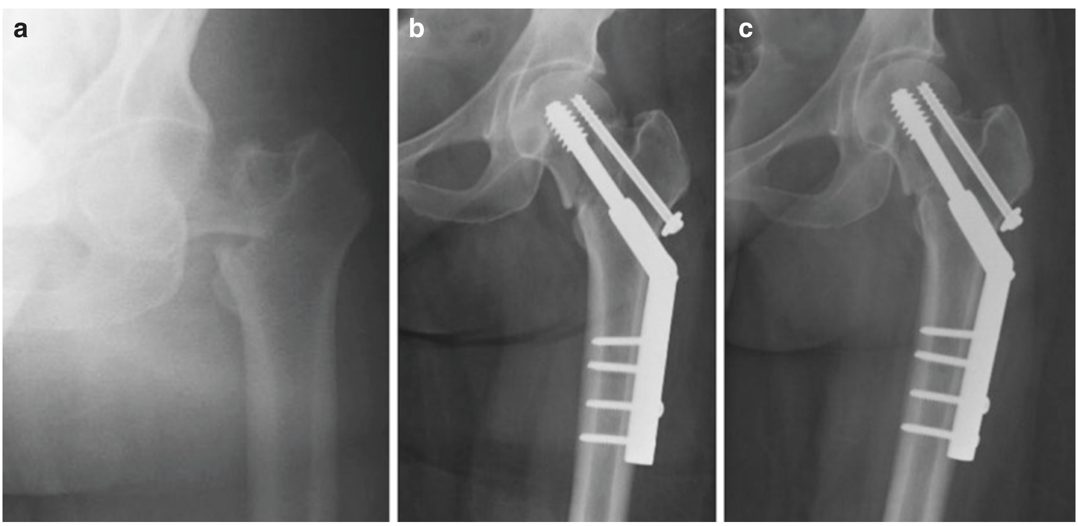

Fig. 9.2 (**a**) Anteroposterior injury radiograph of a 48-year-old female with basicervical femoral neck fracture. (**b**) Immediate postoperative radiograph after treatment with sliding hip and anti-rotation screws with valgus malalignment. (**c**) 6 months postoperative radiograph with healed valgus malunion of femoral neck fracture. The patient remained asymptomatic and resumed regular activities without issue

malunion, to minimize the likelihood of a nonunion. Thus, femoral neck implants, such as sliding hip screws, intentionally allow for malunions, which frequently go underreported.

Femoral neck shortening though can have significant side effects and is fairly common. Stockton et al. reviewed the incidence and magnitude of shortening in femoral neck fractures. Three-quarters of the 65 patients included in their study had displaced femoral neck fractures. Just over 75% of the patients received cancellous screws while surgeons treated the remaining patients with a sliding hip screw and derotational screw. Remarkably, 54% of the patients had at least 5 mm of shortening – 22% shortened 5–9 mm while 32% shortened 10 mm or more. According to their data, displaced fractures shorten significantly more than nondisplaced fractures, and perhaps unsurprisingly given the construct's design, sliding hip screws shorten more than cancellous screws (Fig. 9.3). The authors concluded that nearly one-third of patients with femoral neck fractures heal but in a severely shortened position that can cause clinical sequelae [34].

Another study assessed the incidence and effect on function of femoral neck shortening after fracture fixation with cancellous screws. Zlowodzki et al. conducted an observational study on 56 consecutive femoral neck fractures treated with cancellous screws. They found 30% of all femoral neck fractures treated with cancellous screws shortened with an abductor moment arm at least 10 mm shorter than the contralateral intact side with no significant difference between nondisplaced and displaced fractures. Patients with healed shortened fractures had significantly lower Short Form-36 functional scores than patients who did not experience shortening. Current femoral neck fixation constructs allow for femoral neck shortening at the expense of biomechanics given the emphasis on fracture healing biology. The authors postulated that fixation techniques that allow for compression to maintain positive biologic effect at the fracture site while also preventing shortening may improve biomechanics and functional outcomes following femoral neck fracture fixation [37].

Similarly, Chen et al. analyzed shortening in patients 60 years or older with femoral neck frac-

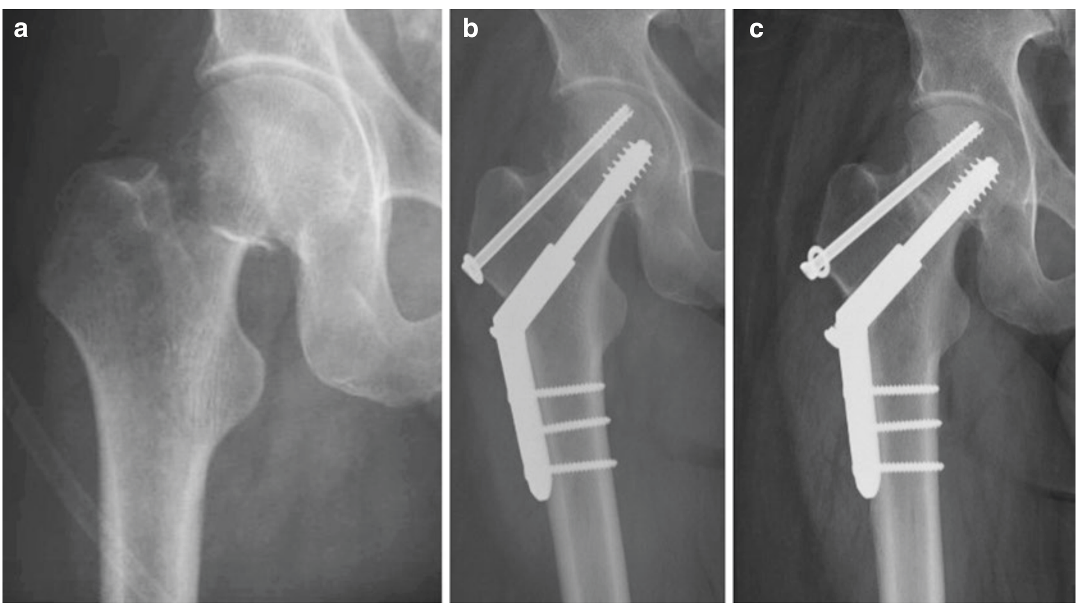

Fig. 9.3 (**a**) Anteroposterior injury radiograph of a 40-year-old with displaced femoral neck fracture treated with sliding hip and derotational screws. (**b**) Immediate postoperative radiograph. (**c**) Six-month follow-up radiograph with mild shortening of femoral neck noted

tures treated with closed reduction and cancellous screws. In their 110 cases, of which 71% were displaced femoral neck fractures, 41.8% had shortened during follow-up with Harris Hip Scores significantly lower in the shortened group versus the non-shortened group. They found shortening in their patients was significantly correlated to poor bone mineral density, age over 70 years, female gender, displaced fracture patterns, and the quality of reduction [38].

Zlowodzki et al. also published a multicenter cohort study analyzing the effects of femoral neck shortening and varus collapse after internal fixation. None of the 70 patients in the study received fixation with a sliding hip screw. All but one of the patients were treated with three cancellous screws while the other fracture was fixed with four cancellous screws. The majority of the fractures, 64%, were nondisplaced femoral neck fractures. At follow-up, 66% of the fractures shortened more than 5 mm, and 39% had more than 5° varus angulation. Nearly one in three patients had severe shortening of over 10 mm while nearly 30% of patients had severe varus collapse of over 10°. Only one third of the patients had neither shortening of 5 mm nor 5° or more of varus angulation. Shortening of the femoral neck again was predictive of a low physical function score [36].

In short, a healed femoral neck fracture in a shortened position changes the femoral offset and creates abductor muscle imbalance, gait problems, impingement, and limited range of motion. Consequently, malunion from significant shortening is another common risk of femoral neck fracture along with high incidences of nonunion, avascular necrosis, implant failure, and reoperation. Femoral neck shortening malunions occur regularly, can cause lifelong morbidity, and increase the risk of reoperation, particularly in young patients.

9.4.1.2 Cam-Type Impingement

Another potential cause of impingement, limited range of motion, and pain in the hip are cam lesions in the femoral neck. While the etiology of cam lesions is not completely understood, it is a common phenomenon that leads to femoroacetabular impingement. Wendt et al. described the incidence of cam-type impingement following fixation of femoral neck fractures in patients younger than 50 years. The authors found 46% of the 70 patients included in the study had an alpha angle greater than 42° on lateral radiographs suggestive of a cam-type deformity. Displaced subcapital femoral neck fractures had the highest incidence of developing a cam-type deformity postoperatively. FAI not only causes pain and limits motion, but it also is increasingly accepted as a cause of labral tears, cartilage damage, and osteoarthritis. The authors noted 31% of all femoral neck fractures and 58% of displaced subcapital fractures had radiographic evidence of degenerative arthritis by final follow-up while 17% developed avascular necrosis. Twenty-one percent of the patients in the study required conversion to a total hip arthroplasty. Of the five patients that required total hip arthroplasty who had no signs of AVN, all were noted to have femoral head asphericity or cam-type impingement. The authors consequently concluded that early detection of femoral neck malunion may allow for early intervention and hip preservation [35].

The definition of cam-type lesions varies across the literature, and whether radiographic prevalence corresponds to symptoms has not yet been well established. These lesions though are common in the general population with a prevalence of 14–17% (Fig. 9.4). Gosvig et al. reported 17% of males and 4% of females had cam-type impingement based on alpha angles measured on standardized AP radiographs, which may develop as a result of a silent slipped capital femoral epiphysis (SCFE) but had no significant association with hip pain, body mass index, occupational exposure to heavy workloads, or acetabular dysplasia [126]. Using magnetic resonance imaging to assess 200 asymptomatic patients with no history of hip surgery or childhood hip problem, Hack et al. reported 14% of subjects had evidence of cam-type impingement with increased prevalence among men and individuals with limited internal rotation [127]. The pediatric orthopaedic literature has demonstrated a strong association between both Legg-Calvé-Perthes and SCFE and the development of femo-

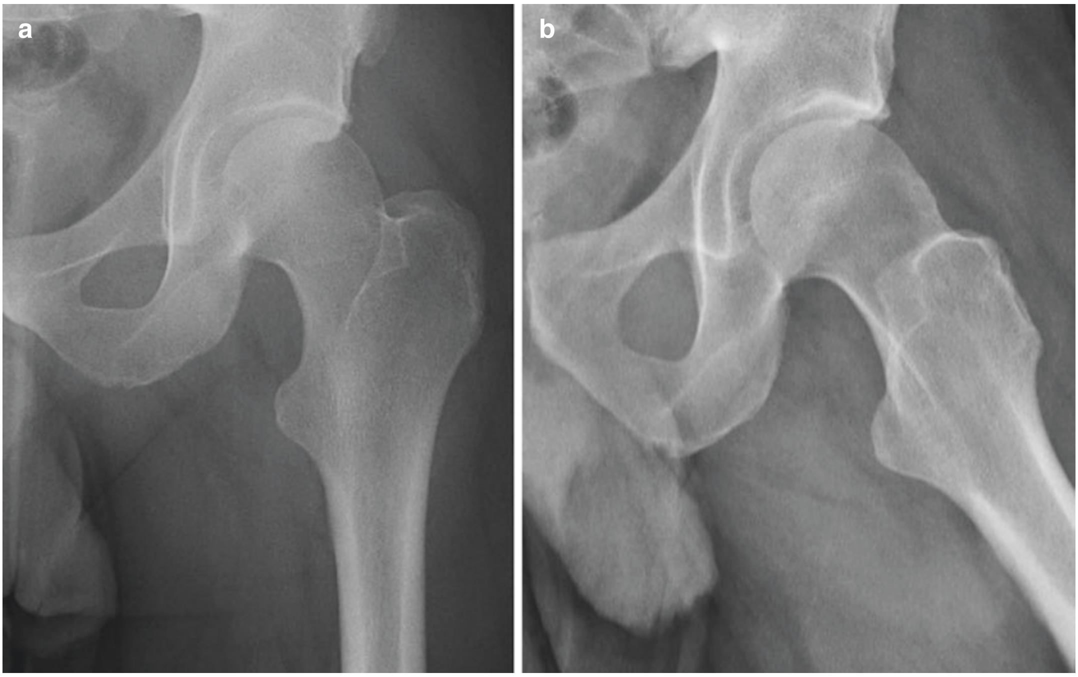

Fig. 9.4 (**a**) Anteroposterior and (**b**) lateral radiographs in a 36-year-old male with left hip pain with flexion, abduction, and external rotation attributable to femoroacetabular impingement from the cam lesion on anterosuperior femoral neck

roacetabular impingement [128]. Given the current standard of treatment for SCFE is an in situ screw without a reduction [129, 130], surgeons accept a malunion as a trade-off to try to minimize osteonecrosis of the femoral head, but both clinical and subclinical SCFE may lead to cam-type impingement and cause a femoral neck malunion. The ensuing deformity subsequently leads to early hip arthrosis by causing damage to the acetabular cartilage and flattening of the anterior acetabulum [131, 132].

Treatment of cam-type impingement lesions can be done both through a surgical dislocation of the hip and arthroscopically. Surgical dislocation provides an unparalleled exposure allowing for direct treatment of deformity through osteoplasty of the femoral head and neck. It may also provide better access to the acetabulum than arthroscopy when assessing complex impingement and its sequelae. As aforementioned in the treatment of femoral head malunions, most orthopaedic trauma surgeons are more likely familiar with the surgical dislocation of the hip, but the total number as well as the complexity and diversity of hip arthroscopy procedures continues to rise in the United States. Additionally, procedures for FAI and labral repairs are being performed more frequently in younger patients, which likely reflects both current evidence-based research indicating improved results in patients who have FAI treated earlier and the improved technical ability of surgeons [133]. A number of surgeons now favor hip arthroscopy to open surgical dislocation for the treatment of FAI given its minimally invasive nature while others use it as an adjunct to treat intra-articular disorders along with a “mini-open” anterior approach to resect the cam lesion [134]. In the past decade, arthroscopically assisted reduction and internal fixation has been an increasingly common approach utilized by surgeons to treat a variety of intra-articular fractures and verify the quality of reduction [135]. Although not without risk, hip arthroscopy consequently may play a larger role in the future to both treat cam lesions and assist with reductions at the time of displaced femoral neck fracture fixation given the increasingly apparent importance of anatomic reduction in minimizing the incidence of malunion, nonunion, avascular necrosis, and implant failure.

9.4.1.3 Loss of Fixation

Another common cause for femoral neck malunion is loss of fixation, or implant failure, which is a multifactorial issue. Given the high complication rate associated with treating femoral neck fractures, surgeons have debated the best way to fix femoral neck fractures for decades. A consensus currently exists that displaced femoral neck fractures in elderly patients are better served with a primary arthroplasty given the high rates of loss of fixation and reoperation when treated with internal fixation (Fig. 9.5). Loss of fixation though still can occur in younger patients leading to varus collapse, shortening, and symptomatic malunion. Numerous studies have shown that this progression can occur secondary to nonunion, malreduction, inappropriate implant selection and placement, osteonecrosis, and poor bone

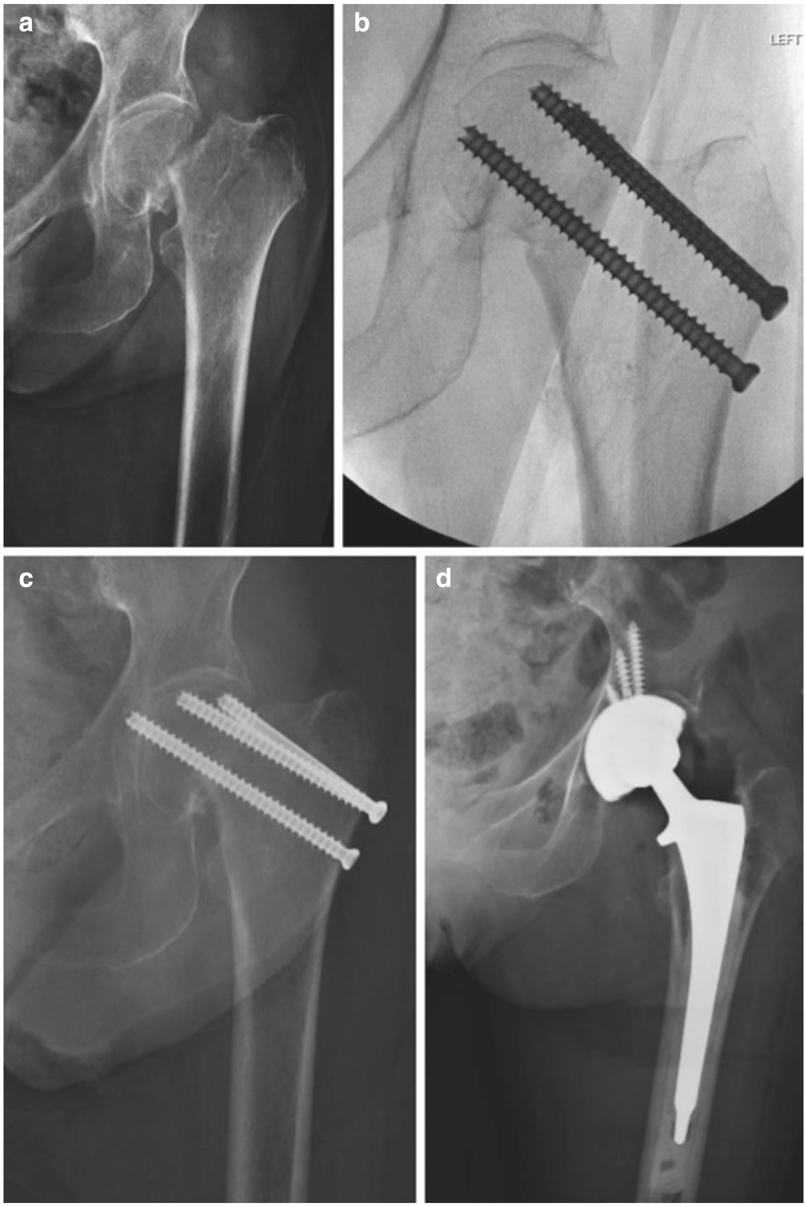

Fig. 9.5 (**a**) Anteroposterior radiograph of displaced femoral neck fracture in an 84-year-old female who declined the recommended hemiarthroplasty and instead elected for closed reduction and percutaneous cancellous screws. (**b**) Intraoperative fluoroscopy. (**c**) 1.5-month follow-up radiograph with loss of fixation, varus collapse, and screw penetration through femoral head. (**d**) Postoperative radiograph after subsequent salvage total hip arthroplasty procedure

quality. The rate of nonunion for femoral neck fractures varies between 7% and 20% of those treated with internal fixation [50, 125, 136]. These figures represent a significantly higher risk of nonunion than the overall risk of nonunion for all types of fractures calculated by Mills et al. to be 1.9% [137].

Failure to adequately reduce the femoral neck fracture recurrently emerges in the literature as one the most commonly cited reasons for complications following femoral neck fracture fixation. Slobogean et al. reported on 6.5% malunion rate in a prospective observational study among three centers in China that treated femoral neck fractures with internal fixation. Among the 107 fractures included, nonunions occurred in 8.4% and 10.3% developed osteonecrosis. Similar to many studies, displaced fractures, which accounted for 62% of those in the study, had a higher rate of complications. All but one case was managed with closed reduction, and 7% received sliding hip screws while the rest received cancellous screws. The study confirmed that closed reduction and percutaneous screw fixation leads to excellent results in most young patients with femoral neck fractures, but it also cautioned that fractures malreduced on at least one radiographic view had higher odds of a poor outcome. Therefore, the authors encouraged surgeons to perform an open reduction to improve radiographic alignment if the fracture remains malreduced after closed reduction [31]. Other studies also have demonstrated associations between radiographic reduction, fracture displacement, and fracture healing complications [50, 138]. As the importance of anatomic reduction has become increasingly clear, some authors have advocated for open reduction and medial buttress plating, particularly for vertical femoral neck fractures, to help obtain and maintain reduction. The medial buttress plate also helps resist shear forces and minimizes the risk of implant failure [139, 140].

Numerous studies have analyzed risk factors for fixation failure in femoral neck fractures. Biz et al. found nearly a 10% failure rate within 6 months for cancellous screws used in nondisplaced femoral neck fractures in patients older than 65 years. Predictors of early failure included nondisplaced Garden type II fractures, Pauwels type II or III fractures, and posterior tilt of more than 18° [141]. Okike et al. also found posterior tilt of 20° or more was associated with a greater than 20% risk of subsequent arthroplasty in elderly patients, and surgeons should consider arthroplasty as the primary treatment in older patients with significant femoral neck posterior tilt [142]. Not only are elderly patients at high risk of loss of fixation, but young patients with displaced femoral neck fractures also frequently have implant-related complications. Among middle-aged patients with displaced femoral neck fractures, Wang et al. found 33% nonunion or early collapse, 14.5% avascular necrosis, and 38% conversion to arthroplasty (Fig. 9.6). They also noted a 39.1% rate of femoral neck shortening and varus malunion rate among the displaced femoral neck cohort [33]. In their analysis of patients under 60 years old with displaced femoral neck fractures, Duckworth et al. found failures occurred significantly more often in patients over 40 years old and in patients who abused alcohol or had preexisting renal, liver, or respiratory disease [136].

Internal fixation remains the standard of care for the majority of femoral neck fractures in young patients, but given the high rate of complications including loss of fixation and subsequent malunion, controversy still exists regarding the optimal implant selection. Surgeons most commonly use multiple cancellous screws or sliding hip screws, but implant companies continue to try to design new systems to minimize the risk of implant failure and varus collapse (Fig. 9.7). In the United States, surgeons most frequently use multiple cancellous screws in nondisplaced femoral neck fractures. In displaced fractures though, surgeons are split with half using multiple cancellous screws while the other half use a sliding hip screw construct, which appears to be an increasingly common method of treatment [143]. Few studies have been conducted regarding the optimal implant choice. In 1986, Linde et al. published one of the few prospective, randomized trials comparing sliding hip screws with cancellous screws for femoral neck fractures finding the sliding hip screw group had significantly more

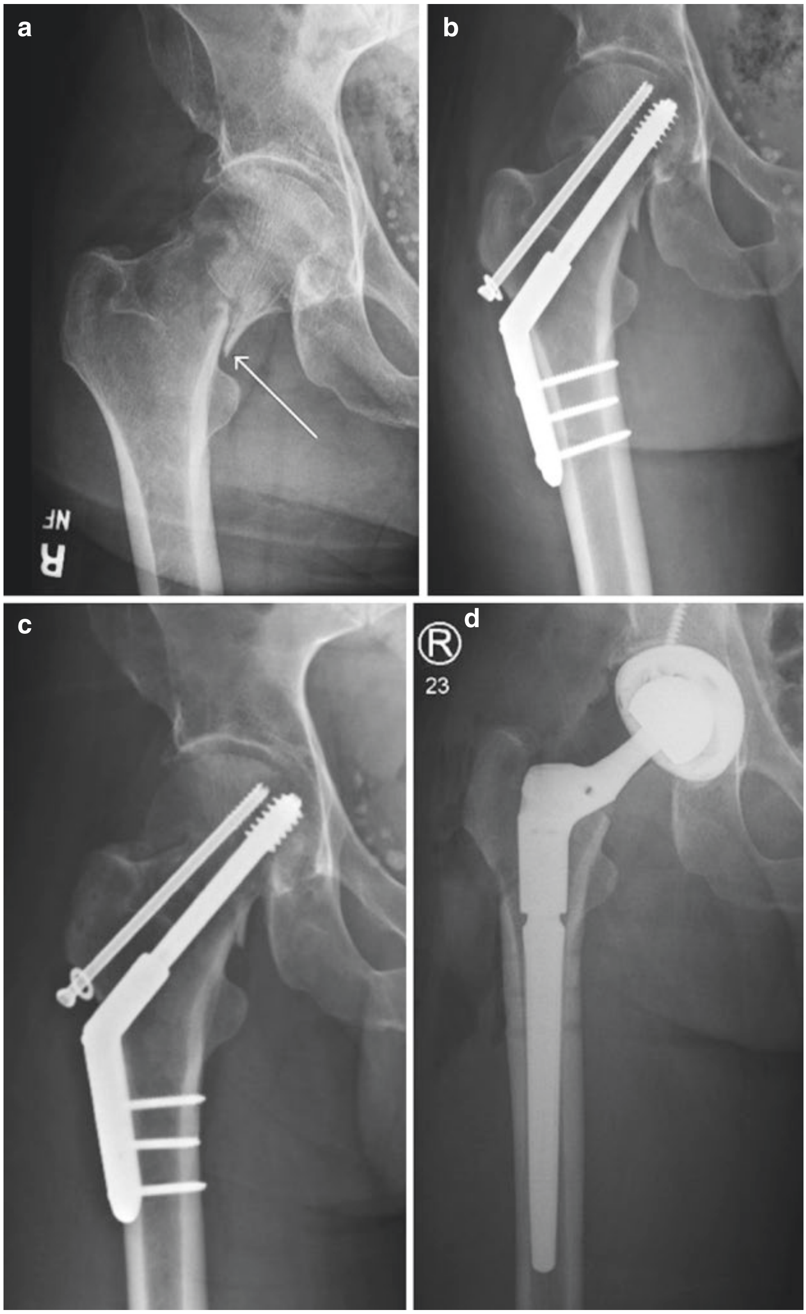

Fig. 9.6 (**a**) Anteroposterior radiograph of displaced femoral neck fracture in a 57-year-old male who was treated with (**b**) closed reduction and a sliding hip and derotational screws. As can be seen on the inferomedial cortex, the reduction was close but not anatomic. (**c**) Six weeks postoperatively, the patient had significant pain with motion of the hip and radiographs revealed femoral neck shortening and sliding hip screw protrusion into the hip joint. (**d**) The patient eventually received a total hip arthroplasty with a diaphyseal fitting femoral stem to bypass stress risers from the screw holes on the sliding hip screw plate

avascular necrosis of the femoral head than cancellous screws despite equivalent degrees of primary displacement and quality of reductions [144]. More recent uncontrolled retrospective studies though have found better results with sliding hip screws with fewer reoperations and nonunions [145, 146]. Gardner et al. revealed both quality of reduction and type of implant are significant predictors for early failure with cancellous screws failing more often [138]. A recent systematic review revealed that although sliding hip screws and cancellous screws have similar functional recoveries, the sliding hip screw group has fewer postoperative complications and faster

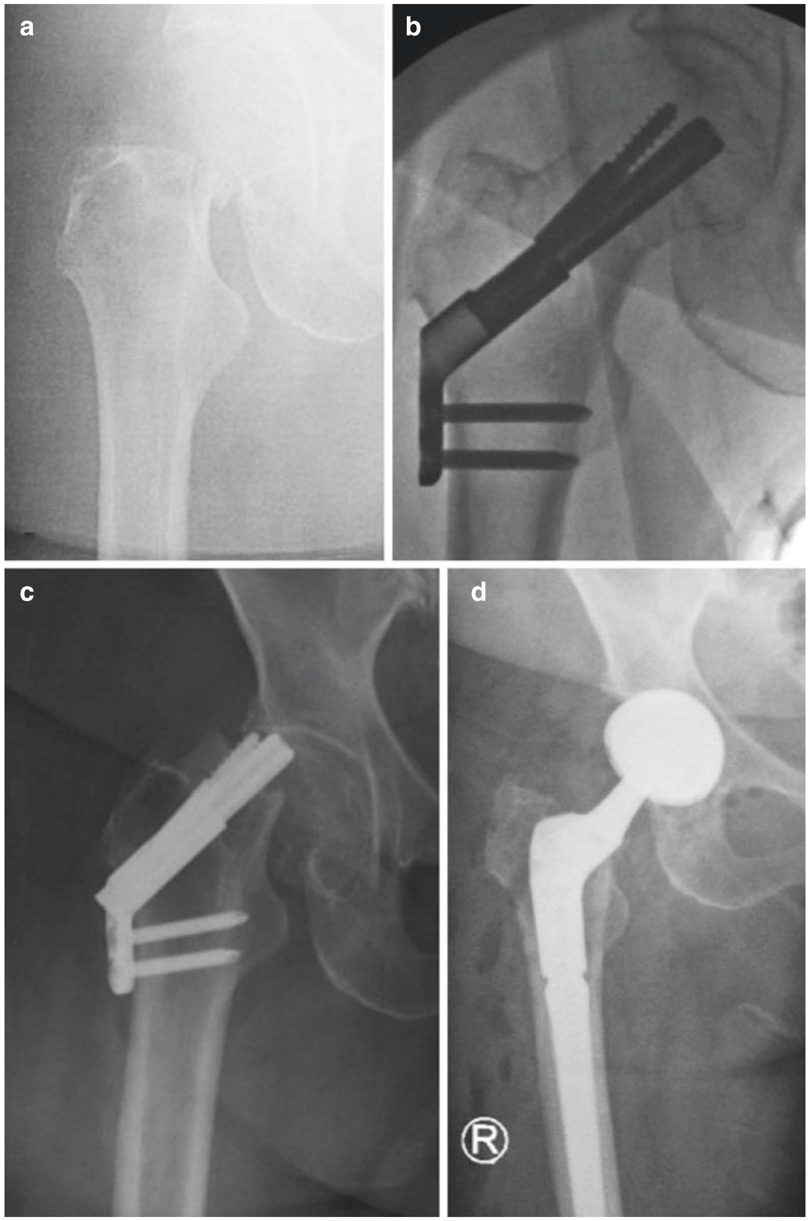

Fig. 9.7 (**a**) Anteroposterior radiograph of displaced femoral neck fracture in a 77-year-old female treated with (**b**) closed reduction and the Femoral Neck System (DePuy Synthes, Johnson & Johnson, New Brunswick, NJ, USA). (**c**) One month postoperatively, the patient had loss of fixation and cutout for which she underwent a total hip arthroplasty (**d**) with a diaphyseal fitting femoral stem

union time [147]. In another meta-analysis of randomized controlled trials directly comparing clinical outcomes of sliding hip screws and cancellous screws, Shehata et al. found ten studies with 1934 patients in which cancellous screws had less intraoperative blood loss, but no other statistically significant differences existed between the two intervention groups [148].

An international randomized controlled trial, the recently published FAITH trial, tried to definitively determine whether sliding hip screws or cancellous screws had superior outcomes. The study enrolled patients 50 years or older with low-energy hip fractures and included 557 patients treated with sliding hip screws and 557 treated with cancellous screws. Investigators concluded reoperations within 24 months and medically related adverse events did not differ between treatment modalities, but sliding hip screws more commonly resulted in femoral head

AVN. Some groups of patients, including smokers and those with displaced or basicervical femoral neck fractures, appeared to do better though with sliding hip screw constructs [149]. Further analysis of the FAITH study results revealed female sex, higher body mass index, displaced fracture, unacceptable quality of implant placement, and smokers treated with cancellous screws had increased risks of revision surgery, and as such, authors postulated that some of these high-risk groups may be better treated with arthroplasty [150]. Although no consensus currently exists among surgeons as to the preferred implant configuration, anatomic reduction is essential at the time of initial fracture fixation to avoid implant failure and subsequent complications including malunions.

In femoral neck fractures that do result in symptomatic malunions, treatment options vary based on the patient's age, bone quality, and activity level. In young patients, joint preservation remains preferable, and surgeons typically elect to perform a valgus intertrochanteric osteotomy. This procedure not only corrects the varus malunion typical of femoral neck malunions, but it also tensions the abductor musculature providing extra stability and improving gait. Symptomatic malunions in older patients with impingement, degenerative joint changes, or poor bone quality may be better treated with arthroplasty, which minimizes the recovery period.

9.4.2 Intertrochanteric Fractures

Similar to femoral neck fractures, intertrochanteric fractures are very common among proximal femur fractures. In elderly patients, intertrochanteric fractures account for over 50% of proximal femur fractures, which almost all occur following low-energy trauma [151]. Malunion and nonunion are uncommon in this region following operative fixation. Intertrochanteric femur fractures frequently unite given the excellent blood supply in the region, and the reported incidence of intertrochanteric nonunions is around 1% [152]. Without surgical stabilization, these fractures frequently form malunions though with coxa vara, shortening, and external rotation. Consequently, intertrochanteric malunions are often seen in developing countries with limited resources as fractures are neglected or physicians have no ability to provide surgical correction. In resource rich nations, malunions in this area are generally secondary to malreduction intraoperatively or loss of fixation whether from implant failure or cutout, which can occur secondary to malpositioned hardware and/or patient biology. Fracture pattern and implant choice also contribute with failure rates of sliding hip screw constructs in unstable intertrochanteric fractures as high as 9–16% [153]. Even in stable intertrochanteric femur fractures, sliding hip screws allow for shortening and a resultant malunion (Fig. 9.8).

Varus malunion or nonunion is the most common biomechanical complication following treatment of unstable trochanteric fractures. A varus malunion leads to limb shortening, imbal-

Fig. 9.8 Anteroposterior radiograph of healed but shortened intertrochanteric femur fracture treated with a sliding hip screw. Consequently, it now has a resultant malunion

ance of the abductor muscles, and limping, which can in turn lead to back and knee pain. Malunions in the intertrochanteric region can be subdivided into two types depending on the level of shortening. Although each patient should be considered individually, leg length differences of up to 2–2.5 cm are generally asymptomatic while larger limb length discrepancies can lead to gait alterations and back pain [154–156]. In a modest leg length difference, a shortening osteotomy of the contralateral side could be considered as an option, but addressing any rotational or angular deformity requires a surgery on the affected limb. In addition to coxa vara, malunions with shortening can have internal or external rotational components. Treatment of malunions with up to about 2.5 cm of shortening generally only need a valgus-inducing intertrochanteric or subtrochanteric osteotomy to correct both the rotation and coxa valga. In severe coxa vara with more significant shortening though, additional efforts should be made to correct the leg length discrepancy as well [157].

A number of studies have reported small cohorts of intertrochanteric femur malunions [158, 159]. Patients typically present with a painful limp and have restricted abduction and internal rotation secondary to coxa vara, shortening, and external rotation. To correct the deformity, surgeons most often use a valgus intertrochanteric osteotomy, which has a high success rate and good reproducibility. Bhowmick et al. also offered a good way to approach intertrochanteric femur malunions by utilizing an algorithm to help guide management of these patients. The authors assessed union, pre- and postoperative shortening, the head-shaft angle, and functional outcomes. Of the 19 malunions included in the study, 16 resulted from neglected intertrochanteric fractures, two previously were treated with sliding hip screw constructs, and one had been treated with cancellous screws. They subdivided these patients based on the duration of the initial trauma into two groups: (1) maluniting less than 3 months since injury, presence of pain, and visible fracture lines on radiographs and (2) malunited more than 3 months since injury without pain and no fracture line visible on radiographs. For the maluniting cohort, they treated these patients with osteoclasis at the fracture site, traction, reduction, and either a sliding hip screw or cephalomedullary nail depending on whether the lateral cortical wall thickness was greater or less than 20 mm, respectively. For the malunited cohort, a valgus intertrochanteric osteotomy either with a sliding hip screw or angled blade plate allowed for correction of the head-shaft angle and restoration of femoral length. Patients did well with less than 2.5 cm shortening, markedly improved head-shaft angles, and acceptable functional outcomes [152].

For intertrochanteric hip fractures complicated by loss of fixation, treatment options include prosthetic replacement and revision internal fixation. Haidukewych and Berry demonstrated good success rates with open reduction and internal fixation with bone grafting using a variety of implants among 20 cases of early loss of fixation [160]. This option is likely ideal for younger patients in whom preservation of bone stock and concerns about demand may preclude arthroplasty as an option. Arthroplasty though is generally a reliable option for elderly patients in whom bone quality may be of concern, particularly if loss of fixation already occurred (Fig. 9.9). A systematic review by Luthringer et al. demonstrated both total hip arthroplasty and hemiarthroplasty are effective salvage procedures [161]. Consequently, if arthroplasty is the chosen salvage procedure, careful evaluation for acetabular-sided defects and the individual surgeon's preference and expertise should guide treatment to ensure optimal outcomes.

Although reliable treatment options exist for intertrochanteric femoral malunions, avoidance of a malunion must still be the goal when treating intertrochanteric femur fractures. Generally reserved as a salvage procedure for these fractures, arthroplasty is an option for acute treatment of intertrochanteric fractures, particularly in the elderly and those with preexisting degenerative joint disease. Arthroplasty would eliminate the risk of developing a malunion, but according to a recent meta-analysis, arthroplasty has a higher risk of 1-year mortality, is technically more difficult, increases blood loss and

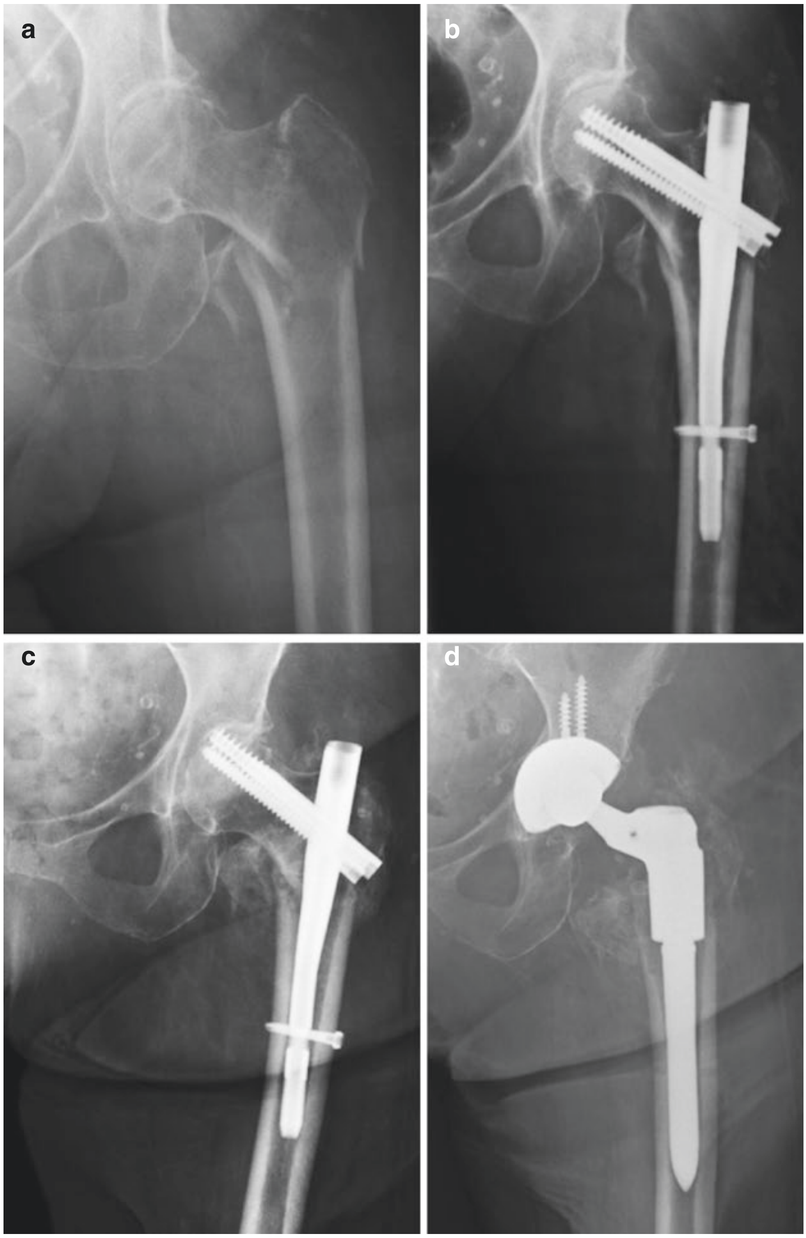

Fig. 9.9 (**a**) Anteroposterior radiograph of displaced femoral neck fracture in a 90-year-old female treated with (**b**) closed reduction and cephalomedullary nail. (**c**) Three months postoperatively, the patient had loss of fixation and cephalomedullary screw cutout for which she underwent a total hip arthroplasty (**d**)

transfusion requirements, and takes longer than cephalomedullary nailing [162]. Consequently, most intertrochanteric femur fractures receive fixation with either a cephalomedullary nail or sliding hip screw. Implant choice for these fractures has been a hotly debated topic. Cephalomedullary nailing has become increasingly popular over the past few decades in the treatment of intertrochanteric fractures, yet outcomes have not changed much. Fortunately, these devices may result in less radiographic shortening [163]. A number of meta-analyses though have demonstrated sliding hip screws have lower complication rates and lower costs in stable intertrochanteric fractures while cephalomedullary nails may prove superior in unstable intertrochanteric and subtrochanteric fractures [164–166]. Implant failure is common among unstable trochanteric fracture patterns and ranges by implant type from 0 to 29% for intramedullary nails, 13–37% for 95° for blade plates and 95° dynamic condylar screws, and 11–56% for dynamic and sliding hip screws [167]. Excessive sliding also occurs in hip screw devices in pertrochanteric fractures with posterior displacement of the head and neck leading to varus malunions and shortening. As a result, Tsukada et al. emphasized the importance of obtaining appropriate reduction on both AP and lateral radiographs intraoperatively prior to fixation [44].

Regardless of implant choice, adherence to a number of technical points will minimize the risk of complications and ensure maintenance of anatomic reduction. Haidukewych highlighted ten salient principles to improve intertrochanteric fracture results: (1) use the tip-apex distance with the lag screw centered in the femoral head within 10 mm of the subchondral bone in all planes; (2) use a cephalomedullary device instead of a sliding hip screw if the lateral wall of the proximal femur is compromised; (3) use a cephalomedullary nail in all unstable intertrochanteric patterns; (4) remain conscious of the femur's anterior bow to prevent anterior cortical perforation of a nail distally; (5) start a trochanteric nail slightly medial to the tip of the greater trochanter to avoid the nail lateralizing the femoral shaft causing both a varus malreduction and superior placement of the lag screw in the femoral head; (6) only ream with the fracture reduced to help the nail reduce rather than malreduce the fracture; (7) avoid using a hammer to seat a nail as it can propagate an iatrogenic fracture; (8) use the relationship between the tip of the greater trochanter and the center of the femoral head to help avoid varus angulation of the proximal fragment, which increases the lever arm on the fixation and the risk of cutout or hardware failure; (9) lock the nail distally if the fracture is axially or rotationally unstable; and (10) avoid fracture distraction, which can increase the likelihood of a nonunion and loss of fixation by requiring too much of the construct, by releasing traction before placing the distal locking screws [168].

9.5 Subtrochanteric Fractures

Although it experiences high levels of stress, the subtrochanteric region of the femur, defined as the distance from the lesser trochanter distally 5 centimeters along the shaft, fractures less often than the femoral neck and trochanteric regions. About 3–10% of proximal femur fractures occur in the subtrochanteric region [13, 169]. Subtrochanteric fractures occur in bimodal age distribution with younger patients often suffering high energy traumas while low energy fractures among elderly, osteoporotic patients are increasingly common [13, 170]. Surgeons most commonly utilize intramedullary fixation, which provides for a shorter lever arm than extramedullary fixation, as it has demonstrated a significantly decreased rate of fracture fixation complications, particularly in elderly patients [171, 172]. In younger patients with good bone quality and minimal comminution though, 95° blade plates also can be used effectively to counteract the deforming forces in subtrochanteric femur fractures [173].

Patients with neglected or nonoperatively treated subtrochanteric fractures frequently present with subtrochanteric malunions with varus, shortening, procurvatum, external rotation, and poor outcomes [174]. Malunions also occur relatively easily intraoperatively secondary to malreduction given the subtrochanteric region's broad metaphyseal medullary canal. Finally, implant failure and loss of fixation occur regularly in this region as a result of the high stress on this part of the femur [175]. Surgeons therefore must take care preoperatively and intraoperatively when managing these fractures as the quality of reduction and fixation stability are factors in their control to help minimize nonunion, loss of fixation, and possible subsequent malunion formation.

Subtrochanteric malunion incidence is not commonly reported in the literature, but a number of studies have provided numbers from which the incidence may be estimated. Shukla et al. examined 60 traumatic, non-pathologic subtrochanteric fractures treated with cephalomedullary nails. They noted 19 fractures were fixed in varus with more than 10° angulation at the fracture site suggesting that malreduction intraoperatively occurred in nearly one-third of cases. While the union rate using cephalomedullary nails was 95%, malunion occurred in 16.7% of all cases. Nearly half of the patients in the study underwent open reduction, and this subset of patients had significantly decreased rates of malunions, nonunions, and implant failure. Consequently, the authors advocated for the use of open reduction when necessary to obtain an anatomic reduction and minimize complications including malreduction and malunion [39]. Riehl et al. also found 20% of their subtrochanteric femur fractures treated with intramedullary nailing had a malreduction greater than 10° in the coronal or sagittal planes, and these cases all developed either a delayed union or nonunion [40]. Jackson et al. echoed the importance of obtaining an anatomic reduction at the time of the definitive fixation as the main cause of malunions and nonunions for subtrochanteric fractures appears to be intraoperative malreduction [169].

If a symptomatic subtrochanteric malunion ensues, providers can utilize a variety of methods to treat the malunion. Surgeons must first ascertain to what degree the deformity involves the coronal, sagittal, and axial planes to help preoperatively plan. The corrective osteotomy needs to account for the degree of shortening, malrotation, procurvatum, and varus typical of these subtrochanteric deformities. If there are minimal procurvatum and rotational components to the malunion, a valgus intertrochanteric osteotomy can be utilized. A posterolateral subtrochanteric opening wedge osteotomy may be needed though with or without bone graft to try to regain length and restore alignment in the shortened, externally rotated, varus, and procurvatum deformity typical of subtrochanteric malunions. If an oblique multiplanar osteotomy proves too risky or challenging, multiple single plane osteotomies may be made to correct a multiplanar deformity, but the surgeon must take care to minimize soft tissue damage, preserve blood supply, and control each segment to avoid nonunion and malreduction in the process of maintaining fixation.

The type of osteotomy, deformity, and previously used approach at the time of initial fixation may dictate what type of implant is utilized during the malunion correction. Converting from a cephalomedullary nail to an angled blade plate or vice versa has been described with good success in the literature for management of nonunions though, so the implant used in the first procedure does not restrict options [176, 177]. Some authors also advocate for the use of allograft strut supplementation when converting to angled blade plates for nonunion management [178]. If utilizing a cephalomedullary nail, maintenance of reduction while reaming and inserting the nail is paramount to prevent malreduction during the malunion correction. Finally, arthroplasty is an option for subtrochanteric femur fractures, particularly in elderly patients or those with arthritic changes in the hip. If converting to arthroplasty, surgeons should utilize a diaphyseal fitting femoral stem to bypass the osteotomy site to minimize the risk of femoral stem loosening and complications (Fig. 9.10). Additionally, care should be taken to maintain femoral offset and soft tissue tension to minimize the risk of dislocation.

As in treating femoral neck and intertrochanteric fractures, avoidance of a malreduction, loss of fixation or hardware failure, and malunion in subtrochanteric fractures at the time of initial fixation must remain the primary goal. Subtrochanteric fractures are independent risk factors for intramedullary nail breakage, and Johnson et al. found young, healthy patients had the highest risk of nail breakage [179]. Consequently, anatomic reduction is critical to minimize strain on and optimally place the implant. Many of the principles with intramedullary nailing for intertrochanteric femur fractures apply to subtrochanteric nailing. In particular, the fracture must be reduced before reaming and while inserting the nail. Additionally, the starting point for trochanteric entry nails is critical as a lateral starting point can cause a varus alignment and superior cephalomedullary lag screw placement increasing the risk of hardware failure and loss of fixation. Consequently, an eccentric starting point just medial to the tip of the trochanter on AP fluoroscopy is recommended to help

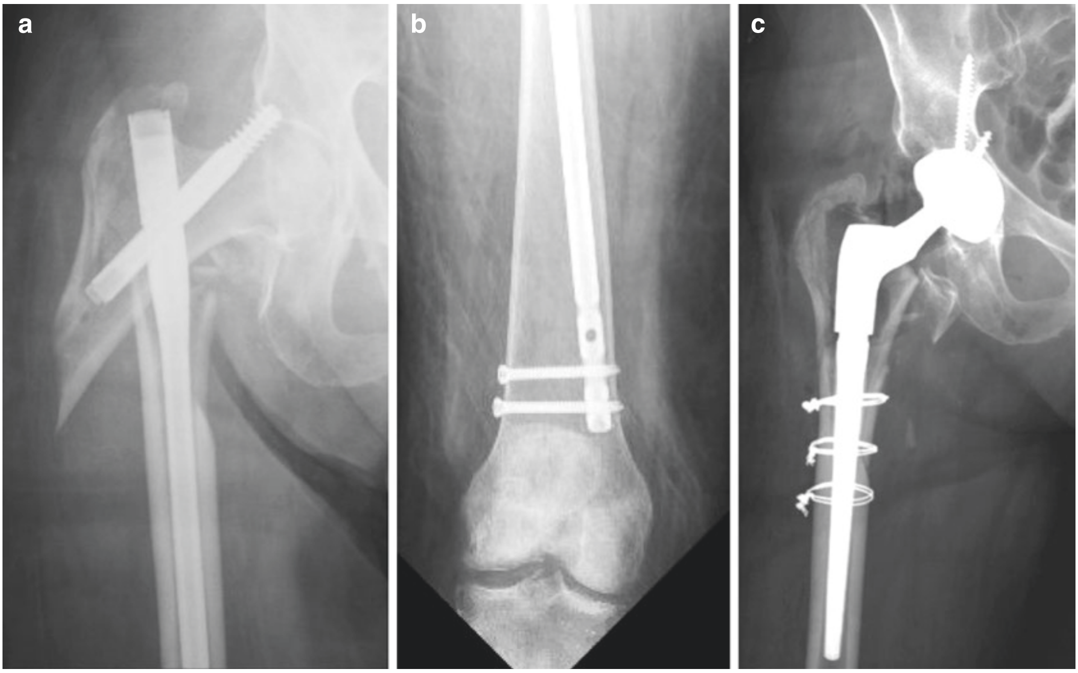

Fig. 9.10 (**a**) Anteroposterior hip and (**b**) femur radiographs of a 90-year-old female with a subtrochanteric femur fracture one-month status post cephalomedullary nail at an outside facility with loss of fixation and screw cutout. (**c**) She underwent a salvage total hip arthroplasty with cerclage cables to assist with fracture reduction and a diaphyseal-fitting femoral stem

avoid a varus malreduction [180]. Berkes et al. emphasized the importance of this medial "trochiformis" starting point using a trochanteric entry nail as well as preferential eccentric lateral endosteal reaming in atypical subtrochanteric fractures to assist with obtaining a valgus alignment with nail placement [181]. Additionally, a larger diameter proximal body for the nail can help fill the proximal femur, which may help particularly in elderly patients with poor cancellous bone quality. Surgeons also can utilize noninvasive and percutaneous reduction techniques, which include, but are not limited to, using Schanz pins, femoral distractor or temporary external fixator, and ball-spike pushers, to help obtain and maintain a reduction while reaming and placing the nail. Subtrochanteric femur fractures frequently require direct visualization and open reduction at which time the surgeon can utilize reduction clamps or provisional plate fixation to help reduce the fracture prior to nailing. Robertson et al. highlighted the advantages associated with provisional plating in which they compared open provisional plating to closed reduction and found 0% and 27.7% rates of malunion, defined as more than 5° of angulation, respectively [182]. Because the quality of reduction and stability of fixation help determine outcomes for subtrochanteric femur fractures, utilizing open reduction techniques must remain an option if closed measures fail to obtain adequate reduction.

9.6 Treatment

When considering the treatment of patients with symptomatic proximal femur malunions, similar principles apply to malunions in the femoral neck, trochanteric, and subtrochanteric regions. The patient's age, patient's future demand on the joint, current function and quality of the joint, bone stock, bone quality, state of the soft tissues, and previous surgery all help guide decision-making. In all malunions, providers must first ascertain what the patient's goals are and help manage expectations. Malunion procedures have significant inherent risks that patients must understand, and for some patients, the functional limitations from a proximal femur malunion may be acceptable relative to the risk of undergoing a corrective procedure. Others, though, may wish to proceed with surgical correction to try to obtain a more functional joint and limb. Each surgery must be tailored to the individual patient to ensure proper malunion correction. For example, if the malunion occurs as a result of broken hardware, surgeons must ensure they plan for ways to remove the implant before the malunion correction can begin during the procedure. Similarly, if an opening wedge osteotomy is performed, the provider should consider whether and what type of bone graft will be used to fill the void. Thorough preoperative planning can help ensure success intraoperatively where appropriate reduction and implant positioning are essential. Part of this preoperative planning includes in-depth patient counseling to help set expectations and review the expected postoperative course as well as potential complications associated with the agreed upon treatment.

9.6.1 Osteotomy

The majority of malunions in the proximal femur result in shortening, varus angulation, and some degree of rotational deformity. Valgus-producing osteotomies, therefore, are the workhorse of malunion correction in the proximal femur, particularly in young patients as arthroplasty in this population is associated with accelerated polyethylene wear and premature implant loosening. Osteotomies on the other hand preserve bone and the longevity of the joint itself by maximizing joint congruency, increasing length, and transferring loading forces to convert shear forces to compressive forces. Patients with chronic proximal femur conditions from congenital and acquired causes frequently develop arthritis secondary to abnormal joint wear. Acquired causes include proximal femur nonunions and malunions while fibrous dysplasia, developmental coxa vara, and developmental hip dysplasia can result in congenital proximal femur anomalies. Regardless of etiology, standard hip replacement techniques and implants often are unsuitable for use in proximal femoral deformities, thereby increasing the complexity of and risks associated with arthroplasty. Proximal femoral osteotomies not only help prevent further joint degradation but also simplify any future arthroplasty by restoring the anatomy. These osteotomies rely on maintaining the integrity of the femoral head. Preservation of the femoral head blood supply is of paramount importance, and to minimize risk of injury to the medial femoral circumflex artery, the predominant vessel supplying the femoral head, proximal femoral osteotomies are performed through a lateral approach.

Surgeons should consider whether previous surgery and hardware have been complicated by infection. Lab studies including inflammatory markers with a white blood cell count, erythrocyte sedimentation rate, and C-reactive protein level preoperatively can help determine whether infection is likely. Infection is a contraindication to a proximal femur osteotomy as treating the infection takes precedence. Similarly, advanced osteoarthritis and osteonecrosis are relative contraindications to an osteotomy as patients with these conditions may need a total hip arthroplasty instead of an osteotomy.

In appropriately selected patients, osteotomies have good track records with unreduced SCFE, femoral neck, intertrochanteric, and subtrochanteric malunions. SCFE can result in both cam lesions as aforementioned and malunions typified by coxa vara, femoral shortening, and femoral neck retroversion with resultant loss of hip motion (Fig. 9.11). A valgus-producing proximal femoral osteotomy can reestablish normal rotation while also correcting varus, which equalizes limb lengths and abductor tension. Femoral neck and intertrochanteric malunions also typically have varus angulation and shortening, which causes shortening of the abductor lever arm, a Trendelenburg gait, and poor hip motion with possible trochanteric-pelvis impingement. Valgus intertrochanteric osteotomies in these patients

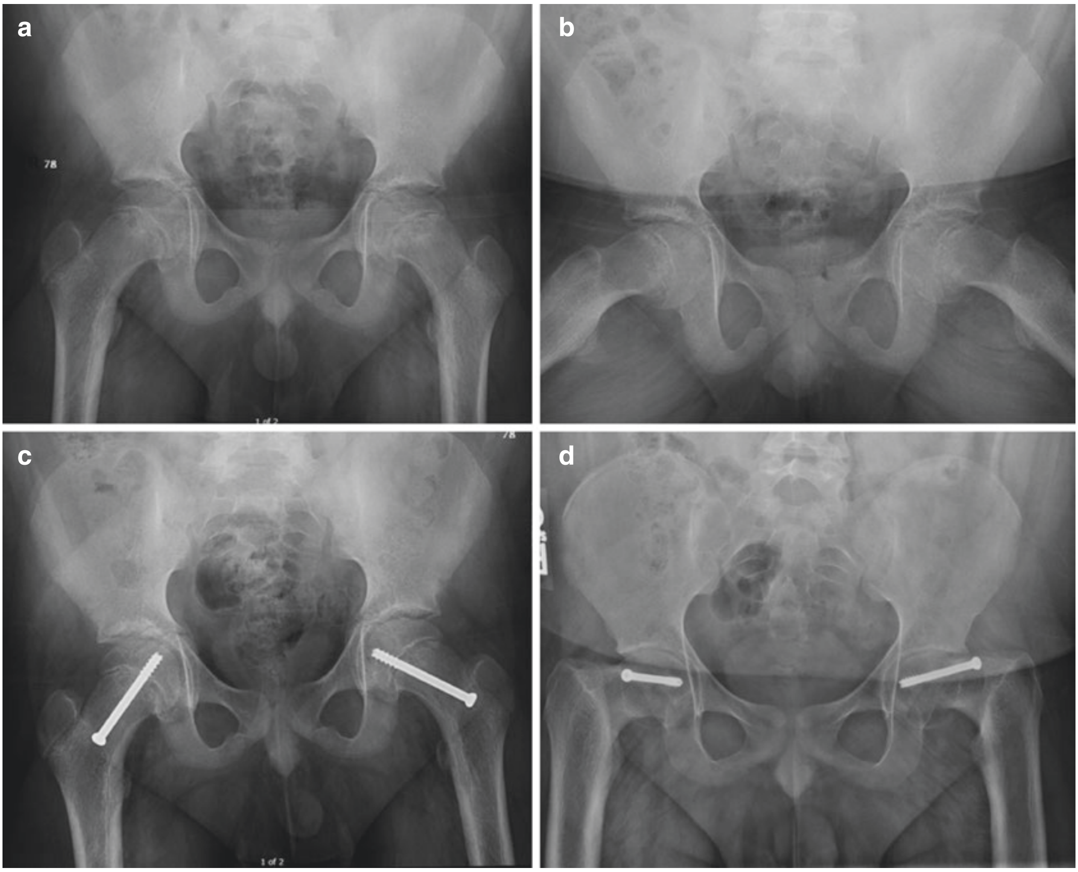

Fig. 9.11 (**a**) Anteroposterior (AP) and (**b**) frog-leg lateral radiographs in a 10-year-old male with bilateral slipped capital femoral epiphyses. (**c**) Immediate postoperative AP radiograph after bilateral percutaneous in situ screws. (**d**) Postoperative AP radiograph 5 years later with significant femoral shortening, severe coxa vara, and femoral neck retroversion bilaterally causing pain and limited range of motion. The patient is being scheduled for bilateral proximal femoral malunion corrections with osteotomies to correct the rotational and coronal plane deformities

help realign the femoral neck-shaft angle, reestablish leg length, and restore abductor mechanics. Subtrochanteric malunions also frequently result in varus and shortening, but these malunions more commonly have rotational and sagittal plane components that must be accounted for when performing valgization osteotomies.

Bartoníček et al. described their experience treating trochanteric malunions as well using a valgus intertrochanteric osteotomy with excellent results. Utilizing a minimum of 2 centimeters of limb shortening as well as limp, abductor muscle insufficiency, hip pain, and back pain as an indication for surgery, the authors removed a lateral wedge, moved the proximal segment into a more valgus anatomic position thereby lengthening the femur and eliminating coxa vara, lateralized the femoral shaft, and held the reduction using 120° double-angle blade plates. Generally, a 30° lateral wedge with lateral displacement of the femoral shaft about 1.5–2 cm will produce lengthening of about 3–4 cm [183]. Nuances about how to perform the osteotomy vary based on personal preference and training, but to better assess the angle of correction as well as rotational control, many surgeons utilize Kirschner wires (K-wires) to assess anteversion, rotation, and the calculated angle for seating the chisel for the blade plate.

While taking care to enter the bone at the ideal sagittal plane angle, the seating chisel is advanced over the K-wire in the femoral neck with any flexion or extension set at this time. Taking a small wedge to improve bone contact at the osteotomy site, the valgus intertrochanteric osteotomy is made at the level of the lesser trochanter after which the plate is affixed to the bone distal to the osteotomy site.

Multiplanar deformities with significant rotational defects can be more challenging in the proximal femur. Marti et al. outlined a one-stage procedure to treat multiplane deformities around the hip with combinations of rotational, angular, and length components. In nine patients, the authors used a trochanteric osteotomy with a step-cut to correct length, angulation, and rotation with good results. Through a lateral approach, the surgeons placed a K-wire along the anterior aspect of the femoral neck to measure femoral anteversion with additional K-wires placed in the sagittal plane proximal and distal to the anticipated osteotomy site to better assess rotational correction after completing the osteotomy. Another K-wire placed in the femoral neck at a predetermined angle based on preoperative imaging and calculations represents the summation angle needed to correct the varus or valgus deformity. Following this summation angle, the chisel for the fixed angle blade plate is inserted into the femoral neck and head. If a sagittal plane deformity such as procurvatum exists, the chisel should be inserted at an angle to correct for this deformity at this time. With the chisel in place, the osteotomy is completed at which time a 95° condylar blade plate replaces the chisel allowing for correction of the varus-valgus deformity. Often, this step alone adds femoral length by eliminating the coxa vara, but if additional length is needed, surgeons can utilize a laminar spreader, manual traction, or an AO distractor and bone graft from the linea aspera or iliac crest. The surgeons then corrected for rotational defects by rotating the distal segment before affixing the blade plate to the distal segment [184].

Instead of using a blade plate, van Doorn et al. described lengthening and derotating shortened malunited femoral fractures using cephalomedullary nails. The study included five patients, one of which had a femoral neck malunion while another had a subtrochanteric fracture malunion. The femoral neck fracture malunion admittedly had previously undergone a Pauwels' osteotomy to correct coxa vara, and consequently only length and rotational deformities remained. Therefore, this particular malunion in the series arguably was treated in a two-stage fashion, but nevertheless, the authors demonstrated a two-stage approach as a viable option for femoral neck malunions. All of the malunions in their series received a Z-osteotomy the planned length of desired correction after which the rotational correction allowed for cortical apposition. Given the great lever arm forces in the subtrochanteric region of the femur, the surgeons then passed a cephalomedullary nail and filled the osteotomy site with bone graft. If angular deformity is not an issue for a proximal femur malunion, this treatment method provides a reliable option to correct length, rotation, or both [185].

A significant downside to this Z-osteotomy is that it leaves a very limited circumference of cortical contact leaving a large defect that requires bone grafting. Farquharson-Roberts proposed an alternative method of correcting both rotation and length in a one-stage procedure with a cephalomedullary nail by making an oblique osteotomy through the femur. As rotation is set, the femur lengthens as the proximal and distal fragments move on the inclined plane between them. The amount of lengthening and rotation needed determines the obliquity of the osteotomy. To correct external rotation, care must be taken to cut the osteotomy from anterosuperiorly to posteroinferiorly and vice versa for internal rotation [186]. This technique provides another alternative osteotomy to correct both length and rotation but not angular deformity for proximal femur fractures.

Although angled blade plate and cephalomedullary nails have become the primary methods of treatment, ring fixators are an option for proximal femur malunion correction. Ilizarov highlighted the treatment of varus deformities of the proximal femur with a frame after a valgus osteotomy and lengthening in patients with coxa vara, shortened femoral necks, and a Trendelenburg sign [187]. Frame constructs can play a pivotal role for restoring length and when previous infection makes conventional open techniques riskier and possibly inappropriate. To achieve stability, two to three pins typically are used in each segment, and surgeons pre-drill the pins to minimize risk of bone necrosis and loosening of the pins. Frames require a thorough understanding of the design, intensive patient counseling, careful patient selection, and close follow-up.

9.6.2 Arthroplasty

Arthroplasty also is a reliable option for proximal femoral malunions, particularly in elderly patients. Conversion to a total hip arthroplasty often is the only treatment modality available for loss of fixation with malunion of the proximal femur and acetabular cartilaginous damage. As newer prosthetic technology, materials, and surgical techniques improve outcomes for and the longevity of total hip arthroplasty, the indications for arthroplasty may expand to younger patients. Surgeons now perform arthroplasty procedures with increasing frequency as the initial treatment for many proximal femur fractures such as femoral neck fractures in middle-aged patients as it may help prevent complications including fixation failure and help avoid a malunion. Primary arthroplasty also has proven to have lower complication rates than salvage arthroplasty for failed fixation for intracapsular femoral neck fractures [188]. Additionally, Zielinski et al. demonstrated inferior functional outcomes among salvage arthroplasty patients for failed fixation in femoral neck fractures relative to patients who healed uneventfully after internal fixation [189]. In a randomized controlled trial, Dolatowski et al. revealed primary hemiarthroplasty in patients 70 years and older with nondisplaced femoral neck fractures improves mobility and decreases reoperation rates when compared to cancellous screw fixation in situ [190]. Primary arthroplasty has long been the agreed upon treatment for displaced femoral neck fractures in elderly patients [191, 192], but in light of recent literature, indications for primary arthroplasty in proximal femur fractures may continue to expand, which could result in decreased proximal femur fixation complications including malunions.

Conversion arthroplasty also is increasingly common for patients who previously underwent failed proximal femur fixation. In a study of nearly 800 patients with femoral neck fractures younger than 50 years old, Stockton et al. demonstrated one-third required a reoperation and nearly 14% are converted to a total hip arthroplasty at a median of 27 months [193]. In elderly patients, there is less reservation about converting to a total hip arthroplasty, and consequently, the arthroplasty rate in elderly patients with failed proximal femoral fixation likely is significantly higher. In a study of proximal femoral nails complicated by cutout, Brunner et al. concluded conversion to total hip arthroplasty was the best salvage procedure [194]. Arthroplasty provides pain relief and functional improvements when used as a salvage procedure for femoral neck fixation failures initially treated with sliding hip screw or cancellous screws [195]. Additionally, total hip arthroplasty is an effective salvage procedure for both failed intertrochanteric and subtrochanteric fixation [196, 197]. Surgeons can correct both length and rotation with the femoral component in salvage arthroplasty, and in malunions with sagittal or coronal plane deformities, an osteotomy during the procedure can correct the alignment as well [198].

Numerous studies have shown better success with conversion total hip arthroplasty after failed proximal femoral nails than sliding hip screw fixation, largely secondary to increased rates of periprosthetic fractures [199, 200]. To minimize this risk, distal fitting femoral stems should be used to bypass the osteotomy site and any defects from previous hardware. Many diaphyseal fitting stems have the added benefit of having a modular metaphyseal and neck component allowing surgeons to set the femoral anteversion and correct rotation while also appropriately adjusting length and femoral offset. Length and offset are important to appropriately tension the abductors and reduce the chance of dislocation. Failure to restore anatomic femoral offset also results in worse functional outcomes [92]. Despite the importance of femoral offset, Ji et al. found nearly a quarter of all hemiarthroplasties performed for femoral neck fractures fail to properly restore the femoral offset [201]. Thus care must be taken to properly plan preoperatively and execute intraoperatively when performing a salvage arthroplasty.

Choice of femoral head size also plays a significant role in minimizing the risk of dislocation. Smaller prosthetic head sizes in total hip arthroplasty historically led to an increase in linear wear on the acetabular polyethylene component, thus increasing the risk for osteolysis, implant loosening, and revision surgery [202]. Polyethylene has since improved in subsequent decades, but smaller femoral head sizes still have a smaller jump distance before impingement of the acetabular component and femoral neck contributes to a dislocation. In an effort to preserve bone in younger patients undergoing total hip arthroplasty, many providers refrain from over-reaming the acetabulum, which may limit femoral head size options in younger patients whose higher activity levels increase their dislocation risk as well. Consequently, many surgeons now use dual mobility femoral heads to try to minimize both impingement and the risk of dislocation, even in younger active patients [203–205]. Acetabular positioning in conversion arthroplasty also is of paramount importance as it is in primary total hip arthroplasty.

Routine preoperative planning includes ruling out infection, particularly when considering arthroplasty in the setting of previous surgery and hardware failure or cutout. Preoperative inflammatory markers including an ESR and CRP should be obtained. It is well established that previous surgery is associated with higher risks of infection in arthroplasty patients. Gittings et al. reported an 18% infection rate among patients who underwent conversion total hip arthroplasty after prior internal fixation and concluded preoperative ESR and CRP were effective screening tools [206]. If these serum markers are equivocal, surgeons also can use other diagnostic tests to help rule out a periprosthetic joint infection including a preoperative aspiration with cell count, culture, and alpha defensin test. If infection is suspected but cannot be confirmed by blood work or aspiration, a triple bone scan can provide additional information. Given the severe morbidity associated with a periprosthetic joint infection, surgeons should ensure patients have cleared the infection prior to any conversion arthroplasty procedure.

Surgeons also should consider the quality of the patient's bone. In the elderly patients, osteopenia of both the proximal femur and acetabulum may be present, and consequently cemented femoral stems may reduce the risk of intraoperative fracture when compared to press-fit components [124]. If cementing the femoral component in the setting of previous hardware, surgeons should employ measures to minimize cement extravasation into the soft tissues. Poor bone quality in the acetabulum also may complicate preparation and placement of the acetabular component with increased rates of medial wall protrusion, excessive medialization, or loss of the posterior wall. Surgeons consequently must deliberately prepare the acetabulum to avoid these problems. In patients with poor bone quality, screw augmentation of cup fixation should be considered to allow for stable ingrowth into the cup. In patients with better bone quality, a press-fit femoral stem often is preferred. Previous implants though can create stress risers increasing the risk of iatrogenic fracture while preparing the femur. Consequently, prophylactic cabling should be considered to help reduce this risk.

In any event, arthroplasty represents a reliable option for patients with proximal femur malunions. Careful planning and execution intraoperatively can help restore function and alignment while allowing for immediate weight-bearing postoperatively.

9.7 Summary

Proximal femur fractures occur frequently, and patients often present with decreased range of motion, pain, and gait abnormalities from resultant proximal femur malunions. These malunions occur as a result of nonoperative management, intraoperative malreduction, and loss of fixation both from cutout and hardware failure. Most malunions in the proximal femur involve some degree of varus and shortening, but surgeons also must carefully check for rotational components to the malunion as well. Correction of the malunion, consequently, typically involves a valgus intertrochanteric osteotomy, but it may require a multiplanar correction depending on the deformity. In some patients though, arthroplasty may provide the best option for malunion correction. Regardless of procedure type, attention to detail preoperatively and intraoperatively improves outcomes and success postoperatively. Similarly, providers must always strive to avoid complications when treating proximal femur fractures initially to minimize the risk of a malunion developing in the first place.

9.8 Case Discussions

Case 1

The patient is an 82-year-old male with multiple medical comorbidities who presented to our institution approximately 1 year after he sustained a fall from standing. At that time, he was found to have a left intertrochanteric femur fracture for which was treated with a cephalomedullary nail at an outside facility. Prior to his fall, he was a community ambulator and ambulated with no assistive devices. He had a history of a deep venous thromboembolism and a pulmonary embolism for which he takes Warfarin. He also has hypertension, benign prostatic hypertrophy, and a small stage II decubitus ulcer under the left ischial tuberosity, which developed after his accident. He noted progressively increasing pain since his surgery and as a result was only able to ambulate short distances with a rolling walker but otherwise was confined to a wheelchair. After visiting his previous surgeon 13 months postoperatively, he was referred to our institution with radiographs revealing loss of fixation, screw cutout and protrusion through the acetabulum, and a shortened and varus proximal femur malunion (Fig. 9.12). He did not have any bowel or bladder symptoms from the cephalomedullary screw protruding into the pelvic cavity. Due to the leg length discrepancy from the proximal femur malunion, he was using a 3-centimeter shoe lift on the left foot. He also had significant stiffness and limited range of motion of the hip as one might expect given his radiographs.

After thorough history and physical in clinic, the surgeons provided extensive counselling to the patient regarding his expectations and the treatment options which ranged from treating him nonoperatively to a hardware removal and total hip arthroplasty. The risks and benefits of each were reviewed after which the patient elected to try to proceed with a total hip arthroplasty. Given the damage to both the femoral and acetabular articular surface as well as the patient's age and bone quality, a corrective osteotomy was not deemed appropriate in his situation. To rule out infection, serum inflammatory markers were obtained in clinic, which returned mildly elevated. Given he had a concomitant urinary tract infection and the aforementioned decubitus ulcer, he may have had a number of reasons for these markers to be mildly increased. In light of these results though, the patient underwent an indium-111 white blood cell, which revealed no signs of acute osteomyelitis in the left femur.

Intraoperatively, the patient was placed in a lateral position, and the operative team utilized a posterolateral approach to expose the proximal femur. A significant amount of heterotopic ossification encased the short external rotators, which required an osteotome to expose those. Under fluoroscopic guidance, the cephalomedullary screw was identified and removed leaving a large central defect in the medial acetabular wall. Leaving the intramedullary nail in place to help prevent intraoperative fracture of the femur, the femoral neck cut was made and the acetabulum sequentially reamed ensuring appropriate abduction and anteversion throughout the preparation process. The acetabular component was then placed with several screws to reinforce its fixation given the medial wall defect as well as the poor bone quality. With the acetabular component and liner in place, the femoral intramedullary nail was removed by using a pencil-tip burr to free the nail proximally after which the nail

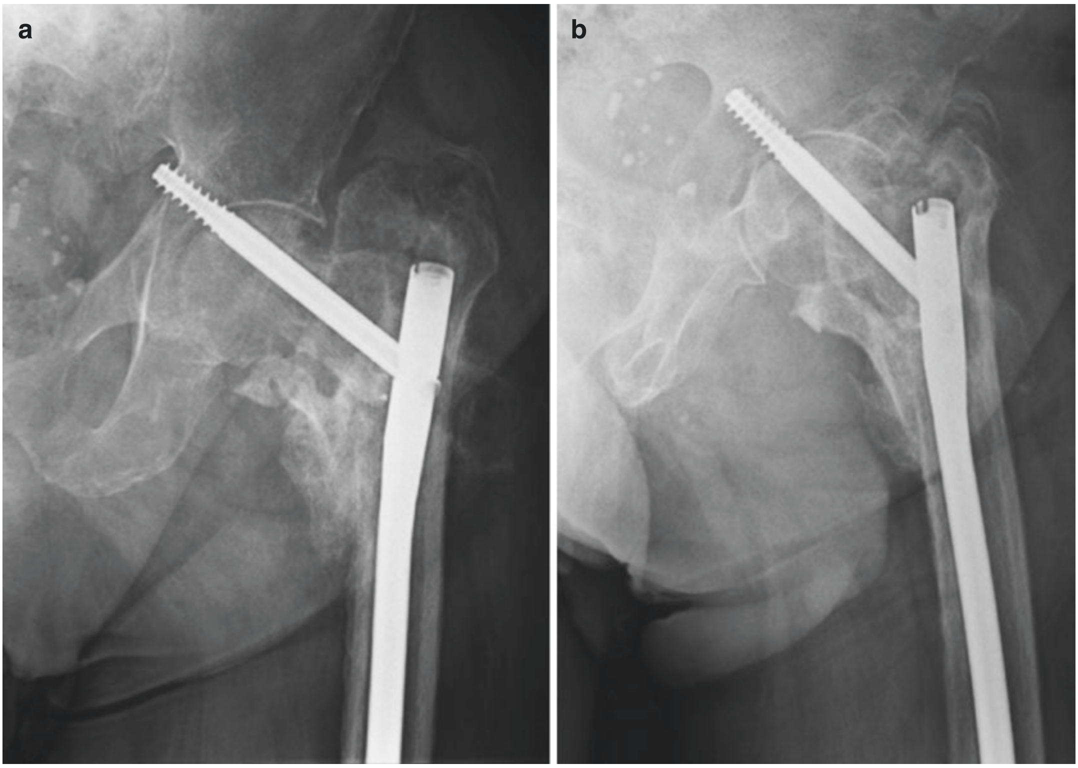

Fig. 9.12 (**a**) Anteroposterior and (**b**) lateral radiographs of an 82-year-old male about 1-year status post intertrochanteric femur fracture treated with this cephalomedullary screw complicated by loss of fixation, proximal femur shortening and varus collapse, and screw cutout with protrusion through the acetabulum with resultant proximal femur malunion

was removed without significant bone loss. Given the previous intramedullary nail and lateral cortical wall defect from the cephalomedullary nail, a diaphyseal fitting Arcos stem (Zimmer Biomet, Warsaw, IN, USA) was used, which is a modular component allowing the surgeon to set femoral anteversion when attaching the metaphyseal and neck piece to the diaphyseal component. Femoral version, offset, and diaphyseal stem fixation were all critical to ensuring stability of the implant in this salvage arthroplasty setting. To minimize the risk of dislocation by increasing the arc of motion prior to impingement, particularly given his previous scar tissue and heterotopic ossification, a dual mobility head was used. With stability confirmed intraoperatively, the scar, pseudocapsule, and short external rotators were repaired back to the proximal femur with Ethibond suture (Johnson & Johnson, New Brunswick, NJ, USA).

Postoperatively, the patient restarted his home Warfarin dose, followed strict posterior hip precautions, and worked with physical therapy. At 1-year postoperatively (Fig. 9.13), he was doing well, ambulating with a cane, and very pleased with his outcome with significantly improved range of motion and quality of life.

Case 2

The patient is a 68-year-old female with numerous medical comorbidities including end-stage renal disease on hemodialysis, diabetes mellitus, chronic obstructive pulmonary disease, atrial fibrillation, a pacemaker, congestive heart failure, obesity, and osteoporosis who presented with right hip pain 3 years after sustaining an intertrochanteric fracture. At that time, she underwent a cephalomedullary nail at an outside facility and reportedly did well for 6 months postoperatively

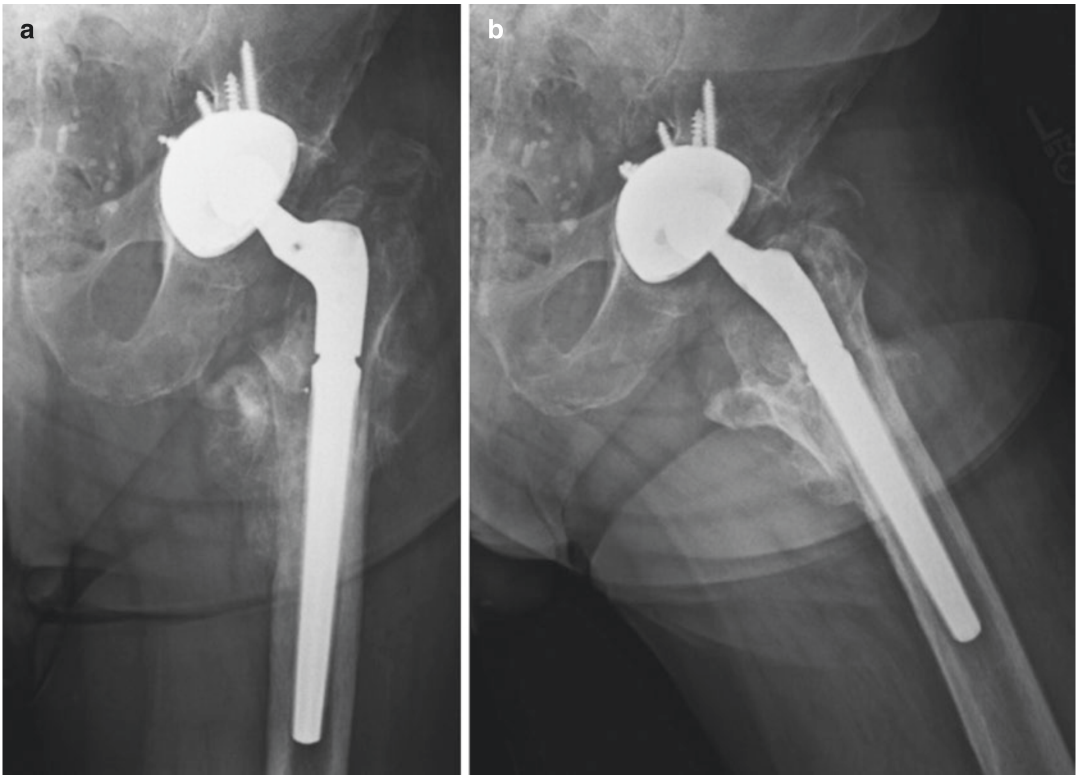

Fig. 9.13 (**a**) Anteroposterior and (**b**) lateral radiographs of an 82-year-old male about 1-year status post intertrochanteric femur fracture treated with this cephalomedullary screw complicated by loss of fixation, proximal femur shortening and varus collapse, and screw cutout with protrusion through the acetabulum with resultant proximal femur malunion

ambulating with a walker. She presented to our clinic though in a power scooter and on chronic pain medications. Radiographs revealed an intertrochanteric malunion with proximal femoral shortening and varus malunion with shortening of the cephalomedullary screw (Fig. 9.14). On exam, she was 3 centimeters shorter on the right lower extremity than the left. Our team thoroughly discussed the risks and benefits of treatment options, which included nonoperative management, hardware removal with a valgus intertrochanteric osteotomy, and a conversion total hip arthroplasty. The patient, whose quality of life had severely been limited by the proximal femur malunion, expressed her desire to proceed with a total hip arthroplasty.

It is important to rule out infection prior to conversion arthroplasty, and preoperative inflammatory markers were within normal limits. Intraoperatively, the team also sent a joint aspiration for cell count, which returned with normal results. After removing the lag screw and cephalomedullary nail, a posterior approach was used for the total hip arthroplasty. A diaphyseal fitting femoral stem was used given the previous implant and lack of adequate metaphyseal fixation for the femoral stem. Unfortunately, the femur fractured intraoperatively, which is a significant risk in osteoporotic patients, particularly with press-fit stems such as the diaphyseal fitting femoral stem used in this case. Cerclage cables were then used to reduce the fracture and the stem was revised to bypass the fracture site (Fig. 9.15).

Postoperatively, the patient did well initially. She worked with therapy, began ambulating, and was pleased with her progress. One month after surgery though, she noted intense pain in the hip and an inability to ambulate after being transferred

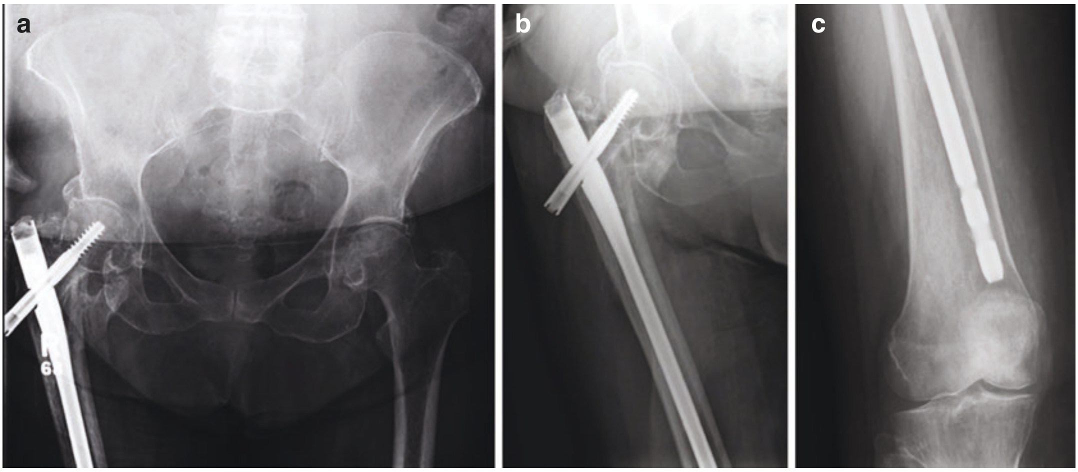

Fig. 9.14 (**a**) Anteroposterior pelvis, (**b**,**c**) AP femur radiographs of a 68-year-old female about 3 years status post intertrochanteric femur fracture treated with this cephalomedullary screw complicated by proximal femur shortening and varus collapse with resultant proximal femur malunion

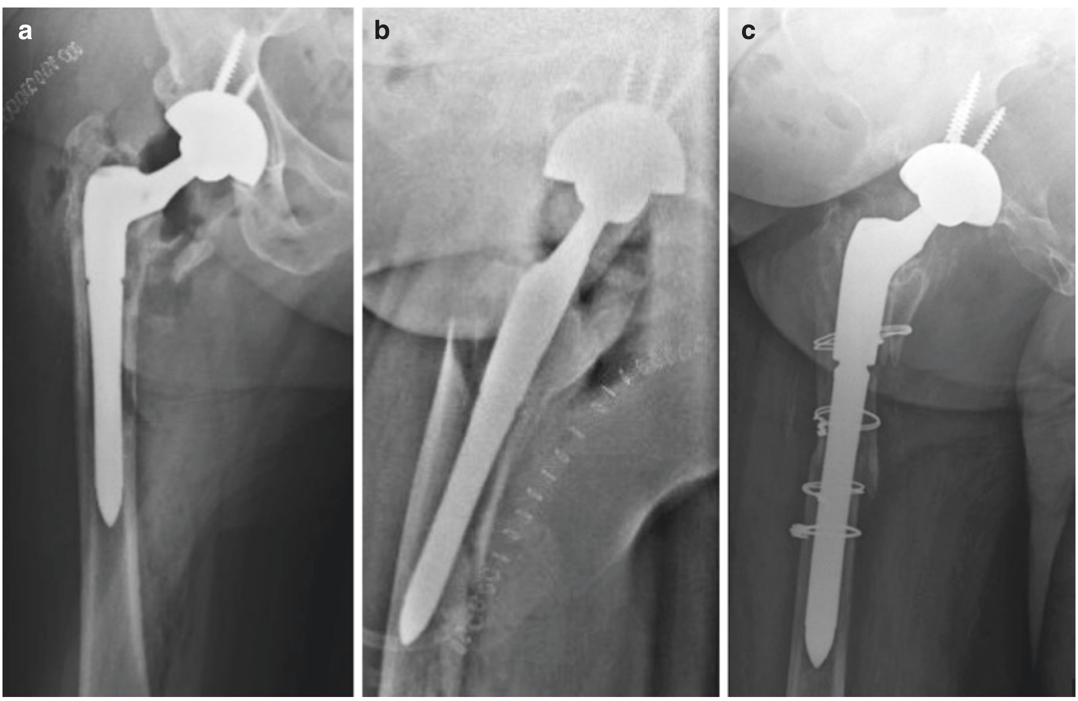

Fig. 9.15 (**a**) Anteroposterior (AP) and (**b**) lateral hip radiographs with intraoperative proximal femur fracture in an osteoporotic patient status post conversion total hip arthroplasty. (**c**) AP hip radiograph after cerclage wiring of fracture site and femoral stem exchange to bypass the fracture and obtain diaphyseal fixation

with therapy at her rehab facility. The facility though took 3 days to obtain radiographs, and once completed, she was transferred to the hospital with a hip dislocation. Upon arrival to the hospital, an attempt at a closed reduction was unsuccessful. The next day, she was taken to the operating room for open reduction (Fig. 9.16). She did well postoperatively and was ambulatory

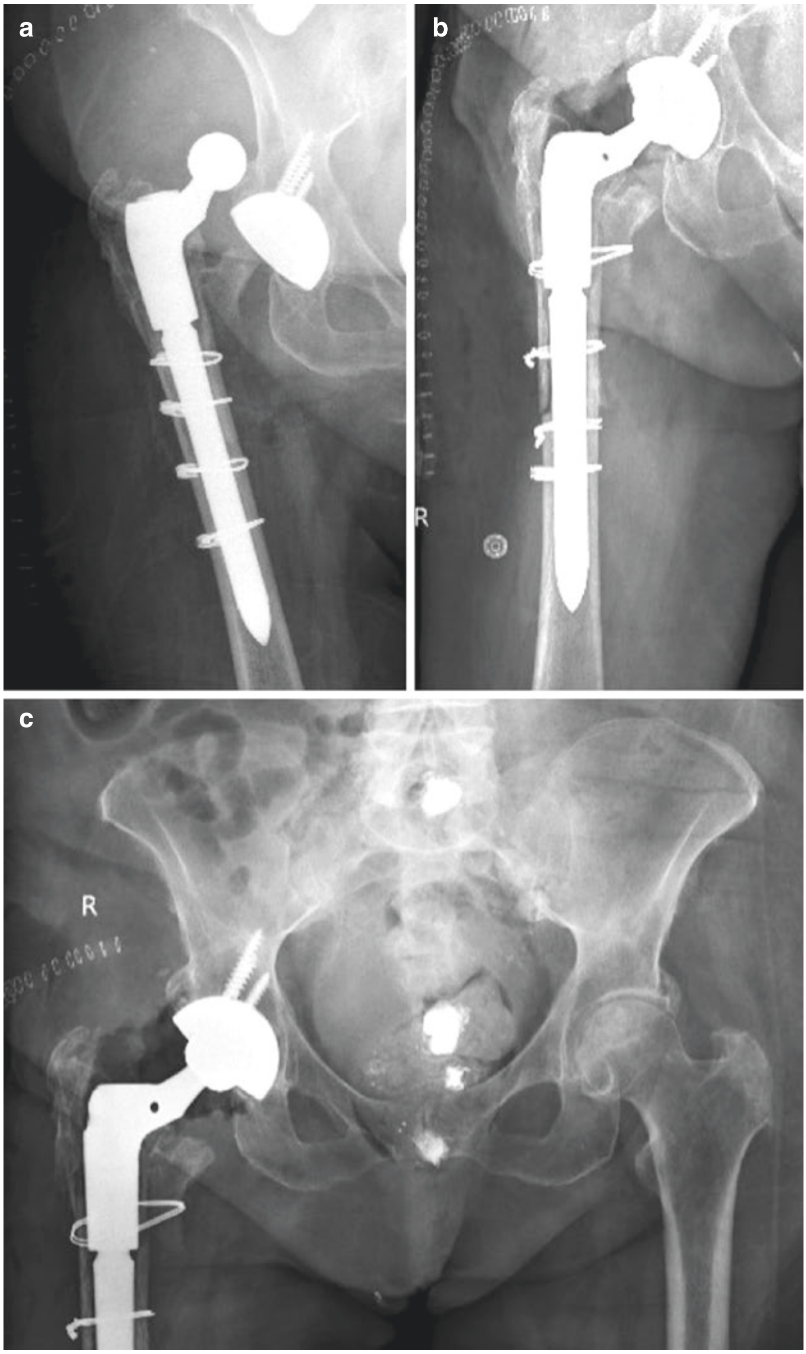

Fig. 9.16 (**a**) Anteroposterior hip radiograph revealing a periprosthetic dislocation. (**b**) AP hip and (**c**) AP pelvis radiograph status post open reduction

with a rolling walker again, but 2 months after the open reduction, she passed away from a presumed cardiac arrest. While this patient's outcome was unfortunate, her case illustrates many of the risks associated with treating proximal femur malunions.

Case 3

The patient is an 84-year-old female with numerous medical comorbidities including atrial fibrillation, a pacemaker, and dementia who presented with left hip pain after a fall from standing. She lives in an assisted living facility and ambulated with a rolling walker before her accident. Given her mental status, history was difficult to obtain and largely obtained from her son, the medial power of attorney. Her hip radiographs revealed a subcapital impacted femoral neck fracture while the CT scan demonstrated some posterior angulation of the femoral head in relation to the femoral neck (Fig. 9.17). The orthopaedic service discussed with the patient's son the various treatment options ranging from nonoperative management to closed reduction and percutaneous cancellous screws to hemiarthroplasty. Nonoperative management carried significant risks of continued pain, inability to ambulate, and fracture displacement. Cancellous screws in an elderly patient with poor bone quality and some femoral head displacement have a significant risk of loss of fixation and hardware failure, but it is far less invasive and a faster procedure than a hemiarthroplasty, which carries the added risk of dislocation in cognitively impaired patients. Consequently, the patient's son elected to proceed with cancellous screws to try to stabilize the patient's femoral neck, minimize her pain, and allow for ambulation.

Intraoperatively, a fracture table was used to obtain a reduction as verified by fluoroscopy. The operative team then placed three 7.0-mm cannulated cancellous screws in an inverted triangle pattern across the femoral neck into the femoral head. The two partially threaded screws were placed first to ensure compression prior to the fully threaded screw to try to add more stability given the poor bone quality.

Postoperatively, the patient worked with therapy and was able to ambulate with a rolling walker. She returned to clinic after 3 months at which time she was having pain in the hip with abduction and flexion, but she no longer was working with therapy and at that time was nonambulatory. After another one and a half months, she returned to clinic with a hip contracture and was unable to fully extend her hip to neutral. She had not ambulated since the last clinic appointment, possibly secondary to therapy no longer working with her in her assisted living facility or her decline mentally. Radiographs revealed a

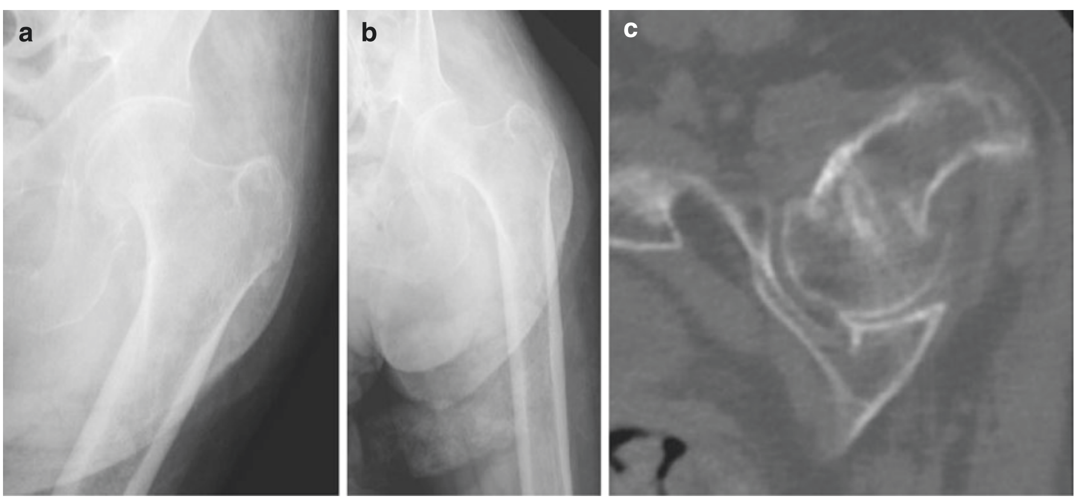

Fig. 9.17 (**a**) Anteroposterior hip and (**b**) AP femur radiographs of an 84-year-old female revealing an impacted subcapital femoral neck fracture. (**c**) Axial CT scan of the impacted femoral neck fracture with posterior angulation

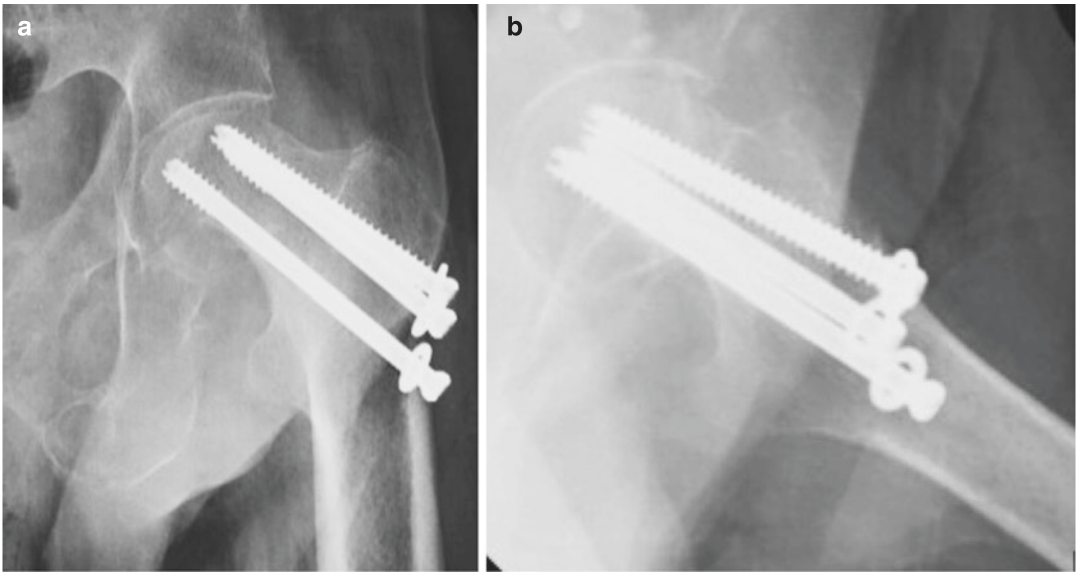

Fig. 9.18 (**a**) Anteroposterior and (**b**) lateral hip radiographs about 4.5 months after closed reduction percutaneous cancellous screw treatment, which resulted in a shortened and varus femoral neck malunion

shortened and varus malunion of the femoral neck with the cancellous screws backing out of the lateral cortex (Fig. 9.18), and her nonambulatory status could have stemmed in part from pain associated from her malunion. In light of her comorbidities and son's wishes, no additional surgery was pursued for the femoral neck malunion at that time.

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Malunions of the Femoral Shaft

10

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10.1 Introduction

10.1.1 Background

Femoral shaft malunions have become an infrequent problem in the developed world; however, they are relatively common problems in developing countries [1–4]. The operative management primarily with intramedullary fixation has revolutionized treatment [5], allowing early weight-bearing and restoring the alignment of the lower extremity. While excellent union rates and clinical outcomes have been reported in the treatment of diaphyseal femur fractures [6, 7], challenges still exist achieving and maintaining anatomic reduction. The failure to recreate normal anatomic structure of the femur can lead to malunion. Femoral deformity can exist in the form of angulation, translation, rotation, and length. The etiology of femoral shaft malunion is multifactorial, but contributing variables include patient factors, such as obesity and noncompliance; fracture personality, such as comminution, bilateral femur injuries, bone loss, and transverse fracture patterns; and surgeon factors, such as inexperience, technical failures, and malreduction.

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Once the fracture has healed, a critical evaluation is paramount to creating a successful operative plan. Evaluation of the original injury and treatment includes investigation of the original fracture, fixation strategy previously employed, signs of infection, and discussion of the postoperative course. Hip to ankle standing films that assess the alignment of the lower extremity including other joints and long bones are important. In addition, orthogonal images should be ordered to evaluate the three-dimensional nature of the malunion and occasionally computed tomography can improve the understanding of complex multiplanar deformities. Commonly however, orthogonal views can miss the severity of the deformity on standard anteroposterior and lateral radiograph views, as the maximum deformity often occurs in an oblique plane. This underlies the rationale behind emerging techniques with 3D limb reconstructions including the use of 3D printing.

Standard laboratory evaluation to rule out infection should be undertaken prior to the operation. Though osteomyelitis is a less frequent phenomena in the context of femoral malunions than it is in nonunions, the surgeon should be vigilant in assessment of radiographs, lab results, or clinical signs that could be consistent with infection.

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Once the character and magnitude of the deformity has been established, the surgeon has a number of techniques at their disposal depending on the clinical situation including osteotomy with plate fixation, intramedullary nailing, and external fixation frames. While this is a rare problem, patients can have significant disability [8–10] and the correction of the deformity can present a significant surgical challenge.

This chapter will discuss the epidemiology of femoral shaft malunions and examine briefly the socioeconomic impact. The etiology of malunions will be covered with special attention to those factors, which are unique to femoral shaft injuries. The diagnosis and evaluation of femoral shaft malunions will be reviewed specifically as it relates to creating a surgical plan. Finally, the treatment option will be discussed for the various types of deformities. The last section will review a few case examples that illustrate some of the challenges and techniques in the treatment of femoral shaft malunions.

10.1.2 Epidemiology

The annual incidence of midshaft femur fractures is approximately 10–37 per 100,000 person-years with the incidence peaking among the young and then again in the elderly [11, 12]. The incidence of femoral shaft malunion has been reported from 6% to 13% [13, 14] although it has been shown to be more common in proximal and distal one third shaft fractures [15]. Clearly, this incidence is dependent on the definition of malunion. Extrapolated from those statistics using a 6–13% malunion rate and the current population in the United States of 313 million each year between 1860 and 4030 patients in the United States will eventuate in a femoral shaft malunion [16]. The most common deformity remain leg length discrepancy and malrotation [17]. It remains unclear what proportion of these patients will become symptomatic and require surgical correction. In a recent retrospective study that looked into AO/OTA type B or type C fractures leg length discrepancy (LLD) was observed in 98% of them but in only 5% returned to the OR for a correction of symptomatic LLD [18]. Patients with malrotation are particularly difficult to predict based purely on the magnitude of deformity [19]. Certainly, what is an unacceptable leg length deformity or malrotation in one patient may be acceptable in another based on functional status and other life context.

10.1.3 Economic Impact

Femoral shaft malunion represents a difficult challenge for the surgeon and the patient and also to the health system as well as the social services supporting them. The disability prior to correction is often significant, limiting patients' activity and ability to work. While no current figures exist as to the exact cost of malunion correction of the femoral shaft, certainly this would increase the overall cost drastically compared to patients who heal their femoral shaft fractures uneventfully. It is important to remember that while implant, surgeon fee, and operating room time are all very expensive, the indirect costs for musculoskeletal conditions represent about 80% of the total costs [20].

10.2 Etiology

Restoring the anatomic morphology after a midshaft femur fracture has historically been accomplished at a very high rate [5–7]. The advent of the intramedullary nail and the popularization of its use have dramatically reduced both the incidence and rate of angular femoral shaft malunions. A recent systematic review reported the incidence of femoral shaft malunion after intramedullary nailing at 8%; however, this likely blends a much higher historical rate with a lower rate seen with modern techniques [17]. A number of specific factors have been associated with an increased risk of malunion. These elements can be divided into three broad categories, specifically patient characteristics, fracture personality, and surgical technique. At the end of the day, the surgeon takes responsibility for all three in their approach and treatment of the femoral pathology. Overall for midshaft fractures, the incidence of malunion has been reported similar for retrograde versus antegrade intramedullary fixation; however, certainly there are fracture patterns and pitfalls to be aware of with each technique. Each of these factors creates a unique surgical challenge that requires both the identification and management of the situation to avoid a malunion. While these will be discussed in isolation the clinical situation often presents multiple factors in the same patient, which can act synergistically.

10.2.1 Patient Characteristics

Patient-specific factors include obesity, compliance, and anatomic variation. With nearly one third of the American population now increasingly obese and the trajectory of the epidemic increasing [21], all surgeons will be faced with the challenge of caring for this group of patients. In addition to the increased complication rate, including DVT [22, 23], obese patients are at increased risk of loss of reduction and malunion because of an inability to adhere to limited weight-bearing or walking aids [24, 25]. Another demographic with increased risk of femoral shaft malunion is the elderly patient population. Angular malunion is a specific concern in elderly patients with capacious canals resulting in poor diaphyseal contact [26]. Numerous intraoperative challenges have been reported when rotational alignment is being evaluated; however, the important patient-related factor that is often overlooked is the variation in femoral neck anteversion. Historically, femoral anteversion has been reported between 0 and 15°; however, historical data suggest that this represents only two-thirds of the population [27]. In a more recent study, the average femoral neck anteversion was reported at 9.7°; however, the standard deviation was 9.2° and the range was 14.6° of retroversion to 35.9° of anteversion [28]. In addition to wide variations between patients, significant variation has been reported from side to side in the same patient. Cadaveric studies have reported up to 12° variation femoral anteversion, which would clearly increase the chance of femoral malunion [29].

10.2.2 Fracture Characteristics

Fracture characteristics of femoral shaft injuries can create a challenging surgical environment and ultimately increase the incidence of malunion. A number of the characteristics have been identified, specifically comminution, bilateral injuries, transverse fracture patterns, and fracture location. Severe femoral shaft comminution creates a challenging environment to reconstruct normal anatomy. The loss of all three principal planes of stability, specifically rotation, length, and angulation, creates a significant problem to the surgeon. Shortening has been reported as a complication after intramedullary fixation particularly in the setting of comminution. The original series from Winquist et al. reported 2% of patients with greater than 2 cm of shortening and the majority had type IV comminution, while 7% of patients in their series had shortening of 1–2 cm with 22% of type IV comminuted fractures compared to 2% for type I, 9% for type II, and 14% for type III. Rotational malunions have been reported as a complication in up to 28% of femoral shaft fractures utilizing intramedullary fixation and 41% in bilateral fractures [30]. There has also been an association of femoral malrotation with pure transverse fracture patterns as well as Winquist III and IV fractures [19]. Another important correlation between malunion and fracture pattern is related to the location of the fracture. Meta-diaphyseal fractures, particularly proximally, are associated with angular malalignment. This has been reported variably in the literature but can reach up to 30% for proximal fracture patterns and 10% in distal fractures [15].

10.2.3 Technical Factors

Technical failures lead to a large percentage of femoral malunions. Certain patient factors such as obesity or age as well as fracture characteristics such as comminution or bilateral injuries can create a more challenging surgical environment; however, many malunions can be avoided by anticipating the problems and maintaining a disciplined technical approach.

Common technical errors include starting point selection, reaming prior to reduction, patient positioning, and a failure to evaluate alignment. The starting point for intramedullary nails has traditionally been described as the piriformis fossa and more recently the 1/3–2/3 junction of the greater trochanter for antegrade nails. Retrograde nails should start at the apex of the Blumensaat and the Whiteside lines. The importance of accurately locating the appropriate start point is magnified with proximal and distal shaft fractures, comminuted segments, or injuries with bone loss [26]. Without the benefit of diaphyseal fit, the malunion rate increases dramatically [15].

A critical but often overlooked concept in femoral shaft fixation is the principle of attaining an anatomic reduction before reaming. Often the presumption is that simply passing a guide wire across the fracture side will result in a clinically acceptable indirect reduction via the intramedullary device after the canal has been reamed. The problem is that when eccentric reaming has already occurred, with asymmetric bone loss on the proximal and distal cortical surfaces, then the intramedullary rod assumes the path reamed and a malunion is established by that point. While this technique may produce acceptable result in some diaphyseal fractures, a more rigorous technique can facilitate anatomic results in more complex fracture patterns, particularly with proximal meta-diaphyseal fractures.

Poor patient positioning can lead to the formation or exaggeration of deforming forces that can alter the surgeon's ability to attain an anatomic reduction. An example of this phenomenon is the "sag" of the operative extremity on the fracture table resulting in the external rotation of the hemi-pelvis and proximal fragment that leads to a predictable internal rotation deformity of the extremity after fixation because the distal fragment is internally rotated relative to the proximal diaphysis [26], while positioning the patient supine with a bump under the hip can result in the opposite deformity [31].

Perhaps the most common technical failure results from the failure to evaluate the alignment of the extremity in the primary planes of deformity length, rotation, and angulation. Numerous techniques have been described to assist the surgeon including the cable technique to evaluate coronal alignment and length as well as meterstick technique specifically for length [32], fluoroscopic preoperative evaluation of contralateral femoral neck anteversion [33], and lesser trochanter shape sign [34] for rotational alignment and recurvatum sign [32] of the distal femur for sagittal alignment in distal shaft or highly comminuted fracture patterns. Another technique which is relevant for both femoral fracture and malunion surgery is to drape both extremities into the field, thus allowing for a template from normal to operated limb. This technique presupposes that the patient is supine and not on a traction table. Numerous techniques have been published and all have weaknesses. Our recommendation is that more than one be utilized and as well as the experience of the surgeon to create an integrated, multifactorial evaluation of the overall alignment of the extremity prior to leaving the operating room.

10.3 Diagnosis

10.3.1 History and Physical Examination

As with all clinical problems, the starting point for evaluation is a thorough history and physical examination. Target areas include a detailed discussion of the original injury with notes on the mechanism, time to treatment, postoperative course, and potential signs of infection such as wound healing issues or fevers. A concerted effort to gather records from previous surgeries can be extremely valuable in understanding the original injury and fixation strategy.

The physical exam should focus on limb alignment, soft tissue envelope, and signs of infection. Evaluation of the soft tissue envelope should provide information regarding both the original injury (open vs. closed), previous soft tissue reconstruction, reduction and fixation strategy (open vs. closed reduction), as well as a careful exam of the vascular status of the extremity. The surgeon should have a high degree of suspicion that femoral shaft malunions may be infected and deserve careful inspection to assess warmth, induration, sinus tracts, fluctuance, and tenderness to palpation.

A detailed radiographic evaluation of the deformity is critical and discussed below; however, the malunion site should be manually stressed to rule evaluate motion and gauge pain. A patient with a solidly healed fracture with deformity should not have pain during manual stressing. In the event that the fracture site has either motion or pain with manual stress, the surgeon should consider the diagnosis of nonunion. Another critical component is the evaluation of adjacent joints. Active and passive motion of the joints proximal and distal to the malunion site should be assessed. A patient with a fixed deformity at the knee must be recognized prior to osteotomy so that treatment does not result in a straight bone with joint contractures [35]. The origin of pain in patients with malunion may be multifactorial and challenging to ascertain. Potential etiologies include overloaded ligamentous structures, local muscle and tendon irritation, asymmetric joint wear, tensile strain on the bone, and pain in other joints and the back due to compensatory gait patterns or leg length discrepancy. The elucidation of the primary or secondary pain generator is critical to consider if a secondary procedure will improve the symptoms either directly or indirectly.

Accurate malunion surgery begins with precise definition of the deformity because the implications of a corrective osteotomy cannot be known unless the malunion is precisely characterized in three dimensions [36]. Leg length can be measured utilizing measured blocks (aka Coleman blocks) and confirmation that the pelvis is level via clinical evaluation. To establish the length of the femur clinically, the contribution of the tibia can be subtracted by having the patient prone and knees flexed 90°. In this position, the discrepancy in sole height usually can be attributed to the femur. Additionally, with the patient supine on the exam table, hips flexed 45° with feet flat, the relative length of the femur left to right can be estimated.

10.3.2 Imaging

Rotational asymmetry of the femur can be estimated by comparing maximal internal and external rotation at the hip; however, clinical evaluation has been proven challenging if not inaccurate [37]. Obtaining a computed tomography scan through the femoral neck, supracondylar femur comparing the rotational position of the two femurs provides an accurate measurement of rotational deformity [38]. Assessment of the mechanical and anatomic axis of the entire lower extremity is mandatory to rule out the contribution of other factors outside of femoral shaft morphology. Once other factors have been excluded, orthogonal full-length radiographs of the femur are critical to the evaluation of the magnitude of the deformity. A line is drawn down the anatomic axis of the femur and the point of intersection of the proximal and distal axes has been called the center of rotation of angulation [39]. If the deformity is an isolated angular malunion, the intersection will occur at the apex of the deformity.

If translation has also occurred in addition to angulation, the center of rotation of angulation is moved away from the site of maximal angular deformity, proportional to the amount of translation. Orthogonal radiographic evaluation has a number of advantages over other technologies. This technique is simple in that sagittal and coronal plane deformity can be estimated from a simple set of radiographs. Another advantage is the minimal cost and efficiency of acquisition of radiographs compared to computed tomography or fluoroscopic evaluation. The primary disadvantage of this technique is that the true magnitude and orientation is rarely in the plain of the radiograph and therefore must be calculated using trigonometric formula [40]. Certainly the more commonplace usage of 3D imaging and 3D printing can help the inexperienced malunion surgeon especially, with diagnosis and preoperative planning.

There are no definitive criteria to determine whether osteotomy is indicated; however, in active individuals common indications for angular malunion correction of the femur include varus malalignment of the knee or ankle >10°, valgus malalignment of the knee or ankle >15°, or a 20-mm medial shift in the mechanical axis [36], rotational deformities of greater than 10°, greater than 10° deformity in the sagittal plane, or greater than 2 cm shortening [41]. Clearly, it is the patient's description of symptoms which correlate with the radiographic deformity which leads the surgeon to determine whether malunion reconstruction would be beneficial. Such a decision must be placed into the context of the patient's preoperative function and desired functional outcome. The key is the identification and evaluation of the deformity and more importantly to listen and understand the patient's concerns. Typically either the deformity creates a functional deficit that limits activity or concerns over the cosmetic appearance.

10.3.3 Infection

Laboratory evaluation for patients with femoral shaft malunions is critical. The exclusion of infection is a multifactorial process; however, preoperative laboratory analysis should include an erythrocyte sedimentation rate, C-reactive protein level, and complete blood count with differential. While not routinely utilized, the literature has suggested some value of radionuclide and indium 111-labeled leukocyte scans in equivocal cases [42]. The gold standard to diagnosis infection continues to be tissue culture. All antibiotics should be discontinued 7–14 days prior to collection which generally occurs during the surgical intervention [43].

10.4 Treatment Options

No universally accepted guidelines exist for defining treatment of diaphyseal femoral malunions. There are different schools of thought and many tools in the armamentarium of the surgeon to consider. A number of fixation options are available to accommodate the osteotomy choice. Certainly describing all the possible osteotomies is beyond the scope of this chapter, but keep in mind that certain fixation strategies work better or worse with specific types of osteotomies.

10.4.1 Plate Fixation

The advantages of plate fixation include rigidity of fixation, correction of deformities under direct visualization, and the ability to add bone graft if needed. Another advantage is the intraoperative technical flexibility to use the plate in compression or bridge mode or for simple neutralization. Another powerful advantage is the use of the plate as a reduction aid during surgery. Disadvantages of this method include soft tissue dissection in the thigh, possible limited early weight-bearing, and the need for a single acute correction versus a gradual correction which could be indicated in certain circumstances.

Locking plates offer increased stiffness and resistance to cutout, particularly in poor quality bone by becoming a fixed angle device. Modern plate techniques utilize both traditional screws for compression and indirect reduction as well as locking screws to create a fixed angle device. In contrast to traditional plate-and-screw constructs, the locked screws resist bending moments and the construct distributes axial load across all of the screw-bone interfaces [44, 45].

Results in the literature for the treatment of femoral shaft malunions with plate fixation are extremely limited; however, the senior author prefers this technique specifically when the intramedullary canal has been obliterated by progression of deformity. Preoperative CT allows the evaluation of the intramedullary canal and appropriate planning. Careful soft tissue dissection is critical when utilizing plate fixation and the preferred approach at our institution is the lateral sub-vastus approach with periosteal dissection only at the planned osteotomy site. In cases with primarily angular deformities plate fixation is utilized in collaboration with the AO tension device to create large compression forces at the osteotomy site. Simple wedge, dome, or single cut osteotomies all compliment this fixation; however, the surgeon must avoid large translational deformities as a result. This is a common problem when center of rotation of angulation (CORA) and correction axis are not located in a similar position, a dome osteotomy through the CORA or a wedge osteotomy through correction axis will result in a translational deformity that is poorly tolerated using plate fixation [35].

10.4.2 Intramedullary Nail

Intramedullary nail fixation may be used for midshaft femur malunions when the medullary canal is patent and accessible. The biomechanics of this fixation strategy allow load-sharing and subsequently early weight-bearing. Often rotational deformities can be corrected with limited dissection or even intramedullary saw osteotomy limiting the biologic insult. Additionally, the reamings may offer some adjunct to healing an osteotomy site and when combined with early weight-bearing may create an optimized biologic and biomechanical environment for healing. Rotational correction using intramedullary fixation has been well described [46–48]. Endomedullary osteotomy and subsequent locked intramedullary nail has been reported with a high union rate 90–100% [47, 48] and with restoration of near physiologic rotation ranging from 0° to 4° [48]. Open osteotomies have also been shown to be highly effective, utilizing a technique with Steinman pins to act as a goniometer to track rotation [49]. Results reported in the literature show an average of 78% correction achieved and average residual deformity of 5° [3].

Intramedullary fixation has also been reported for more complex malunion correction. In the developing world, conservative treatment of femoral shaft fractures is not uncommon and frequently results in significant deformity [1, 50]. Malunion correction of complex deformities has been reported using a single cut osteotomy with excellent results. Average leg length discrepancy preoperatively was 3 cm and less than 1 cm postoperatively while time to union at 3 months was observed in 94% [2]. Other types of complex diaphyseal deformities of the femur can be corrected using a technique called the *clam shell osteotomy*. This technique utilizes an open segment-type osteotomy in the area of the deformity followed by intramedullary stabilization and reported complete correction of multiplanar femoral shaft malunion with 100% union rate at 6 months [51].

10.4.3 External Fixation

External fixation including Ilizarov techniques has traditionally been the preferred modality for managing malunions. Proponents of this technique would point to a number of advantages: (1) requires only minimal soft tissue dissection, (2) can stimulate formation of osseous tissue, (3) can be utilized in the face of acute or chronic infection, (4) creates stabilization of small intra-articular or metaphyseal bone fragments, (5) allows immediate weight-bearing, (6) temporal flexibility allowing augmentation or modification of the treatment as needed through frame adjustment, and (7) tensioned wires allow the “trampoline effect” of sequential axial loading and unloading during weight-bearing activities [35]. The Ilizarov external fixator can function in a variety of treatment modes including distraction lengthening. This technique can be done in isolation, described as monofocal that involves a single site or bifocal that denotes two lengthening sites simultaneously. Unfortunately, the downsides of these devices include the following: (1) pin site infections, (2) nonunion, (3) long duration of use, (4) and perhaps, most importantly, most inconvenient device for patients and surgeons [41].

The soft tissue envelope of the thigh provides a challenging location for patients to tolerate most complex ring fixators; however, unilateral external fixators have been advocated as a simple, low-cost, and resource-independent means to treat diaphyseal malunions in the femur [41]. Deformity correction has been demonstrated utilizing this technique with results approaching 100% union at an average 3.6 months [52]. The duration of time spent in the frame is a critical point of consideration, for both medical and psychological reasons. Utilizing a combined technique of external fixation over an intramedullary device has been shown to reduce the duration by up to 50% in situations where lengthening the femoral shaft is indicated [53].

10.5 Case Examples

10.5.1 Case 1

A 45-year-old male who sustained a femur fracture as a teenager presented with complaints of chronic knee pain, onset of lower back pain, and an abnormal gait. He had no prior history of surgery. His physical exam revealed an asymmetric gait disturbance, with external rotation measured at 20° and shortening of 2 cm on the right side. His knee range of motion was 10–130° with pain at maximal flexion. Management of this case is documented in Fig. 10.1.

10.5.2 Case 2

A 63-year-old male presented 22 years after a femur fracture sustained in a motor vehicle accident. He presented with a varus deformity and an apparent leg length discrepancy. His chief complaint was a painful knee with associated back pain and an awkward gait. Management of the patient's case is documented in Fig. 10.2. (Note that the patient was lost to long-term follow-up.)

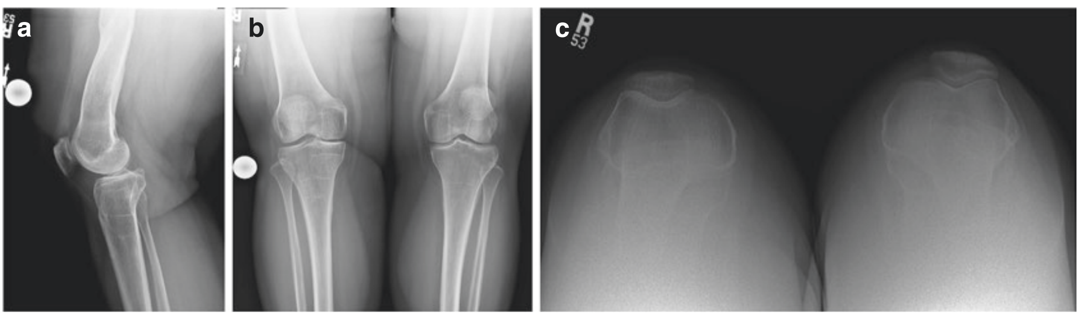
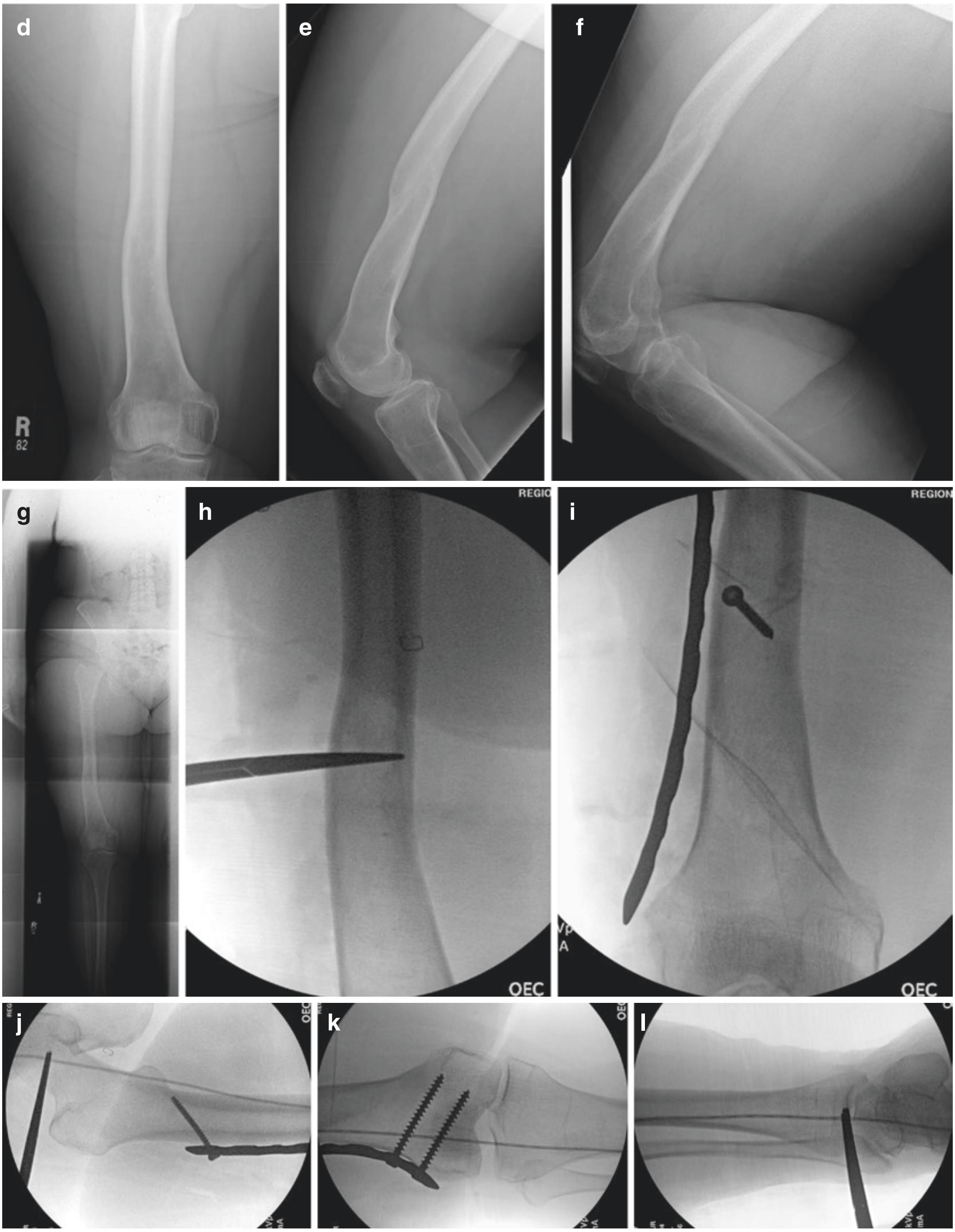


Fig. 10.1 (**a**) Lateral of the right knee, (**b**) bilateral standing, (**c**) anteroposterior knee radiographs showing medial joint space narrowing on the right side with subchondral sclerosis. Shown at the bottom are sunrise views of the right and left patellae. On the right, the patella tilt and joint space narrowing of the trochlea are evidence of a longstanding rotational deformity. (**d**, **e**) Lateral view helps to allow a measurement of the varus (10°) and flexion (10°). (**f**) This view is the patient with the knee flexed to 90° foot flat on the table with the knee pointed to the ceiling. Based on the femoral condyles and tibia plateau, it is clear there is a large rotational abnormality. (**g**) A long leg anteroposterior view is paramount when assessing limb alignment, especially to determine mechanical axis. It is always helpful to have a bilateral view. (**h**, **i**) An intraoperative C-arm view to determine the apex of the deformity and axis of rotation for correction. On the left is revealed a screw placement after the cut is made, around which the osteotomy can rotate. This is a biplanar osteotomy to account for a valgus and rotational correction. (**j**–**m**) The images above show three C-arm spot views detailing the Bovie Cord method to assess alignment after osteotomy correction. The Bovie Cord is placed directly over the center of the femoral head proximally and over the middle ankle distally while the leg is in neutral rotation. The middle of the cord should then pass through the center of the knee in the normal (or corrected) patient with a normal mechanical axis. The image at the bottom shows an intraoperative image of the Bovie Cord across the anterior surface of the patient. The surgeon is getting ready for C-arm flouro views. (**n**–**p**) To right, the proximal, midshaft, and distal fixation with a large fragment plate contoured to the femur. In the middle view, three lag screws across the long oblique osteotomy are shown gaining maximum compression and stability. (**q**–**s**) These three C-arm images are pieced together to show the intraoperative lateral femur images, the plate position, and the corrected deformity. (**t**, **u**) One year postoperative, the anteroposterior and lateral femur view demonstrate a healed femur. The patient normalized his gait disturbance and was pleased with the length restoration



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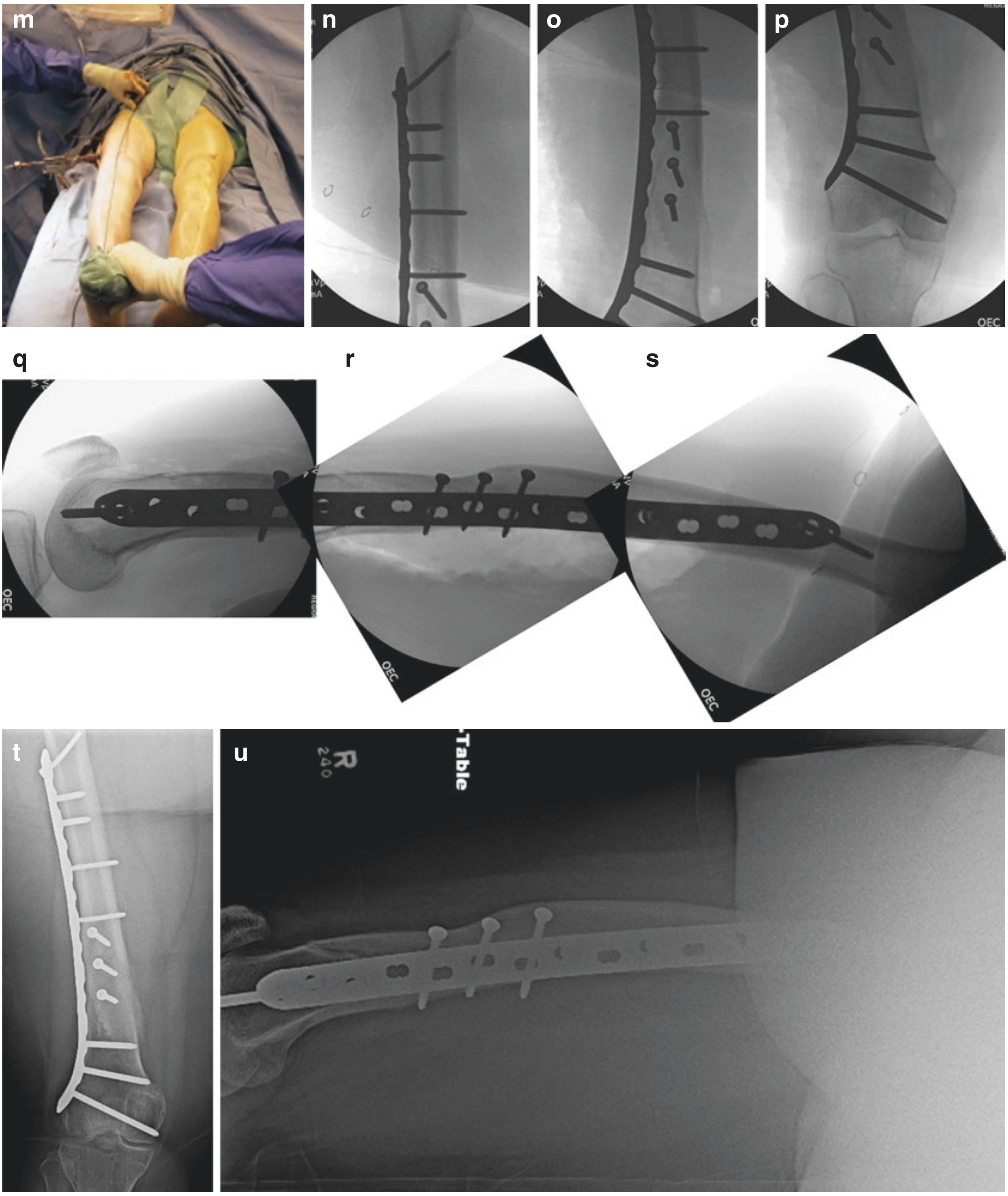

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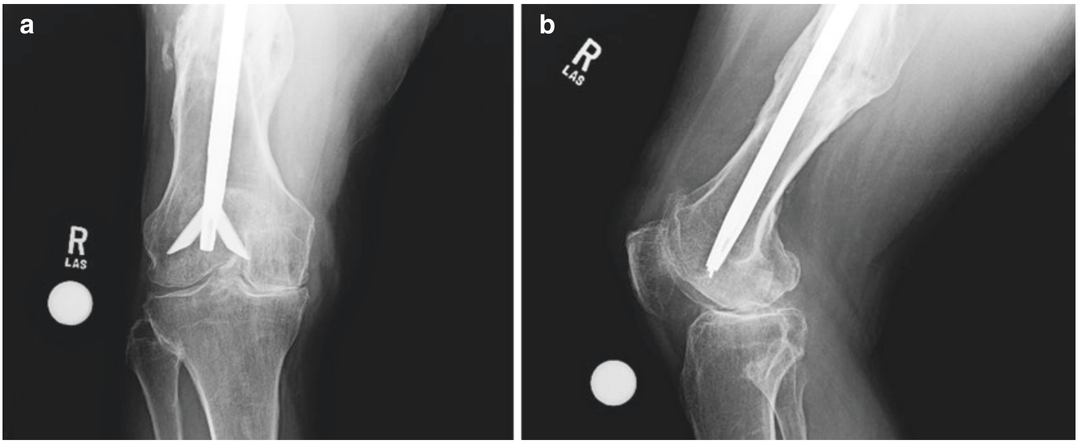
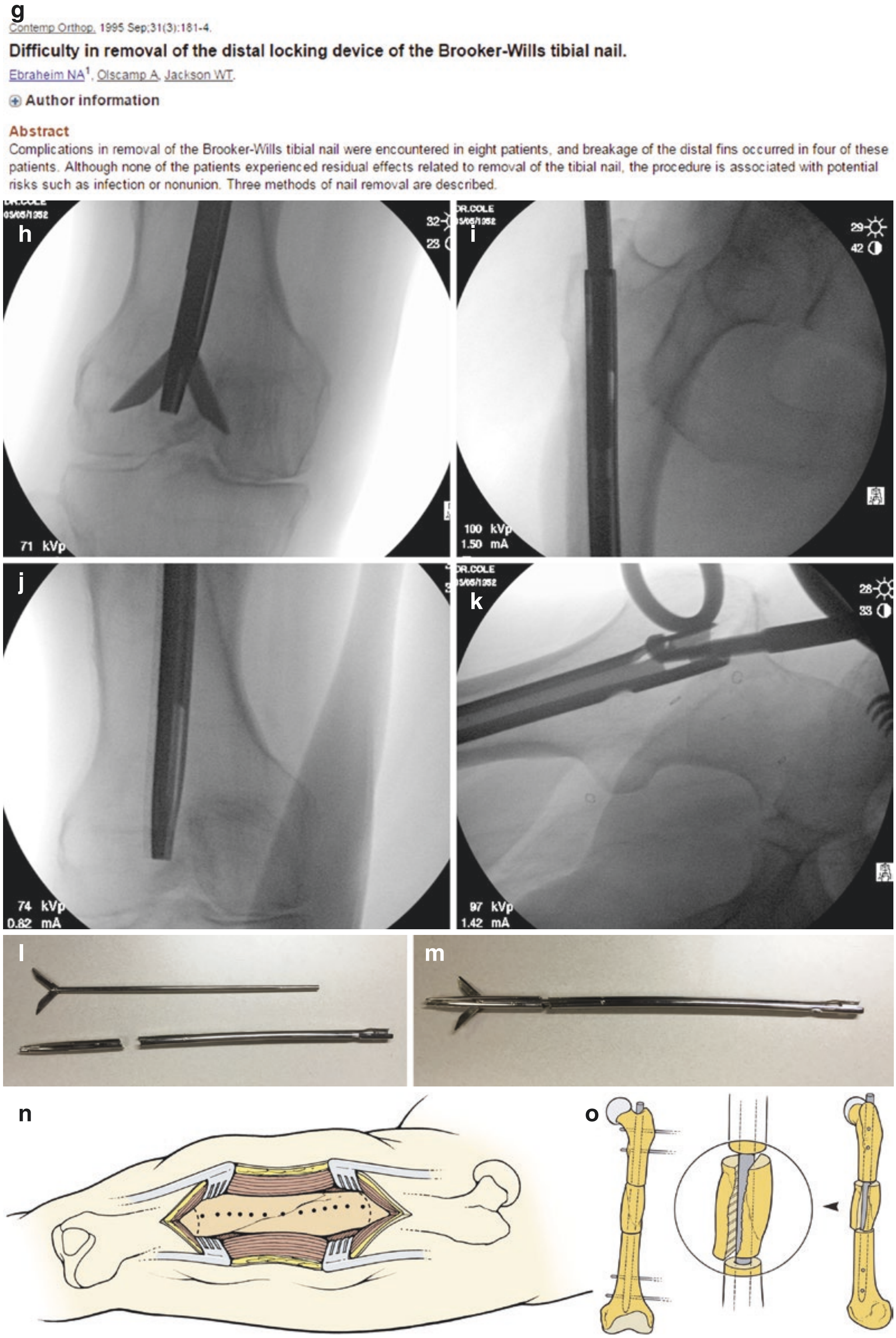


Fig. 10.2 (**a**, **b**) Anteroposterior and lateral knee radiograph revealing that the patient's femur was rodded with a Brooker-Wills nail. Obvious deformity is detected and requires further workup. The patient has tricompartmental arthritis of the knee and his excessive medial weal with bone on bone changes is typical of chronic changes from varus malalignment. (**c**, **d**) Femur anteroposterior (AP) and lateral view demonstrate a healed diaphyseal fracture with significant varus as seen on the AP in the coronal plane. If this is hard to distinguish, simply outline the metaphysis of the femur and draw a parallel line across the joint line. The lateral radiograph reveals slight extension at the fracture site. A retained cerclage wire is noted embedded in bone around the diaphysis. The fins of the Brooker-Wills nail are deployed making extraction challenging. (**e**) This anteroposterior long leg bilateral alignment film demonstrates the remarkable varus deformity, as the mechanical axis is far medial to the knee on the right relative to the mild genu varus as seen on the left side. In addition, there is a 3.5 cm leg length discrepancy. Note the relative levels of the hips and the ankle joints right to left. This is a striking deformity. These measurements must be evaluated clinically and radiographically. (**f**, **g**) It is important to research the type of implant requiring removal, as understanding the extraction methods is vital. This reality is common in the field of malunion surgery and particularly for femur malunions. The Biomet Brooker-Wills technique guide and relevant literature [53] was reviewed prior to the procedure, underscoring the significant planning that goes into the planning of such a case. (**h**–**k**) This implant requires the removal of an inner core mechanism that withdraws through the rod, the locking flanges which characterize the historic Brooker-Wills system. Once the inner mechanism is removed, the broken rod must be captured with rod removal hooks that slide through the core of the nail. Preoperative planning requires knowledge of the devices, which needs to be addressed intraoperatively, without which would lead to certain frustration or failure. (**l**, **m**) The disassembled and reassembled broken and retrieved Brooker-Wills nail. Now it is time to proceed to the clamshell osteotomy, which is optimal for the multiplanar femoral nonunion deformity. (**n**, **o**) These illustrations [51] show the concept of creating a cylindrical osteotomy with a proximal and distal transverse cut, followed by a split in the cylinder to open the area of malunion through which an intramedullary nail is passed. (Courtesy of AO Foundation. ©AOTrauma, AO Foundation, Switzerland). (**p**, **q**) This is an intraoperative anteroposterior and lateral view of the femoral deformity after the two transverse cuts were proximal and distal with a sagittal saw. Lots of cooling saline is used to minimize heat formation and osteonecrosis during the osteotomy. On the lateral view, drill holes are shown which will help to guide the chisel cuts to split the segment longitudinally. The retained cerclage wire from the original surgery was left in place having been overgrown with bone. (**r**, **s**) The intramedullary guide rod for reaming is placed across the osteotomized segment. A ball spike pusher is used to tip the distal metaphyseal segment, and a *poller blocking screw* is placed to guide the reamer across the segment. Accurate reaming along a preplanned mechanical axis is important to accomplish the predetermined femoral alignment. (**t**) Lateral image of the segmental split after rod deployment and autogenous iliac crest augmentation inside the clamshell. Based on preoperative planning, intentional lengthening as indicated by the gap was accomplished with distraction. Twenty-two millimeters of length was restored by a combination of distraction and angular correction. (**u**, **v**) An accurate anteroposterior and lateral fluoroscopy view of the knee is key to assess implant position. Final locking of the retrograde nail with a distal helical blade and two locking screws, combined with the reduced intramedullary diameter conferred by the blocking screw, provides satisfactory stability to the distal segment. (**w**, **x**) Final postoperative femur views on a long cassette help to assess alignment. Compared to the preoperative status, both radiographic and clinical rotation and alignment were entirely corrected, but the patient remained short by intention by approximately 1 cm. A correction of greater than 2.5 cm of leg length can be harmful to the neurovascular integrity of the extremity, with neuropraxia and compartment syndrome previously reported in acute lengthening of greater than this distance

Fig. 10.2 (continued)



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Contemp Orthop. 1995 Sep;31(3):181-4.

Difficulty in removal of the distal locking device of the Brooker-Wills tibial nail.

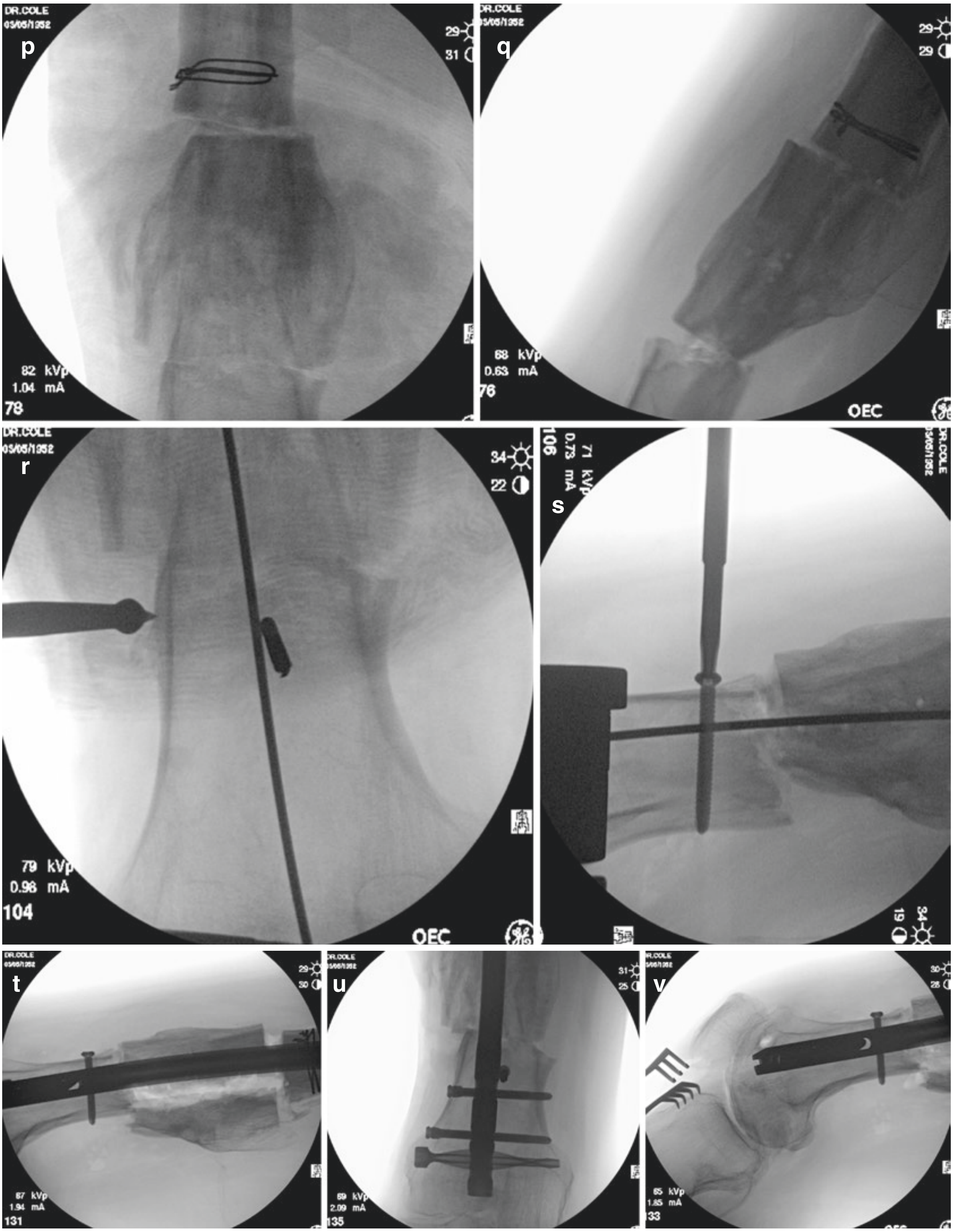
Ebraheim NA[1], Olscamp A, Jackson WT.

Author information

Abstract

Complications in removal of the Brooker-Wills tibial nail were encountered in eight patients, and breakage of the distal fins occurred in four of these patients. Although none of the patients experienced residual effects related to removal of the tibial nail, the procedure is associated with potential risks such as infection or nonunion. Three methods of nail removal are described.

Fig. 10.2 (continued)



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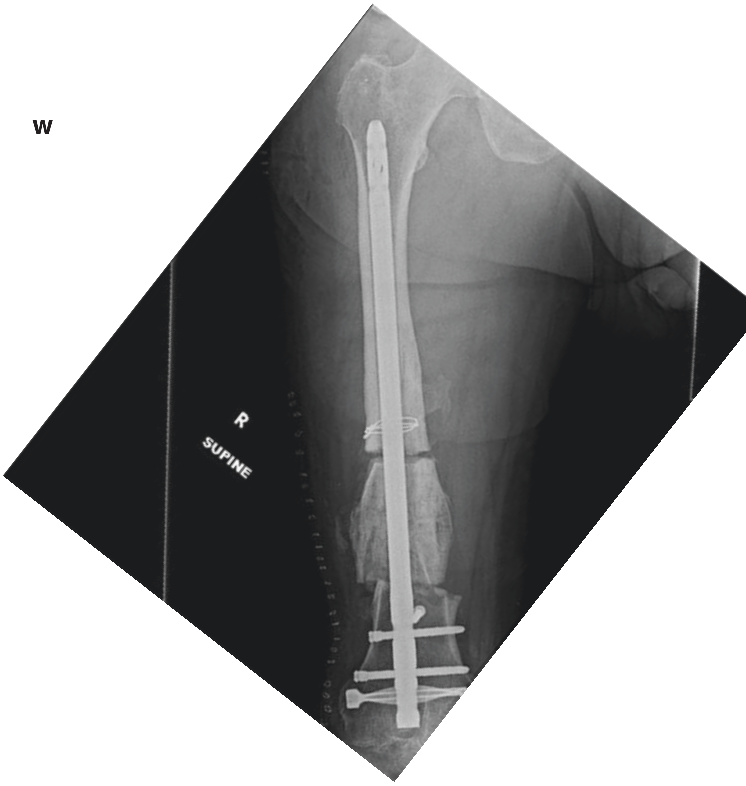


Fig. 10.2 (continued)

10.5.3 Case 3

A 38-year-old female who emigrated from Nigeria several years previously described having broken her legs when she was less than 20 years old when she was struck by a car. She recalls recovering while lying in bed, never having recalled any traction treatment. Her primary complaint was difficulty walking, requiring a cane, and it was clear that she described emotional pain from social marginalization. Management of her case is documented in Fig. 10.3.

10.6 Discussion

Femoral shaft malunions represent a challenging problem for patients as well as a diagnostic and technical challenge for orthopedic surgeons. Patients may suffer from clinical deformities, gait abnormalities, multiple surgical procedures, and psychological impairment. As reviewed in this chapter, a systematic approach to the evaluation and treatment of femoral malunions is required for patients to have a successful outcome with attention to patient characteristics, fracture characteristics, and technical characteristics.

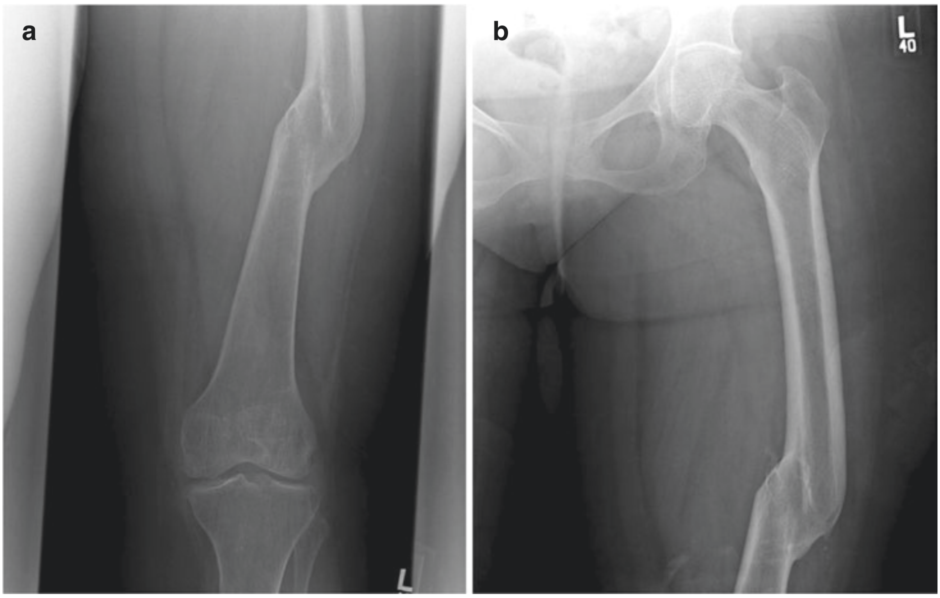


Fig. 10.3 (**a**, **b**) The images reveal anteroposterior views of the femur proximal and distal. A malunited diaphysis is evident with approximately 15° of varus and 100% medial translation of the distal segment. The hip and knee joints demonstrate relatively normal articulation without arthritic changes. (**c**, **d**) The images are lateral views of the femur mid diaphyseal and proximal, respectively. There is approximately 5° of extension deformity and 100% translation in the sagittal plane as well with the distal segment posterior. (**e**, **f**) Impressively, the right femur radiographs proximally reveal a varus deformity with medial and posterior translation of the distal relative to the proximal segment. Note the striking tension trabeculae on the anteroposterior view of the femoral neck due to the great tension forces across this anatomy due to her varus deformity. (**g**) The patient's long leg alignment films are interesting. Her mechanical axis suggests a net valgus deformity of her left lower extremity, though she is really not far off axis, despite a grotesque gait and noteworthy radiographic deformity. (**h**, **i**) Intraoperatively, the leg is positioned over bumps to help with closed reduction, and a universal distractor applied to the anterior femur, through 1 cm stab incisions. It must be secured with all joints tightened securely, as the amount of force applied across the pins will be great. This device will allow maintenance of femur position during and after the cut. It will also allow for traction to be applied. (**h**) The cut has been made through the apex of the deformity in a plane to correct coronal plane alignment. (**i**) The plate has been applied in line with the proximal femur and subsequently will be used as an aid to reduction, because one can assume that the precontoured plate can be used to "straighten the bone." (**j**) What is most remarkable about this image is that it highlights how far the distal femoral segment needs to travel in order to become reduced. A massive correction in valgus and extension is needed. (**k**, **l**) The first image shows a flouro view in which reduction instruments are applied. First, there is an anterior to posterior 4.5 mm "axis screw" around which the distal fragment will pivot. This screw is placed without compression across the osteotomy to be the axis of rotation. This assures that there will be no shortening during the realignment. Next a distal 4.5 screw is placed into the diaphysis through the plate to draw the distal fragment out of varus. Then to follow this step, because of the forces necessary for the correction, two extra-long Schanz pins are applied through approximation handles that come from the Minimally Invasive Osteosynthesis Reduction Toolset (Johnson & Johnson/DePuy Synthes, Paoli PA, USA). At this point, the 4.5 screw through the plate and the approximators can all be used to draw the distal femur to the plate. Before doing this however, the 4.5 "axis screw" must be "released." It has served its purpose and now must allow the distal fragment to travel distal and into valgus. (**m**, **n**) These two anteroposterior C-arm views show the sequential reduction of the distal femur to the plate, docking it, and securing it with distal fixation in the diaphysis. At this point, all screw lengths are adjusted; 5.0 mm locking screws were chosen for fixation. (**o**) The proximal fixation with the large residual deformity, which highlights the correction. (**p**) The deformed residual segment was osteotomized or amputated from the distal segment. It was morselized and used for bone graft. The "axis screw" of course was discarded. (**q**, **r**) These two lateral C-arm views show the proximal and distal segments with alignment of the plate to bone and final correction of the sagittal plane deformity. (**s**) Long cassette radiograph view intraoperatively post-fixation, ensuring femur alignment after bone graft. One should not trust the 9″ or 12″ flouro-spot films to assess long bone alignment. (**t**) This image shows a bilateral femur anteroposterior view showing the correction on the left and the residual deformity on the right. Consideration for bilateral simultaneous reconstruction was given, but the surgeon chose to reconstruct the most symptomatic side first. (**u**, **v**) The two images show an anteroposterior and lateral radiograph view of the healed femur after consolidation. The patient was very pleased, even to an extent that her symptoms and gait improved to an extent that she did not desire to have her femur reconstructed on the right. "Good enough!" (**w**) Bilateral long leg alignment image showing a good restoration of the mechanical axis on the left

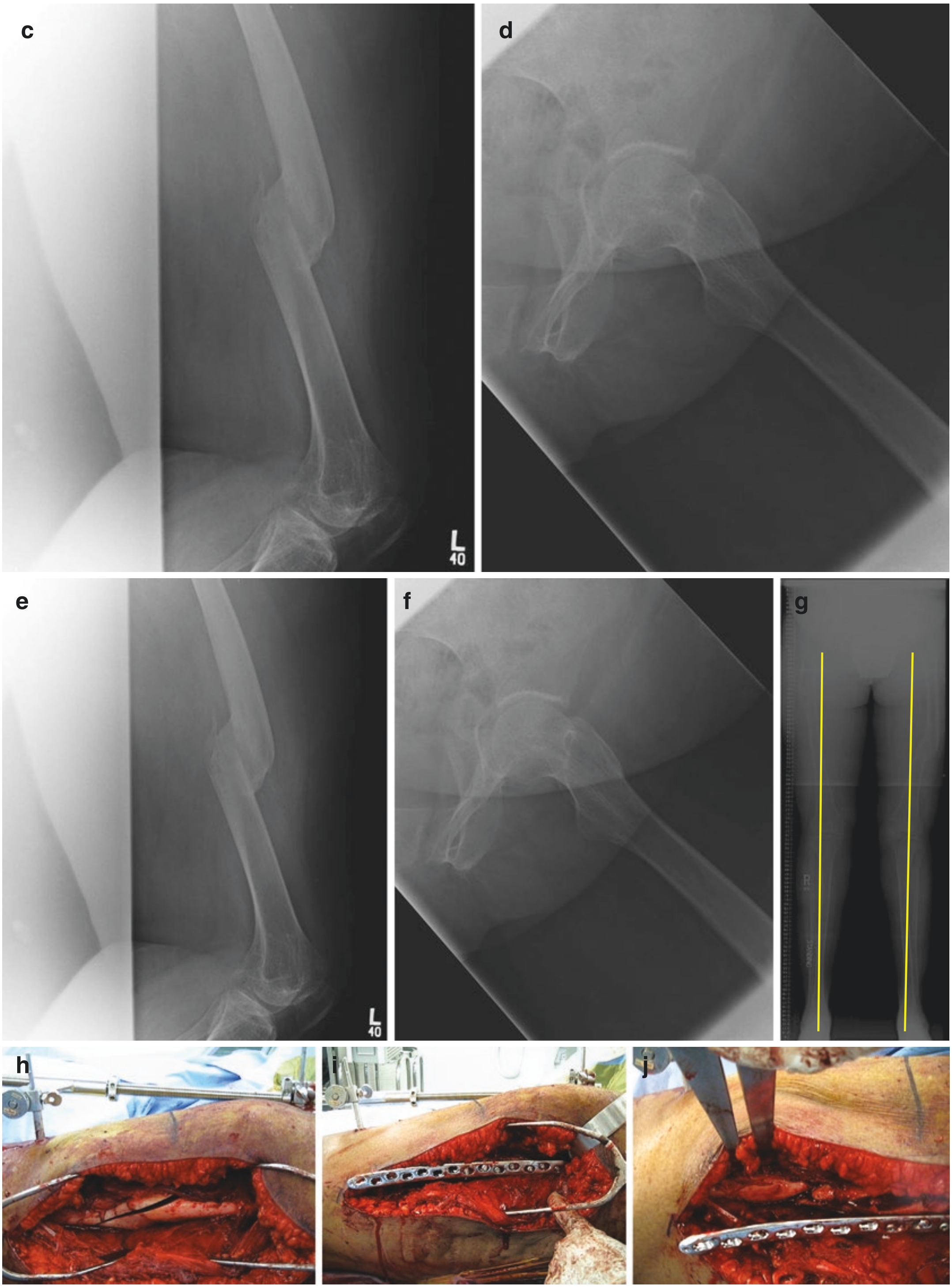
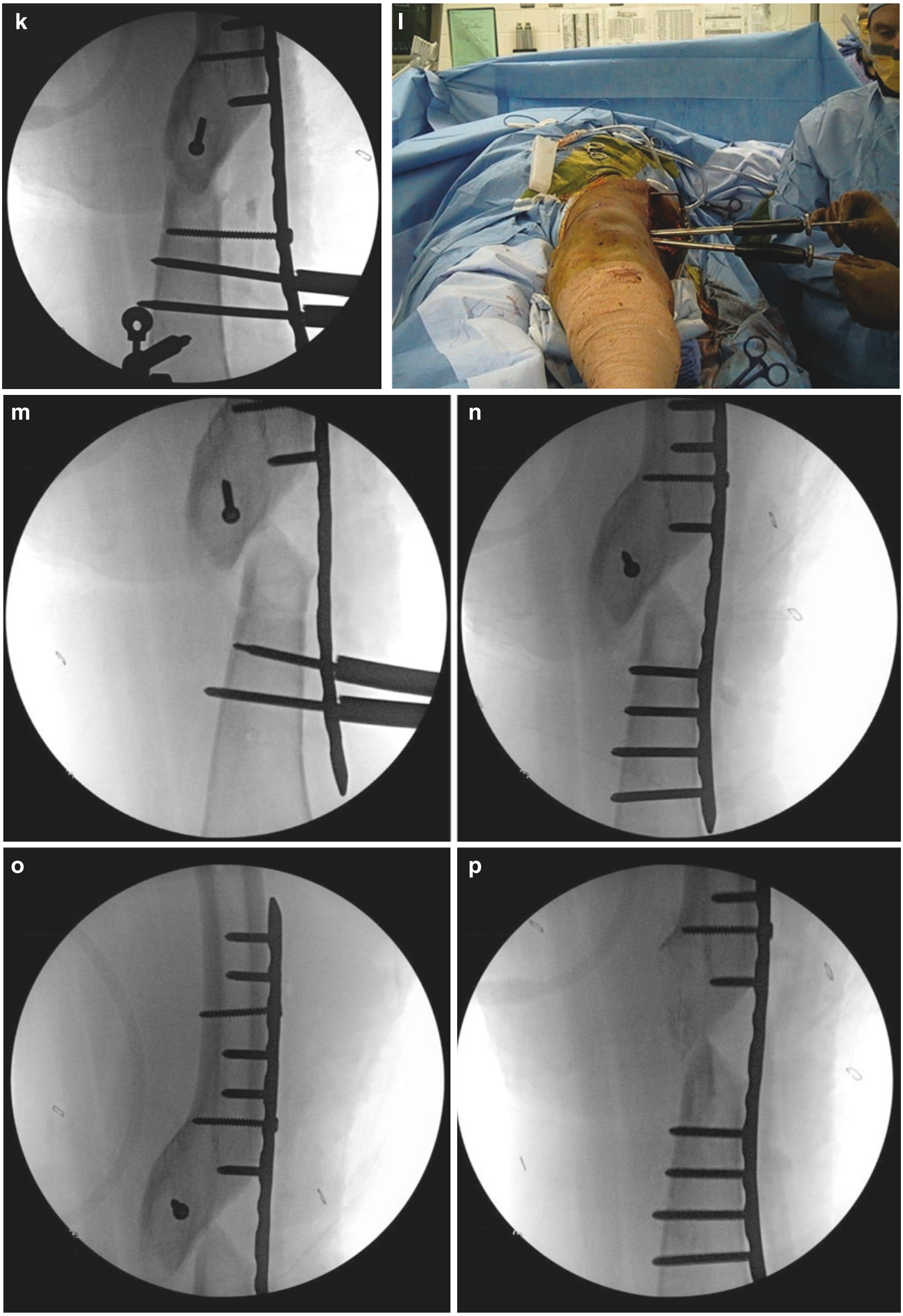


Fig. 10.3 (continued)



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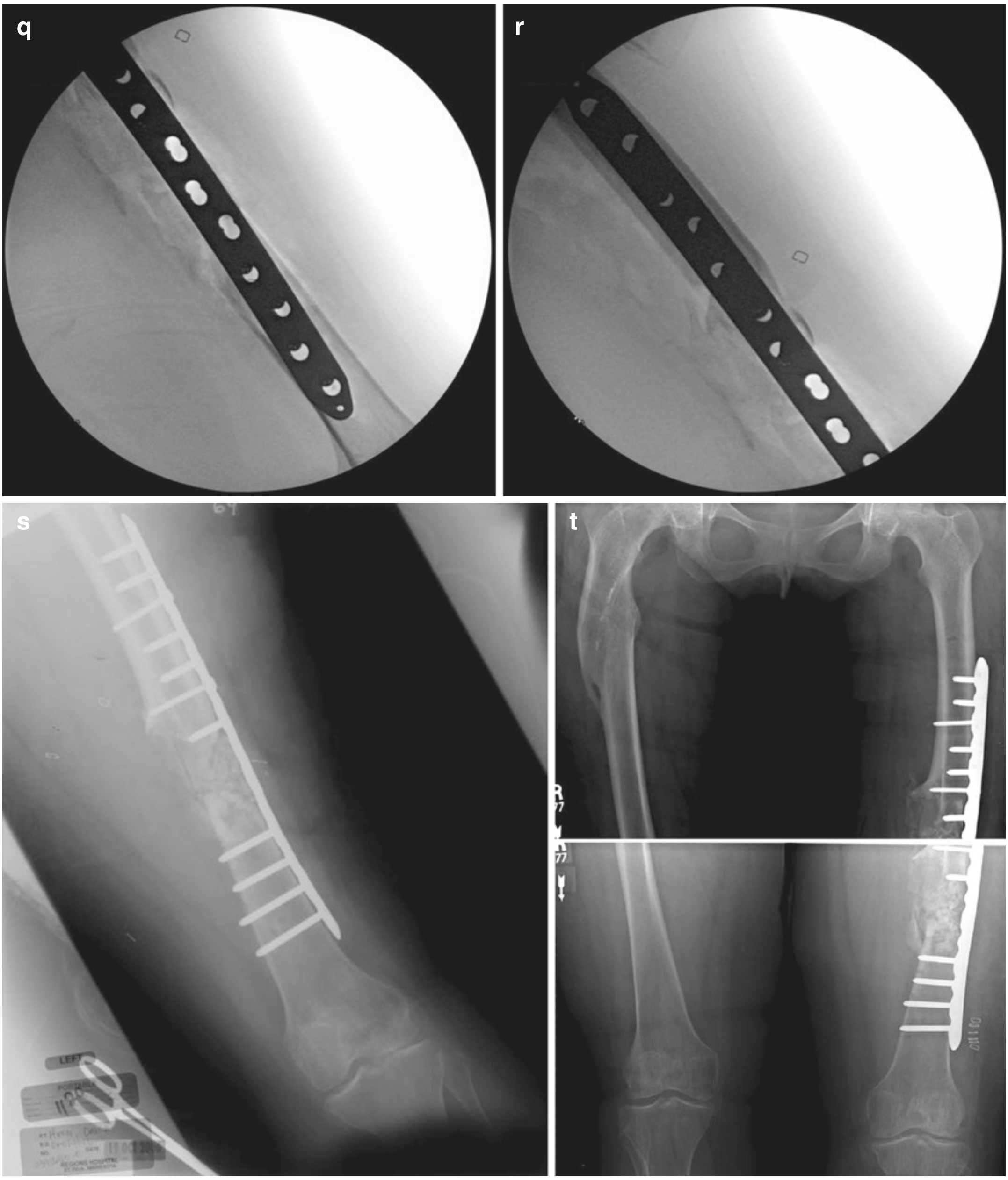

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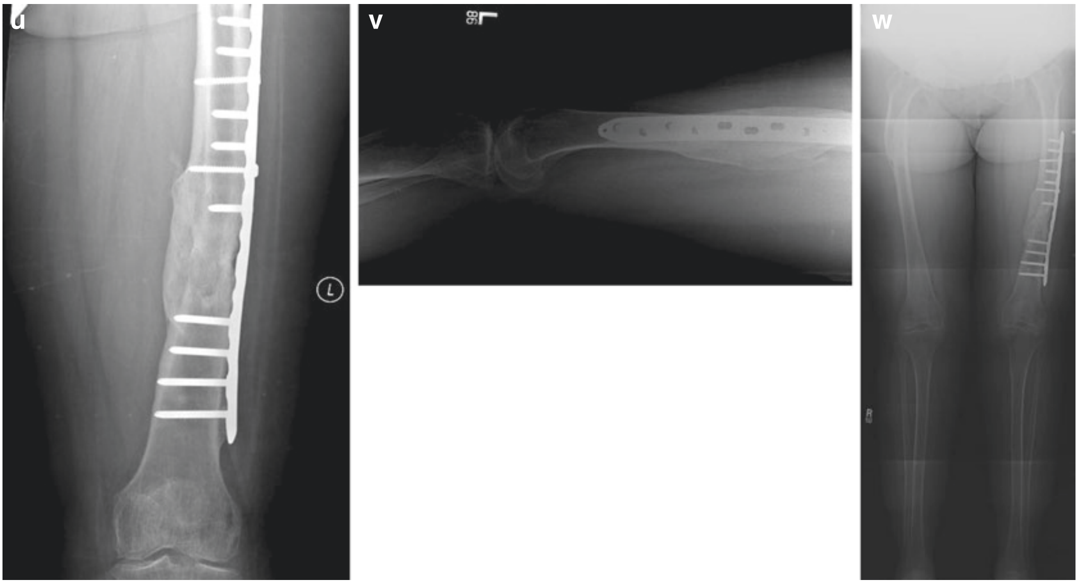

Fig. 10.3 (continued)

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Malunions of the Distal Femur

11

Thomas L. Hand and Animesh Agarwal

11.1 Introduction

11.1.1 Distal Femur Fractures and Types of Malunions

Fractures of the distal femur are considered to be those occurring within the distal 15 cm of the femur [1, 2]. Depending on the fracture pattern (i.e., extra-articular, partial articular, or complete articular) and relative level of comminution and/or bone loss, the introduction of risk for various types and combinations of malunions will undoubtedly present themselves in the treatment process. Commonly accepted categories of distal femur malunions include malrotation, coronal plane deformity, sagittal plane deformity, limb length discrepancy, intra-articular malunion, and multiplanar deformities [3]. Varying criteria for malunions of the distal femur are found throughout the literature, but it is generally accepted that symptoms begin to occur with coronal plane deformity >5°, sagittal plane deformity >10°, rotational deformity >10–15°, and limb shortening >2 cm [4–7].

There is a relative paucity of literature regarding distal femur malunions compared to the remainder of the femur and lower extremity. Rather, much of the available literature concerning distal femur fractures tends to focus on acute management, prosthetic replacement, and nonunion treatment [1]. Aside from the studies regarding deformity correction of the distal femur, the crossover of concepts to other lower extremity malunions, native deformities, and nonunions allows for extrapolation. It is important to note, however, that distal femur malunions can be much more variable with regard to treatment due to dependence on the proximity to the articular surface, available bone for fixation, surrounding muscular envelope, and unique deforming muscular forces.

11.1.2 Incidence of Malunions

Distal femur fractures account for 3–6% of all fractures of the femur with an estimated annual incidence of 37 per 100,000 person-years [2, 8–11]. Malunions of the distal femur are overall a fairly rare event [3], the exact incidence of which is difficult to decipher among the literature given the various types of malunions, differing parameters for malunion, and variability of treatment options. Evaluating the different types of malunions individually perhaps provides a better idea of their incidence based on available literature. In a series of 59 distal femur fractures

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treated with various methods, Zehntner et al. reported varus/valgus deformity >5° in 26% of fractures, procurvatum/recurvatum >5° in 22% of fractures, and rotational deformity >5° in 19% of fractures [12]. Rotational malunions of the femoral shaft exceeding 15°, including the distal one-third femur, have been shown to have reported rates between 20% and 30% when treated with intramedullary nailing [13, 14]. With minimally invasive plate osteosynthesis (MIPO) of distal femur fractures, the incidence of rotational malunions >10° has been reported to be as high as 35–43% [6, 15, 16]. Varus collapse >5° has been observed to occur in 42% of patients treated with lateral condylar buttress plate alone [17]. Intra-articular malunions can be difficult to quantify unless intraoperative identification or radiographic malunion deformity or step-off is confirmed. There is a reported incidence of 23–36% of post-traumatic arthritis following intra-articular distal femur fractures [18–20]. However, in addition to intra-articular malunion as a cause for these high rates, mechanical damage during the traumatic event, chondrocyte death and dysfunction, and inflammatory cell-mediated response all present potential confounders to the development of post-traumatic arthritis [18, 20]. Despite the etiology, distal femur fractures represent a relatively common fracture with numerous potential complications. In a systematic review of 1670 distal femur fractures, the rate of secondary surgery for all causes was 16.8% including 6% for nonunion alone, whereas malunions were not specifically distinguished [21].

11.1.3 Ramifications of Malunions

Distal femoral malunions to a significant degree can undoubtedly have detrimental effects to the patient's function with possible cosmesis issues. All of the various types of malunions can result in altered knee biomechanics and/or contact pressures and result in eventual post-traumatic osteoarthritis. Rotational malunions ≥15° are typically noticed by patients and are associated with articular cartilage deterioration, distortion of knee biomechanics, and overall decreased function [5, 6]. Rotational malalignment of the femur is also associated with a higher trend in difficulty with stairs, running, and sports [5]. On computer-generated models, femur rotational malunions of any degree cause posterior displacement of the weight-bearing axis, and supracondylar rotation greater than 30° to 45° results in frontal plane malalignment and knee joint malorientation [22]. In addition, patellofemoral contact pressures have been found to increase nonlinearly with increasing rotational deformities over 20° [23]. With coronal plane deformity, varus or valgus malunion of the distal femur leads to increased contact forces in the medial or lateral compartments of the knee, respectively, which can eventually cause deterioration of the articular cartilage and premature osteoarthrosis [24, 25]. Sagittal plane deformity leading to genu recurvatum or genu procurvatum can result in pain, loss of knee flexion or extension, feelings of instability, and muscle weakness [26]. Additionally, distal femur procurvatum can lead to a limp as a result of restricting the swing phase of gait, while recurvatum deformity can cause a posterior thrust and painful gait [27]. Symptomatic leg length discrepancies >2.0 cm can be associated with quadriceps weakness, gait asymmetry, feeling of imbalance, and low back pain [28]. Lastly, intra-articular malunions can conceivably lead to direct mechanical destruction of the involved articular surface and contribute as well to the aforementioned 23–36% rate of post-traumatic arthritis following intra-articular distal femur fractures [18–20].

11.2 Causes of Malunions

The etiology of malunions of the distal femur is multifactorial with varying levels of contribution from the surgery itself, the implant factors, and patient factors. Oftentimes, the contributing etiology can be retrospectively identified, though this may not always be the case. In a series of 22 distal femur malunions by Rollo et al., the etiology of malunion was attributed to poor fracture reduction in almost 60% of the total cohort, highlighting the importance of the index surgery [3].

Iatrogenic factors certainly play a role, which may be as simple as not utilizing some of the preventative strategies discussed below when indicated for rotational, length, and mechanical axis assessment (See Sect. 11.2.1); however, implant type, choice, and application can contribute as well to malalignment in the index surgery.

Implant choice for distal femur fractures remains a controversial topic. A recent meta-analysis comparing the outcomes of 279 patients treated with retrograde intramedullary nailing versus plating revealed no clear superiority of one implant choice over another with regard to malunion [29]. However, different types of distal femur fractures may dictate implant type, as not all fractures are amenable to retrograde intramedullary nailing [30]. When utilizing a lateral distal femur locking plate for these fractures, it is important to note that plate-bone mismatch is still a problem, even with the modern designs of the available pre-contoured plates. Thus, sole reliance on the plate as a reduction tool may itself contribute to malreduction [31]. A recent study of 53 patients with atraumatic femora underwent digital templating with superimposed distal femur plates from four common manufacturers, which all demonstrated mismatch secondary to under-contouring of the plates, even worse so after total knee arthroplasty [32]. Additionally, there are several common mistakes when utilizing lateral distal femur locking plates that have been identified as contributors to malunion. The much-discussed "golf-club" deformity with medialization of the distal femur can be a result of plate placement too distal and/or too posterior on the lateral femoral condyle [27, 30, 33]. Procurvatum and recurvatum deformity can be induced by plates applied in a flexed or extended fashion, respectively [27]. Failure to align the distal screw trajectory parallel to the distal femoral condyles in certain plate designs can lead to valgus application of the plate and coronal plane deformity [27]. Even after fixation with a laterally based plate, the aforementioned study by Davison showed a postoperative varus collapse in excess of 5° prior to union in 42% of patients treated in his series of 26 comminuted distal femur fractures [17].

Minimally invasive techniques and poor preoperative planning have also been associated with malunions of the distal femur. Minimally invasive plate osteosynthesis (MIPO) technique for distal femur fractures has been shown to be advantageous from a soft tissue preservation aspect [34]; however, several recent studies have shown it to be significantly associated with rotational malunions [6, 15]. One study of 13 femoral shaft fractures and 38 distal femur fractures treated with MIPO technique demonstrated satisfactory rotational alignment in only 56.9% of patients on postoperative CT scans [15]. Additional care to evaluate rotational profile compared to contralateral radiographs as described below can help to perhaps mitigate this risk (See Sect. 11.2.1). As for intra-articular malunions, poor visibility can contribute to poor reduction, as can unrecognized complexity of the fracture. Coronal plane "Hoffa" fractures of the femoral condyle(s) have been described to be associated in about 40% of intercondylar distal femur fractures [35], highlighting the need for preoperative CT scans and appropriate preoperative planning and fixation.

Malunions identified as a result of collapsed nonunion or delayed union emphasize patient factors important to consider as causes of eventual malunion. These have been well described in the literature and include diabetes, obesity, smoking, poor bone quality, and the presence of an open fracture [36–38]. Recognition of these factors may necessitate alternative treatment strategies or heightened vigilance for early recognition and intervention if necessary.

11.2.1 Preventative Strategies for Malunion

Timely healing of the fracture and restoration of the length, alignment, rotation, and articular reduction are paramount to the prevention of malunions. Unfortunately, this may be difficult to directly visualize, particularly in AO type C3 fractures due to comminution and introduction of multiplanar deforming forces [12, 39]. There are, however, several techniques to assist in prevention of the various types of malunions in distal femur fractures that have been proposed.

Rotational malunions represent an unfortunately common type of deformity following treatment of femur fractures. Numerous methods have been theorized to assess intraoperative and postoperative rotational profile. Many of these methods rely on an intact contralateral femur with an absence of preexisting deformity. A 3D CT study of ten randomly selected patients with atraumatic femora showed symmetrical rotational and translational profiles when bilateral femurs were superimposed [40]. Reliance on contralateral imaging is the hallmark of the most commonly employed method for rotational assessment – the lesser trochanter profile (LTP). This method involves obtaining a true AP of the uninjured knee, which can be obtained after 90° C-arm rotation from true lateral with superimposed condyles, followed by an AP of the uninjured hip with leg held in rotation. These views should be saved on the c-arm. An AP of the affected knee should be obtained first after reduction and temporary stabilization of the fracture and then similarly an AP of the injured hip is obtained. This AP of the uninjured hip is then compared to the then subsequently obtained AP view of the injured hip [41]. At this point, any differences in the LTP should be addressed as needed. A recent study evaluated this technique with 19 matched pairs of sectioned cadaveric femora. The authors found that the size of the lesser trochanter was a reliable approximation of rotation with 10% differences in lesser trochanter size correlating to approximately 7° of malrotation [41]. Another method known as the true lateral technique (TLT), originally described by Tornetta et al., can be done by obtaining a true lateral of the knee, then recording the degrees of rotation needed of the C-arm to obtain a true lateral of the hip [42]. A recent survey of 85 surgeons analyzing images of cadaveric femora, however, found only 53% of responders able to identify a 20° malrotation with the TLT method, compared to 67% accuracy utilizing the LTP method [43]. Nevertheless, either or both methods can be employed as another piece of information to help mitigate the risk of rotational malunion.

Prevention of coronal plane malunion can be done with proper plate placement by avoiding the pitfalls as discussed above (see Sect. 11.2) and with reliance on restoration of the mechanical axis. This can be measured with an intraoperative radiopaque thread or rigid guidewire or stretched flexible wire (i.e., Bovie cord) from the center of the femoral head to the center of the ankle joint [44]. In standard cases, this line should pass just medial to the tibial spine of the fully extended knee [45]. However, baseline mechanical axis can be variable among patients, especially those with preexisting knee osteoarthritis. Comparison to the contralateral mechanical axis measured in a similar fashion provides an accurate comparator assuming there is no presence of a contralateral deformity. With retrograde nailing where knee extension is not possible with the nailing jig in place, ipsilateral mechanical axis can be estimated or even calculated by measuring the angle between the plane of the distal articular surfaces of both the medial and lateral femoral condyles and the nail attachment stem of the retrograde nail. In normal cases, this should be a valgus angle of 5–7°, correlating to the average difference in the anatomic intramedullary axis of the femur and the mechanical axis of the lower extremity [45]. This can be estimated radiographically or if the femoral condyles are accessible with the chosen surgical approach can be done with a flat surface spanning both condyles or, alternatively, a goniometer. And lastly, a full-length femur portable X-ray can be used to assess gross coronal plane deformity difficult to accurately detect with fluoroscopy or other means.

Sagittal plane deformity is perhaps the most difficult malunion to accurately prevent. The deforming forces of the gastrocnemius on the distal condylar segment frequently will try to induce a recurvatum deformity and must be resisted with either direct manipulation of the distal segment, a posterior bump under the knee, and/or manual downward traction [46]. Lateral fluoroscopic images may be misleading and may even be partially obstructed by fixation implants or jigs. Obtaining perioperative true lateral images of the contralateral femur with overlap of the distal and posterior aspects of the condyles with the diaphysis in the field of view can be helpful to recreate the flexion/extension component of the injured distal femur relative to the shaft. The relationship of Blumensaat's line to the long axis of the femur or, alternatively, the anatomic posterior distal femoral angle (aPDFA) can be estimated or measured on the lateral femur view from the relationship of the sagittal distal femoral joint line to the long axis of the femur compared to the contralateral [25, 46]. Depending on the proximal extent of the fracture and relative comminution, fluoroscopy may be unreliable if the intact portion of the femur proximal to the fracture is unable to be visualized in the same field of view, and a lateral portable X-ray may be needed to assess the position and sagittal rotation of the articular surface to the intact femoral diaphysis. Finally, an anteroposterior (AP) fluoroscopic view of the distal femur may also provide a hint of sagittal deformity needing correction with the appearance of a "paradoxical notch view" distally [46].

The risk of leg length discrepancy via femoral shortening, or rarely lengthening, can be mitigated by one of two methods if direct fracture reduction is not achievable for reference, which is often the case in highly comminuted fractures. Comparison of limb length based on the palpated level of bilateral patellae, heel pads, and/or medial malleoli can provide a rough estimate of symmetrical limb length. This is dependent on symmetrical positioning of the femoral heads relative to the operative table axis and can be done with the contralateral limb prepped in or under the surgical drapes. When utilizing a retrograde nail for primary or additional fixation, this method may not be useful prior to removing the nailing jig secondary to obstruction of knee extension and migration of the patella during nailing. Use of an intraoperative radiopaque ruler to measure the contralateral and ipsilateral femurs at proximal and distal reference points (i.e., tip of the greater trochanter to the medial femoral condyle distal articular surface) provides the most accurate reproduction of symmetrical femur length assuming pre-injury symmetry.

Adequate surgical exposure for direct visualization or, at minimum, direct palpation of the articular portion of an intra-articular distal femur fracture is critical to avoid step-off and intra-articular malunion. Preoperative identification of articular fractures, via CT scan, that require reduction is key as they may dictate which main surgical approach is preferred. In some cases, these may require an additional direct medial, direct lateral, or parapatellar exposure to confirm reduction and properly place implants. Sole reliance on fluoroscopic imaging for reduction of posterior coronal plane condyle fractures such as Hoffa fractures should be done with caution and only when necessary, such as when concomitant soft tissue injuries prevent exposure. Otherwise direct exposure and visualization, or at a minimum, palpation, is preferred for articular reduction.

11.2.2 Patient Considerations

The biologic, socioeconomic, and behavioral factors of a patient are vital considerations when choosing whom to revise safely, how extensive the revision can or should be, and identifying conditions amenable to preoperative optimization. Obesity, diabetes, smoking, and preoperative reduced albumin levels have all been shown to be independent risk factors for surgical site infection and failure in distal femur fractures [36, 47]. Treating distal femur fractures acutely will likely not allow for considerable modification of these risk factors, but in consideration of deformity correction, smoking, nutritional status, weight loss, and diabetes typically can be addressed and/or counseled. Depending on the level of deformity, timing of reconstruction may be limited and thus, preoperative planning may need to be adjusted to compensate. For instance, obesity results in a conceivable increased demand on implants with increasing patient body weight and perhaps should merit more robust fixation options for any revision surgery if weight loss is not achieved or possible in the timeframe. Patient compliance and need for faster return to work may or may not be modifiable but warrant the opportunity for counseling and shared decision making and perhaps a patient agreement for "buy-in" of the planned treatment. Age and life expectancy are non-modifiable risk factors that deserve central attention as well. With the goal of faster ambulation and return to activities of daily living to avoid complications as a result of immobilization, prosthetic replacement becomes a reasonable option for complex distal femoral malunions or nonunions in the elderly or those with a life expectancy less than 10 years [48–50].

11.3 Evaluation and Diagnosis

11.3.1 History

As with any orthopaedic evaluation, a detailed history can be the most important tool in the assessment and diagnosis of distal femur malunions. A good history should start from the beginning with questions regarding baseline health, smoking status, illicit drug use, comorbidities, housing status, pre-injury activity level, occupation, and hobbies. This can help to better assess patient outcome expectations and provide insight for later discussions regarding the management of realistic expectations. In the setting of an initial consultation for malunion, the mechanism of injury and a thorough timeline should be established. The timeline should highlight the timing of surgery, time to full weight-bearing status, initial identification of gross deformity or symptoms associated with malunion, and timing and duration of rehabilitation thus far. Any history of wound healing difficulty, open fracture, drainage, postoperative oral antibiotic therapy, or any additional surgeries, procedures, or treatments to the incision should be further explored and raise flags for potential infectious contributions to malunion. Compliance with postoperative protocol should be assessed and any inconsistencies in the above history, especially when compared to available documentation, may suggest possible noncompliance that needs to be further explored. Patient self-assessment of function and/or deformity is critical to evaluate and will likely coincide with their chief complaint. In the setting of gross deformity, the chief complaint may be related to cosmesis, but frequently patients with malunions will tend to report difficulty with ambulation, feeling of imbalance or unequal leg length, easy fatigue of knee extensors or flexors, tripping over their feet, and/or anterior knee pain. In the absence of obvious deformity, any of these above symptoms may be reported in isolation or in combination and will likely have persisted despite proper rehabilitation.

11.3.2 Physical Examination

Following a thorough history, the physical examination should begin with inspection of the overall patient appearance, hygiene, and body habitus. Full inspection of gait and simultaneous evaluation of bilateral lower extremities while supine and standing should be performed. The location and appearance of incisions and/or wounds should be noted. Gross deformities may be obvious, but more subtle deformities may need to be pointed out by the patient. The proximity of the medial aspect of the knee joints may clue the examiner into varus or valgus deformity of the affected extremity. The position of the feet should be noted in relation to one another while both supine and standing. Quadriceps atrophy may be obvious, but a cloth ruler to measure bilateral thigh circumference at a given reference point (i.e., 10 cm above the superior patellar pole) will provide more objective and reproducible data.

Rotational malunions can be additionally examined with seated assessment of bilateral hip internal and external rotation, with care to note any differences if observed. If body habitus allows, the trochanteric prominence angle test (TPAT) can be a reliable method to objectively measure bilateral femoral anteversion and thus any rotational abnormalities [51]. This is performed in the prone position by palpating the greater trochanter with the knee flexed to 90°. With gentle internal and external hip rotation, the rotation which yields the most lateral prominence of the palpated greater trochanter is held in place. The resulting angle of the tibial axis relative to a midline imaginary vertical line is recorded. This can be measured with a goniometer or roughly estimated compared to the angle observed in the contralateral extremity.

Leg length can be assessed while lying supine on the examination table and comparing the heel pads and medial malleoli position during full knee extension and with comparative patellae palpation during equal knee flexion to 90°. While standing, the height of the patellae and palpated spatial relationship of the iliac crests should also be noted. If leg length discrepancy is suspected, utilization of varying thicknesses of blocks under the sole of the shortened extremity will provide an objective measurement for perceived limb length discrepancy when the patient reports the feeling of equality. Care should be taken to note any ipsilateral knee flexion contracture or sagittal deformity as this may exacerbate perceived limb inequality [52]. Knee range of motion should likewise be examined bilaterally as well as any detected crepitus, mechanical blocks to motion, hyperextension, or flexion contracture. A ligamentous knee exam should be performed to evaluate for any concomitant ligamentous knee injuries or even laxity secondary to malunion. Strength testing of bilateral lower extremities should be tested entirely to include hip, knee, and ankle motor grades. Bilateral lower extremity neurovascular examinations may also be helpful to assess for nerve injury, neuropathy, and vascular status.

11.3.3 Laboratories

Malunions frequently occur in the setting of normal lab values. If any red flags for infection are noted in the above history and physical, baseline infection labs should be obtained such as complete blood count (CBC), erythrocyte sedimentation rate (ESR), and C-reactive protein (CRP). History of delayed union or late collapse of fracture prior to union should merit additional nonunion lab workup such as complete metabolic profile (CMP), vitamin D, calcium, and endocrine labs if suspected. Hemoglobin A1C values should be obtained for all diabetic patients or those with significantly abnormal glucose values in standard preoperative labs. Strict glucose control is imperative to limit infectious complications and optimize treatment outcomes. Nutritional labs for healing potential, even in obese patients, such as albumin and pre-albumin levels should be strongly considered and any abnormalities addressed preoperatively.

11.3.4 Radiographs

Standard anteroposterior (AP) and lateral X-rays of the femur, hip, and knee should be obtained as part of the initial workup. Kellgren-Lawrence grade of arthrosis can be roughly determined on plain radiographs of the knee for consideration of patients with significant grade III and IV preoperative osteoarthrosis [53]. Standing full-length bilateral lower extremity anteroposterior X-rays with the patellae facing forward and midline radiopaque ruler (i.e., X-ray scanogram) can be obtained for quantification of deformity and objective measurement of limb length discrepancies if applicable. Mechanical femorotibial angle (mFTA), mechanical axis deviation (MAD), and mechanical lateral distal femoral angle (mLDFA) can be likewise measured on full-length standing anteroposterior X-rays [25, 54]. The mLDFA is measured as the angular difference between the femoral mechanical axis and the femoral joint line [55] and can be used to define the magnitude of the coronal plane distal femur deformity, with a standard value of 87° +/− 3° [25, 54]. The anatomic posterior distal femoral angle (aPDFA) can be measured on a lateral femur X-ray to assess for the degree of sagittal plane deformity (mean normative value of 83°) by the relationship of the sagittal distal femoral joint line to the long axis of the femur [25]. The center of rotational angulation (CORA) can be obtained radiographically for preoperative planning with plain X-ray technique at the point where the radiograph shows intersection of the proximal mechanical axis and the distal mechanical axis [54].

11.3.5 Computed Tomography and Magnetic Resonance Imaging

Computed tomography (CT) is the advanced imaging study of choice for additional deformity quantification and preoperative planning. CT scan of the involved extremity can help evaluate for healing, consolidation, canal patency, and bone stock in addition to deformity. Anteversion CT of both lower extremities can be used to objectively measure rotational alignment and degrees required for derotation [15]. A CT scanogram can offer quantifiable mechanical axis deviation (MAD) measurements utilizing the malalignment test if desired [54]. CT scans that include the entire distal femoral articular surface can also be used to evaluate for any intra-articular malunion or subchondral/articular deficit [25]. However, any existing hardware may result in artifact preventing complete visualization and metal suppression techniques should be employed. Magnetic resonance imaging (MRI) is rarely needed unless suspicion of infection based on history and/or abnormal inflammatory laboratory values. If MRI is obtained for any reason, however, the degree of cartilage thickness can be assessed according to the modified Noyes classification for prognostic data or consideration of arthroplasty if indicated [56, 57].

11.4 Treatment Based on Malunion Type

11.4.1 Rotational Malunion

In the absence of other deformities, isolated rotational malunions can be relatively easily addressed through a variety of methods. With any technique employed, it is imperative that the degree of axial derotation be determined preoperatively with CT imaging or anteversion CT protocols of both lower extremities. Fixation of the derotational femoral osteotomy can be done with either intramedullary nail, distal femoral locking plate, or external fixation depending on the canal patency, level of osteotomy, preexisting hardware, and quality of bone available for distal fixation [58–60]. In some rare occasions, intact existing hardware (such as a femoral nail) can be retained and used for stabilization of the derotational osteotomy after removing and replacing proximal screws in the corrected position [34]. The site for the derotational osteotomy can be selected according to surgeon preference and amenability of soft tissues without a definitive superiority of one technique. This can be carried out through the supracondylar region of metaphyseal bone or metadiaphyseal junction or through the prior fracture site [58–60]. The technique for osteotomy can be performed closed via intramedullary saw (if available) or in an open fashion with multiple drill holes completed with osteotome, akin to the De Bastiani technique, or oscillating saw. Muckley et al. evaluated a series of 30 derotational femoral osteotomies carried out with either a closed intramedullary saw technique ($n = 18$) or an open drill hole/oscillating saw technique ($n = 12$). In both groups, percutaneous Kirschner wires above and below the osteotomy site were used to gauge derotation and fixation was performed with intramedullary compression nailing. There were no statistically significant differences noted in complication rates between the two groups, though two cases of insufficient correction occurred in the closed technique [58]. Stahl et al. reported on a series of 14 patients with rotational femur malunions utilizing an intramedullary saw for a closed osteotomy technique followed by static intramedullary nail placement after derotation. Amount of necessary derotation was determined preoperatively by CT scan, and intraoperative assessment of derotation was also made by rotation of two percutaneously placed Kirschner wires in the femoral neck and transversely across the femoral condyles. Postoperative CT scans revealed less than 4° of residual deformity in all of the patients in their series. Average time to consolidation was 10–12 months and, notably, 12 out of 14 patients were able to return to work [60].

11.4.2 Coronal Plane Malunion

The end goal of coronal plane deformity correction is re-establishment of the mechanical axis of the lower limb to its normative value [61]. The degree of correction should first be determined by what is needed to restore the center of the mechanical axis to the center of the knee or just medial to the tibial spine [45]. This can be determined with mathematical calculations or through digital templating software if available, such as TraumaCad (Brainlab Inc., Westchester, IL, USA). Calculation of the mechanical axis deviation (MAD) and mechanical lateral distal femoral angle (mLDFA) can quantify the degree of coronal plane deformity and the correction needed to return to the contralateral limb mLDFA or its normative value of 87° +/− 3° [25, 54]. Identification of coexisting deformities, such as limb-length inequality or complex multiplanar deformity, are common and should be carefully scrutinized as they may require different treatment strategies (see Sect. 11.4.5).

Options to achieve coronal plane correction include medial opening wedge osteotomy (for varus), lateral closing wedge osteotomy (for varus), medial closing wedge osteotomy (for valgus), lateral opening wedge osteotomy (for valgus), dome osteotomy, oblique osteotomy in the sagittal plane, double oblique osteotomy as described by Miranda et al. (See Sect. 11.4.5), and osteoplasty in the method of Ilizarov with gradual correction [39, 54, 56] (Fig. 11.1). The pros and cons of opening and closing wedge osteotomies are well described and frequently extrapolated from native knee deformities or high tibial osteotomy (HTO) literature [54, 55, 62–64]. It is important to consider that closing wedge osteotomies offer improved bony contact for stability and to promote union [55], but at the cost of potential femoral shortening [39]. This may be advantageous in those patients who are at higher risk of nonunion with the sacrifice of leg length or in the rare case of patients with overlengthening following index surgery. Opening wedge osteotomies are inherently less stable with less bony contact at the site of correction and may require more robust fixation and usually with augmentation with bone grafting (autogenous, allograft, or bone void fillers) [25, 62]. Supracondylar dome osteotomies and oblique sagittal plane osteotomies of the supracondylar femur offer the potential advantages of improved bony contact without significantly altering the length of the extremity, though their documented use in malunions of the distal femur is lacking [39, 54, 63, 64]. Advantages for these single-stage osteotomies over that of osteoplasty with Ilizarov style frames include avoidance of prolonged time in external fixation, pin site infections, additional knee stiffness, and psychological and social difficulties associated with Ilizarov frame treatment [65, 66]. In the setting of a diagnosis of infection or history suggesting infectious contribution, external fixation can provide an advantage with avoidance of hardware placement directly in the zone of infection [4].

In a series of 15 patients with distal femur varus malunions, He et al. utilized a medial opening wedge supracondylar osteotomy with dual plate fixation medially and laterally. Single and biplanar osteotomies were carried out according

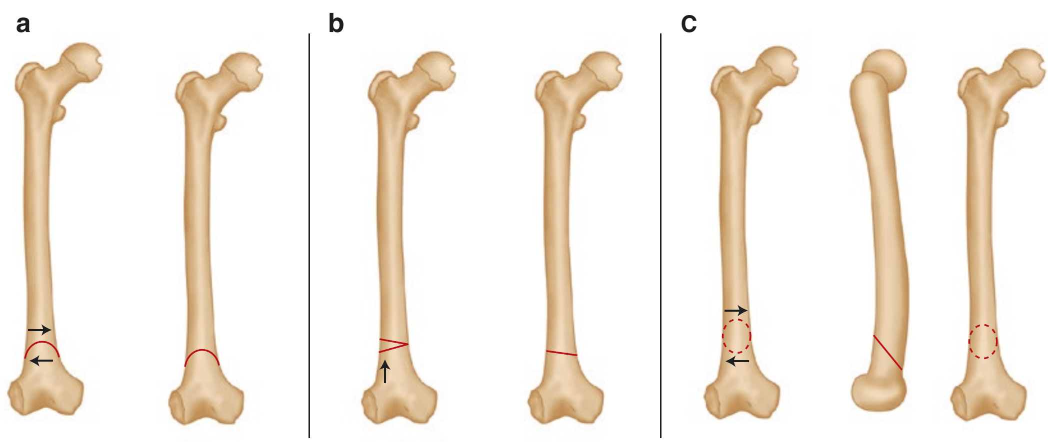

Fig. 11.1 Example of various types of osteotomies for varus coronal plane deformity correction (*A* = dome osteotomy, *B* = lateral closing wedge osteotomy, *C* = sagittal oblique osteotomy)

to preoperative templating and osteotomy sites were guided intraoperatively by placement of supracondylar Kirschner wires. Average mLDFA was corrected from 102.3° to 85.2° and any coexisting limb length discrepancy (LLD) corrected from 3.38 cm to 0.8 cm. Time to union was 4.1 months (range, 2.5–6 months). They reported overall good functional outcomes and no fixation failures or secondary surgeries with average long-term follow-up of 7.4 years [25].

Native varus or valgus deformities of the distal femur resulting in ipsilateral unicompartmental knee osteoarthrosis overshadow much of the remaining literature regarding coronal plane correction. In a series of 15 patients with 16 native distal femur varus deformities, van der Woude et al. utilized lateral closing wedge osteotomies of the distal femur in single and biplanar techniques with lateral plate fixation (n = 12) or medial plate fixation (n = 4) based on surgeon preference. Correction was achieved in all but one patient. Average time to union was 4 months for biplanar closing wedge osteotomy compared to 6 months for uniplanar [55]. Two additional series utilized femoral dome osteotomies for correction of native coronal plane deformity, one of which (n = 16) used external fixation and the other series (n = 12) with a single lateral distal femur locking plate. The first of these series reported good correction and functional outcomes and average union time of 19.4 weeks in 14 patients, with two patients excluded for infection and arthroplasty conversion [63]. The latter series reported full correction with no failures or reoperations and improvement in functional outcome metrics with good patient satisfaction. Average time to union was 13.8 weeks [54].

Though a rare but serious complication, peroneal nerve palsy can be associated with correction of severe valgus deformity especially with significant chronicity of the malunion. A recent cadaveric force transducer study showed significant reduction in rigidity of the peroneal nerve after prophylactic decompression and varus correction with no difference in tension before and after deformity correction [67]. Simultaneous prophylactic peroneal nerve decompression in these select patients with severe chronic valgus deformities should be considered [67, 68].

11.4.3 Sagittal Plane Malunion (Procurvatum/Recurvatum)

Many of the above principles discussed in coronal plane correction (see Sect. 11.4.2) apply similarly to sagittal plane deformities. Determination of the degree of deformity and quantification of the necessary correction must be made preoperatively and can be estimated intraoperatively with the assistance of anterior to posteriorly placed Kirschner wires proximal and distal to the osteotomy site. Preoperative measurement of the anatomic posterior distal femoral angle (aPDFA) can be done on a lateral femur X-ray or CT scan of the entire femur to assess for the degree of sagittal plane deformity. As previously described, the relationship of the sagittal distal femoral joint line to the long axis of the femur should be restored to either a mean normative value of 83° or equal to the contralateral femur aPDFA [25]. Recurvatum is typically the more common presenting deformity secondary to the deforming force caused by the gastrocnemius muscle [27]. Opening or closing wedge osteotomies present similar pros and cons in the sagittal plane as in the coronal plane with accompanying limb lengthening or shortening, respectively, as well as differences in stability. Osteoplasty in the method of Ilizarov can likewise be done, but again may introduce additional risks associated with prolonged external fixation compared to single-stage osteotomy and internal fixation [65, 66].

In a series of 22 distal femur malunions by Rollo et al., which included five patients with procurvatum deformities and 17 patients with recurvatum deformities, osteotomies were performed at the prior malunion site and stabilized with lateral condylar blade plates. Osteotomy sites were augmented with allograft bone struts as well as morselized bone graft and “bone paste” in the opening wedge gap if present. Nine complications were noted to include death (n = 1), deep infection (n = 1), delayed wound healing (n = 3), deep vein thromboembolism (n = 2), and broken hardware (n = 2). Average time to union of the osteotomy was 34.7 weeks with good improvement of functionality following union. However, average persistent leg length discrepancy following deformity correction and union was 3.3 cm [3].

11.4.4 Leg Length Discrepancy

Preoperatively identifying an objective measurement of limb inequality must be done to determine the amount of lengthening required. This can be done with full-length standing radiographs of the lower extremity and either direct measurement with radiopaque ruler, digital templating software, or with blocks under the ipsilateral foot until leveling of the pelvis is observed on X-ray [68]. Symptomatic leg length discrepancies greater than 2 cm requiring lengthening of the malunited femur can be corrected through the process of distraction osteogenesis. This process has been both well described and accepted among the literature, but does require reliable patient compliance. Ilizarov's principles for this method classically involve gradual controlled lengthening through an osteotomy site at a rate of 1 mm per day followed by a consolidation phase [69]. Multiple techniques for distraction osteogenesis have been described in addition to newer Ilizarov style frames alone such as the Taylor spatial frame (Smith and Nephew Inc., Memphis, TN, USA). Lengthening over the nail (LON) technique represents one such method combining external fixation via Ilizarov style frame or monolateral rail frame with an intramedullary nail to guide the bone during distraction osteogenesis [70]. Results for several such series have shown this to be a successful method with less total time in the external fixator, as the intramedullary nail can be locked and external fixator removed during the consolidation and remodeling phases [70, 71]. This method does, however, require additional surgical procedures and relies on the presence or ability to establish a patent medullary canal for nail insertion. Recently, magnet-operated telescopic internal lengthening nails such as the PRECICE nail (NuVasive, San Diego, CA, USA) have gained traction with less required total surgeries, better tolerance, and less minor complications, such as pin site infections commonly associated with external fixation [72, 73]. These devices do require regular motorized lengthening appointments and may not be an ideal option for patients with profound femoral bows given the straight design of the nail. The cost of magnetic lengthening nails (MLN) has also been a concern; however, a recent cost comparison showed no statistical difference between the LON technique (n = 19) and MLN (n = 39). This was largely attributable to fewer overall procedures with the MLN. And notably, the MLN method was found to have a statistically significant shorter time to union (100.2 versus 136.7 days) [74].

11.4.5 Multiplanar Deformity

Many malunions of the distal femur represent a heterogeneous deformity requiring the surgeon to simultaneously address deformities in differing planes with or without limb inequality. Patient considerations merit central attention in multiplanar deformity when determining the appropriate treatment pathway, as prosthetic replacement may be a more reasonable option in the elderly, terminally ill, or those with significant preoperative osteoarthritis. When assessing the deformity for planned correction, identification and quantification of the deformities in each plane can be done manually or, rather, with digital templating software, such as the aforementioned TraumaCad (Brainlab Inc., Westchester, IL, USA). Depending on the degree of deformity, options for treatment of multiplanar malunions consist of osteoplasty with Ilizarov style frame, double oblique osteotomy, biplanar osteotomy, and prosthetic replacement typically involving a distal femoral megaprosthesis.

Circular frame treatment of deformities in the method of Ilizarov affords the opportunity to compress or distract in differing planes and, thus, can allow for multiplanar correction. Corrections can additionally be fine-tuned throughout the treatment process prior to consolidation [75]. However, careful patient selection and counseling of complications is a necessity when engaging into deformity correction via circular frame application. Fixation of rings to the femur requires traversing through the thick muscular envelope which surrounds the bone, resulting in restricted range of motion and inevitable degree of knee stiffness [68]. In addition to this, nearly all patients treated with the Ilizarov style frame will experience wire or pin site infections, plus an additional major complication rate up to 33%, even in experienced surgeons [65]. However, there is an advantage to the variability in ring fixation methods, as they allow for distal fixation in a relatively short segment of bone. If correction must be done in close proximity to the articular surface, extension across the knee joint may be required [76]. The site of osteotomy should be weighed for appropriate capability of correction according to preoperative templating and to allow the most variability of distal options for fixation of the distal ring. Prior to performing the osteotomy, stable fixation of the proximal and distal rings should be performed according to preference with preliminary placement of non-obstructing struts [68, 75]. Osteotomy can then be performed with multiple drills holes completed by an osteotome as described previously. After final construct and spatiotemporal data have been obtained, gradual correction of deformities and/or lengthening at 1 mm/day can then ensue according to vendor software after an initial latency period, usually about 1 week [68]. Weight-bearing as tolerated can typically be allowed immediately after surgery.

Another option for correction of multiplanar deformities is the single-stage double oblique osteotomy, described by Miranda et al. Based on preoperative templating, three total osteotomies are made. These include two oblique osteotomies above and below the deformity to create a wedge of metadiaphyseal bone allowing for medialization and length if needed, followed by a closing wedge osteotomy to correct additional coronal deformity. According to their technique, fixation can be obtained with an angled blade plate, condylar buttress plate, or dynamic condylar plate. In their series of eight distal femur malunions, correction was able to be achieved in all patients to normative values. Average time to union was 4.25 months for the malunion cohort, with one patient requiring an additional bone grafting procedure [39].

The process of decortication and osteotomy for multiplanar correction has also been described for femoral diaphyseal malunions by Middleton et al. In their series of seven patients, they describe careful periosteal flap elevation at the osteotomy site with creation and preservation of attached cortical bone chips, followed by osteotomy and correction of length and deformity. A lateral locking plate was utilized so as to not disrupt the endosteal blood supply, per the authors. Full correction of deformity was achieved in only five out of seven patients, with a staggering time to union of 16.3 months. An average of 1.5 operations per patient were required to achieve union, with one patient having a refractory nonunion at the osteotomy site despite multiple revisions [77].

If parameters allow, some multiplanar deformity may also be simply addressed through a biplanar osteotomy as described by He et al. For simultaneous correction of varus deformity, flexion deformity, and leg length discrepancy, for instance, the authors describe a biplanar medial opening wedge osteotomy with eccentric distraction of the osteotomy gap to open more posteriorly in addition to medially [25].

In the elderly, special considerations must be made regarding function, life expectancy, and time of immobilization. With the exception of Ilizarov style frames, the other described methods of multiplanar malunion correction are typically associated with prolonged periods of immobilization [39]. Acute distal femur fractures in the elderly have been shown to already have poor outcomes with only 18% return to unassisted ambulation and higher perioperative mortality rates when compared to other fragility fractures [78]. With some authors even advocating for primary distal femoral replacement in acute fractures of the elderly [79, 80], substantial consideration should be made for prosthetic replacement in the setting of malunion. Immediate full weight-bearing can be allowed to minimize additional complications related to either immobilization or external fixation. Several series report on megaprosthesis as a viable option for elderly distal femur nonunions, with the majority of surviving patients returning to acceptable functional outcomes and activities of daily living [48–50]. Patient longevity must be carefully weighed with that of the implant; however, as a recent long-term follow-up 144 non-oncologic distal femur replacements revealed an all-cause 10-year revision rate of 27.5% [81].

11.4.6 Intra-articular Malunion

If an intra-articular step-off or loss of reduction is diagnosed early with advanced imaging, correction prior to union is paramount and should be considered with regard to patient age, functional status, and soft tissue conditions. If identification of a healed intra-articular malunion is made prior to the development of premature osteoarthritis, every effort should be made to correct the deformity if possible. Sasidharan et al. and Iwai et al. have described case reports of young patients in their 30s with malunited coronal plane Hoffa fractures treated with osteotomy and cannulated screw fixation at 9 and 6 months post-injury, respectively [82, 83]. Both of these case reports showed reasonable to good short-term outcomes within a year, but long-term and high-quality data are lacking for this salvage operation. Unfortunately, however, the majority of intra-articular malunions may not be discovered until the process of posttraumatic osteoarthritis has already begun. Salvage of articular surface incongruence at this point is difficult given the degeneration of the knee joint, leaving arthroplasty as a reasonable option if age appropriate. Haidukewych et al. presented a series of 17 patients with a mean age of 66 that underwent total knee arthroplasty as a salvage procedure following failed distal femur fracture treatment all of which were nonunions. Three of these patients went on to fail, but they reported an 83% 5-year overall survivorship free of any revision. The authors concluded that total knee arthroplasty does provide reliable pain relief and functional improvement for the majority of the patients in their series, but intraoperative and postoperative complications were common [84]. Lonner et al. reported on a series of ten patients with complex distal femur malunions that underwent simultaneous total knee arthroplasty with distal femur osteotomy and deformity correction. Extra-articular osteotomy sites were fixed with either angled blade plate, retrograde nail, or long press-fit femoral stems. At average follow-up of just under 4 years, no revisions had been performed. Overall function and range of motion had significantly improved from preoperative levels, despite one osteotomy nonunion spanned by a press-fit femoral stem [85].

11.5 Author's Preferred Methods of Treatment

The definitive treatment can often be dictated by the previous fixation implants, surgical approaches used, and any soft tissue considerations along with the patient's expectations and desires. In most cases, treatment requires removal of preexisting hardware either as a staged procedure or simultaneously with the treatment depending on the type of hardware and method of treatment, either of which is acceptable. Our preferred technique is to remove preexisting hardware as a first stage, followed by a second stage for definitive treatment. The interval can allow for further evaluation as well as to ensure that no underlying subclinical infection is present.

1. *Asymptomatic Malunions*

Unless degree of deformity is concerning for malorientation of the knee joint and development of premature osteoarthritis is likely, no treatment is necessary with follow-up X-rays and clinical exam in 6–12 months to evaluate for joint stability/congruence.

2. *Rotational*

Derotational supracondylar osteotomy is made with drill holes and osteotome, K-wires proximal and distal to osteotomy site to evaluate for degrees of correction, with fixation utilizing static retrograde intramedullary nail, irrespective of the type of preexisting hardware. Previous plate fixation requires complete removal. Previous nail fixation can possibly be retained with osteotomy, removal of the proximal locking screws, followed by correction and proximal relocking. In some cases, previously well-fit nails may require complete removal to obtain the rotational correction.

3. *Coronal Plane*

Open exposure lateral closing wedge osteotomy for varus deformity without the presence of additional limb length inequality. Medial opening wedge osteotomy for varus deformity with limb length inequality <3.0 cm. For valgus deformity, lateral opening wedge or medial closing wedge depending on respective concomitant limb length inequality. Fixation typically with intramedullary nail (if plausible route) or lateral distal femur locking plate, contoured to accommodate for corrected deformity.

4. *Sagittal Plane*

For recurvatum deformities (most common), lateral approach with anterior opening wedge osteotomy versus posterior closing wedge osteotomy, decision based on bone quality, healing potential, and concomitant limb length inequality. For procurvatum deformity, anterior closing wedge osteotomy versus posterior opening wedge osteotomy. Fixation typically with intramedullary nail (if plausible route) or lateral distal femur locking plate.

5. *Leg Length Discrepancy*

Distraction osteogenesis is a reliable process to gradually correct leg length malunions. Patient disposition, competency, compliance, and understanding of options for various treatment methods for distraction osteogenesis are critical. Magnetic lengthening nail is preferred if the indications and anatomy allow, otherwise lengthening via Ilizarov style frame. Osteotomy site is typically at the metadiaphyseal junction via drill holes and osteotomy.

6. *Multiplanar Deformity*

Biplanar osteotomy in the case of "simple" multiplanar deformity; otherwise, osteoplasty in the method of Ilizarov with Taylor spatial frame (Smith and Nephew Inc., Memphis, TN, USA) and gradual correction.

7. *Prosthetic Replacement*

All elderly patients with symptomatic malunions merit consideration for prosthetic replacement unless immediate weight-bearing will be allowed. In patients with poor bone quality, limited life-expectancy, and/or presence of advanced post-traumatic osteoarthritis, arthroplasty is also the preferred option. If deformity permits correction with bone cut adjustments or simple augmentation(s), primary or revision total knee arthroplasty components can be utilized, otherwise megaprosthesis with distal femoral replacement if necessary.

8. *Intra-articular Malunion*

In the rare case of a patient with early malunion prior to development of post-traumatic osteoarthritis, salvage osteotomy and cannulated screw fixation +/− bone graft is a reasonable attempt to delay premature osteoarthritis and need for early arthroplasty. In older patients, and those with existing or worsening signs of post-traumatic osteoarthritis or worsening preexisting osteoarthritis, total knee arthroplasty is preferred.

11.6 Case Discussions

11.6.1 Case 1

The patient is a 56-year-old male restrained driver status post high-speed motor vehicle collision in 2016. The patient sustained a left distal femur fracture with metadiaphyseal comminution and intercondylar extension, AO type C2, as well as an ipsilateral basicervical proximal femur fracture, AO type A1 (Fig. 11.2). Initial workup revealed a history of coronary artery diseases status post bypass, hypertension, and a current one pack per day smoking history. The day after presentation, the patient underwent fixation distally with three percutaneous 7.3 mm partially threaded cannulated screws across the intercondylar fracture line followed by long antegrade cephalomedullary locked nail (Fig. 11.3). He was

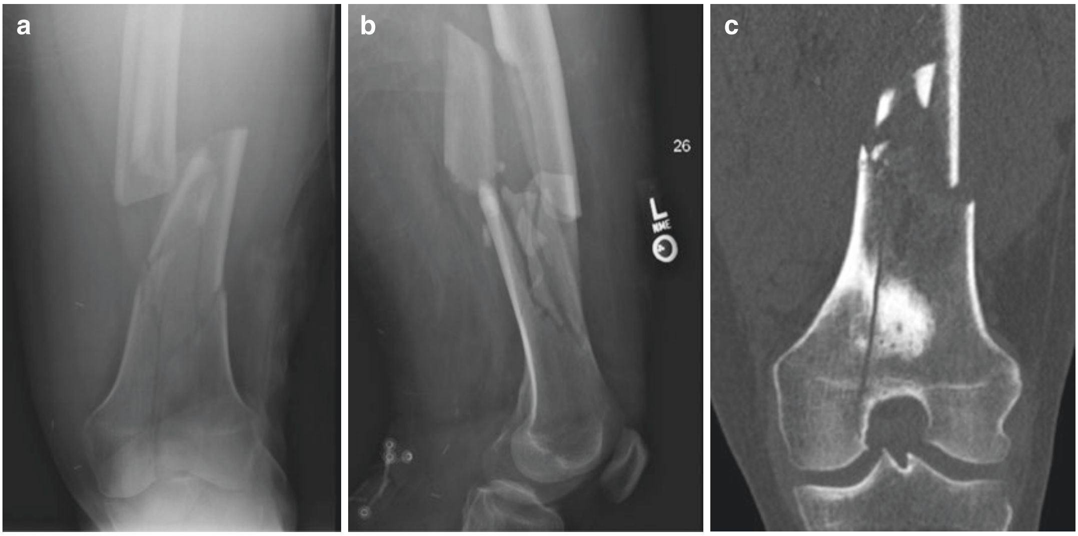

Fig. 11.2 (**a**) Anteroposterior and (**b**) lateral injury radiographs and (**c**) coronal CT slice of the left distal femur showing metadiaphyseal comminution with intercondylar extension, AO type C2

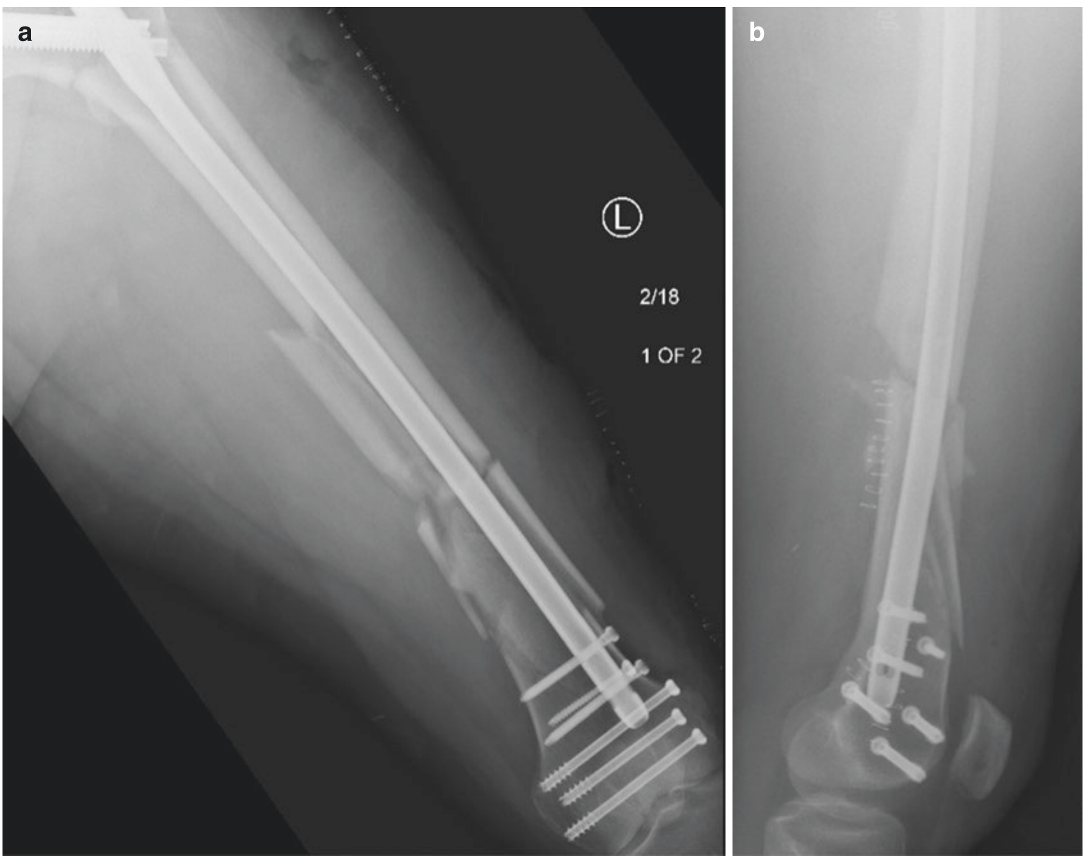

Fig. 11.3 (**a**) Anteroposterior and (**b**) lateral immediate postoperative radiographs of the left femur

discharged to inpatient rehabilitation on post-op day 3, but readmitted and taken back to the OR at 2 weeks post-op for persistent drainage from the proximal hip incision with methicillin-sensitive *Staphylococcus aureus*-positive cultures. Appropriate intravenous antibiotics were tailored to cultures and he underwent two additional washouts over the next several weeks before eventually clearing the infection. X-rays at his 3-month postoperative visit began to show signs of medial translation and several degrees of varus collapse of the comminuted metadiaphyseal component of the distal femur fracture with backing out of several of the distal interlock screws (Fig. 11.4). The patient was then subsequently taken back to the operating room where fracture mobility allowed for valgus stress to re-establish the mechanical axis of the extremity through the fracture site. Several distal intercondylar screws were exchanged, and a blocking screw was utilized laterally to confine the distal tip of the nail while the distal interlock screws were replaced (Fig. 11.5). Postoperatively, he was kept non-weight-bearing for a period of 10 weeks. Union of three out of four cortices was achieved 8 months after revision, but the varus deformity had recurred and a nonunion of the proximal femur persisted. Malunion evaluation with X-ray

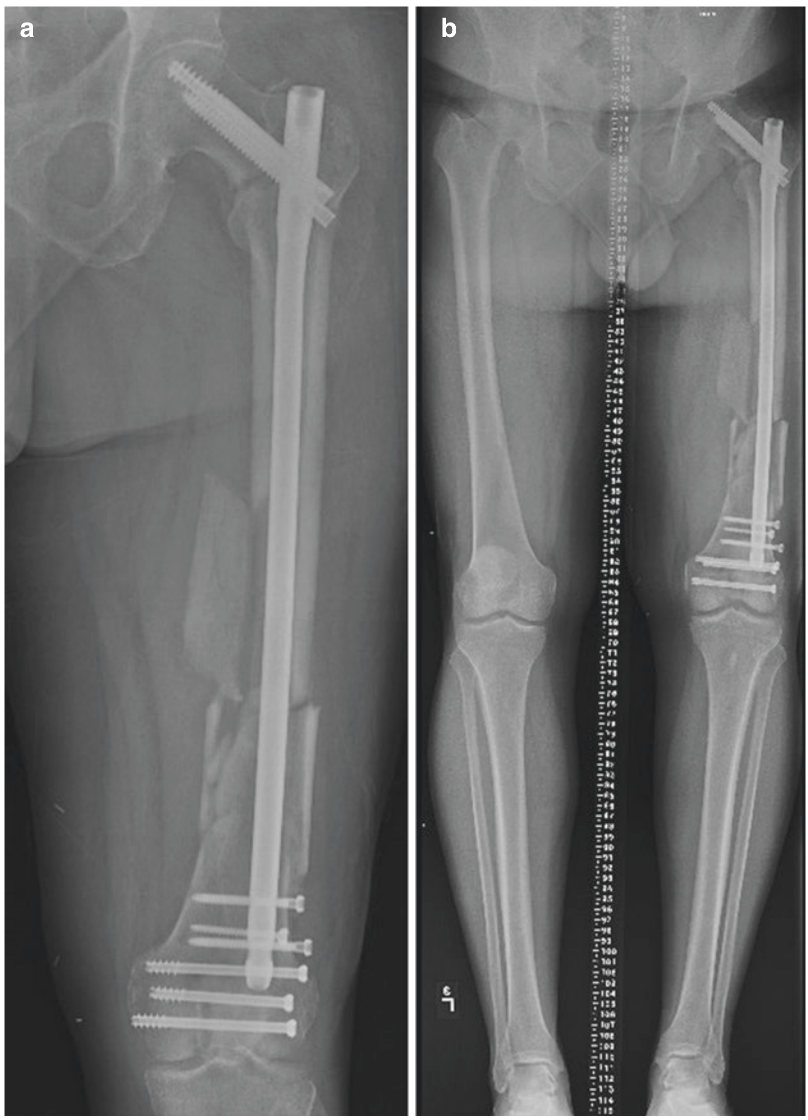

Fig. 11.4 Three-month postoperative (**a**) anteroposterior femur radiograph and (**b**) X-ray scanogram demonstrating varus collapse and distal interlock screws backing out

Fig. 11.5 Immediate (**a**) anteroposterior and (**b**) lateral distal femur postoperative radiographs after valgus manipulation and distal screw exchange

scanogram (see images 8/22/18) showed mechanical axis deviation (MAD) of 30 mm, varus deformity of 6°, mLPFA 94°, and mLDFA 93° (Fig. 11.6). Preoperative templating utilizing TraumaCad (Brainlab Inc., Westchester, IL, USA) software calculated a planned 7 mm medial opening wedge osteotomy.

The patient underwent malunion correction with medial opening wedge osteotomy at the previous fracture site according to preoperative templating. Multiple drill holes were utilized at the osteotomy site, completed with a straight osteotome. Compression of the lateral cortex was achieved with drill holes on either side of the osteotomy and pointed reduction forceps. Local biologic augmentation was provided at the osteotomy site with a bone void filler. A second lateral distal femur blocking screw was then placed. Open reduction and bone grafting of the proximal femur nonunion were simultaneously performed, and a long revision cephalomedullary nail was placed bypassing the osteotomy site. Distal interlock screws were placed distal to the osteotomy site (Fig. 11.7).

The patient did well postoperatively. He achieved solid union of the distal femur osteotomy at 6 months postoperative from final revision and was ambulating without assistive devices. He reported he was able to return to 300-pound leg press weightlifting following union at last follow-up 18 months postoperative from last deformity correction (Fig. 11.8).

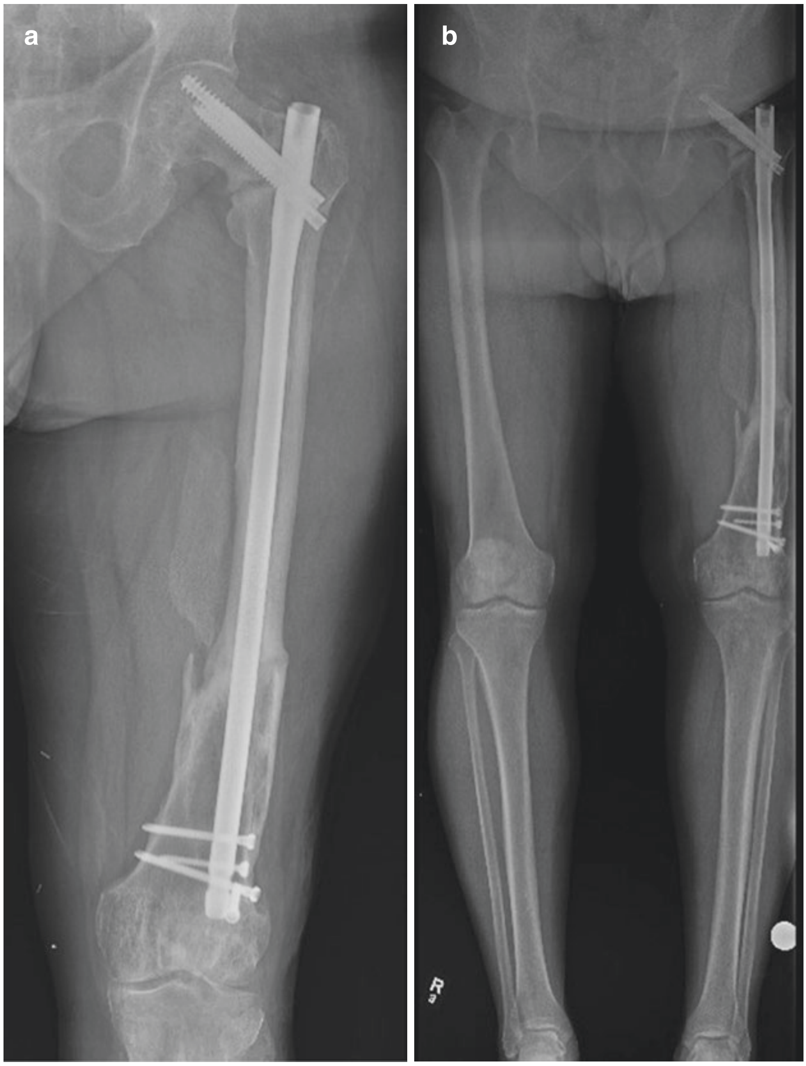

Fig. 11.6 (**a**) Anteroposterior and (**b**) X-ray scanogram following union of the distal femur showing varus malunion

11.6.2 Case 2

The patient is an 18-year-old otherwise healthy male referred to our clinic following treatment of a pediatric right distal femur fracture at the age of 12. He reportedly sustained a Salter-Harris type 3 fracture of the lateral distal femur epiphysis that was treated by an outside provider with open reduction internal fixation via distal femur partially threaded screws, followed by subsequent hardware removal. He went on to develop a gross valgus deformity with internal rotation of the distal femur and a leg length discrepancy of 3 cm (Fig. 11.9). He reported difficulty with strenuous activities as well as a visible deformity. After discussion of the options, the patient elected to proceed with Ilizarov style frame and osteoplasty for simultaneous correction of leg length discrepancy and valgus deformity. Preoperative templating utilizing TraumaCad (Brainlab Inc., Westchester, IL, USA) revealed mLDFA of 73 and planned lengthening of 2 cm with 12.8° correction.

The patient underwent Taylor spatial frame (Smith and Nephew Inc., Memphis, TN, USA) application utilizing hybrid fixation of 6 mm hydroxyapatite-coated pins and Ilizarov tensioned wires. A metadiaphyseal osteotomy site

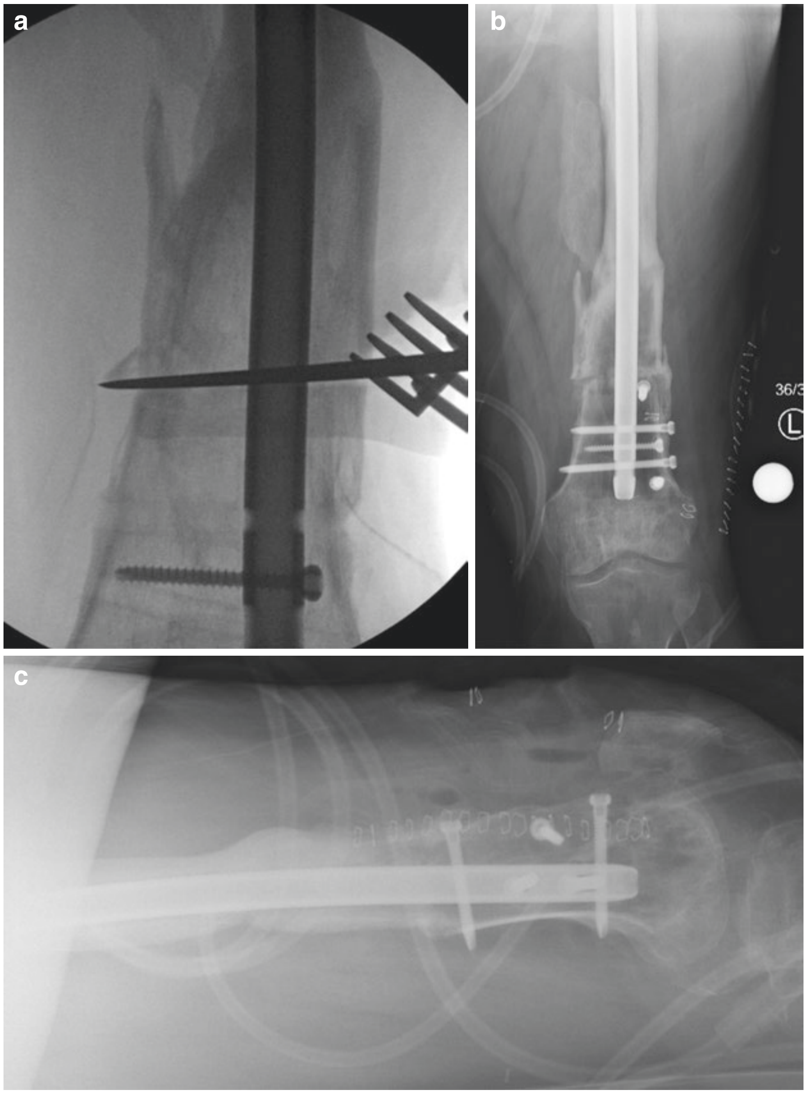

Fig. 11.7 (**a**) Intraoperative fluoroscopic view of completion of metadiaphyseal osteotomy with osteotome and immediate postoperative (**b**) anteroposterior and (**c**) lateral distal femur radiographs following deformity correction

was chosen and carried out with drill holes, completed with osteotome (Fig. 11.10). Gradual distraction and osteoplasty was performed over the following 50 days (Fig. 11.11), with consolidation phase of 100 days after completion of correction (Fig. 11.12). He did experience proximal pin site infections toward the end of the consolidation phase that were treated with oral antibiotics without issue. His frame was removed at 5 months postoperative. Continued weight-bearing with crutches was allowed following removal.

The patient was doing well at his follow-up 6 months after initial frame application, after which he was unfortunately lost to follow-up (Fig. 11.13). He had returned to normal activities and reported feelings of symmetry. He was ambulating without pain and without assistive devices, though he did have ipsilateral knee stiffness and range of motion 0–80° at last follow-up.

11.6.3 Case 3

The patient is a 66-year-old female with well-controlled type 2 diabetes mellitus who is status post primary left total knee arthroplasty by an

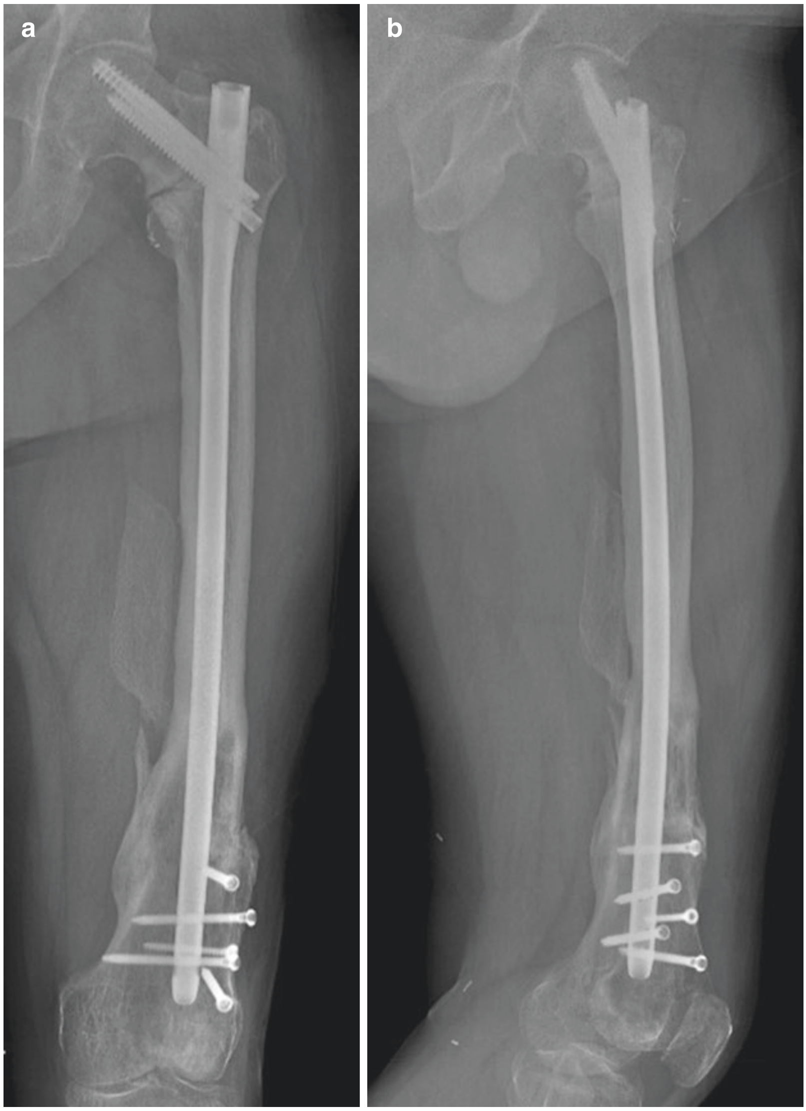

Fig. 11.8 (**a**) Anteroposterior and (**b**) lateral radiographs of the left femur at 18 months postoperative from deformity correction

outside provider 2 years prior to presentation. Three months after surgery, the patient's postoperative course was complicated by a fall and subsequent periprosthetic distal femur fracture treated with open reduction internal fixation utilizing a lateral distal femur locking plate. She reported gross varus deformity several months after fracture fixation and continued pain in the knee. She was referred to our clinic 21 months after fixation with imaging consistent with collapsed malunion in 16° of varus (Fig. 11.14). There was no history of wound healing difficulties, antibiotic use, or additional procedures related to the incisions. Preoperative lab work revealed normal inflammatory markers (CBC, ESR, CRP) and hemoglobin A1C < 7.

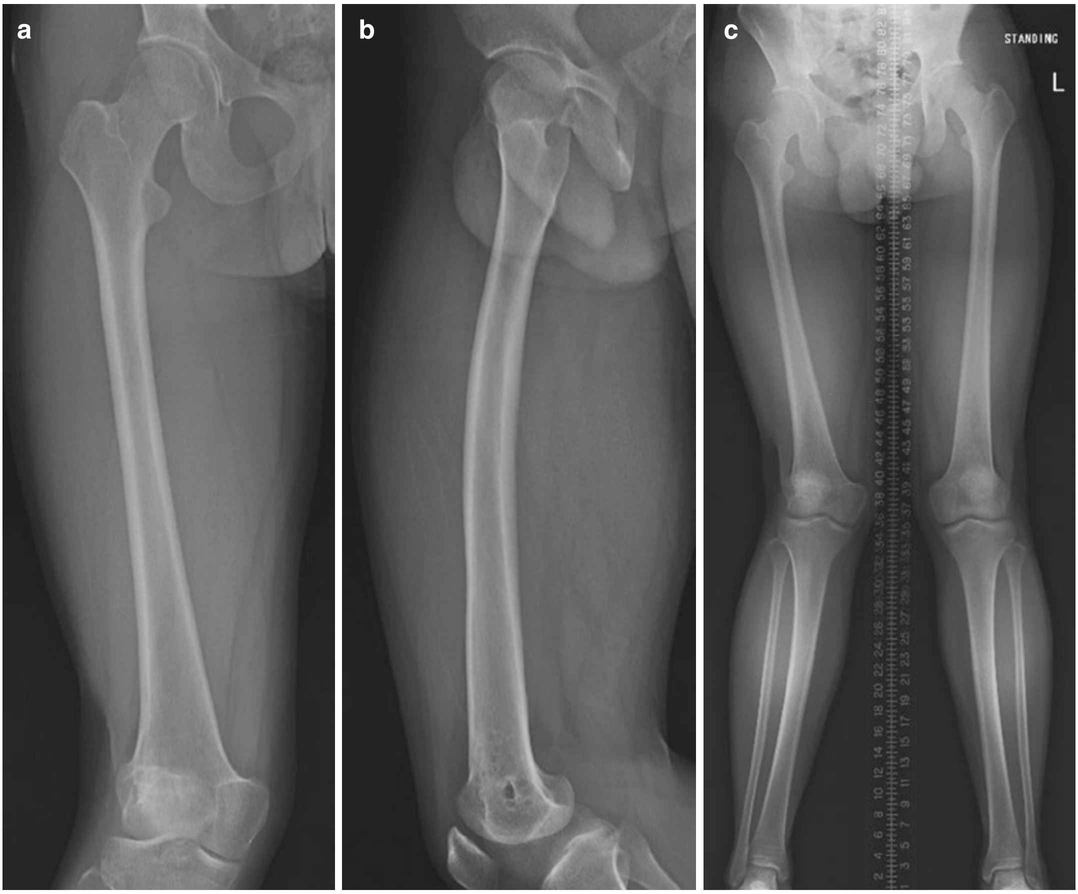

Fig. 11.9 (**a**) Anteroposterior and (**b**) lateral radiographs of the right femur and (**c**) X-ray scanogram at time of consultation showing valgus deformity of the right femur and leg length discrepancy

Following appropriate workup and clearance, she underwent cemented distal femoral replacement with removal of the lateral distal femoral plate/screws and osteotomy above the site of the malunion (Fig. 11.15). Immediate weight-bearing and rehabilitation was allowed. She did well in the early postoperative phase, but unfortunately sustained a fall with therapy 6 weeks postoperatively and was found to have a patellar tendon avulsion off the tibial tubercle and dislocation of the tibial post (Fig. 11.16). Subsequent open reduction of the prosthesis was performed with heavy #5 Ethibond (Johnson & Johnson, New Brunswick, NJ, USA) suture repair of the patellar tendon avulsion. Immediate weight-bearing was again allowed with hinged knee brace locked in extension. Three months following repair, she was found to have recurrent patella alta on radiographs and continued discontinuity of her extensor mechanism on exam. The patient desired no further surgeries and at 6 months postoperatively was ambulating in an extension brace with a rolling walker without significant pain (Fig. 11.17).

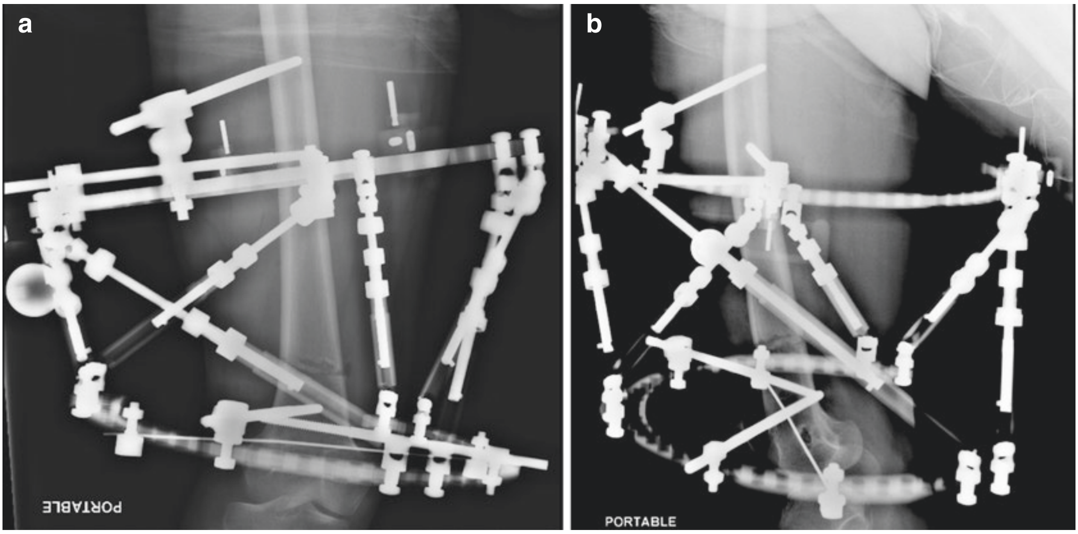

Fig. 11.10 Immediate postoperative (**a**) anteroposterior and (**b**) lateral radiographs of the right distal femur after osteotomy and spatial frame application

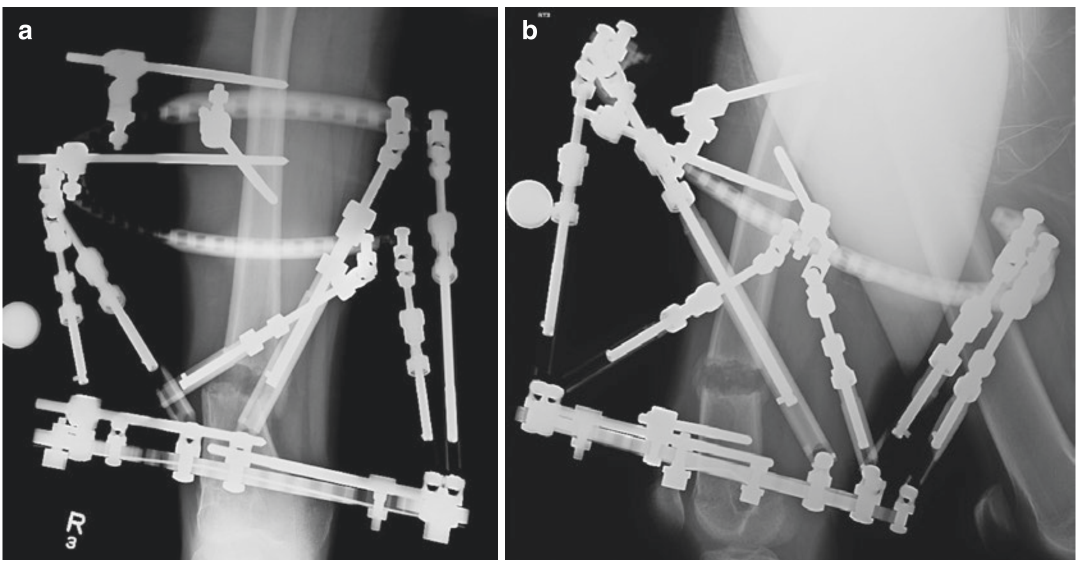

Fig. 11.11 (**a**) Anteroposterior and (**b**) lateral radiographs of the right distal femur at end of correction phase, 50 days postoperative

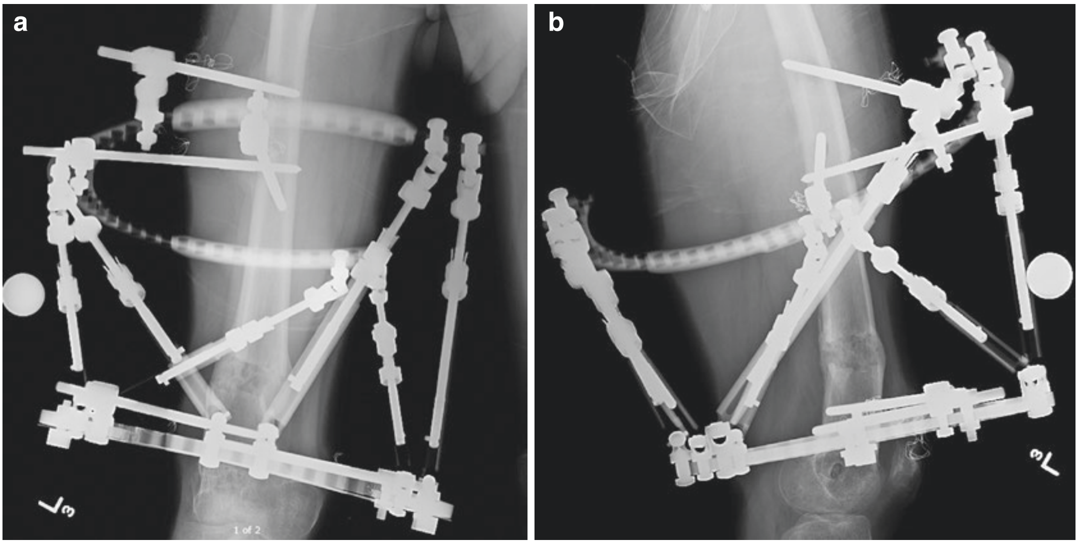

Fig. 11.12 (**a**) Anteroposterior and (**b**) lateral radiographs of the right distal femur at end of consolidation phase, 5 months postoperative

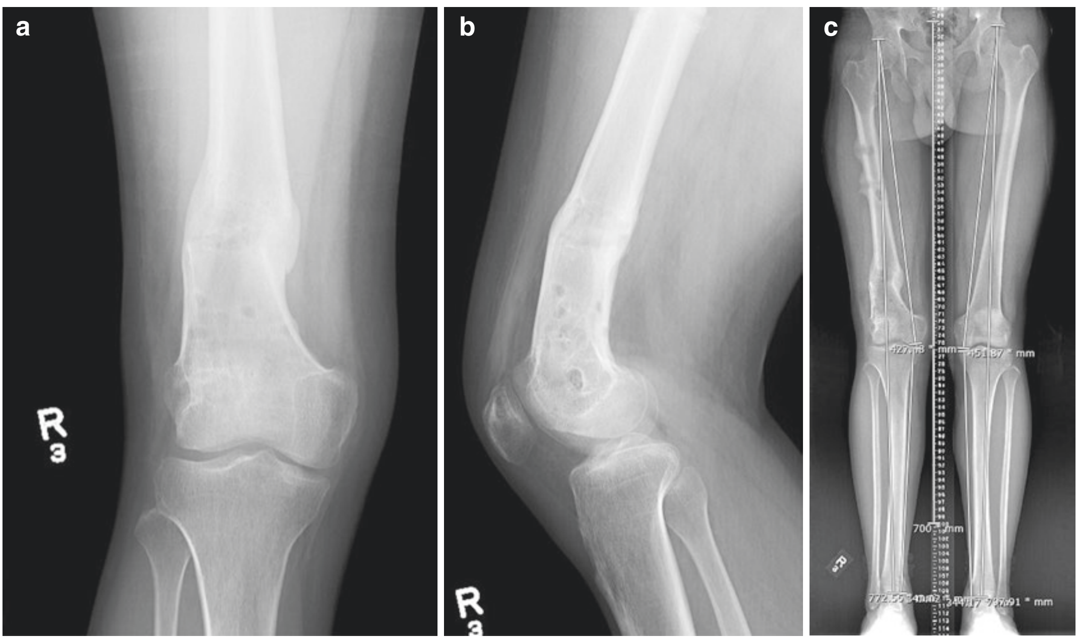

Fig. 11.13 (**a**) Anteroposterior and (**b**) lateral radiographs of the right distal femur and (**c**) X-ray scanogram at final follow-up, 6 months postoperative

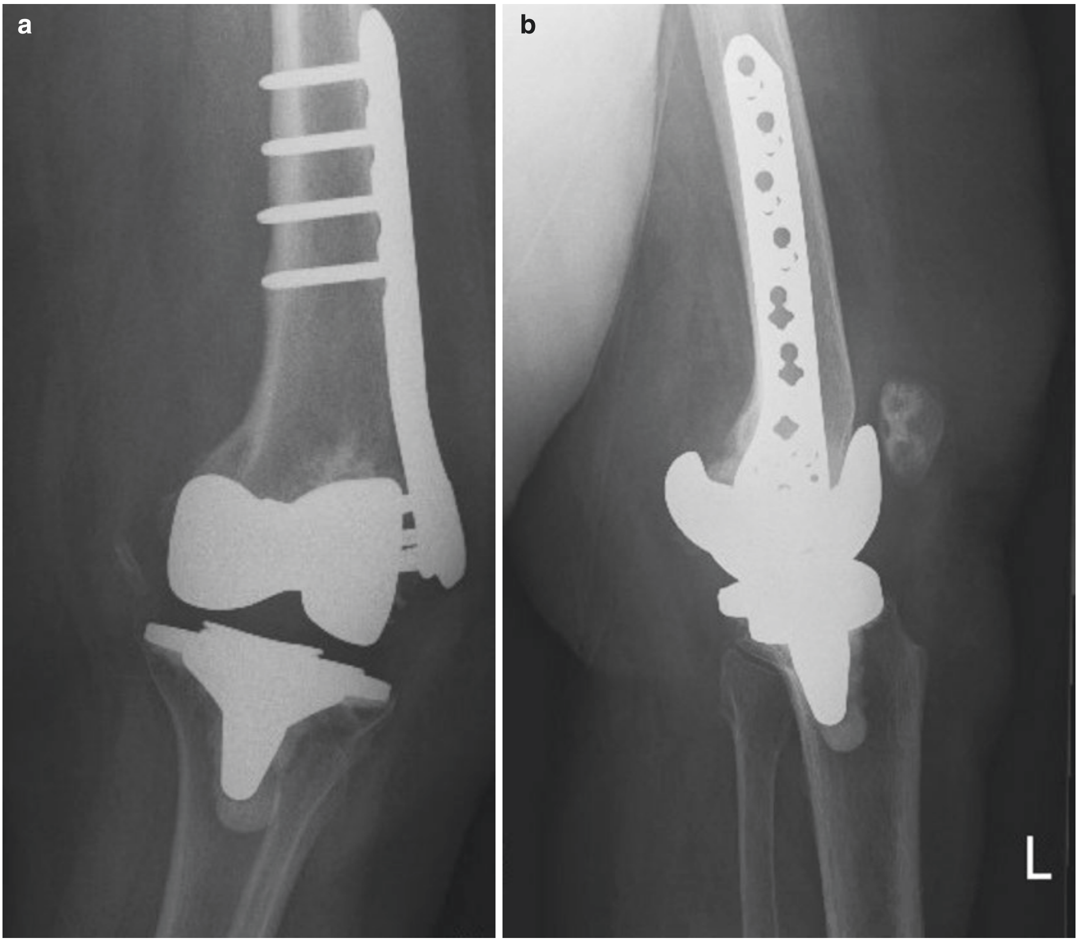

Fig. 11.14 (**a**) Anteroposterior and (**b**) lateral radiographs of the left knee at time of consultation demonstrating varus periprosthetic malunion

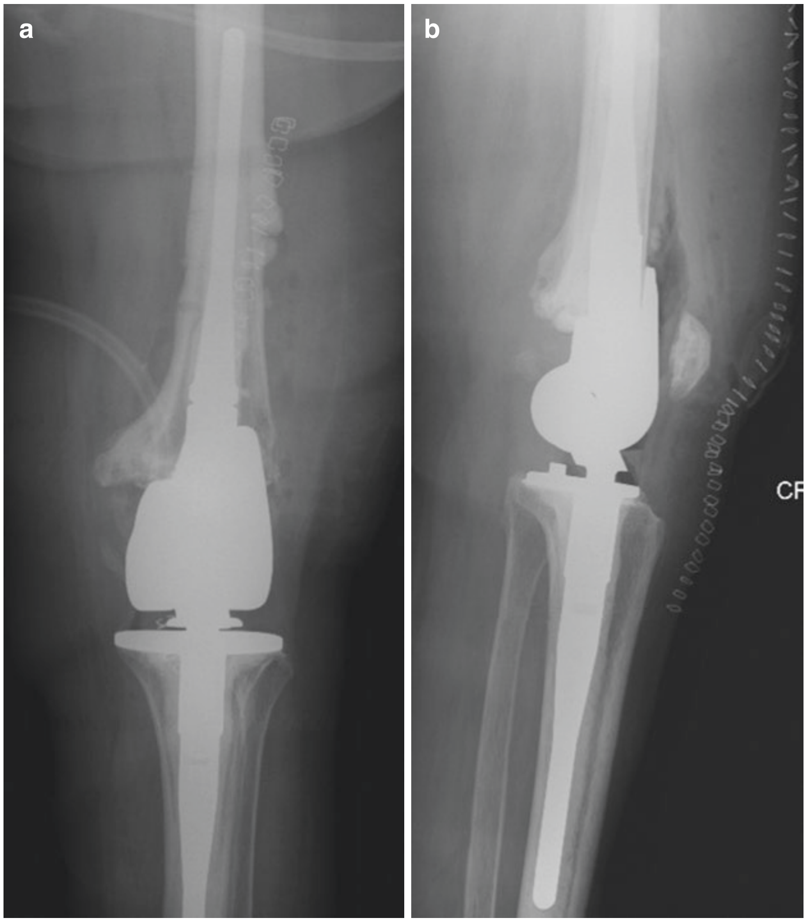

Fig. 11.15 (**a**) Anteroposterior and (**b**) lateral radiographs of the left knee immediately postoperative following left distal femur replacement with resection of malunion

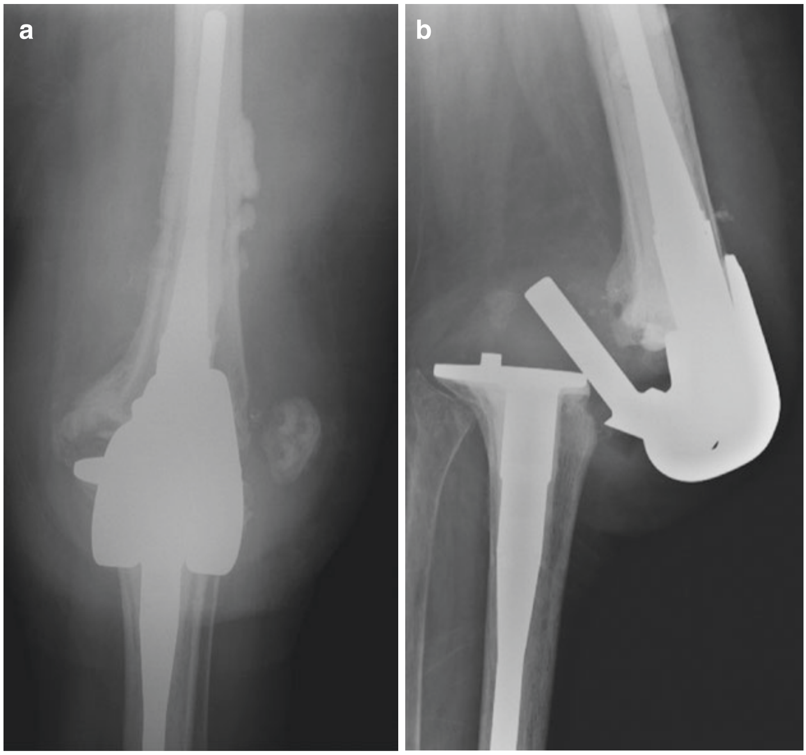

Fig. 11.16 (**a**) Anteroposterior and (**b**) lateral radiographs of the left knee 6 weeks postoperative after fall with dislocation of the tibial post and patellar tendon avulsion

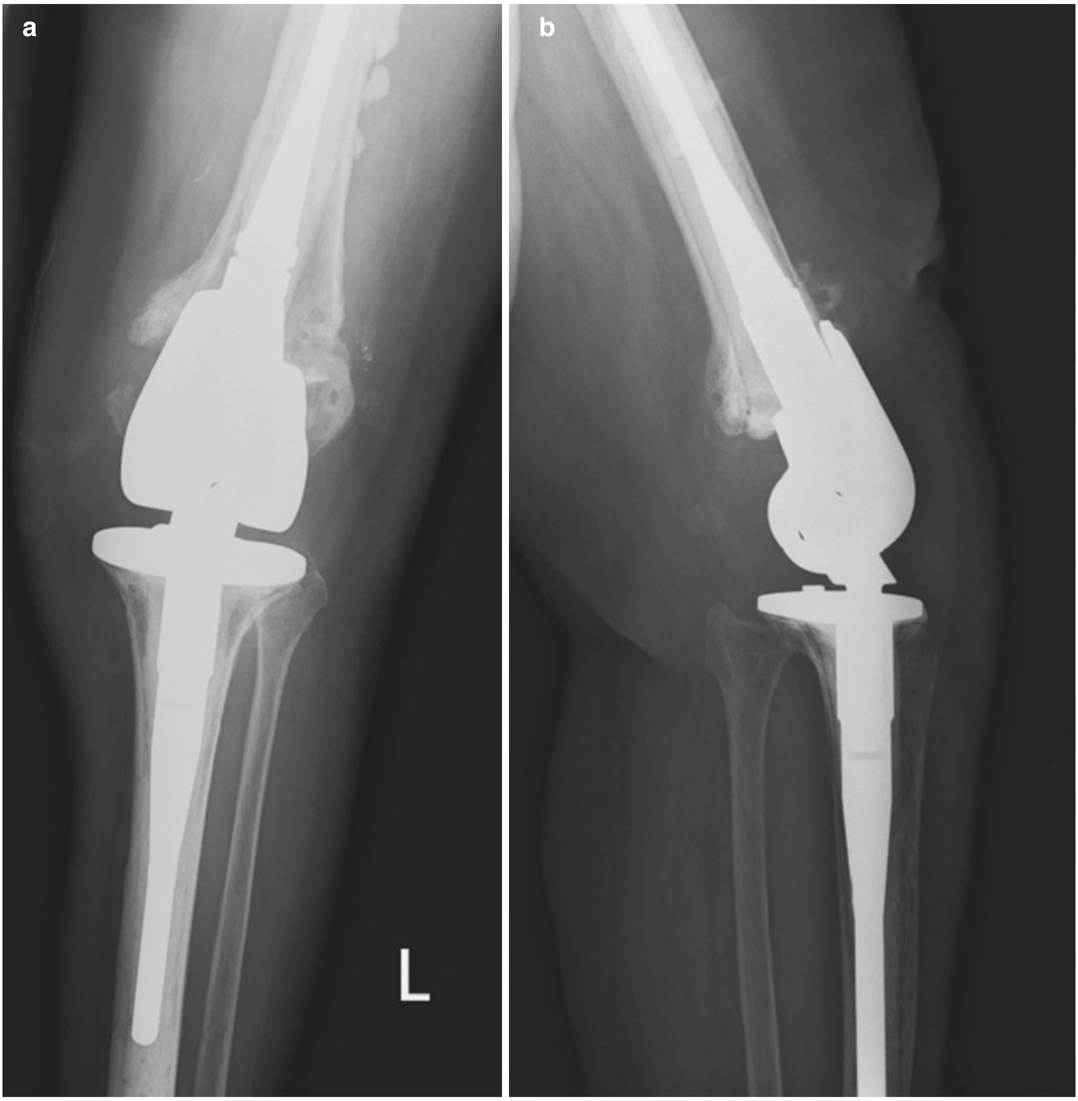

Fig. 11.17 (**a**) Anteroposterior and (**b**) lateral radiographs of the left knee at last follow-up, 6 months postoperative

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12 Malunions of the Proximal Tibia and Tibial Plateau

Animesh Agarwal

12.1 Introduction to Proximal Tibia Fractures and Malunions

12.1.1 Proximal Tibia Fractures

Proximal tibia fractures account for approximately 1–2% of all fractures with a bimodal distribution [1]. These fractures are in the proximal metaphyseal region of the tibia but can extend into the joint. They can be entirely extra-articular or extend into the knee joint where they involve the tibial plateau. Proximal tibial extra-articular fractures account for 5–11% of all tibia fractures [2].The Schatzker classification is often used to describe the various tibial plateau fractures. The AO classification can also be used to distinguish between the extra-articular types (AO Type A), partial articular types (AO Type B), and those that are the true intra-articular types (AO Type C). The AO Type B and C fractures overlap with those described by Schatzker. Schatzker types 1–3 involve only the lateral tibial plateau and are considered partial articular types, with type 1 being a nondisplaced split, type 2 a split depression fracture, and type 3 pure depression. Schatzker type 4 involves the medial tibial plateau only and usually is considered a fracture-dislocation equivalent, and thus one should have high suspicion for associated neurovascular injuries. Bicondylar tibial plateau fractures, Schatzker V and VI, are also high-energy injuries, but they involve both the medial and lateral joint surfaces with metadiaphyseal extension in type 6. These bicondylar fractures account for anywhere from 18% to 39% of all tibial plateau fractures [3].

These fractures can be highly problematic due to the small size of the proximal fragment(s) that can occur especially in the highly comminuted fractures [4]. The amount of "real estate" available for fixation may both guide and limit the treatment options available. Although nonoperative management can still be an option, it is usually reserved for completely nondisplaced injuries or those with significant comorbidities precluding surgical intervention. Majority of displaced fractures and those with intra-articular involvement certainly will benefit from anatomic reduction with rigid stabilization of the joint and realignment of the mechanical axis of the tibia and lower extremity. When these fractures go on to a malunion and affect the mechanical axis of the limb, corrective osteotomies may be required [5]. The goal of treatment of these fractures is to restore the anatomical articular surface, restore the condylar width, realign the mechanical axis, create a stable joint, and repair any soft tissue injuries [6].

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Due to the difficulty in the management of these fractures, malunions can develop. The extra-articular proximal tibia fractures can develop into isolated varus malunions (most common), valgus malunions, or sagittal plane deformities. If the original injury is a partial articular fracture, failure to either obtain or maintain the reduction of the joint can result in an intra-articular malunion. In the Schatzker V or VI injuries, either one or both intra-articular and extra-articular malunions could develop. It is important to properly diagnose the location of the malunion as well as causes that led to the development.

12.1.2 Incidence of Malunions

A malunion of the proximal tibia can occur after a fracture and, just like fractures, can be classified similarly: extra-articular, intra-articular or both. The cause is often multifactorial [7]. A more complete classification was described by Krettek et al., which was based on location (medial, lateral, combined, intra-articular, extra-articular or both, condylar or intra-condylar), geometry, progression, and severity [8]. The normal alignment of the proximal tibia is usually described in terms of the medial proximal tibia angle (MPTA) and is usually 87° ± 3° as well as the posterior proximal tibia angle (PPTA) on the lateral view which is 80° ± 3° (Fig. 12.1). The other relevant angle to assess is the lateral distal femoral angle (LDFA) which is usually 88° ± 3°. For the tibia, the anatomic and mechanical axes are identical. A malunion can occur in the coronal plane and sagittal plane and can be multiplanar, rotational, axial, or a combination of any of the above. In general, any deviation from the normal alignment parameters would be considered a malunion although strict parameters for a malunion vary in the literature without consensus [9]. Johner and Wruhs reported on a series of tibial shaft fractures and provided a classification scheme and looked at functional results classifying them as poor to excellent depending on a variety of outcomes. Based on this classification scheme, varus/valgus malunion of >10°, sagittal plane malunion of >20°, rotational malunion of >20°, and shortening of >20 mm were all classified as a poor outcome [10]. Additionally, a step-off in the joint of at least more than 2 mm has been considered an intra-articular malunion, although the amount acceptable has been debated. Therefore, common guidelines for surgical intervention are varus at the knee greater than 10°,

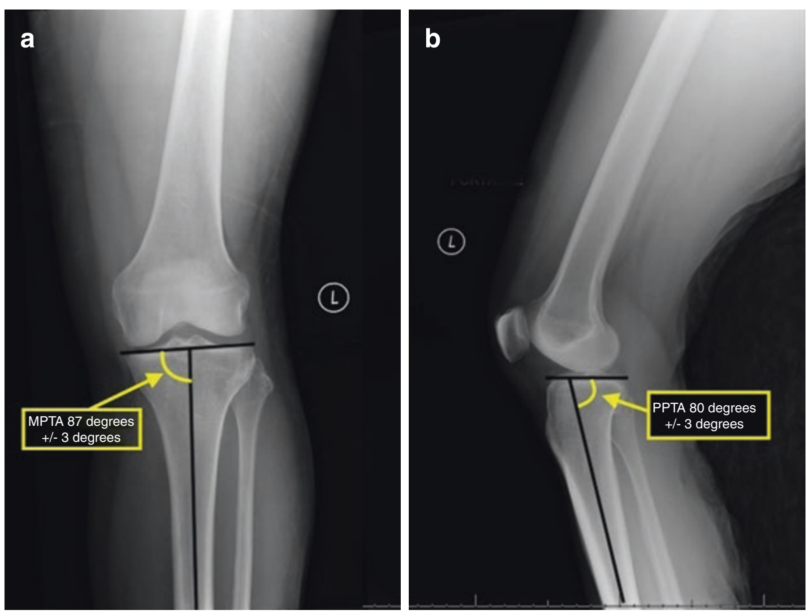


Fig. 12.1 (**a**, **b**) AP and lateral radiograph of a normal left knee showing the average MPTA and PPTA

valgus malalignment at the knee greater than 15°, greater than 2 cm leg length discrepancy (LLD), or rotational malalignment of greater than 10° [11, 12]. The incidence of malunion in the proximal tibia after surgical treatment has been reported to be anywhere from 0% to 79% with the latter being in the elderly population over the age of 60 [2, 7, 9, 13–16]. Malunion can occur in the form of angular deformities, intra-articular malalignment, limb length discrepancies, or rotational malalignment.

In a large series of all types of tibial plateau fractures, Rademakers et al. had a 4% incidence of malunions out of 209 patients. The unicondylar fractures had better functional results than bicondylar fractures [13]. Barei et al. reported their complications in high-energy bicondylar tibial plateau fractures utilizing dual incisions. They had a 9% incidence of coronal malalignment, 28% incidence of sagittal malalignment, and only 62% satisfactory articular reductions [17]. Ruffolo et al. reported only 1 varus malunion out of 140 bicondylar tibial plateau fractures treated with dual plating through two incisions [18]. The finding of sagittal plane deformity was found to be even more prominent in a study by Streubel et al., where they evaluated 74 patients with bicondylar tibial plateau fractures [14]. They found that 56% of the lateral tibial plateaus were angulated more than 5° from the normal anatomic slope with the majority angulated posteriorly. The medial side showed similar findings with 58% angulated more than 5° from the normal but with less posterior inclination than the lateral side. Long-term outcome of the effect of this was not studied. In their series of 140 patients with bicondylar tibial plateau fractures, Weaver et al. reported a 15% incidence of malreductions and highlighted the advantage of dual plating over single lateral locked plating in certain bicondylar fractures [15]. Over time, 54% of the fractures had a change in their alignment with 44% having varus malunion up to 13° and 11% developing valgus malunion up to 4.5°.

Proximal tibia fractures treated with intramedullary nails historically have had high rates of malalignment ranging anywhere from 8% to 84% [4, 19–21]. The typical deformity is that of valgus and procurvatum, which results from the increased tension on the extensor mechanism while in flexion during nailing as well as muscle imbalance [4, 22]. Newer nailing systems and techniques have alleviated this issue (see Sect. 12.2.3). Due to the malalignment issues with IM nailing, locking plates became a commonplace implant for the treatment of these extra-articular proximal tibia fractures. The Less Invasive Stabilization System (LISS) ™ was widely used for the management of such fractures [14, 23, 24]. The system was designed to be placed in a minimally invasive fashion and only provided lateral column support, but was a fixed angle construct. Stannard et al. reported their results in 39 fractures and had no loss of alignment in long-term follow-up. They did report two patients with a malunion (5%). They felt that the LISS had significant advantages over traditional plates [24]. Cole et al. reported their series of 77 proximal tibia fractures treated with the LISS and had a malunion incidence of 10.4%. The majority were sagittal plane deformities [14]. Ricci et al. reported a 17.9% incidence of malunion in their series of 28 consecutive patients treated with the LISS for comminuted fractures of the proximal tibia metaphysis. They also did not have long-term varus collapse despite the lack of a medial plate [23].

In a study by Buckley et al., there was a 50% incidence of malrotation of proximal tibia fractures treated with a minimally invasive percutaneous osteosynthesis technique [12]. They defined malrotation as a side-to-side difference of >10°. The mean difference in their study was 16.2° but was not found to be statistically significant. Naik et al. treated 49 proximal tibia fractures with percutaneous locked plating and found a malunion incidence of 20%. They also had two rotational malunions and leg length discrepancy of 1 cm in two patients due to the comminution [2]. Malrotation is even commonplace in tibial shaft fracture management with intramedullary nails [25]. Thieriault et al. showed a 41% incidence of rotational malalignment of >10° when using CT scanning of the bilateral lower extremities [26]. Most recently, Cain et al. found a 36% incidence of rotational malalignment in following

IM nailing of tibial shaft fractures [27]. Puloski et al. reported on a small series of patients, using postoperative CT scans, and found a much higher than expected rate of malalignment after intramedullary nailing. The rotational malreduction occurred anywhere from 15° of internal rotation up to 22° of external rotation. There was a 22% incidence of malrotation greater than 10° [28].

12.1.3 Ramifications of Proximal Tibia Malunions

Proximal tibia malunions can have detrimental effects to the patient's function. Cosmesis is usually a secondary issue if at all and should not necessarily be the sole reason for treatment of a malunion. Any malalignment of the lower extremity can result in mechanical axis deviation with resultant post-traumatic arthritis due to overload of the joint from abnormal stresses. The normal mechanical axis of the lower extremity runs through the knee joint about 1 cm medial from the center. Excessive varus or valgus malalignment of the proximal tibia results in mechanical axis deviation either medially or laterally, respectively, with resultant abnormal forces on the joint predisposing the patient to PTOA [29, 30]. Palmer et al. recently published a longitudinal cohort study looking at 1329 knees in 955 individuals. They found that the MPTA was significantly associated with structural progression of arthritis. For every one degree more of varus in the MPTA, there was 21% increase in the odds ratio of joint space narrowing progression in the medial compartment [29]. Even rotational malalignment has been shown to lead to the earlier development of PTOA most likely from abnormal shear forces on the cartilage [12, 31–33].

Numerous animal studies have shown that malalignment can lead to PTOA. Reimann created a 30-degree valgus osteotomy in the proximal tibia of adult rabbits. Subsequently, these animals all developed degenerative changes in the knee joint and concluded that altering the mechanical axis can alter the load bearing resulting in the development of arthrosis [34]. Wu et al. performed a similar procedure on adult rabbits but created either a 30-degree valgus or varus osteotomy of the proximal tibia. In addition to the degenerative changes in the cartilage, they also found an increased thickness of the subchondral bone and a decrease in the trabecular porosity [35]. The alteration in the mechanical axis leads to increased contact pressures in the knee joint, with the greatest effect being on the joint closest to the deformity, e.g., proximal tibia malunion causing biggest pressure change in the knee [36, 37]. The altered loading results in high shear in the cartilage surface with subsequent splitting and degeneration of the cartilage [38].

Clinical studies have shown similar findings of an increased risk of PTOA with malalignment, but the data has been controversial. Van der Schoot et al. followed 88 patients with a fracture of the tibia for an average of 15 years. Although these were tibial shaft fractures, they found a 49% incidence of a deformity of 5° or more, and these malaligned joints had significantly more degenerative changes than the uninjured side [33]. Milner et al. also found a trend toward more arthritis in the medial tibial plateau of many tibial shaft fracture patients; they felt that the true cause was multifactorial [32]. Kettelkamp et al. followed 14 patients over an average of 31.7 years that had degenerative arthritis with a history of either a tibial or femoral fracture. Using a mathematical static force analysis, they found an increased force on the medial or lateral tibial plateau due to either varus or valgus deformities at the knee, respectively [31]. They felt the degenerative arthritis that these patients developed was from these increased forces on the joint. It is also well established that increased varus inclination of the articular surface of the proximal tibia leads to osteoarthritis [39–42].

Despite malalignment affecting the mechanical axis of the limb, intra-articular malunions can be of issue when the joint is involved. Malreduction of the joint in articular fractures has been shown to result in PTOA [17, 43–45]. Although the eventual development of PTOA can still occur in the face of an anatomic reduction, which is usually due to the chondral joint damage that can be associated with such high-energy articular fractures, it is still important to obtain and maintain an anatomic reduction to give the patient the best outcome possible [25]. Fortunately, the tibial plateau is able to tolerate larger articular step-off than other joints, but anatomic reduction is still warranted [13, 46]. Associated instability and total meniscectomy are also predictive in the development of PTOA, and thus stability should be addressed and the meniscus preserved as best as possible [25, 47–50]. The risk of PTOA in tibial plateau fractures has been reported to be anywhere from 23% to 44% [13, 43, 51, 52]. Rademakers et al. in their series of 209 patients with tibial plateau fractures showed that despite an overall incidence of malunion of 4%, long-term follow-up of 109 patients showed that 31% of patients developed PTOA but was well tolerated by the majority of those patients (64%). However, those with malalignment of greater than 5° developed a moderate to severe grade of PTOA more often than those with an anatomic knee axis (27% vs. 9.2%; SS at $p = 0.02$). Articular step-off of 2 mm to 4 mm was found not to have an increased development of PTOA compared to a step-off less than 2 mm [13]. This underscores the multifactorial etiology of PTOA in articular injuries.

12.2 Causes of Malunions

Malunions of the proximal tibia can occur for a multitude of reasons. The etiology is often multifactorial and can occur from the surgery itself and can be related to the implant or attributable to the patient. Additionally, fracture characteristics can contribute to malunion development. Johner and Wruhs emphasized that comminution could lead to malalignment due to the lack of cortical contact and result in instability at the fracture site [10]. This is obvious as well, since with a good cortical read, anatomic restoration of not only the alignment, but the length and rotation become much simpler. When there is loss of the cortical read due to extensive comminution, the surgeon must rely on contralateral imaging and examination of the lower extremity for rotation for potential clues to determine the proper alignment. Prevention is the best treatment, thus minimizing iatrogenic factors which include implant type and application of the implant. Improper positioning of the plate can lead to inadvertent malalignment during the index procedure. Inadequate fixation can lead to loss of reduction and subsequent failure of the entire construct. Articular fractures require absolute stability with rigid fixation and failure to do so can result in subsidence of the joint surface and resultant intra-articular malunions. Attention should be paid to length, alignment, and rotation to insure restoration of the mechanical axis of the lower extremity.

12.2.1 Surgical Considerations

Implant choice for extra-articular (AO type A) proximal tibia fractures remains a controversial topic and can be amenable to intramedullary nailing, plating, or even small wire external fixation. As mentioned previously, IM nailing of proximal tibia fractures can result in valgus with apex anterior deformities if care is not done to obtain and then maintain the alignment while placing the nail [4, 19–22].

If utilizing a proximal locking plate for these fractures, it is important to note that the plate-bone mismatch is still a problem, even with the modern designs of the available pre-contoured plates. Thus, sole reliance on the plate as a reduction tool may itself contribute to malreduction. Many plates are put in percutaneously since the joint is not involved. Unfortunately, even minimally invasive plate osteosynthesis (MIPO) techniques have been associated with malunions of the proximal tibia. Although this MIPO technique for proximal tibia fractures has been shown to be advantageous from a soft tissue preservation aspect, several recent studies have shown it to be significantly associated with rotational malunions [12]. It is important to evaluate the rotational profile compared to contralateral radiographs to mitigate this risk (see Sect. 12.2.3).

12.2.2 Patient and Injury Considerations

One of the biggest factors to the development of a malunion is the fracture pattern itself.

Comminuted fractures or fractures with bone loss result in an inability to accurately piece together the fracture, and often rotation, length, and alignment have to be determined by comparison of the opposite side. This itself is problematic since there are side-to-side differences that occur naturally. Additionally, fluoroscopy only provides a very narrowed view, and assessment of the mechanical axis intraoperatively is difficult.

There is a higher risk of need for revision ORIF procedures in patients with bicondylar fractures, associated with a tibial shaft fracture, open fracture, and surgery performed at odd hours (evening/weekends/after midnight) [53]. Henry et al. published their results of 8426 patients over a 13-year period and had an 8.2% revision ORIF rate but only 0.82% incidence of osteotomy for malunion, but did not report on overall alignment [53].

Malunions, identified as a result of collapsed nonunion or delayed union, emphasize patient factors important to consider as causes of eventual malunion. Diabetes and smoking can contribute to delayed healing which ultimately could result in failure of the construct prior to healing [17, 18]. Osteoporosis could result in loss of fixation early, prior to healing. In a study by Ali et al., they showed an 85% loss of fixation in the elderly patient due to significant osteoporosis. Elderly was defined as greater than 60 y/o. Additionally, noncompliance with weight bearing in this group contributed to failure as well [9]. All of these factors can allow the fracture site to collapse, providing compression with eventual healing if the patient fails to follow-up in a timely fashion or if there is failure to timely intervene to correct the malalignment. This may be subtle or significant enough to potentially require treatment. Noncompliance with weight bearing restrictions can also result in loss or failure of fixation with the same end result of a malunion under the same situations as mentioned previously.

12.2.3 Preventative Strategies for Malunion

Bicondylar tibial plateau fractures provide special challenges to the orthopedic surgeon [53]. Although many of these require dual plating, many can still be treated with a single lateral locked plate. The challenge lies in making the correct decision as to which one can be treated with a single plate vs. a dual plate. Gosling et al. reviewed their series of bicondylar tibial plateau fractures treated with a single lateral locked plate. They found a 15% incidence of malreduction, but more importantly 11% had loss of coronal reduction with resultant varus collapse of >5° [54]. Careful scrutiny of the preoperative CT scan can define the fracture morphology of the bicondylar plateau with special emphasis placed on the plane of the medial plateau fracture. In cases where the medial plateau fracture is a posterior or posteromedial fragment, buttressing of that fragment with a medial plate is probably warranted for stabilization. If the fracture plane on the medial side is strictly sagittal, then screws from a single lateral locked plate can often provide enough stability to maintain the medial plateau alignment and prevent varus collapse [3]. Weaver et al. showed that lateral locked plating is sufficient for bicondylar tibial plateau fractures when the medial fracture is in the sagittal plane or a large single fragment. Those fractures that had coronal plane involvement of the medial side did significantly better in terms of maintaining the reduction with dual plating than with single locked lateral plating [15]. Although they reported an overall 15% malreduction rate, the coronal medial fracture group treated with a lateral plate had a 14% loss of reduction compared to 0% in the dual plating coronal medial fracture group. Keep in mind that anatomic restoration of the articular injury is paramount, and rigid fixation of the articular injury is needed to prevent an intra-articular malunion. In cases of significant joint comminution, gaps are tolerated better than step-offs, and thus every attempt should be made to create a congruent joint surface with sufficient subchondral support with bone graft or bone graft substitutes as needed to prevent subsidence of the joint fragments. These cases are best done during daytime hours as opposed to odd hours, which has been shown to be a risk for revision ORIF [53]. Restoration of the joint requires visualization which can be obtained by performing a sub-meniscal arthrotomy. Visualization of the reduction is aided by fluoroscopy, but direct visualization through the arthrotomy is paramount. The joint should be reduced and supported by bone graft or a graft substitute. These techniques can help reduce the chance of an intra-articular malunion [55]. Obtaining and then maintaining the reduction is the key to avoiding failure and malalignment of the metadiaphyseal component as well.

Tibial plateau fractures involving the lateral tibial plateau fracture require anatomic restoration of the joint surface by elevating the depressed segments and bone grafting underneath followed by stabilization [56]. Subchondral rafting screws can help minimize or prevent subsidence of the joint over time. This can aid in preventing loss of reduction of the articular surface and an intra-articular malunion which is very likely to progress to PTOA. The lateral condyle should be buttressed when it is completely off. Failure to buttress could lead to displacement and subsequent valgus malunion of the joint with subsidence of the lateral side. This is especially true for the medial side where anatomic restoration of the medial side with compression of the fracture plane and buttressing are needed. Due to the normal MAD being through the medial compartment, the knee wants to fall into varus and insufficient fixation will lead to failure.

Proximal extra-articular fractures that are amenable to either plating or nailing can still be problematic. As mentioned before, nailing of such fractures is especially problematic due to the muscle forces acting on the short proximal fragment. Often the malreduction with nailing results in valgus and procurvatum [4, 22]. Preventative strategies have been described for nailing of these proximal tibia fractures and include blocking screws, more lateral starting point, semi-extended approach, supra-patellar nailing, use of a universal distractor, and an anterior unicortical plate across the fracture site [22, 57–60]. It is important to understand that the reduction should be obtained before and during reaming.

These fractures can be plated as well in a fairly minimally invasive technique (MIPO), but as previously mentioned still can have a higher than expected rotational malalignment. Additionally, since the plate is only on the lateral side of the bone, the entire construct can fall into varus depending on the comminution at the fracture site [4]. To avoid a rotational malunion, it is important to accurately assess the patient's contralateral limb to determine what the patient's normal rotation is. The more comminution and inability to obtain a cortical read for reduction, the more important and useful this technique becomes. Fluoroscopy is used to obtain a perfect lateral of the knee of the uninjured side (femoral condyles perfectly overlapped) followed by moving the c-arm down to the ankle and obtaining a view of what the ankle looks like with the knee held in this perfect lateral position. Most patients have slight external rotation of the ankle on this view when compared to the knee lateral. This allows for a comparative reference when either nailing or plating the extra-articular fracture or even in cases of bicondylar fractures. In a study by Yoon et al., combining plating and nailing of proximal tibia fractures led to 0% malunion rate. They reported on 27 patients with adequate follow-up over an average time of 20 months. They had a 93% union rate with no loss of alignment [16].

12.3 Evaluation and Diagnosis

The general evaluation and diagnosis of a malunion has been covered in Chap. 1. The same principles apply. However, specific points to address in relation to a malunion of the proximal tibia or tibial plateau will be discussed below.

12.3.1 History

As in evaluating any new patient, it is important to understand the original mechanism of injury, the severity of the injury (e.g., open vs. closed, comminution), and treatment course which has now resulted in the malunion. If it was open, how many surgeries were performed prior to definitive fixation? What was done at the time of the original surgery? If the injury films, if available, indicated that the best course of action at the time was felt to be operative management, but closed treatment was performed, why was that the case?

In certain situations, the patient may have been too sick from the initial trauma to undergo operative fixation. In other circumstances, the patient may have opted for nonsurgical management. If the patient is referred in, requesting the medical records from the original surgeon can be very helpful. Did they have any problems with fixation, and did they comment on the patient's bone quality which could have led to failure after fixation? Careful assessment of the original postoperative films, if available, can help elucidate the etiology of the malunion. Obviously, failure to obtain the reduction would be obvious on these images. Obtaining an accurate history regarding any previous infection is also important. It is important to determine when weight bearing began especially if alignment was acceptable postoperatively and/or when there is hardware failure resulting in malalignment. If there was early failure, it may indicate noncompliance with the postoperative regimen. Therefore, a timeline of when the failure occurred in relation to the original surgery may indicate delayed healing which resulted in loss of alignment during the healing phase. Often the collapse that occurred allows the delayed union to then proceed to a malunion. The reason for lack of follow-up in those cases is also useful to determine the nest treatment regimen, as certain treatment options require close follow-up and compliance. A complete social history should be obtained to include the use of nicotine, narcotics, and illicit drugs as well as any pain management issues they may have had. A careful medical history, to determine if any comorbidities contributed to the development of any delayed union, in cases of hardware failure, especially diabetes, is crucial.

12.3.2 Physical Exam

The patient's physical exam should include an assessment for range of motion of all joints in the affected extremity with a comparison to the opposite normal extremity. Knee motion and stability should be specifically assessed. Many of these patients may have concomitant ligamentous injuries of the knee, which may have gone unrecognized. Looking at the patient's gait is also helpful to assess for an instability in the knee. It should also be inspected for scars, especially adherent soft tissue to the bone, signs of infection such as erythema, or draining sinus tracts. Standing clinical evaluation of the alignment of the limb should be performed to assess for clinical alignment, and obvious varus or valgus at the knee is easily seen even in obese patients. The patient should be evaluated for leg length discrepancy utilizing various sized blocks to re-establish the patient's subjective and clinical leg length which can be based on an assessment of the pelvic obliquity. In cases where the hardware has failed, the hardware may be prominent as well and along with the deformity may be causing pressure sores. A thorough neurovascular exam should be performed of the lower extremity.

12.3.3 Laboratory Studies

Laboratory studies can be helpful in those cases that may have a history of infection. Often, however, laboratory values are normal. If there is a history of infection, baseline labs should be obtained such as complete blood count (CBC), erythrocyte sedimentation rate (ESR), and C-reactive protein (CRP). This is especially true in cases of retained hardware or failed hardware to make sure that there is no underlying low-grade infection. In many cases, the patient may have had a delayed union which eventually had hardware failure resulting in a deformity which then, because of collapse, goes on to heal. Such a history also warrants a metabolic workup to evaluate for causes of the delayed union including a complete metabolic profile (CMP), vitamin D, calcium, and endocrine labs if indicated. Patients with chronically low vitamin D levels may have secondary hyperparathyroidism which should be corrected on vitamin D supplementation. Diabetic patients should have an assessment of their glucose control with a hemoglobin A1C. Nutritional status should also be evaluated with albumin and pre-albumin levels to insure the patient's ability for wound healing after surgery.

12.3.4 Radiographs

Radiographic examination should begin with standard anteroposterior (AP) and lateral X-rays of the knee on a large cassette for better visualization of both the distal femur and the proximal tibia, as well as an AP and lateral of the affected tibia. A standing AP of both knees, with the patellae facing forward, should supplement the imaging to evaluate for joint space narrowing. A complete evaluation of the mechanical axis of the lower extremity is required and can be accomplished by obtaining a full-length standing AP of bilateral lower extremities as well as laterals. The AP can be obtained with a radiopaque ruler to aid in assessing for limb length discrepancies. My preference is also for a spherical marker of known size (CAD ball™) for magnification purposes as well as for preoperative planning with TRAUMACAD™ software *(see Case Discussions: Case 2)*. It is important to assess both the femur and tibia for underlying deformities to ensure that the deformity is isolated to the tibia. The following parameters should be measured on the AP standing long leg film: the mechanical medial proximal tibia angle (mMPTA = 87o ± 3°), mechanical lateral distal femoral angle (mLDFA = 88° ± 3°), and mechanical axis deviation (MAD = 10 mm medial to the center of the joint). The long leg sagittal film should be evaluated for these parameters: anatomic posterior proximal tibial angle (aPPTA = 81° ± 3°) and anatomic posterior distal femoral angle (aPDFA = 83° ± 4°) [30]. The deformity itself is defined by the center of rotational angulation (CORA). This is measured by drawing the anatomical axis of the proximal segment of the tibia and the distal segment of the tibia. The point of intersection defines the angulation of the deformity and is obtained on both the AP and lateral views. Standing knee radiographs should be evaluated for the Kellgren-Lawrence grade of arthrosis, especially for those patients with significant grade III and IV preoperative osteoarthrosis where arthroplasty may be a consideration [6]. This is especially important for intra-articular malunions where arthrosis is more likely.

12.3.5 Computed Tomography and Magnetic Resonance Imaging

Computed tomography (CT) is the best advanced imaging study to evaluate the malunion site. Although the patient may be referred for a “malunion,” oftentimes the CT scan may show a “malaligned nonunion.” It provides additional quantification, evaluates the bone at the malunion site, and provides better visualization of the intramedullary canal for patency. It is the gold standard for assessing lower extremity malrotation [12, 27, 28, 61]. CT scan imaging may be obscured by preexisting hardware, but metal suppression techniques can be used to limit artifact. Sagittal, coronal, and 3D reconstructions can be obtained to better define the anatomy. The CT images and subsequent 3D reconstructions can be helpful in guiding osteotomy planning as 3D plastic models can be created from which preoperative planning can be done [62]. Yang et al. reported their results with this technique in a group of patients with intra-articular malunions of the lateral tibial plateau. They created 3D printed models from CT scans in seven patients to obtain accurate measurements and make a detailed preoperative plan for intra-articular osteotomy procedures. All patients did well and went on to heal with significant improvements in their postoperative outcome scores. They felt that utilizing this technique helped in their accuracy for preoperative planning, reduced the risk of postoperative deformity, and decreased intraoperative blood loss and operative time with better outcomes [62]. CT scan imaging of the contralateral normal side is also useful with subsequent 3D reconstructions created. These contralateral side images can be used and flipped to create 3D models of what the injured side should look like. They then have been able to create intraoperative osteotomy guides based on the opposite normal to aid with the surgical correction. This technique was applied to three patients with tibial plateau malunions [63]. Two of the three patients had complete correction, whereas one patient had an incomplete correction secondary to the inability to mobilize the fragment completely and was considered a failure of "execution of the procedure." The guides created were all successful in helping with the osteotomy [63].

Magnetic resonance imaging (MRI) can provide some useful information with regard to associated ligamentous instability that may be detected on clinical exam as well as evaluate the joint for arthritis and meniscal integrity. Since many of the tibial plateau fractures can have associated ligamentous and meniscus injuries, patients presenting with malunions from such injuries may have had undiagnosed soft tissue injuries. The 3.0-T MRI can also better evaluate the cartilage of the knee joint which may be crucial in determining the best course of action in older patients with associated arthrosis along with a malunion [64]. Retained hardware can however limit adequate visualization of the joint, and special metal suppression techniques should be employed if possible. Alternatively, both MRIs and CT scans can be obtained after hardware removal in cases where staged reconstruction has been decided upon. MRI can also provide useful information in cases of suspected infections.

12.3.6 Nuclear Imaging

These can be useful in evaluating malunions when there is concern for infection, especially if there is retained hardware. Often, the existing hardware can limit CT or MRI scans due to artifact. Nuclear medicine studies may be beneficial if laboratory studies (CBC, ESR, CRP) are elevated. If the patient has a history of infection during the initial treatment phases of the original fracture, these studies may be useful.

12.4 Management of Malunions

Many patients who develop a malunion may also present with varying degrees of PTOA in addition to the deformity. The biggest question for many patients is whether a revision procedure to correct the deformity is worthwhile or is going to a total knee arthroplasty (TKA) the better treatment. Many factors come into the decision-making, and in the elderly patient with a mild to moderate degree of malalignment, total knee arthroplasty that can also correct the deformity through appropriate cuts is probably the best option. In most cases with a severe deformity, a correction may be required prior to the TKA. However, in some of these cases, correction of the deformity with re-establishment of the mechanical axis can result in pain relief and extend the life of the native knee. Kloen et al. concluded in their study of 27 patients with revision of tibial plateau fracture fixation within 1 year felt that attempts at salvage were worthwhile in young patients. There were ten patients with true malunions, defined as malalignment of >15° or an intra-articular step or gap of >2 mm, with the majority being intra-articular. It was noted that the malreduction group fared the best, and they recommended that early revision should be performed once the malreduction is diagnosed. Treatment of the malunions should be individually based, they concluded [65].

Nonoperative management of the malunion (+/− PTOA) may be indicated in the asymptomatic patient or with minimal symptoms. Older patients with symptoms that can be controlled with other modalities and wish to avoid surgery also can be managed conservatively. The mainstays of conservative treatment are nonsteroidal anti-inflammatory agents, other nonnarcotic analgesia medications, intra-articular injections (PTOA; corticosteroids or viscosupplementation), and the use of unloading braces when malalignment is present. Other modalities that can help include weight loss in the overweight/obese patient and physical therapy to strengthen the lower extremity and maintain ROM.

In the highly symptomatic young patient with a malunion and PTOA of the knee joint, either high tibial osteotomy (HTO) or distal femoral osteotomy (DFO) has been suggested as the treatment of choice. This can be done alone, with overcorrection to "unload" the affected joint, or in addition to cartilage resurfacing procedures such as osteochondral allografts [66]. An HTO or DFO is indicated in the active patient that is less than 60 that has mild unicompartmental arthritis (medial or lateral) with a normal patellofemoral joint and the other compartment. Knee exam should show good ROM and no flexion contracture. The osteotomy can be opening wedge, closing wedge, dome, or with distraction osteogenesis with an external fixator [68–70].

12.4.1 Rotational Malunion

Isolated pure rotational malunions of the proximal tibia can occur especially when there is no cortical read (comminution) at the metaphyseal area. This usually occurs in type A fractures that have been treated with MIPO techniques [12]. The exact amount of rotation is best determined by CT scans. In the cases of symptomatic rotational malunions, correction can occur by a de-rotation osteotomy and stabilized with IM nailing. This obviously will depend on the preexisting hardware and whether a staged approach will be performed. The IM nailing allows for immediate weight bearing after stabilization as opposed to plate fixation. In the instance where the preexisting hardware may preclude IM nailing after osteotomy, plate fixation or external fixation can be a viable option. The advantages of immediate fixation of the osteotomy, with either an IM nail or plate, allow for the avoidance of pin tract infections associated with an external fixation. The disadvantage is that the final correction cannot be changed. A Taylor Spatial Frame™ (TSF) can allow "dialing" in of the rotation to obtain as precise of a correction as possible [66–70]. The standard disadvantages to external fixation apply, such as pin tract infections, external device, and length of time in a frame. The ultimate treatment should always be individualized.

12.4.2 Coronal Plane Malunion: Extra-Articular

The normal mechanical axis deviation is on average approximately 10 mm medial to the joint line but does vary by individual. A complete assessment of the patient's lower limbs is required, and correction to the opposite (hopefully uninjured) side is needed. The goal is to restore the patient's anatomy to their native anatomy, although overcorrection may be considered in cases where the joint is already showing signs of PTOA. Re-establishing the mechanical axis of the limb is the ultimate goal. For isolated coronal plane malunions, a high tibial osteotomy is sufficient for the correction. The type of osteotomy can vary from closing wedge, open wedge, or dome osteotomy [71, 72]. It can also be accomplished with an external fixator utilizing distraction osteogenesis [68]. Use of a TSF can allow for gradual correction with precise control over the final MAD to aid in achieving overcorrection when needed for unicompartmental arthritis [69]. The surgeon's own surgical abilities should be taken into consideration when undertaking malunion correction.

12.4.2.1 Varus Malunion (± Intra-articular Malunion)

The most common treatment is a high tibial osteotomy, which can either be a medial opening wedge (MOWHTO) or closing wedge on the lateral side (LCWHTO), for a malunion up to 15° [66, 70, 71, 73]. The effects of each osteotomy should be taken into consideration, lengthening for open wedge and shortening for closing wedge. Additionally, the LCWHTO requires either a fibular osteotomy or proximal tib-fib joint disruption and dissection and protection of the peroneal nerve. Although the literature is scarce regarding comparative techniques, the overall choice is surgeon preference. In cases of greater than 15° of malalignment, either a dome osteotomy or use of external fixation and distraction osteogenesis is warranted [66, 73]. Various types of implants can be used to stabilize the osteotomy [71]. Wu reported on the use of a blade plate to stabilize medial opening wedge osteotomies in 25 patients with malunions. He found the technique to be successful in obtaining and maintaining the correction of the MPTA. The preoperative MPTA was 72° and postoperatively, 90°. Knee function was improved in 88% of patients [74]. Sundararajan et al. performed MOWHTO in 18 patients with minimal arthritic changes and varus malunions of tibial plateau fractures. The majority (72%) were malunited Schatzker IV tibial plateau fractures. Despite the majority being isolated malunions of the tibial plateau, a complete MOWHTO of the entire proximal tibia was successful in their series. The mean preoperative MPTA was 75° which was corrected to 83.8°. They reported 77% good to excellent results with 100% union [75]. The TSF can also be used to correct varus malunions [66–70]. Da Cunha utilized either a monolateral fixator or TSF for genu varum in patients with pain. The patients had native bilateral genu varum, not malunions, but use of the external fixator was successful in correcting both sides. They also showed that significant improvements in knee kinetics and kinematics occur. They felt that although use of external fixation worked well, they now reserve it for varus deformities of >12° or complex multiplanar deformities [70]. Xu described a technique of using an intra-articular corrective osteotomy combined with an external fixator for the associated knee deformity. The deformities were either due to skeletal dysplasia or post-traumatic. Although the patient had a myriad of etiologies, the combined technique of elevating the hemi-plateau and osteotomy of the femur or tibia metaphysis was successful in addressing both malunions [76].

12.4.2.2 Valgus Malunion (± Intra-articular Malunion)

Patients that have developed isolated valgus alignment with or without PTOA, if symptomatic, may be candidates for proximal tibia varus osteotomy, but osteotomies of the distal femur can also be performed. This can either be a lateral opening wedge (LOWDFO) or medial closing wedge osteotomy (MCWDFO). The normal MAD is through the medial side of the knee joint, but in those with valgus deformities, the MAD is shifted to the lateral compartment. Varus osteotomy of the proximal tibia has been shown to be successful and is essentially a high tibial osteotomy but in the opposite direction. Marti et al. managed 36 patients with an opening wedge proximal tibial varus osteotomy (LOWHTO) in patients with isolated valgus and lateral compartment arthritis [77]. The average valgus malalignment was 11.6°, although the cause of the valgus was post-traumatic in 23 (average = 10.6°), post-meniscectomy in 5 (average = 9.2°), previous osteotomy in 4 (average = 18.3°), and idiopathic in 2 (average = 9.5°). On final follow-up (5–21 years, average = 11 years), the overall alignment was 5.1° of valgus. They had good to excellent results in 88% of the patients based on Lysholm and Gillquist knee scores. Three patients did have a transient peroneal nerve palsy, which can be a problem with varus-producing osteotomies. The opening wedge on the lateral side can result in effective lengthening of the peroneal nerve especially in long-standing valgus malunions [78]. Collins et al. published a case series of 23 patients that underwent LOWHTO, for valgus malalignment not malunion. They reported significant improvements in function and outcome scores in all patients; however, the valgus malalignment was small. They concluded that their technique worked well for small degrees of correction, as the fibula did not require osteotomy [79].

If the patient has both an intra-articular malunion and a valgus proximal extra-articular malunion, correction of both is required. Van Nielen et al. published their technique of utilizing a combination of five osteotomies for such situations. They performed a mid-shaft fibula osteotomy (allows for varus correction), Gerdy's tubercle osteotomy (better joint visualization), fibular head osteotomy (better visualization of posterolateral portion of lateral tibial plateau), and proximal tibia varus-producing osteotomy. They had managed 35 patients with this technique with good functional outcomes and minimal progression of radiographic arthritis [80]. Marti et al. described a similar technique of performing a lateral opening wedge osteotomy of the proximal tibia, an oblique osteotomy of the middle third of the fibula, and intra-articular correction of the depressed lateral plateau. The joint is corrected through subchondral impaction of cancellous bone grafts through the osteotomy. If there is posterior depression of the lateral tibial plateau, only then did they recommend osteotomy of Gerdy's tubercle to gain better visualization. If further exposure of the joint surface is required, then an oblique fibular head osteotomy was performed. The peroneal nerve should be dissected out if this is the case [77]. Kerkhoffs reported on their results using this technique on 23 patients. They were able to correct both the intra-articular malunion and the valgus malunion in all patients. Overall, they had excellent results in 17 (74%), good in 3, fair in 1, and poor in 2. At a mean follow-up of 13 years (range 2–26 years), 15 did not have progression of their PTOA [81].

12.4.2.3 Sagittal Plane Malunion (Procurvatum/Recurvatum)

Sundararajan et al. performed MOWHTO in 18 patients with malunions of tibial plateau fractures. Although, the majority (72%) was malunited Schatzker IV tibial plateau fractures in varus, 12 had anterior sloping of the proximal tibia and 6 had excessive posterior sloping. They corrected not only the MPTA but also re-established the posterior slope of the proximal tibia in 12 patients that had an anterior slope. They corrected the excessive posterior slope in the other 6 [75].

12.4.2.4 Multiplanar Deformity

Multiplanar deformities can be particularly challenging especially when trying to do a single-cut osteotomy to deal with all the planes. Sangeorzan et al. described a mathematically derived technique to best determine the osteotomy plane. This allowed for complete correction of the deformity with stabilization using internal fixation. The cut surfaces were opposed allowing for rigid fixation. They had complete correction in the four patients with tibial malunions [82]. It is very elegant but the planning is highly labor-intensive. Feldman et al. used the TSF in 18 patients, of which 11 had tibial malunions. They had successful correction of the multiplanar deformities. Most common complication was development of superficial pin tract infections which can be treated with oral antibiotics. They concluded that use of the TSF was effective and advantageous for multiplanar deformities [67]. Fadel and Hosny used the TSF to perform deformity correction in 22 cases. It was used for lengthening only in eight cases, deformity correction in eight cases, and both in six cases. Only three cases were for tibial malunions. Overall, they had excellent results in 18, good in 2, and fair in 2 [68]. Hughes et al. used a TSF to perform the correction followed by immediate fixation of the correction with an intramedullary nail. They performed this in 12 consecutive patients, of which 4 had a malunion of the tibia. The technique was successful in obtaining the correction with the TSF and then maintaining the correction with the nail. The challenge is in placing the pins and wires for the TSF, keeping them out of the way for placement and locking of the nail [83].

12.4.3 Leg Length Discrepancy (LLD)

Although many deformities have a component of leg length discrepancy, length is often re-established with open wedge osteotomy procedures. Accurate analysis of the deformity and the leg length discrepancy is required with preoperative planning to ensure that this will be the case. If the length regained from the correction will be insufficient to correct the leg length discrepancy, then additional lengthening may be warranted. The deformity correction along with additional length is best done through external fixation with distraction osteogenesis, usually with a hexapod type of fixator [66–70].

In isolated leg length discrepancy without significant deformity, an internal lengthening nail can be used [84–86]. This is unusual in the case of the proximal tibia or tibial plateau, but with enough comminution in the metadiaphyseal area, inadvertent shortening could occur. Kirane et al. used an internal lengthening nail in 24 patients with a wide variety of etiologies for their leg length discrepancy. In their series, only four were from malunion. The techniques does allow for acute rotational correction in addition to the lengthening. They had a mean lengthening of 35 mm with an accuracy of 96% [84]. In most situations where there is a significant deformity, narrow canals, or absent medullary cavities, an internal lengthening nail has been contraindicated [85]. However, recently, Rozbruch reported on using an internal lengthening nail for a tibial malunion that had both a 9° valgus deformity and 25 mm LLD. Patient had complete correction of both deformities with full ROM of both the ankle and knee [86].

12.4.4 Isolated Intra-articular Malunion

Intra-articular malunions can be most challenging. The osteotomy has to be precise so as not to injure the normal joint. Intra-articular osteotomies have been described [87]. In cases where the medial tibial plateau is malunited, which is usually tilted in varus, an intra-articular opening wedge osteotomy can be performed to elevate the medial side and stabilized with a plate. The lateral side usually has significant depression and widening. The lateral side needs to be narrowed with the defect either resected or elevation of the depressed segment and bone grafted with fixation. In cases where the medial side has PTOA and depression along with lateral subluxation of the tibia with varus stress, medial plateau elevation with the intra-articular osteotomy and a combined extra-articular osteotomy to unload the medial side has been recommended. These methods have been shown to be successful in treating tibial plateau malunions [87].

Although large published studies in the best treatment for isolated intra-articular malunions are lacking, there are many case reports. Mastrokalos et al. described a technique of creating an open book osteotomy of the lateral plateau to gain access to the healed depressed joint surface. This allowed the joint to be elevated and bone grafted followed by a lateral plate [88]. Singh published a small series of seven patients that all had malunions of a tibial plateau fracture. Five were from conservative treatment and two after operative fixation. All were varus malunions of the medial plateau and underwent medial opening wedge osteotomies of the medial hemiplateau. They had complete correction in five and <2 mm residual articular surface depression in two. Fixation of the construct is key since it is an open wedge osteotomy. It did correct their mild medial ligamentous laxity associated with the varus deformity [89]. This unicondylar osteotomy has been shown to correct not only the coronal plane but also the sagittal plane without affecting the alignment of the lateral tibial plateau [90]. Adjunctive arthroscopy has been advocated by some to better evaluate the joint prior to the osteotomy [91].

Detailed preoperative plans can assist in performing these complex intra-articular malunions. Yang et al. used 3D printed models of the deformity to create such a preoperative plan to carefully lay out a detailed osteotomy plan for the lateral tibial plateau intra-articular malunion in seven patients. They had complete correction with significant improvement in Rasmussen anatomy and functional scores. No complications were encountered with 100% union [62]. Furnstahl et al. used both the injured side and the contralateral normal side and created 3D surgical guides to help perform the osteotomies. These guides can be created for a simple single-plane osteotomy or multiplanar osteotomies. Three patients underwent correction with these guides, with complete correction in two. One was considered a failure of the execution despite performing the osteotomy successfully [63]. Use of such technology can greatly enhance the ability to perform such difficult intra-articular osteotomies where accuracy is so crucial. Unfortunately, the techniques are labor-intensive and require significant resources which are not widely available, along with an increase in cost and radiation.

12.4.5 Osteoarticular Allografts

Osteoarticular allografts have been used to treat large PTOA defects in the proximal tibia [92, 93]. This can occur when there is significant joint comminution or loss of joint, either from open fractures or ballistic injuries. The patients should have isolated medial or lateral compartment arthritis and a normal corresponding femoral articular surface. These can be challenging as a fresh frozen allograft that is size-matched has to be found. The meniscus along with the tibial plateau surface has to be transplanted. The graft should be unloaded with a realignment osteotomy of the distal femur. This should be either a medial or lateral closing wedge osteotomy of the distal femur [66, 92, 93].

Drexler et al. treated 27 patients (average age 41.2 y/o; range 17–62 y/o) who all had failed lateral tibial plateau surgery with continued pain. They essentially developed PTOA from intra-articular malnunions. They performed a distal femoral varus osteotomy combined with a fresh osteochondral allograft. Long-term follow-up showed an 88.9% survivorship at 10 years, 71.4% at 15 years, and 23.8% at 20 years. They were able to significantly delay the need for a TKA in these patients [93].

12.4.6 Arthroplasty

12.4.6.1 Unicompartmental Knee Arthroplasty (UKA)

Medial or lateral UKA can be an option for some older patients with an intra-articular malunion with PTOA [73]. The ideal patient should be >60 y/o who is not overweight and low demand having only minimal pain at rest. They must have a stable knee with ROM >90°, less than 5° flexion contracture, and less than 10° of axial malalignment that can be corrected passively to almost neutral [66].

12.4.6.2 Total Knee Arthroplasty (TKA)

Unfortunately, many of the long-term functional results show that age at time of presentation of the original tibial plateau fracture can be a poor prognostic indicator, with older patients having worse outcomes [52]. As such, some have suggested that performing a TKA in the acute setting for an elderly patient with osteoporotic bone and a tibial plateau fracture [94]. Proponents of this technique quote high failure rates of ORIF of tibial plateau fractures in elderly patients with osteoporotic bone [9]. In the elderly patient with preexisting arthritis who sustains a periarticular knee fracture, performing a TKA has been successful [94].

In the setting of a malunion with PTOA, a TKA is certainly a valid option. The ability to perform the TKA depends on the amount of deformity present and where it is. In intra-articular malunions with a fairly normal mechanical axis of the tibia, a TKA can most likely be performed without issue and have comparable results to TKA for primary osteoarthritis (OA) [95]. The conversion of previous ORIF of tibial plateau fractures to TKA has been estimated anywhere from 3% to 7.3% at 10 years [94]. Unfortunately, TKA for PTOA with or without a malunion after tibial plateau fractures has been associated with a higher rate of complications when compared to primary TKA for primary degenerative joint disease [95, 96]. Scott et al. reported on their results in 31 patients that underwent TKA after a tibial plateau fracture. The time to TKA after the fracture varied widely from 2 to 124 months with an average of 24 months. Those that had a nonunion, an instability, or an intra-articular malunion underwent TKA earlier. Although complication rates were higher in the TKA after tibial plateau fracture group compared to a primary osteoarthritis group, the patient-reported outcomes and satisfaction were comparable [96].

If there is a significant malunion in the metaphyseal region in addition to the PTOA, it is crucial to realign the limb to insure long-term survival of the prosthesis [95, 97]. In small deformities, <10° in both coronal and sagittal planes, TKA can be performed with adjunctive soft tissue releases and modified bony resections to restore the mechanical axis [98]. A posterior-stabilized implant may also help in these situations [95]. Larger deformities will probably require a corrective osteotomy followed by TKA, which can be performed in a staged fashion or simultaneously [95, 99]. It is important to note that a malunion may preclude the use of the normal intramedullary alignment jigs. Extramedullary instrumentation or computer navigation can be helpful in this setting [100].

In the staged situation, correction of whatever deformity exists is probably ideal. This may require several procedures such as (1) removal of preexisting hardware, (2) correction of malunion, and then (3) TKA but could be performed in any combination. Hosokawa et al. performed a one-stage TKA with an extension corrective osteotomy for a malunion of the proximal tibia in the sagittal plane. A stemmed prosthesis was used to stabilize the osteotomy. Patient was allowed to weight bear at 6 weeks and was walking without assistance [101]. In the younger patient, correction of the deformity and restoring the mechanical axis can provide relief and delay the need for a TKA [100]. Correction of the malunion prior to TKA can be performed in a number of ways depending on the plane of deformity and previous surgeries. Consideration of implants should be undertaken to minimize interference with the subsequent TKA, unless removal is planned.

12.5 Author's Preferred Methods of Treatment

The definitive treatment can often be dictated by the previous fixation implants, surgical approaches used, and any soft tissue considerations along with the patient's expectations and desires. In most if not all cases, our preferred treatment is performed in stages with the first stage of treatment removing all of the preexisting hardware. This is then followed by a second stage for definitive treatment. The interval can allow for further evaluation as well to ensure that no underlying subclinical infection is present. The time interval can vary depending on the invasiveness of the first stage. In cases where minimal incisions can be made to remove implants, the second stage can occur sooner than later. This is done also to ensure that no postop issues arise that could compromise the malunion repair, if done at the same time as the hardware removal.

12.5.1 Asymptomatic Malunions

Unless the degree of deformity is concerning for malorientation of the knee joint and development of premature osteoarthritis is likely, no treatment is necessary with follow-up X-rays and clinical exam in 6 to 12 months to evaluate for joint stability/congruence. In cases where cosmesis is a concern only and without functional limitation, one should proceed with caution as the patient's expectations may not be met.

12.5.2 Rotational

If the malunion is entirely extra-articular and rotational only with or without minimal angular deformity (<5°), de-rotation osteotomy with IM nailing is the preferred option. This allows for immediate weight bearing.

12.5.3 Coronal Plane

In isolated coronal plane deformities, a proximal tibia osteotomy is preferred. In varus malunion, a proximal MOWHTO is ideal to correct the deformity and regain any length that has been lost. If the malunion is valgus, either a LOWHTO or MCWHTO can be used. The LOWHTO results in lengthening and thus may stretch the peroneal nerve and has a greater risk for compartment syndrome [73].

12.5.4 Sagittal Plane

Isolated sagittal plane deformity is rare. Often it is associated with proximal tibia fractures nailed and include a valgus component. In the case of an isolated sagittal plane deformity, it is important to assess the original fracture pattern to determine which plateau is malaligned or if the entire proximal tibia is involved. In the case of a procurvatum deformity, a closing wedge extension osteotomy can correct the deformity and provide bony contact for healing. Conversely, in a recurvatum deformity, a flexion osteotomy (open wedge) with bone graft or bone substitute inserted into the opening is warranted.

12.5.5 Leg Length Discrepancy

In situations where there is isolated leg length discrepancy greater than 2 cm, osteotomy and lengthening can be considered. For shortenings up to 2 cm, conservative measures with shoe lifts can be tried. Patient satisfaction with shoe lifts becomes the limiting factor as many patients dislike wearing shoe lifts especially if it is on the outside of the shoe. Lengthening can be performed either by an internal lengthening nail or external fixation. Utilizing a monolateral rail external fixator has been very successful in lengthening of the tibia and can be better tolerated by the patient compared to a circular fixator. However, both circular fixation and monolateral fixators work well. An internal lengthening nail is also a very viable option; however, cost and logistics become the limiting factors. A thorough discussion with the patient regarding the risks and benefits of each treatment option is required to determine the best individualized treatment option. In cases where there is a history of infection, external fixation is preferred but the infection should be cleared.

12.5.6 Multiplanar Deformity

Complex deformities of the proximal tibia that are extra-articular are managed with distraction osteogenesis after osteotomy utilizing a Taylor Spatial Frame to simultaneously correct all deformities. The TSF allows precise multiplanar correction with the advantage of continued correction as necessary along with lengthening. In the event an intra-articular malunion is also present, then that should be treated as indicated below. This may require staging or may be done in a single stage depending on the deformities involved. In some situations, a single-plane osteotomy can be performed when the patient does not want external fixation as an option, but can be more challenging in determining the perfect direction for the osteotomy. Careful preoperative planning should be performed. Preoperative CT scanning with 3D reconstructions can help as well as getting a 3D model made to "trial" the osteotomy. Cost and logistics can be problematic, but as the technology improves and 3D printing becomes widely available, this may become more readily available.

12.5.7 Intra-articular Malunion

Intra-articular malunions, in the young active patient, generally require corrective osteotomy. If the joint depression is >3 mm, an intra-articular osteotomy of the hemi-plateau with elevation, bone grafting, and fixation is indicated. This is true for either the medial or lateral side as the "deformity" is more related to depression of the entire surface – varus collapse for the medial side and valgus collapse for the lateral side. In cases of significant depression and a split with widening of the condyle, resection of the depressed segment with a sagittal osteotomy and reestablishing the width of the condyle with compression screws and buttress plating is preferred. If the intra-articular malunion is <3 mm on the lateral side, an extra-articular LOWHTO can be performed to realign the MAD. This does not result in excessive obliquity of the joint line and is well tolerated despite it being an intra-articular malunion. On the medial side, usually varus collapse of the entire hemi-plateau occurs, and thus an intra-articular opening wedge osteotomy of the medial condyle will correct the deformity.

12.5.8 Prosthetic Replacement

Prosthetic replacement is usually indicated in cases of intra-articular malunion, usually depression or advanced PTOA that cannot be corrected. Ideally, the patient is older. In cases of extra-articular malunion and PTOA, often the amount of deformity may not be able to be corrected with the TKA itself. Often deformity correction should occur first followed by TKA at a later point. In some instances, with severe deformity, correction of the mechanical axis with slight overcorrection to unload the more affected joint can lead to resolution of their PTOA symptoms and delay the need for a TKA. If all compartments are affected, then TKA is warranted in an age-appropriate patient. Unicompartmental arthroplasty can be a viable option for isolated single compartment arthritis in the older, low-demand patient. We have little experience in this.

12.5.9 Osteoarticular Allografts

In isolated single compartment PTOA that occurs in the young patient, OA allograft can be a viable option. The limiting factor is the availability of a size-matched fresh frozen OA allograft. The procedure can be combined with an extra-articular osteotomy of the femoral side to unload the graft. In cases of lateral OA allograft, a MCWODFO should be performed and conversely a LCWODFO for a medial OA allograft.

12.6 Case Discussions

12.6.1 Case 1

A 60-year-old Russian female presented to the joint service for total knee arthroplasty for severe arthritis in the right knee. Due to the extensive varus deformity, she was referred to the trauma service to undergo correction of the deformity prior to TKA as the surgeon did not feel that the deformity as it was amenable to TKA due to extensive augments that would be required. Patient had a history of an open proximal tibia fracture at the age of 14 that also required soft tissue coverage. She was unable to give us any other details about the surgeries she underwent at such a young age. On clinical exam, she had an obvious varus deformity of the right knee compared to the left. There was a "caved in" appearance on the medial proximal tibia due to the severe varus deformity. There were no signs of infection. The skin on the medial aspect was adherent to the bone and immobile. Figure 12.2a, b shows the AP and lateral right knee. Figure 12.2c shows a repeat lateral performed orthogonal to the joint to better assess the joint itself. This also reveals a slight recurvatum (sagittal plane) deformity otherwise not appreciated on the initial lateral view. AP and lateral of the tibia are shown in Fig. 12.2d, e. Long leg standing AP and lateral images of the entire extremity are done for preoperative planning (Fig. 12.2f, g). Figure 12.2f shows the mechanical axis deviation (marked as the dashed yellow circle) which is normal on the left side but located outside the knee joint on the right side due to the severe deformity. Deformity analysis showed that the deformity was isolated to the proximal tibia. This was important to establish since the injury was long ago. The anatomic lateral distal femoral angle (aLDFA) was 79° on the left and 78° on the right. Her proximal tibia deformity measured 28° varus and 8° recurvatum (apex posterior) (Fig. 12.2h, i) The center of rotation and angulation (CORA) is determined on the AP by drawing the proximal tibial joint line (mMPTA 90° off the joint based on contralateral imaging; orange line) and drawing the anatomical axis of the tibia shaft (also the mechanical axis in case of the tibia; green line). Similarly, the intersection on the lateral of the proximal tibia joint line (mechanical posterior proximal tibia angle mPPTA = 81° based on contralateral image; orange line) and drawing the anatomical axis of the tibia shaft (also the mechanical axis in case of the tibia; green line) determines the CORA.

After discussion of options, and the potential for TKA after correction, gradual correction via osteotomy and distraction osteogenesis with a Taylor Spatial Frame (TSF) was determined to be the best option for this patient. This would allow for both multiplanar correction and re-establishment of the 2 cm leg length discrepancy. Additionally, there would not be any implanted hardware that would require removal (besides the ex fix) prior to TKA. Figure 12.2j, k shows the immediate postoperative films with the TSF and osteotomy. After the initial correction (Fig. 12.2m; AP and lateral), correction should be assessed with evaluation of the anatomical axis of the tibia and long leg films to reassess if the MAD should be performed (Fig. 12.2n). The MAD now crosses at the center of the knee. Clinical leg length assessment was performed based on the patient's perception of leg length discrepancy utilizing blocks and was felt to be equal. The frame was maintained in place during consolidation. An Exogen stimulator was prescribed to accelerate the consolidation phase. Figure 12.2o, p shows an AP and lateral of the right tibia immediately prior to frame removal. Final follow-up films at 1 year show excellent realignment with re-establishment of MAD and complete correction of the multiplanar deformity and restoration of the LLD (Fig. 12.2q, r). Interestingly enough, the patient's knee pain resolved and she declined a TKA.

12.6.2 Case 2

A 57-year-old Latin American male who was involved in a motorcycle collision 15 years prior to presentation. Patient was treated nonoperatively and

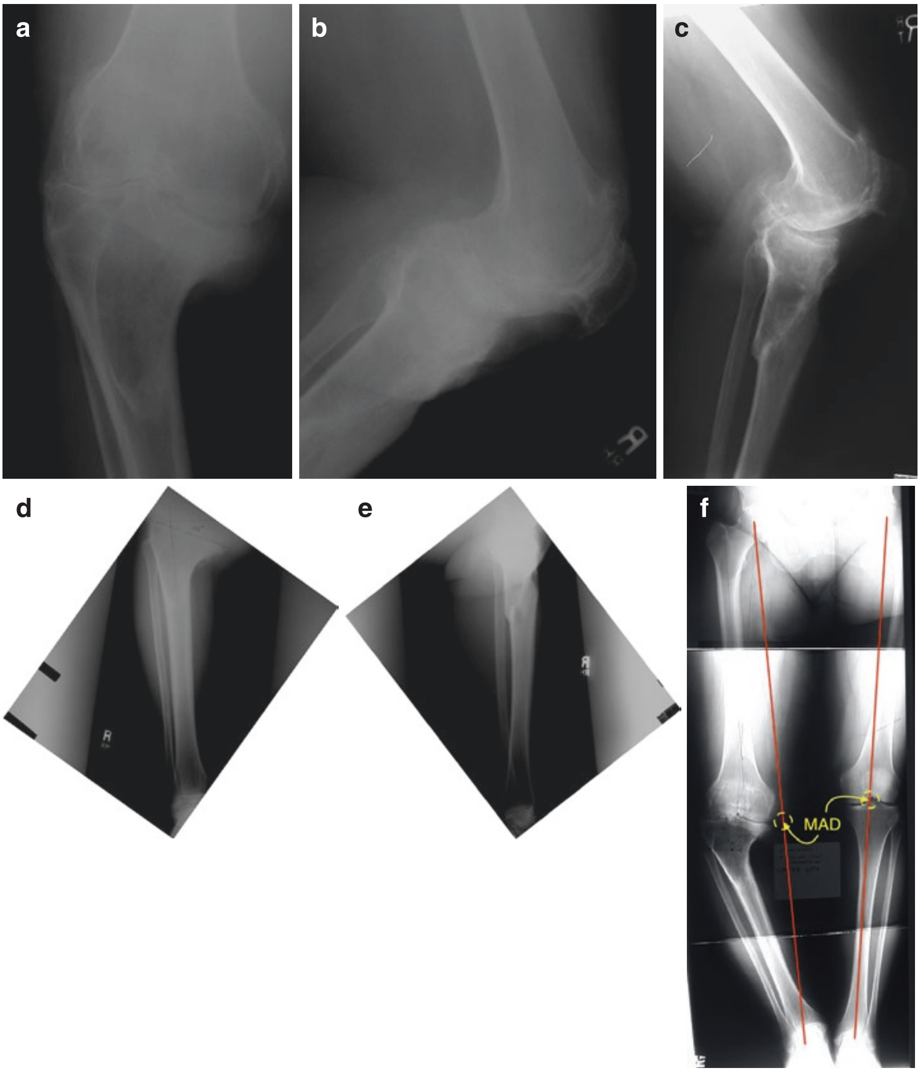


Fig. 12.2 (**a**, **b**) AP and lateral radiograph of the right knee showing severe deformity with PTOA. (**c**) Lateral radiograph of the knee taken 90 degrees to actual deformity to show the knee joint better. (**d**, **e**) AP and lateral radiographs of the right tibia showing deformity localized to the proximal tibia. (**f**) Standing AP bilateral lower extremity showing the MAD (red line) for each limb. The varus deformity of the right proximal tibia is clearly visualized. The MAD on the left is the normal value for this patient, and the right MAD is well medial to the joint itself. (**g**) Standing lateral of the affected leg showing that a proximal sagittal deformity exists as well. (**h**) Magnified AP view of the right proximal tibia showing the CORA for this patient and the 28-degree varus deformity in the coronal plane. The orange line is marked from the normal for this patient of a 90° mMPTA. The green line is the anatomical or mechanical axis of the tibia shaft, as determined by the centerline finder method. The intersection of the orange and the green line defines the CORA. Local length analysis was also performed, seen in writing, showing a 2 cm LLD. (**i**) Magnified lateral view of the right proximal tibia showing the sagittal plane deformity and the CORA as determined by the same method as for the coronal plane deformity. The patient has a 28° varus deformity and a 10° recurvatum (apex posterior) deformity with a 2 cm LLD. (**j**, **k**) AP and lateral radiographs of the right tibia after placement of TSF and osteotomy. (**l**, **m**) AP and lateral radiographs of the right tibia after the initial correction showing the realignment of the tibia mechanical axis in both the coronal and sagittal planes. The orange line indicates the proximal segment mechanical axis line and the green line, the distal segment mechanical axis line. (**n**) Standing AP of the right lower extremity to evaluate the MAD which is now in the center of the knee joint (*red line*). (**o**, **p**) AP and lateral radiographs of the right tibia showing consolidation of the osteotomy just prior to removal of the TSF. (**q**, **r**) AP and lateral radiographs of the right tibia showing complete healing at 1 year with resolution of knee pain

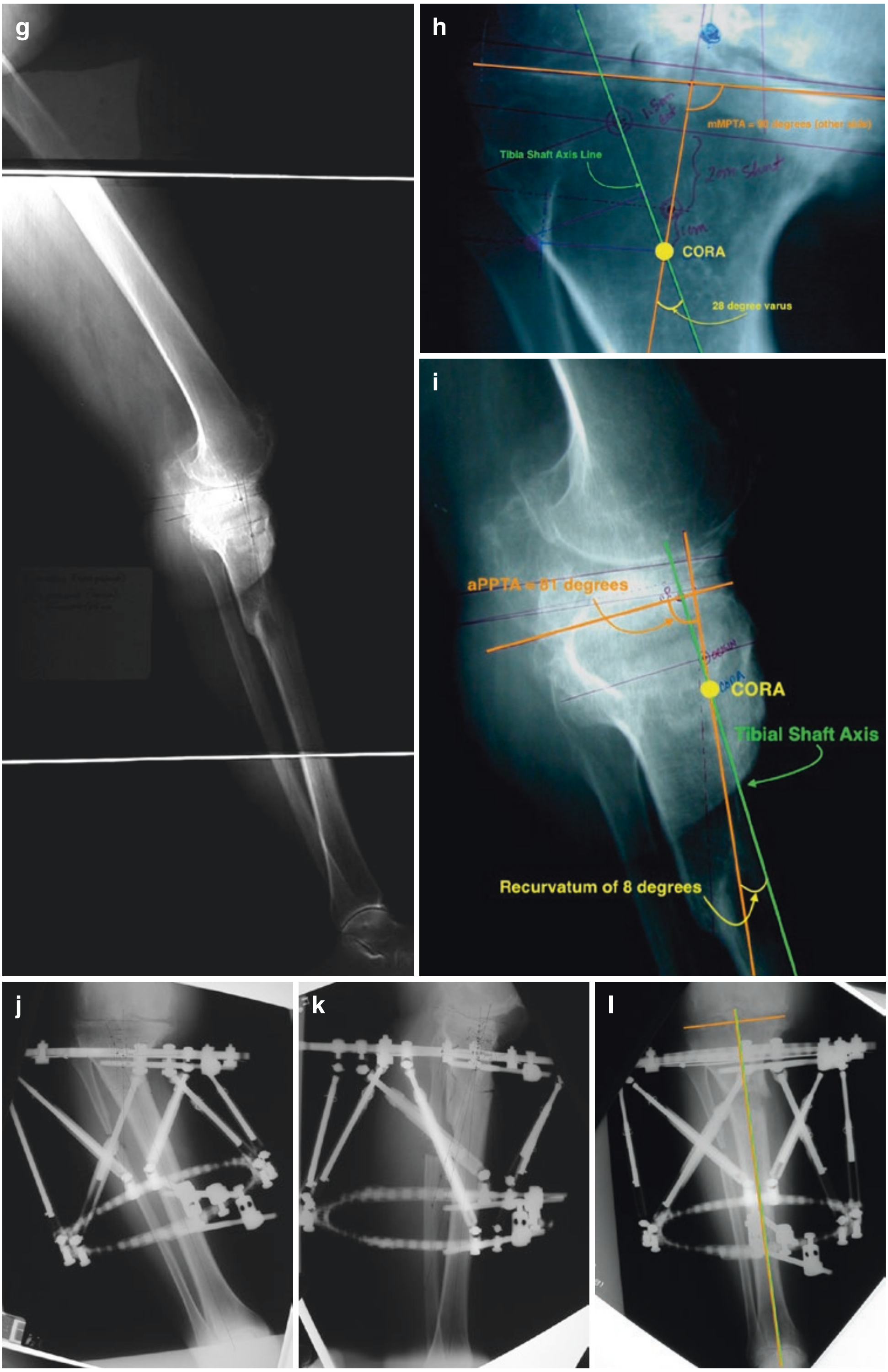


Fig. 12.2 (continued)

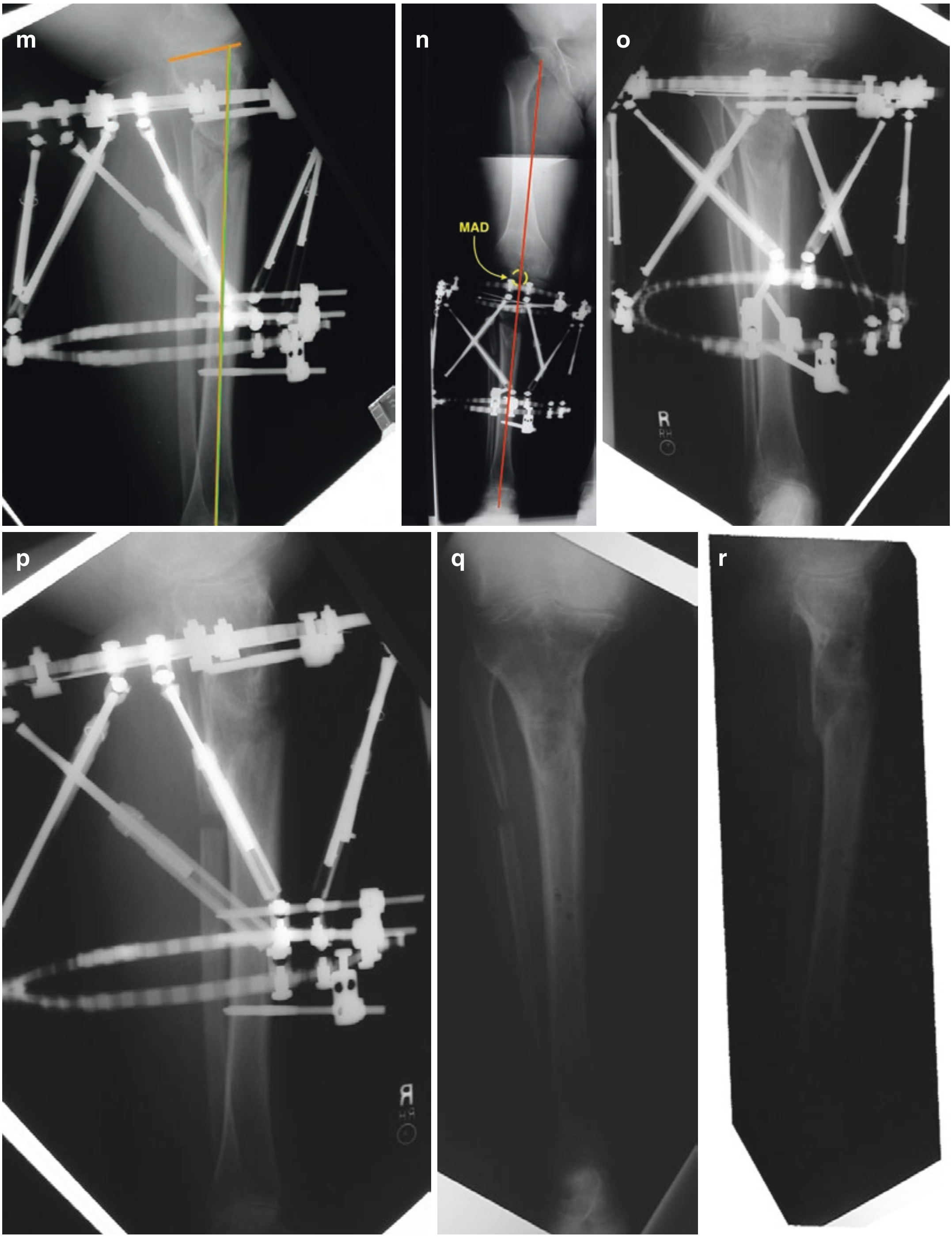


Fig. 12.2 (continued)

presented with increasing knee pain. Figure 12.3a, b shows AP and lateral images of the patient's right knee, showing a valgus deformity with lateral compartment arthritis. Full-length AP and lateral tibia films are seen in Fig. 12.3c, d and shows the full extent of the valgus deformity at the proximal tibia. Figure 12.3e, f is full-length AP and lateral standing of both limbs. The deformity is isolated to the tibia, 24° of valgus and 10° of recurvatum (apex posterior). After a lengthy discussion, and because the patient had significant PTOA in the right lateral compartment, a total knee was certainly an option. However, the severe deformity could not be corrected by a TKA alone. Therefore, correction of the valgus and procurvatum to realign the limb was performed in hopes of realigning the limb to make a TKA more straightforward at a later date. Patient underwent Gigli osteotomy of the metadiaphyseal region of the tibia and an osteotomy of the fibula with application of a Taylor Spatial Frame (Fig. 12.3g, h). Trauma CAD software with the Spatial Frame module was used to determine the frame and deformity parameters (Fig. 12.3i). The peroneal nerve was at risk for stretching, and thus the correction was performed at a slightly lower rate than normal due to the proximity of the nerve to the CORA. Patient underwent gradual correction until the desired alignment was obtained. Figure 12.3j, k is an AP and lateral at 2 weeks after correction began, and notice the improvement in alignment. Figure 12.3l, m shows full correction and continued consolidation of the osteotomy. At 9 months (Fig 12.3n, o) the osteotomy was felt to be completely healed and subsequently, the TSF was removed. Patient's overall alignment had improved significantly as did his pain. Final follow-up films at 21 months are shown in Fig. 12.3p, q.

12.6.3 Case 3

A 54-year-old white male who was driving his moped when he wrecked. Patient sustained a left Schatzker IV tibial plateau fracture that was treated with ORIF 4 weeks prior to presentation. Patient was seen at 2-week follow-up with his surgeon and was told that he had collapsed of the fracture with loss of reduction. He was then referred to me for further evaluation and management. He presented approximately 4 weeks out from the original surgery with the AP and lateral shown in Fig. 12.4a, b. A CT scan was obtained to better evaluate the tibial plateau, and CT scan images are shown in Fig. 12.4c–e (axial, coronal, and sagittal). The CT scan showed clear step-off of the posteromedial tibial plateau with some consolidation at the metaphyseal region. The patient required revision ORIF of the malaligned fracture. Patient subsequently underwent hardware removal and revision ORIF, although at the time of surgery, the fracture for all practical purposes was healed sufficiently that the fracture site with the callous had to be carefully taken down. Figure 12.4f, g shows the immediate postop films (AP and lateral left knee) of the anatomic reduction with buttressing of the posteromedial tibial plateau. The patient went on to heal and regain normal knee motion and function. Figure 12.4h, i shows his AP and lateral left knee at 6 months post-revision ORIF. Last radiographs (Fig. 12.4j, k) at 1-year post-revision show well-healed medial tibial plateau without evidence of PTOA.

12.6.4 Case 4

Patient is a 51-year-old white male who initially sustained multiple injuries in a motor vehicle accident. He had a left grade II open tibial plateau fracture Schatzker VI (Fig. 12.5a, b) in addition to many other injuries. He eventually went on to heal his left Schatzker VI tibial plateau fracture (Fig. 12.5c–d). Incidentally, he also had a left ankle fracture and a left calcaneus fracture that had gone on to heal uneventfully. He also had sequelae from his other injuries including AVN of his left hip which went on to a total hip arthroplasty and a nonunion of the right tibial shaft with a comminuted right bicondylar tibial plateau fracture (healed). The nonunion was addressed with hardware removal and IM nailing, which then eventually healed. His left tibia healed without issues, but due to his other injuries requiring further management, he never noticed any issues with his left tibia. After all his other injuries had been addressed, he started having symptoms of pain and discomfort in the left leg and knee at 2.5 years out. He also complained of "intoeing" of his left leg. Evaluation revealed a 24° internal rotation deformity of the left side relative to the right side. Figure 12.5e, f shows the CT scan cuts through the proximal tibia and the ankle showing the rotational deformity. The patient elected to have corrective surgery. He underwent hardware removal with a transverse osteotomy at the metadiaphyseal junction with de-rotation and IM nail-

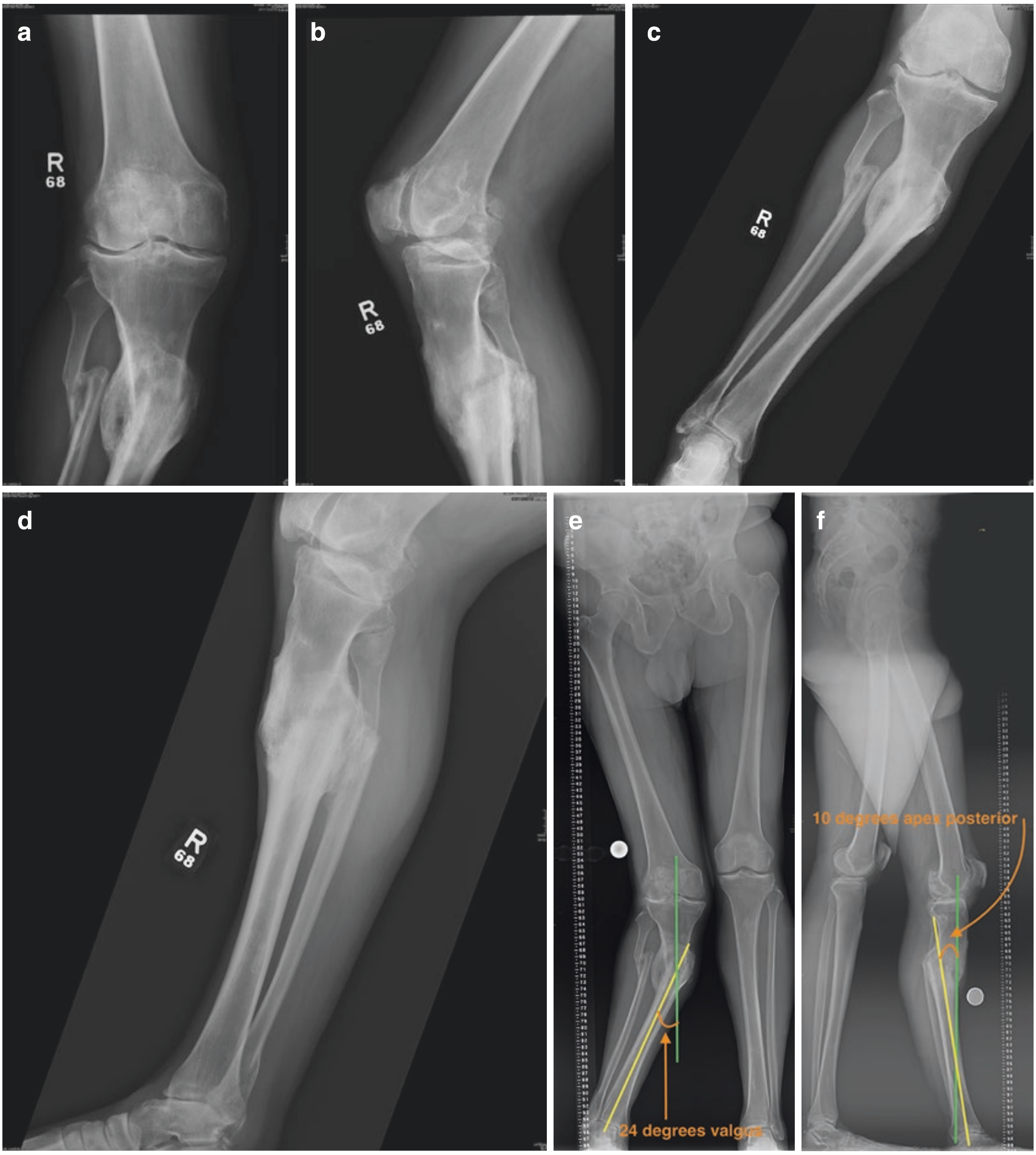


Fig. 12.3 (**a**, **b**) AP and lateral radiographs of the right knee showing the valgus malunion of the proximal tibia along with PTOA in the knee, mainly in the lateral compartment. (**c**, **d**) AP and lateral radiographs of the right tibia showing the valgus deformity being isolated to the proximal tibia with a normal ankle joint. (**e**) AP standing of the entire right lower extremity with ruler and CAD ball. Shows the amount of valgus deformity (24° valgus). (**f**) Lateral standing of the entire right lower extremity with ruler and CAD ball. Shows the amount of sagittal deformity (10° recurvatum). (**g**, **h**) AP and lateral radiographs of the right tibia after application of the TSF and osteotomy. (**i**) PACS output generated from TRAUMA CAD™ showing the deformity parameters and the mounting parameters. It also indicates the deformity itself. (**j**, **k**) AP and lateral radiographs of the right tibia after 2 weeks of correction showing some correction. (**l**, **m**) AP and lateral radiographs of the right tibia after the end of the initial program showing full correction. (**n**, **o**) AP and lateral radiographs of the right tibia after complete consolidation just prior to removal of the TSF. (**p**, **q**) AP and lateral radiographs of the right tibia at his final follow-up at 21 months

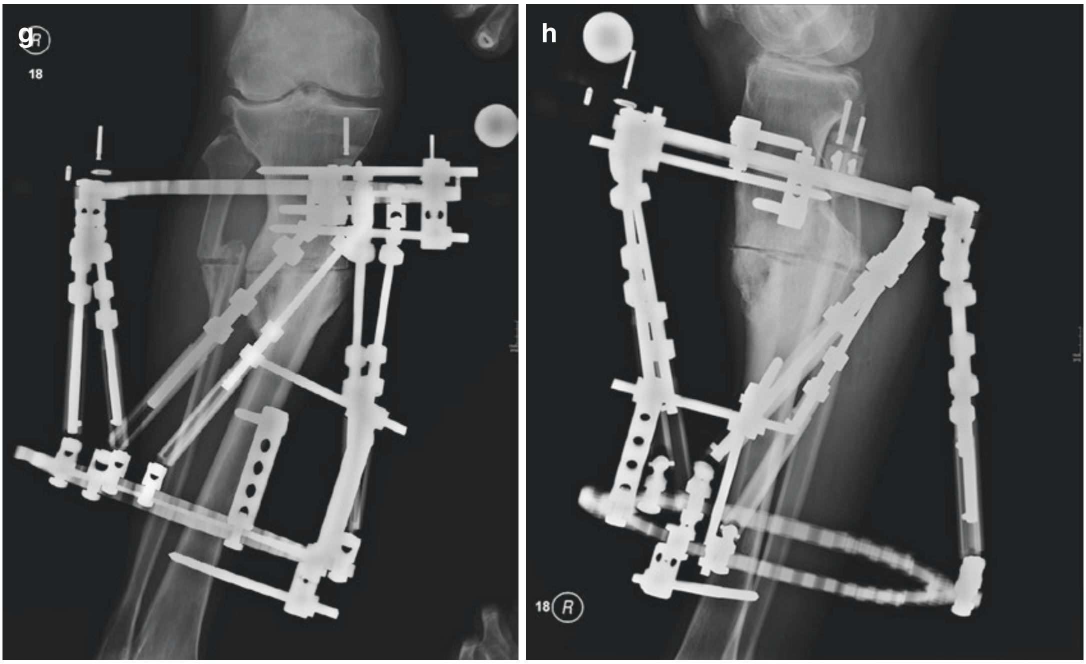


Fig. 12.3 (continued)

i

All information received from the software as output must be clinically reviewed regarding its plausibility before patient treatment!

TraumaCad®
Pre Operative Planning Report

Your LOGO

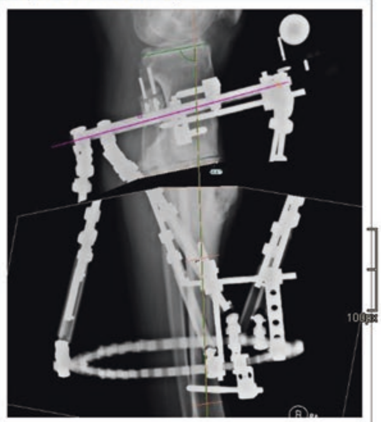
[redacted]

Lateral View:

Measurement Tools Information	
Taylor Spatial Frame	
Deformity Parameters	
AP Angulation	24° Valgus
AP Translation	7.8 mm Medial
LT Angulation	10° Apex Posterior
LT Translation	14.1 mm Posterior
Axial Translation	15.2 mm Short
Mounting Parameters	
AP Frame Offset	13.9 mm Lateral
LT Frame Offset	5.2 mm Anterior
Axial Frame Offset	46.3 mm Proximal
Frame Rotation	24° Internal
Structure at Risk Parameters	
SAR AP Translation	52.3 mm Lateral
SAR LT Translation	18.9 mm Posterior
SAR Axial Translation	51.5 mm Proximal

Original image

Image After Pre-Planning

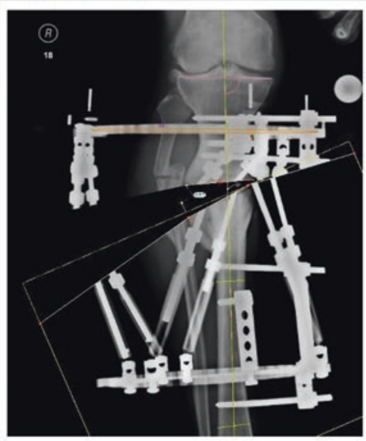


AP View:

Measurement Tools Information	
Taylor Spatial Frame	
Deformity Parameters	
AP Angulation	24° Valgus
AP Translation	7.8 mm Medial
LT Angulation	10° Apex Posterior
LT Translation	14.1 mm Posterior
Axial Translation	15.2 mm Short
Mounting Parameters	
AP Frame Offset	13.9 mm Lateral
LT Frame Offset	5.2 mm Anterior
Axial Frame Offset	46.3 mm Proximal
Frame Rotation	24° Internal
Structure at Risk Parameters	
SAR AP Translation	52.3 mm Lateral
SAR LT Translation	18.9 mm Posterior
SAR Axial Translation	51.5 mm Proximal

Original image

Image After Pre-Planning



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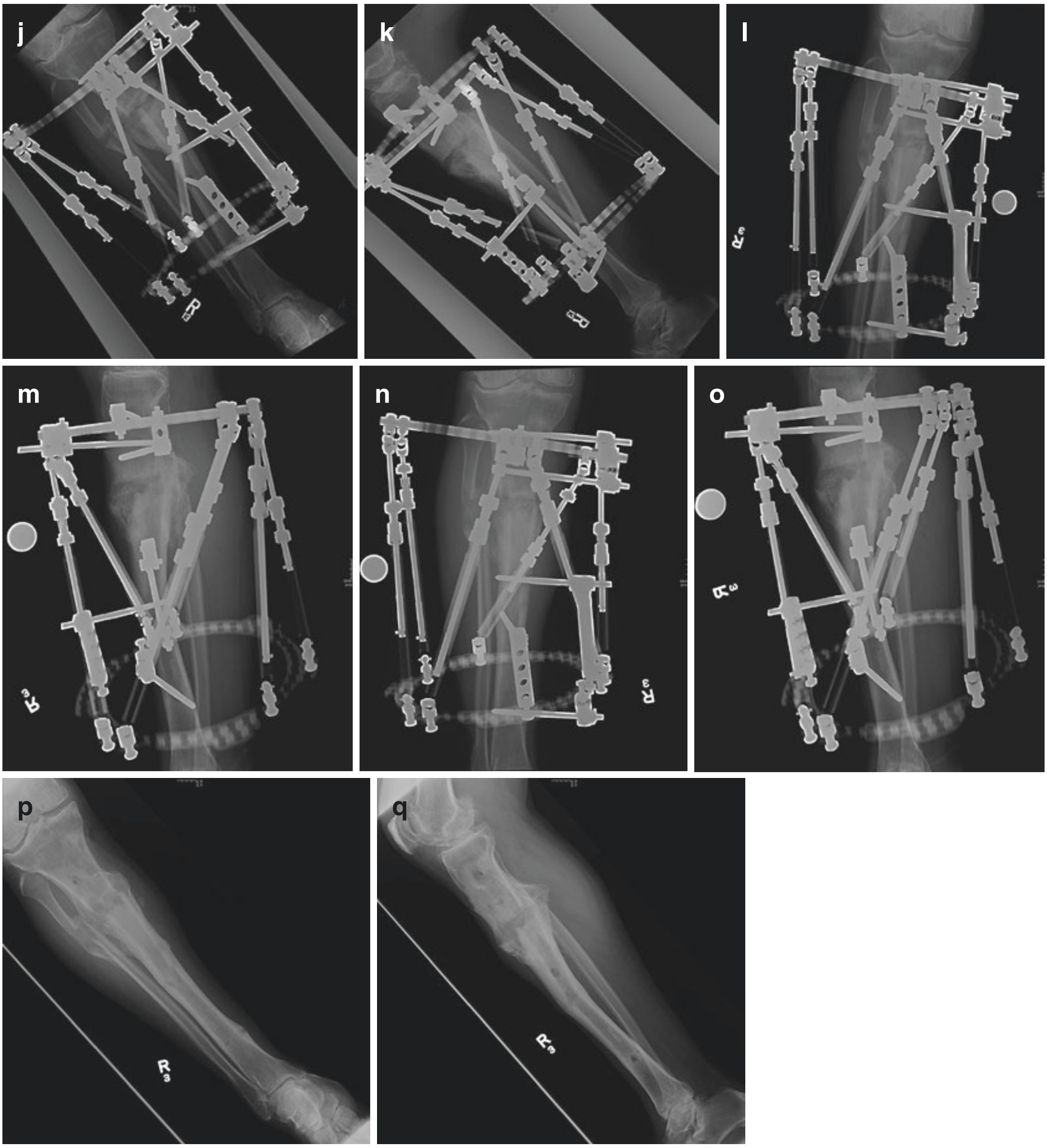


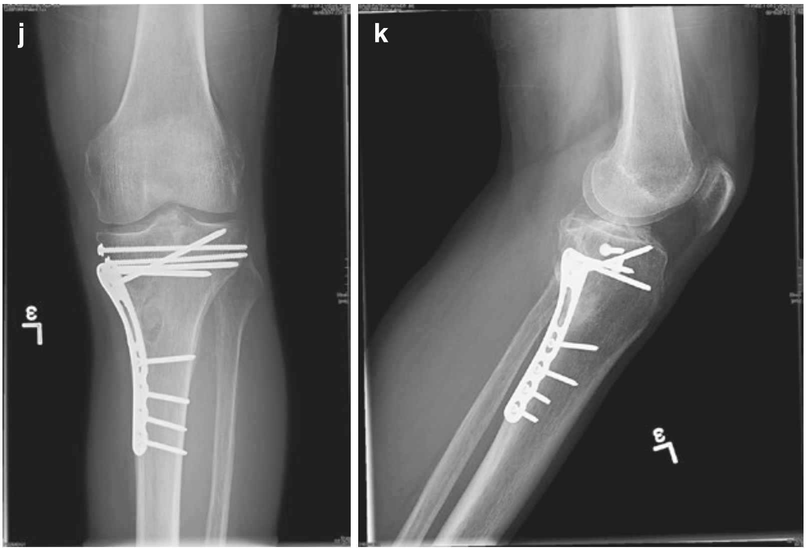
Fig. 12.3 (continued)

ing (Fig. 12.5g, h). Patient went on to uneventful healing, and last radiographs at 1 year show complete consolidation of the osteotomy site (Fig. 12.5i, j).

12.6.5 Case 5

A 53-year-old white female was skiing, injuring her left knee and sustaining a highly comminuted lateral tibial plateau fracture 4 months prior to presentation. Patient was treated at an outside facility with ORIF. She subsequently developed loss of the joint reduction with collapse and was referred to me for instability and a malunion of the lateral tibial plateau. Figure 12.6a, b shows AP and lateral of her left knee upon presentation. Patient had a CT scan obtained which showed that the metaphyseal region had healed as well as the lateral joint, but in a malaligned, collapsed position. Due to her young age and no evidence of medial or patellofemoral arthritis, reconstruction

Fig. 12.4 (**a**, **b**) AP and lateral radiographs of patient's left knee after failed ORIF showing the varus malalignment of the medial proximal tibial plateau. (**c-e**) Axial, coronal, and sagittal CT cuts showing the malaligned medial tibial plateau fracture with consolidation of the metaphyseal bone. The step-off on the sagittal view is clearly visible. (**f**, **g**) Immediate postoperative AP and lateral radiographs of the left knee showing anatomic reduction after takedown and osteotomy of the fracture plane for revision ORIF. (**h**, **i**) AP and lateral radiographs of the left knee at 6 months showing complete healing and maintenance of the joint without evidence of PTOA. (**j**, **k**) AP and lateral radiographs of the left knee at 1 year showing maintenance of the joint without evidence of PTOA



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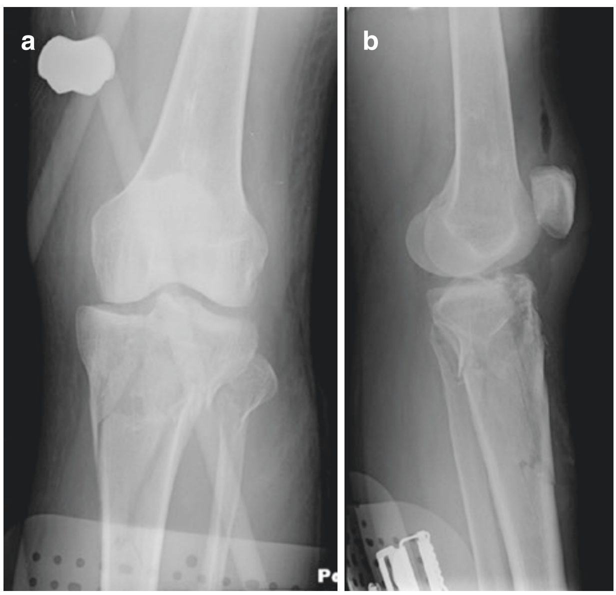
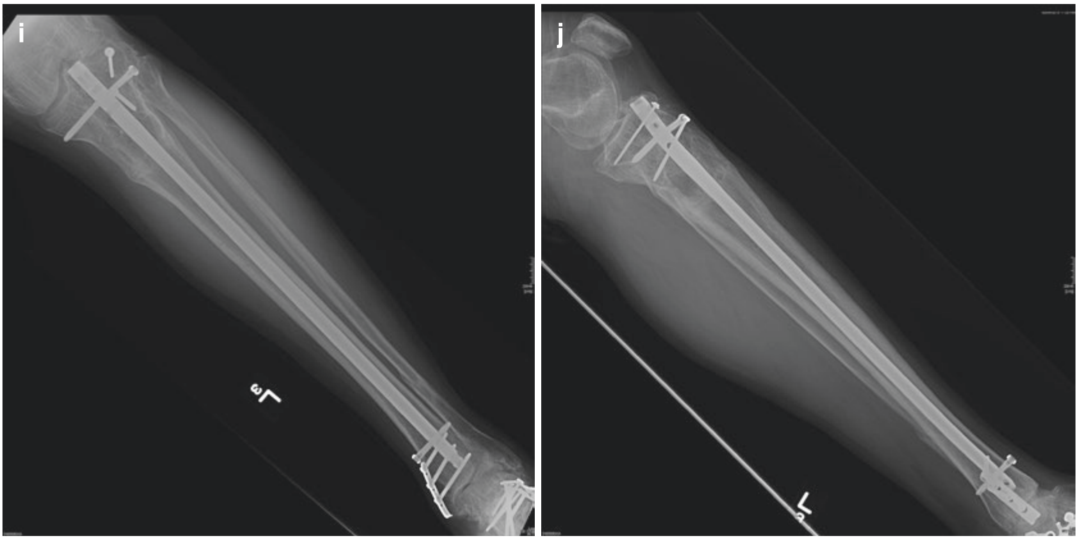


Fig. 12.5 (**a**, **b**) AP and lateral radiographs of left knee after initial spanning ex fix showing the Schatzker VI tibial plateau fracture. The involvement of the tibial tubercle is seen on the lateral image. (**c**, **d**) AP and lateral of the left tibia 2.5 years later showing healed bicondylar tibial plateau fracture. The ankle hardware and calcaneus hardware are also seen. (**e**, **f**) CT scan of the bilateral tibias with select cuts through the (e) proximal tibia, showing the relative external rotation of the left knee compared to the right, and (f) distal tibia, showing the relative internal rotation of the left distal tibia compared to the right. The net result was a 24° internal rotation deformity on the left side. (**g**, **h**) Postoperative AP and lateral radiographs of the left tibia after transverse osteotomy and correction of the rotational malalignment with intramedullary fixation. (**i**, **j**) AP and lateral radiographs at 1 year showing a healed osteotomy site and correction of the rotational deformity. The patient's discomfort and knee pain had resolved

Fig. 12.5 (continued)



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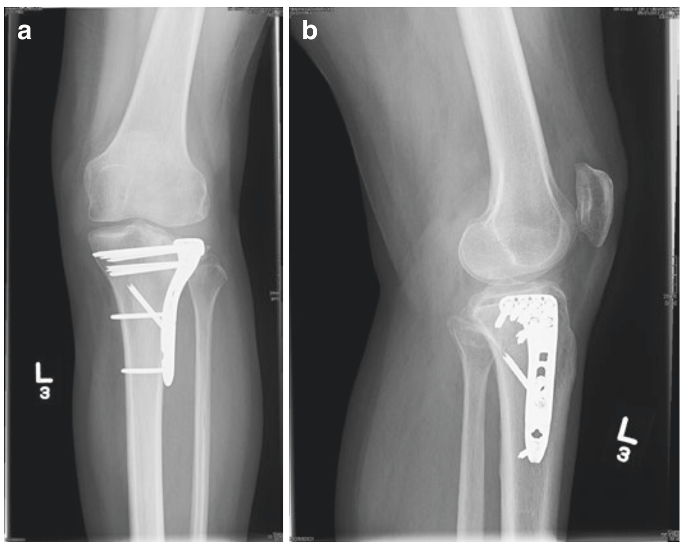
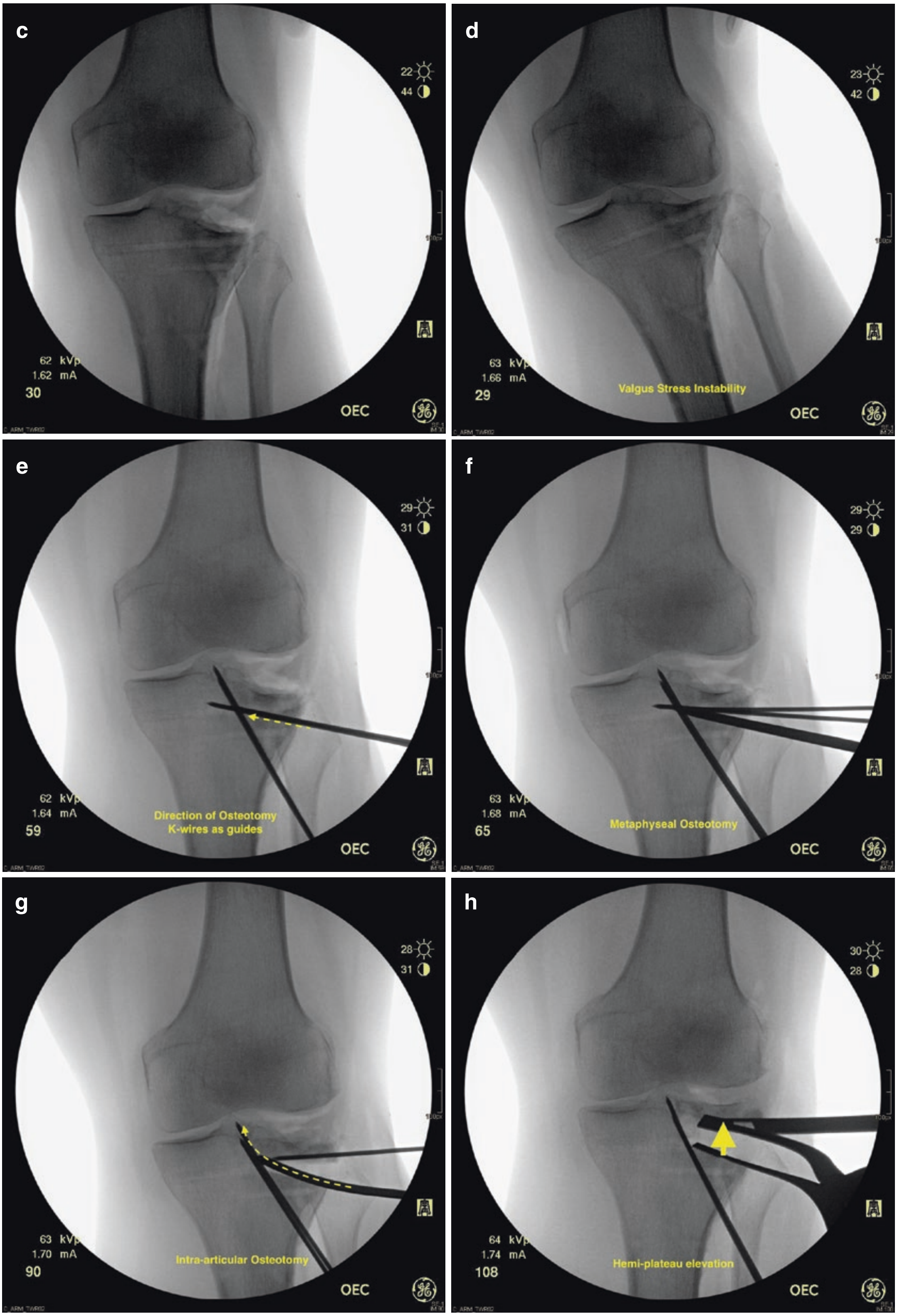


Fig. 12.6 (**a**, **b**) Presenting AP and lateral radiographs of the left knee showing the collapse of the lateral tibial plateau with an intra-articular malunion. (**c**) Intraoperative film showing the depressed lateral tibial plateau after hardware removal. (**d**) Intraoperative film showing the valgus stress instability. (**e–m**) Intraoperative images showing the technique for osteotomy and elevation – (**e**) K-wires placed to help guide osteotomy – direction of osteotomy shown by *yellow dashed line*; (**f**) metaphyseal osteotomy; (**g**) curved osteotome used to take osteotomy to joint; (**h**) AP view showing use of the lamina spreader to elevate the hemi-plateau; (**i**) lateral view showing use of the lamina spreader to elevate the posterior aspect of the hemi-plateau (dotted line); (**j**) placement of K-wire to help stabilize the hemi-plateau; (**k**) placement of bone graft into osteotomy site and second pin placed into hemi-plateau; (**l**, **m**) AP and lateral intraoperative images after placement of plate to support hemi-plateau elevation and span osteotomy site. (**n**, **o**) Immediate postoperative AP and lateral radiographs of the knee showing reduction of the lateral tibial plateau after osteotomy. (**p**, **q**) AP and lateral radiographs of the knee at 6 weeks postoperatively showing fair maintenance of the joint with some collapse. (**r**, **s**) AP and lateral radiographs of the knee at 3 months postoperatively showing healed osteotomy site with some loss of the joint. (**t**, **u**) AP and lateral radiographs of the knee at 1 year postoperatively showing some loss of the joint space out laterally. (**v**) AP standing of bilateral knees at 1 year showing minimal valgus alignment on weight bearing on the left compared to her varus alignment on the right. (**w–y**) AP standing of bilateral lower extremities at 2 years showing the MAD. The yellow dashed line shows the MAD on the right side through the medial compartment. The green dashed line shows the MAD on the left side going through the medial aspect of the lateral joint



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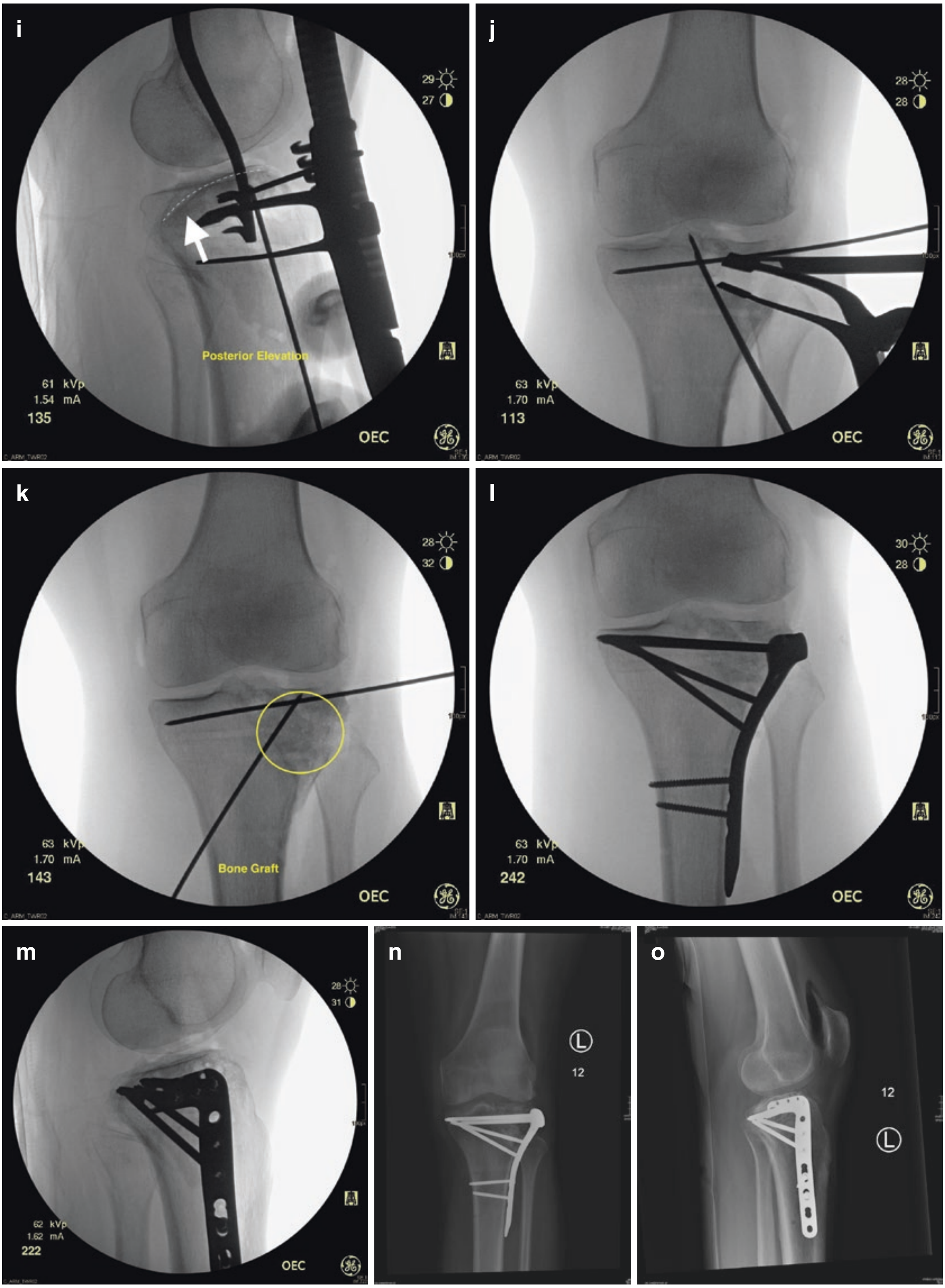

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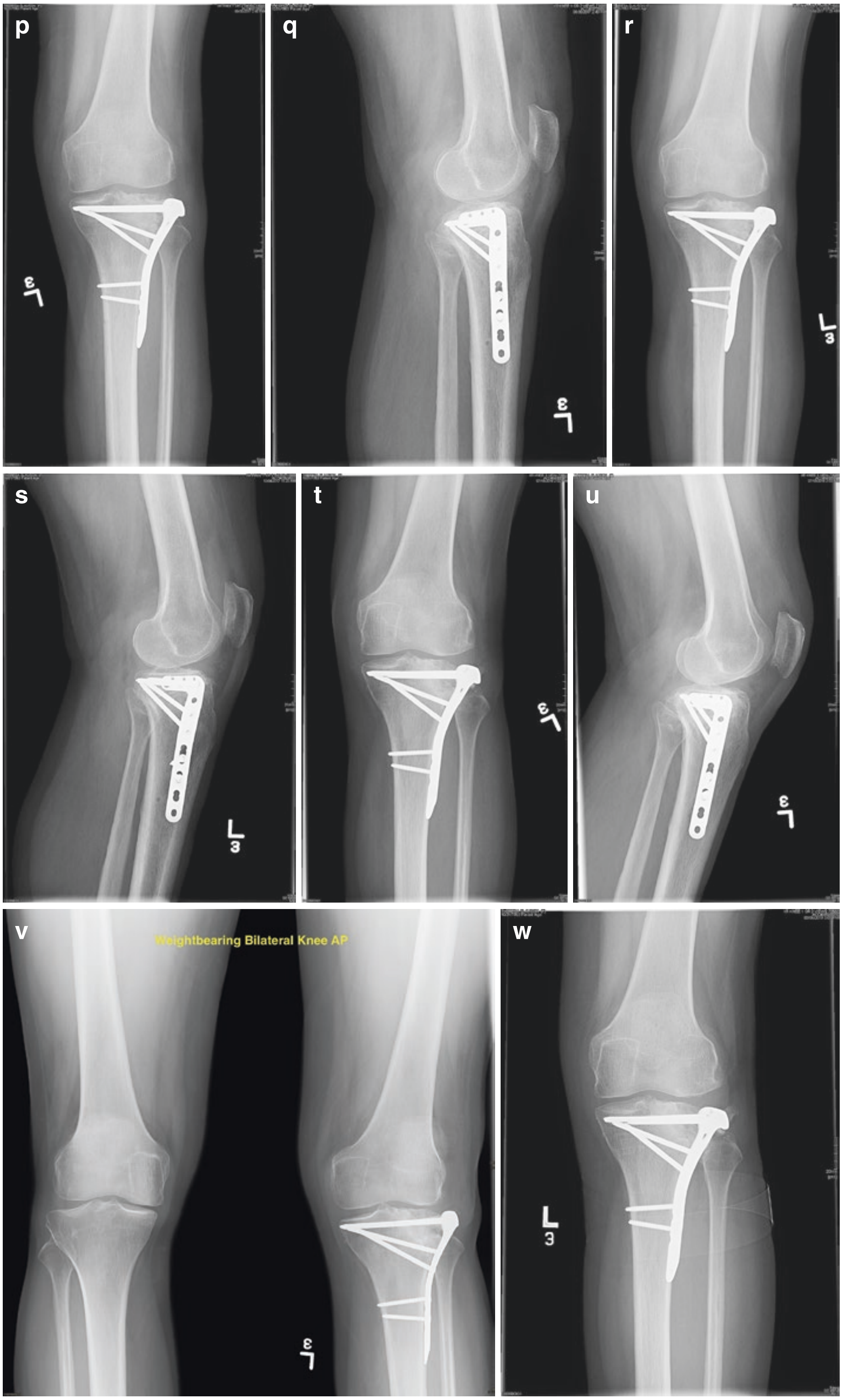

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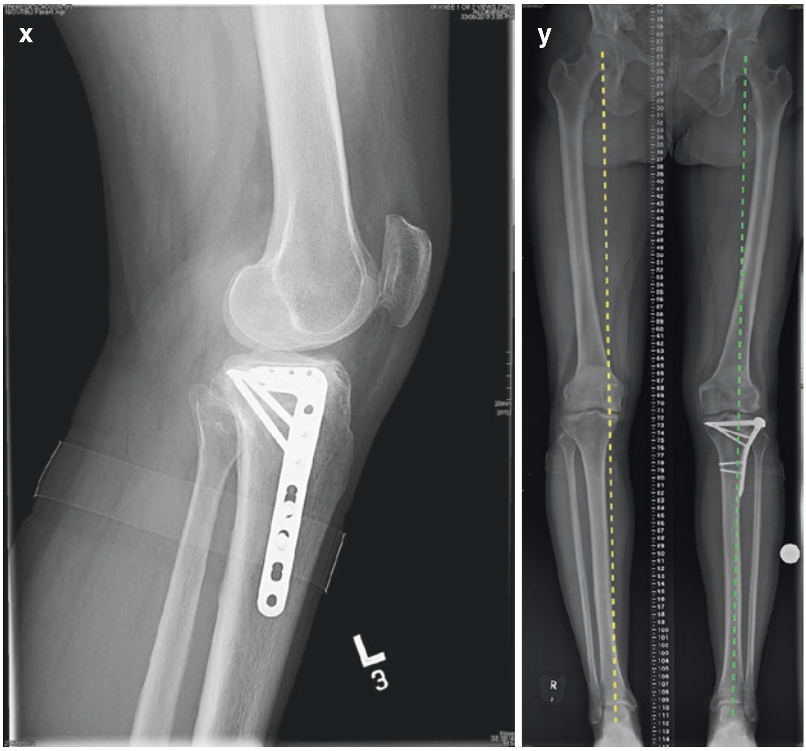

Fig. 12.6 (continued)

with an intra-articular osteotomy was planned. Patient was taken to the operating room where the hardware was removed and the knee evaluated. She had valgus instability with a malunion of the entire tibial plateau and preservation of the meniscus (Fig. 12.6c, d). Intraoperative images show the technique used to create an intra-articular osteotomy, elevation of the hemi-plateau, followed by bone grafting, and ORIF (Fig. 12.6e–m). Immediate postoperative films show correction of the intra-articular malunion with plate application (Fig. 12.6n, o). Patient went on to heal although there was some loss of bone on the lateral side (Fig. 12.6p, q, 6 weeks; Fig 12.6r, s, 3 months). Patient did wear hinged knee brace for 3 months and then transitioned to a varus knee brace. The laxity improved with time. At 1 year, the patient had minimal discomfort and had actually returned to skiing (Fig. 12.6t, u). Figure 12.6v is a standing bilateral AP of both knees showing mild valgus alignment compared to the right, but clinically stable. At her last follow-up (20 months), the patient was doing well and continued to improve (Fig. 12.6w–y). A long leg standing AP of bilateral lower extremities showed that her MAD was approximately 8 mm lateral as opposed to her right knee which showed excessive varus with a MAD of 26 mm media.

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Malunions of the Tibial Shaft

13

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13.1 Introduction

Tibial shaft malunions are a poorly studied subset of complications following healing of tibial shaft fractures. Malunions result in deformity of the tibia in multiple axes and are frequently associated with limb length inequality. Derangements of the mechanical axis lead to adjacent joint degenerative changes and alterations in gait. Patients with tibial malunion tend to have significant functional impairment, dissatisfactory cosmesis, and chronic pain preventing them from working and their activities of daily living. They tend to present to the orthopedic traumatologist with a long and complicated medical and surgical history, often with previous failed management and/or infection. Historically, the treatment of tibial shaft malunions was limited and morbid, but with the advances in limb lengthening techniques and angular correction technology, we are better armed to help patients with this complex problem.

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13.1.1 Midshaft Tibia Fractures

Tibial shaft fractures are the most common long bone fractures and due to the relationship of the tibia and the adjacent soft tissues, the most common open fractures seen and treated by the orthopedic surgeon [1]. The incidence of tibial shaft fractures ranges from 16.9/100,000/year to 22.0/100,000/year [1, 2]. Tibial shaft fractures tend to occur from direct trauma such as direct impact in motor vehicle collisions and motorcycle crashes. These fractures can also be caused by indirect trauma such as falls. Due to the higher energy mechanisms of open tibial shaft fractures, these fractures often occur in the multiply injured patient. Midshaft tibia fractures are defined by the fracture pattern involving primarily the diaphyseal portion of the tibia – AO/OTA 42-A/B/C. These can be further subcategorized as proximal 1/3, middle 1/3, and distal 1/3 tibial shaft fractures. By definition, these fractures are extra-articular, but can be associated with ipsilateral intra-articular fractures that should not be missed, such as the posterior malleolus fracture seen in distal 1/3 spiral tibial shaft fractures.

Treatment of adult midshaft tibia fractures depends on the mechanism of injury and the resulting fracture pattern. Acutely, midshaft tibia fractures should be preliminarily stabilized with a splint to allow for fracture immobilization in the setting of soft tissue swelling. Low-energy, simple fractures that are well-aligned can be treated nonoperatively with cast followed by

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fracture brace immobilization. This treatment decision also applies to patients who are nonambulatory or too sick to undergo surgery. However, the vast majority of tibial shaft fractures tend to occur with higher energy mechanisms and are not amenable to nonoperative management. Operative fixation depends on surgeon preference as well as fracture pattern and if the fracture is open with a wide variety of options including intramedullary nailing, conventional plating, uniplanar external fixation, circular external fixation, and computer-assisted angular correction with circular external fixation. The treating orthopedist has a wide array of adjunctive tools and options to ensure adequate reduction, maximize union of the fracture, and minimize the risk of malunion and nonunion including blocking screws, external fixation assistance, and unicortical plating [3].

There are currently no large prospective, long-term studies evaluating the prognosis of these fractures. Lefaivre et al. demonstrated that the functional outcome scores (SF-36 and Short Musculoskeletal Functional Assessment) of 56 patients at a median of 14 years of follow-up after tibial shaft fracture intramedullary nailing were equivalent to population norms, but of note, they commented that they had a low enrollment rate demonstrating the instability and difficulty in follow-up in a trauma population [4]. However, advances in the treatment algorithm and treatment techniques of midshaft tibia fractures have allowed the general orthopedist to successfully treat these fractures and minimize associated complications.

13.1.2 Definition of Malunions

Tibial shaft malunion is often defined as shortening of the tibia greater than 20 mm compared to contralateral leg or malalignment of greater than 5° in any plane including coronal (valgus and varus deformities), sagittal (procurvatum and recurvatum deformities), and rotational (internal and external rotation deformities). However, these numbers are somewhat arbitrary as most tibial shaft malunions include a combination of the aforementioned planar deformities and malalignment less than that noted above can be symptomatic in some patients. The amount of acceptable angulation in each plane following a deforming fracture has not been clearly agreed upon [5]. A review of the collective literature assessing these parameters results in the following acceptable alignment criteria, although these numbers should always be considered in the context of the clinical examination and patient-reported symptoms:

- Shortening <10 mm [6]
- Coronal angulation <5° [7]
- Sagittal angulation <10° [8]
- Oblique plane angulation <10° [9, 10]
- Translation <50% of cortical width [11]
- Rotational deformity <10° [10]

13.1.3 Incidence of Malunions

A review of the literature and studies evaluating malunion after tibial shaft fracture fixation reports an incidence between 7.1% and 40.9%, but these studies were primarily evaluating proximal tibia fractures (AO/OTA 41) [12–15]. There is a paucity of literature regarding the incidence of malunions after management of isolated midshaft tibia fractures. As such, the true incidence of tibial shaft malunions is currently unknown.

13.1.4 Ramifications of Malunions

Malunions of the tibial shaft can be very disabling and prevent patients from returning to work or from even performing their activities of daily living. Many patients with a disabling tibial shaft malunion have a clinically significant limb length inequality due to a combination of the angular deformities and bone loss from either the initial trauma or subsequent surgeries. Additionally, patients may present with compensatory soft tissue contractures of the foot and ankle. Chronic malunions have been demonstrated to lead to increased degenerative joint disease in the knee and ankle. In a rabbit model in which 30° angular malunions were created in the tibia, Wu et al. observed histologic changes in both cartilage and bone on the overloaded condyle over a 34-week period [16]. These findings have also been demonstrated in cadaveric models. McKellop et al. used pressure-sensitive film to demonstrate that simulated 20° malunions of the tibia in both varus and valgus directions led to doubling of contact pressure across the knee [17]. Tarr et al. demonstrated that simulated malunions in the distal third of the tibia altered the biomechanics at the ankle joint [18]. Retrospective clinical study by Kyro et al. compared the function of 17 patients with tibial malunion to that of 47 patients without malunion. The study found significantly more subjective complaints and functional limitations in patients with tibial shaft angulation >5° [19]. Additionally, many patients report dissatisfaction with the overall cosmesis of their leg deformity. When combining all of the aforementioned factors leading to pain and poor function, tibial shaft malunions have significant detrimental effects on the everyday life of the affected patient.

13.2 Considerations in Evaluating Malunions

There have not been studies that have identified the primary etiology leading to tibial shaft malunions after treatment, but rather it appears to be a multifactorial problem. In the following sections, several considerations in evaluating tibial shaft malunions will be discussed.

13.2.1 Mechanical Considerations

In order to understand the pathomechanics of the tibial shaft malunion, it is important to understand the normal biomechanics of the lower extremity. The mechanical axis of the lower extremity passes from the center of the femoral head to the center of the ankle (or calcaneal tuberosity). The average mechanical axis using these landmarks crosses the knee 10 mm medial to the center of the knee in the frontal plane, which coincides with the location of the medial tibial spine [20]. In the sagittal plane, the mechanical axis lies just anterior to the center of rotation of the knee joint, which is optimal as it allows for passive locking of the knee in full extension [20]. The mechanical axis of the lower extremity coincides with the anatomical axis of the tibia [20]. Malunions of the tibial shaft in the coronal and sagittal planes result in a dissociation of the anatomic and mechanical axes of the tibia leading to functional impairment.

Both the knee and the ankle joints must be taken into consideration when evaluating a patient with a tibial shaft malunion. Although the malunion of the tibial shaft is by definition extra-articular, it can have profound effects on the biomechanics of the knee and ankle joints as described previously. Increased contact forces, early cartilage wear, and asymmetric ligamentous laxity are the repercussions of a malaligned tibial shaft from the lower extremity's normal mechanical axis [16–19]. Kettelkamp et al. reported that >5° coronal plane deformity predicted ipsilateral knee arthritis in a study of 15 tibia fractures treated nonoperatively with a mean follow-up of 37 years [21].

The presence of an intact fibula at the time of tibial shaft fracture fixation increases the risk of malreduction and resulting malunion. Varus malunion in proximal third tibial shaft fractures tend to occur when there is an intact fibula as the fibula functions as a lateral buttress during weight-bearing, leading to varus deformity [22]. Sarmiento et al. documented conservative management in 68 patients with a nonarticular proximal tibia fracture and found that 61% of patients had >5° of varus malalignment when the fibula was intact [23].

13.2.2 Patient Considerations

There are several patient comorbid conditions that should be considered when evaluating a patient with a tibial shaft malunion and considering operative correction. Nutritional status is important when evaluating a patient for corticotomy union and soft tissue/wound healing. It is common to focus on calcium and vitamin D when discussing fracture healing and bone health. However, healthy bone requires not only sufficient quantities of calcium and vitamin D but also sufficient amounts of other micronutrients that support the structure of collagen such as vitamin C, lysine, and proline amino acids [24]. Guo et al. evaluated the effects of different nutritional measurements on wound healing status after hip fracture in the elderly. They measured serum albumin, serum transferrin, serum prealbumin, and total lymphocyte count levels as parameters indicative of nutritional status. According to their study, 22.2% suffered complications due to delayed wound healing associated with malnutrition [25]. Tobacco use has been linked with delayed fracture healing and nonunion [26]. These patients should be counseled on the importance of smoking cessation and be provided resources to help them quit smoking. Diabetes has been demonstrated to negatively impact fracture healing and wound healing [27]. Patients with diabetes should be counseled on their increased risk and the importance of tight glycemic control and optimization of hemoglobin A1c.

Patient noncompliance should be carefully assessed as compliance during the postoperative course after corrective osteotomy and fixation is critical to its success, especially with the patient-centric labor-intensive six-axis deformity correction circular external fixators. Patients with a history of poor follow-up or malunion resulting in part from weight-bearing restriction noncompliance and noncompliance with proper rehabilitation protocol should have a discussion regarding the consequences and worse outcomes with noncompliance.

In addition to patient noncompliance, there are several patient demographic and socioeconomic factors that have been linked to overall worse outcomes. Baseline poor social support systems, low self-efficacy, poverty, and substance abuse are more frequent among high-energy trauma patients. These patient factors are associated with a heightened psychological distress response after trauma and with lower rates of return to employment and worse functional outcome scores [28–30]. Other studies support these conclusions, including additional patient factors such as lower education, poor coping, and mental illness as predictors of poor functional outcome [31]. These studies demonstrate the need for optimization of the patient's social milieu and psychological counseling to maximize patient outcomes and help patients return to work and their activities of daily living.

13.3 Evaluation and Diagnosis

The basic principles of a thorough history and physical examination, coupled with appropriate imaging and laboratory tests, are the core components in the general workup and evaluation of a patient presenting with a midshaft tibia malunion. In the upcoming subsections, specific points in the evaluation and workup pertaining to tibial shaft malunions will be discussed.

13.3.1 History

It is paramount to fully understand a patient's clinical course leading to the midshaft tibia malunion. These patients often have a complex history with significant variation from one patient to another. The initial portion of the history gathering should be devoted to understanding the mechanism of injury – high energy versus low energy. The management and clinical course varies depending on the mechanism of injury. Additionally, the clinician should identify if the patient sustained an open or closed fracture. Open fractures should prompt an investigation into the size of the wound, the contamination, the number of surgeries before the definitive fixation, and the soft tissue coverage used. Understanding the patient's soft tissue coverage is critical as it affects the planning and the corrective procedure for the tibial shaft malunion. Additionally, clarifying if the patient had complications associated with infection, whether superficial or deep and acute versus chronic, is important for the surgical planning as it provides an idea of the quality of the patient's soft tissues and the quality of the remaining bone stock. A comprehensive understanding of a patient's previous clinical course can be difficult to obtain based on the patient's recollection and as such, it is suggested that the patient obtain all relevant clinical documents, including detailed operative reports.

After obtaining a thorough history of the patient's clinical course leading up the malunion, a carefully medical history should be obtained for concomitant medical comorbidities such as diabetes, osteoporosis, HIV, and other immunocompromised states to determine the patient's risk for decreased bone healing and union, soft tissue healing, and ability to tolerate the procedure and the extensive postoperative rehabilitation course. A social history is very important in this patient population as any tobacco use would predispose the patient to additional complications from the planned intervention and risk causing more harm than good. A patient's narcotic and illicit drug histories are important to obtain as chronic opioid and illicit drug use also lead to postoperative complications and difficulty with postoperative pain control.

13.3.2 Physical Examination

Malunion of the tibia results in a myriad of angular deformities in varus, valgus, procurvatum, recurvatum, external rotation, internal rotation, and shortening with many combinations of the aforementioned deformities. An initial inspection of the affected leg also yields a significant amount of information in addition to the gross deformity. The overall skin and soft tissue quality should be assessed. Previous skin grafts or flap coverage should be noted. The presence of erythema, warmth, and/or sinus tracts should raise concerns for acute and chronic soft tissue infection and osteomyelitis.

Knee and ankle range of motion should be assessed as best as possible as patients will often present with limitations from pain and/or contractures. A ligamentous exam should also be documented as derangements in the mechanical and anatomic axes of the leg can lead to ligamentous laxity and imbalance. Muscle strength and size should be assessed to ensure that the patient has the capacity for postoperative rehabilitation and return to function.

Additionally, the evaluating clinician should be vigilant for limb length inequalities which are very common in this subset of patients. Limb length can be clinically assessed with calibrated blocks leveling the anterior superior iliac spines. The contribution of the tibia to the total limb length inequality can then be assessed with the patient in prone with the knee flexed to 90° and measured against the contralateral leg.

13.3.3 Laboratory Tests

In addition to the standard complete blood count (CBC) and the basic metabolic panel (BMP), patients should be worked up with c-reactive protein (CRP) and erythrocyte sedimentation rate (ESR) to rule out any infectious processes that may be smoldering or active. Endocrinopathies and nutritional deficiencies that may have led to delayed healing should be assessed with the appropriate laboratory studies and corrected by an endocrinologist or nutritionist if necessary. Patients with diabetes should have a hemoglobin A1c and blood glucose checked. These patients should strive for optimal glycemic control with their primary care provider or endocrinologist prior to undergoing corrective surgery for their malunion as uncontrolled diabetes increases the patient's risk of postoperative complications.

13.3.4 Radiographs

Standard anteroposterior (AP) and lateral radiographs of the entire tibia and fibula should be obtained. Additionally, it is paramount to also obtain full-length standing AP and lateral radiographs of the bilateral lower extremities (standing modified teleoroentgenogram) using computed radiography to minimize the magnification error [32]. This study provides clear information regarding the limb length inequality and complements the clinical evaluation. Radiographs of the knee in the AP, lateral, merchant, and notch views are helpful in assessing the extent of the patient's degenerative joint disease. Standing AP, lateral, and mortise radiographs of the ipsilateral ankle provide similar information for the ankle joint.

13.3.5 Advanced Imaging

Computer tomography (CT) should be obtained to better assess the planes of deformity and to provide a three-dimensional representation of the tibia and fibula. The CT scan provides detail that orthogonal plain radiographs cannot fully capture allowing the clinician to better understand the combination of the rotational, coronal, and sagittal malalignments. Puloski et al. demonstrated that CT scan was an effective study to evaluate tibial shaft rotation where they found a higher incidence of malrotation than previously reported using non-CT modalities [10]. Additionally, in order to perform the computer-assisted correction with the six-axis circular external fixator (Taylor Spatial Frame [TSF], Smith and Nephew, Memphis, USA), a CT scan is required to design the postoperative correction protocol.

Magnetic resonance imaging (MRI) provides valuable information when attempting to better understand the soft tissue and bone quality. It should not be used instead of the CT scan to assess osseous architecture, but rather should be used as an adjunct in cases where there is a need to better assess the presence and extent of soft tissue infection and osteomyelitis.

Nuclear imaging is an option when there is a suspicion for infection that is not clearly delineated on the MRI. Typically, these studies are not necessary for the evaluation and preoperative planning for tibial shaft malunions but should be considered in the scenario where the patient has laboratory values concerning possible infection in the setting of an equivocal MRI. Many patients who present for management of their tibial shaft malunions have undergone several surgeries with or without soft tissue mobilization and coverage which can distort the interpretation of the MRI.

13.4 Treatment

The first step in treatment is to synthesize the information available to determine what patient complaints must be addressed. It is also critical to understand the history of the injury and prior treatments as this often provides valuable insights into the potential for latent infection, viability of bone segments, and potential for soft tissue problems during reconstruction.

In patients presenting with mild deformity that are primarily complaining of symptoms related to limb length inequality, it is prudent to attempt conservative nonoperative management initially. Load-transferring braces and shoe orthoses can be employed. Shoe lifts including inserts, custom soles, or "even-up" external devices play an important role in addressing symptoms and also serve as an important clinical test to determine the actual limb length inequality prior to attempts at correction. Patients presenting with adjacent joint stiffness and contractures as well as muscle atrophy and weakness should undergo a course of physical therapy and rehabilitation to maximize joint range of motion and muscle strength prior to corrective surgery.

Patients presenting with an underlying infection diagnosed by history, physical exam, imaging, or elevated inflammatory laboratory values must be thoroughly evaluated prior to surgical correction. The method of correction may be seriously influenced by the presence or absence of infection. If internal fixation is to be used for correction of the deformity, then treatment of the infection must be done prior to corrective surgery. This can include bone biopsy to ideally identify the offending organism and directed treatment. In addition, a thorough debridement and placement of local antibiotic delivery devices may be necessary to eradicate the infection. In the case that an organism is not identified, the osteomyelitis should be empirically treated with intravenous broad-spectrum antibiotics and demonstrate clinical resolution prior to surgery. External fixation is more forgiving in the face of infection and it is often possible to proceed with treatment of the malunion while simultaneously addressing infection. This is especially true when resection of an infected segment of osteomyelitis with subsequent bone transport is planned as the reconstructive pathway.

Soft tissue quality and coverage is often a concern in this patient population. High energy mechanisms of injury and multiple surgeries compromise the adjacent and surrounding soft tissue envelope which complicates the approach for the corrective procedure. Preoperative planning for potential soft tissue coverage and consultation of the plastic surgery are important considerations before attempting a large surgical correction of the tibial shaft malunion.

Thorough radiographic evaluation and characterization of the malunion is mandatory prior to corrective surgery. Most malunions of the tibial shaft have a single center of rotation and angulation (CORA) around which the correction can be planned, but if the deformity is multifocal, this must be identified in the planning stage. Ideally, correction of the deformity is performed with an osteotomy through the CORA. An osteotomy performed through the CORA allows for simple angular correction without the need for translation. However, soft tissue constraints or issues with the underlying bone sometimes make this inadvisable. It is critical to preoperatively plan where the osteotomy will be performed and how the bone segments must move to completely correct the deformity. This information will allow the surgeon to determine what fixation options can be used for stabilization when the correction is complete. For instance, when correction of the alignment requires significant translation of the osteotomy site it may make intramedullary fixation impossible. Therefore, it would be necessary to use external fixation or plate fixation in this patient.

It is also critical to understand the impact of limb length discrepancy. Significant limb length discrepancy more than a small amount is often impossible to correct with standard plates and intramedullary nails. Correcting limb length is most effectively accomplished with either external fixator such as an Ilizarov-type fixator construct or hexapod external fixator such as the TSF versus an internal magnetic lengthening nail such as the PRECICE or Fitbone nails.

13.4.1 Authors' Preferred Methods of Treatment

1. *Tibia osteotomy techniques*: Both multiple drill hole "DeBastiani" and Gigli saw techniques can yield good results when used for tibial corticotomy. The authors prefers variations of the multiple drill hole technique and believes that depending on the exact circumstances of the case, there are significant advantages. If an acute correction of a deformity with internal fixation is being performed, it is possible to perform a neutral and closing wedge-type osteotomy using multiple drill holes by comminuting the wedge. The osteotomy is completed with a hexagonal handled Ilizarov osteotome that is advanced across the bone under fluoroscopic guidance and then spun with the assistance of a large wrench applied to the handle. This method allows for deformity correction while increasing the bony contact surfaces and creating additional bone graft in the area, which the author feels adds to the potential for healing. This method is especially useful when stabilization with an intramedullary nail is planned.

   An alternative method is often used when a corticotomy is performed for distraction osteogenesis with a circular fixator. In this scenario, the bolts or nuts that lock the top ring to the threaded rod are temporarily removed to allow for rotation of the top two rings relative to each other. The area of the bone that has been weakened by the drill holes fails in rotation and the osteotomy is thereby completed with a rotational osteoclasis. A rotational osteoclasis can similarly be performed using a hexapod external fixator by temporarily unlocking fast-fix struts or temporarily removing one side of the struts from the rings. When completing the osteotomy for balanced cable transport with circular external fixation, either a large wrench is used with an osteotome as described above or a variation of rotational osteoclasis can be applied. This variation entails temporarily placing a half pin in the transport segment and then using the half pin to apply a rotation moment to complete the osteotomy. After the osteotomy is completed, the half pin is removed.

In contrast to these methods, osteotomies of the tibia performed with a saw need to be undertaken with great care. Osteotomies are most often performed with a saw when there is a plan for plate and screw fixation. The advantage is that cuts can be made at angles that allow sliding of the bone and fixation with lag screws while minimizing the chances of unintended fracture lines that could compromise the ability to optimally apply this kind of fixation. However, this type of osteotomy requires a much larger incision and much more soft tissue stripping in the area of future bone healing. It is important to perform constant irrigation of the saw during cutting to prevent burning of the bone, which is quite easy to do with a large saw.

The authors prefer to use sterile frozen saline, which comes as a double packed sterile bag and can be added to regular saline on the back table to create a chilled liquid that is ideal for cooling the saw blade. The author typically only uses a saw for osteotomies in the tibia to resect segments of infected or necrotic bone or to prepare bone ends for docking by making flat surfaces. The author uses a micro-100 saw in order to further decrease the risk of thermal necrosis as well as to limit the travel of the saw blade that can risk soft tissues when used in tight spaces.

2. *Fibula osteotomy techniques*: The authors typically prefers to perform a fibular osteotomy using a micro-100 saw. The osteotomy is typically made as an oblique fashion and is completed by twisting an osteotome within the bone after the bone cut has been made. The oblique nature of the cut allows the bone ends to slide past each other and still maintain proximity to each other with either lengthening or shortening of the tibia. It may seem contradictory that a saw is used preferentially for the fibular osteotomy and not for the tibia; however, the fibula behaves very differently than the tibia. The fibula has a much greater reserve for healing and in fact often unites earlier than would be preferred for healing of the tibia. In addition, it is more difficult with this much smaller bone that is deeper in the soft tissues to safely perform a drill hole osteotomy through a percutaneous incision without risking injury to the superficial peroneal nerve or peroneal artery. Therefore, an osteotomy performed through a 2–3 cm incision with retractors protecting the surrounding structures is optimal and does not impede osteotomy healing in an unfavorable way. That said, the author avoids removing a large wedge of the fibula as part of the osteotomy. Although this may encourage consolidation of the tibia, it will sometimes result in a nonunion of the fibula. Fibular nonunion in the midshaft is believed by some to be unimportant. However, the author has cared for patients in which this is symptomatic, especially with the use of boots in activities such as skiing or snowboarding, and therefore believes it should be avoided.
3. *Malalignment with minimal limb length difference*: In the absence of infection, when deformity is present with no significant limb length discrepancy (less than or equal to 5 mm), or a difference that will be easily corrected to within 5 mm by straightening the angulated bone, then internal fixation is the preferred method of stabilization. The author strongly prefers the use of fixation with intramedullary nails whenever possible. The nail is applied with additional screws applied as blocking and stabilization screws to help achieve deformity correction and optimize stability. Intramedullary fixation is more soft tissue friendly and minimizes soft tissue stripping compared with fixation using plates and screws. The authors uses an external fixator-assisted method of intramedullary nailing to obtain and maintain correction during the stabilization process.

Intramedullary fixation is not preferred in several scenarios. Intramedullary fixation is not possible when an osteotomy is performed at a site remote to the CORA when aligning the limb will require major translation at the osteotomy site. In this scenario, the anatomic axis of the tibia is not collinear with the mechanical axis making passage of the nail impossible. Plate fixation is still possible and would be used if internal fixation is still desired in this scenario and the soft tissues are amenable. Alternatively, circular external fixation provides great flexibility in performing gradual correction and can allow for tweaking of the alignment postoperatively. The author generally finds that if an osteotomy is not being performed at the site of the CORA that it is usually because of soft tissue concerns, so most often circular external fixation is preferred.

4. *Malalignment with limb length difference > 1 cm*: Significant limb length discrepancy alters the surgical approach to deformity correction. Correction of up to 2 cm with sliding osteotomies using plate fixation has been reported and can be used for deformity correction with more mild limb length differences. Apart from this, standard internal fixation with plates and screws cannot reliably achieve the goals of both deformity correction and limb length correction. There are times when it may be optimal to choose standard internal fixation to correct alignment and accept a difference in leg length. However, addressing all problems requires other means.

   Most often circular external fixation with either an Ilizarov or hexapod construct will prove most effective. The author believes that there are significant advantages to the use of Ilizarov constructs in the treatment of complex pilon and tibial plateau fractures, but generally finds that hexapod external fixators, such as the TSF, are the most powerful and user-friendly method of correcting tibial shaft deformity. Hexapod external fixators provide the opportunity to correct deformity in six axes, lengthen the bone, and easily adjust the alignment postoperatively without major changes to the external fixator.

   Alternatively, internal magnetic lengthening nails can be employed to gain length using distraction osteogenesis. These devices have been highly effective and in fact revolutionary in the world of limb lengthening surgery. These devices can theoretically be used to stabilize a bony osteotomy used to correct deformity with subsequent application of bone lengthening assuming that the alignment of the bone will permit intramedullary fixation. This is an appealing approach in that it allows for deformity and limb length correction without the use of an external device. The authors believes that this is a legitimate option in some circumstances and has seen this approach succeed. However, this method should be undertaken with a number of caveats.

   The first is that internal distraction devices behave very differently than standard intramedullary nails. It is imperative that the nail be captured by either cortical contact or cortex replacing stabilization screws on both sides of the osteotomy at the time of surgery. If this does not occur, the bone will develop a progressive deformity during the lengthening phase. Secondly, bone formation with internal nails is much poorer in the tibia than with circular external fixation and therefore healing can be quite slow. The formation of relatively weaker regenerate bone is compounded by the fact that acute deformity correction at the osteotomy site also tends to decrease callous formation and bone healing in general. Taken together, acute correction of a large magnitude combined with internal lengthening can be risky in terms of bone healing. Currently, there is limited published data to evaluate the overall success of this approach versus other methods, but the author believes that with time this approach will likely prove its value in some circumstances.

5. *Severe valgus deformity*: Severe valgus deformity merits special attention because of the risk to the peroneal nerve when performing corrective surgery. Correction of tibial deformity from valgus to varus, and from external rotation to internal rotation, places the peroneal nerve on stretch and may risk a peroneal nerve palsy. It is unclear exactly what amount of acute correction is acceptable and this is

likely variable among patients. It is also likely that correction of fracture malunion is more forgiving in this regard than congenital deformity. For these reasons, exact limitations do not exist, but many surgeons will not perform more than a 10–15° correction of valgus acutely unless a complete neurolysis of the peroneal nerve is performed. Generally, the authors prefers to use a hexapod external fixator to correct a valgus deformity greater than 15°, especially in the proximal half of the tibia, to avoid risk to the nerve. It should be noted that if a simultaneous correction of external rotation deformity with valgus correction is planned, the magnitude of acute correction accepted would decrease accordingly.

6. *History of infection*: The presence of infection is a very important consideration in planning for correction of a tibial deformity. Infection should ideally be eradicated prior to performing an osteotomy for treatment of a tibial malunion when stabilization with internal fixation is planned. In contrast, external fixation is more forgiving in the face of infection because there is minimal disruption of local biology and no deep implant to become colonized. Therefore, external fixation can often be employed concurrently to the treatment of infection.

   The extent of the infection has significant implications on the treatment plan. Infection can be localized such as around existing fracture fixation hardware. Optimally, the hardware would be removed and infection treated prior to performing an osteotomy of the tibia for correction of alignment. More extensive infection including a sequestrum within the bone may not be amenable to this approach. When such a situation is present, it is necessary to perform a more aggressive debridement that often involves segmental resection of the compromised bone. Radical resection of the infected bone segment will eliminate the underlying infection burden and therefore allow for use of internal or external fixation at that same setting. However, especially for internal fixation, the author typically prefers a staged approach returning when the patient has had a short course of treatment with antibiotics for definitive reconstruction.

   Once eradication of infection has been accomplished, the surgeon can use the particulars of the deformity and site of planned osteotomy together with status of soft tissue presence of a bone defect or limb length inequality to guide decisions in terms of what fixation strategy is best. The authors finds that in the treatment of infected tibia malunion the use of circular external fixation is the most forgiving in terms of preventing recurrence of infection, obtaining complete correction of the deformity, and equalizing limb lengths. However, there are times when risk of reinfection is low and deformity correction is amenable that internal fixation may be preferred.

13.5 Case Discussions

13.5.1 Case 1

The patient is a 34-year-old man with a history of rickets as a child. He had an unsuccessful tibial osteotomy performed as a teenager that resulted in worsened valgus deformity and a limb length discrepancy. The medical history is complicated due to renal failure resulting in two kidney transplants. The kidney is now functioning well, but medications caused bilateral femoral head avascular necrosis resulting in collapse and subsequent bilateral hip replacement at age 32. He then suffered a work accident where a forklift ran over his foot causing severe injuries.

He initially presented complaining of a chronic valgus deformity and limb length discrepancy that has caused him problems for many years. The situation became increasingly problematic after the foot injuries because an optimal reconstruction of these cannot be performed until his limb alignment is corrected.

Evaluation of the leg revealed a good soft tissue envelope and no signs of infection. Lab tests revealed no signs of infection, and the endocrine workup was normal except for a mildly decreased vitamin D for which treatment was instituted. Radiographs reveal a combined 10° valgus and

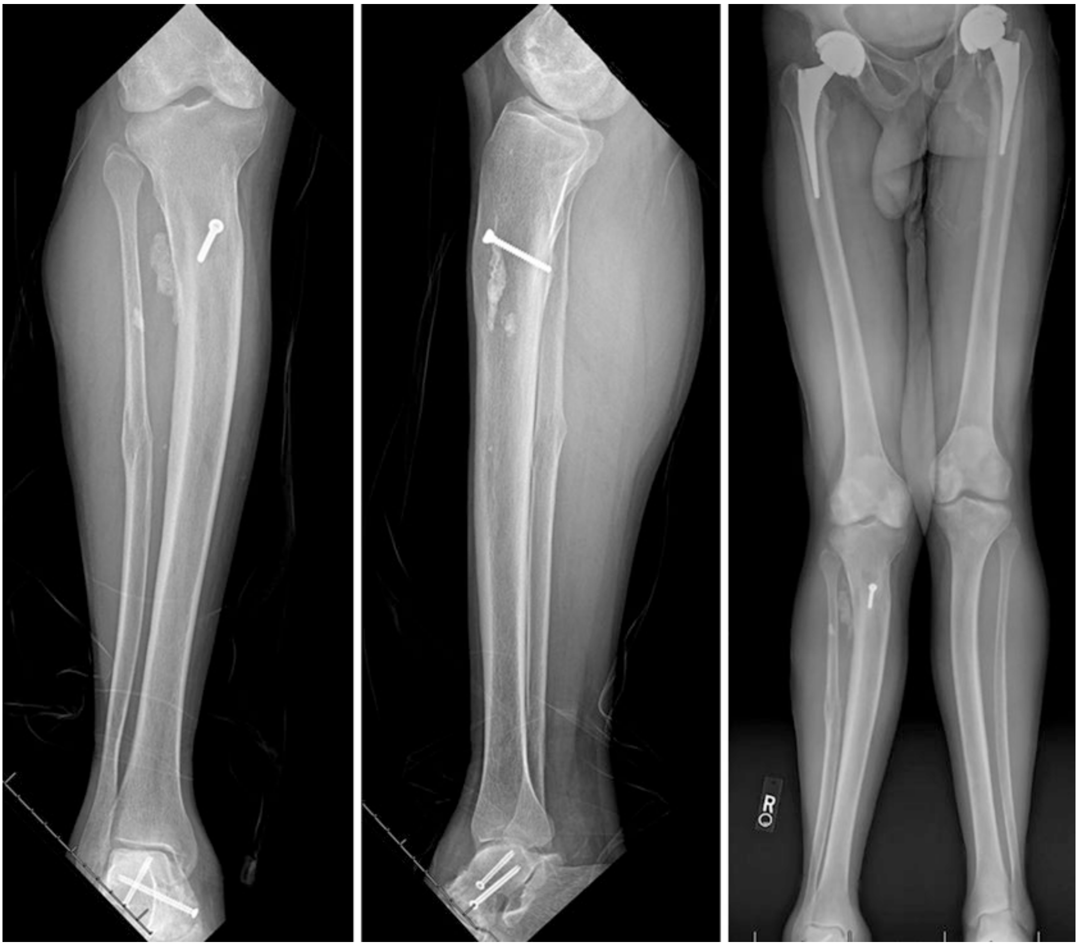
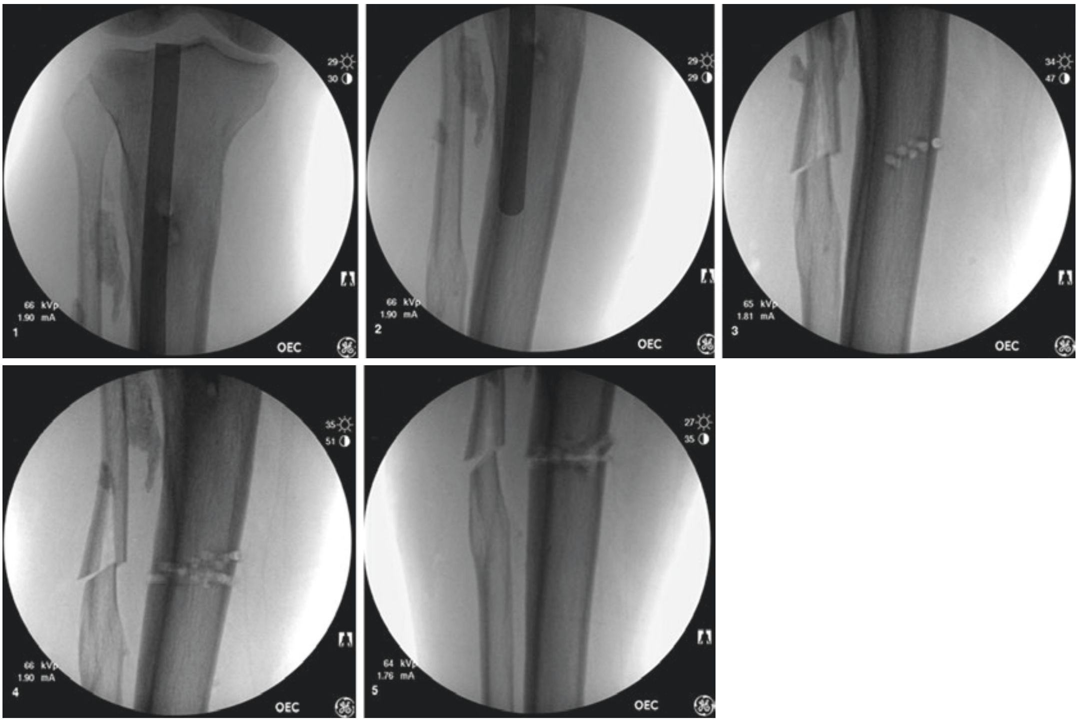


Fig. 13.1 Anteroposterior and lateral radiographs of the right tibia demonstrating a combined 10° valgus and 11° apex anterior proximal tibial metadiaphyseal deformity with no significant rotational abnormality. Limb length radiographs demonstrate a 13 mm discrepancy with the right shorter than the left

11° apex anterior proximal tibial metadiaphyseal deformity with no significant rotational abnormality (Fig. 13.1). There is a limb length discrepancy of 13 mm with the right shorter than the left. Deformity analysis revealed that a correction of the alignment and joint angles would be possible with a single proximal tibial metaphyseal osteotomy.

We discussed several options for treatment including acute correction with a fixator-assisted intramedullary nail, acute correction with a plate and screws, gradual correction with a TSF, and acute correction with subsequent lengthening using an internal magnetic lengthening intramedullary nail. The patient said that, although he would like to have his leg lengths equalized, he did not feel this was a priority. What was most important to him was to have the alignment corrected and the bone healed as soon as possible so that he could have his foot addressed. In addition, the length discrepancy was not severe and the patient has contralateral deformity that will likely undergo correction after the foot is addressed allowing for equalization of the leg lengths at that time if desired. Therefore, we felt that external fixation-assisted intramedullary nailing would be the most efficient method of correcting the deformity and returning him to function.

The site of the osteotomy was marked out using a radiopaque ruler as seen in Fig. 13.2a, b. A neutral wedge osteotomy was then performed with a multiple drill hole osteotomy (Fig. 13.2c–e).



Figs. 13.2 Intraoperative fluoroscopic series demonstrating the radiopaque ruler marking out the planned osteotomy site followed by multiple drill hole osteotomy to create the neutral wedge osteotomy. The irregular bone edges can be visualized through this technique which also provided a local autograft effect as seen in the osteotomy site in the bottom right image

This type of osteotomy increases bony contact at the site of deformity correction and also provides a sort of local bone graft. The osteotomy is done through a percutaneous incision overlying the tibia. The fibula osteotomy was done with a micro-100 saw and finished with an osteotomy rotational osteoclasis.

A tension wire spanning fixator was applied next with one reference wire proximally and another distally to assist in obtaining and maintaining reduction during nailing (Fig. 13.3). A suprapatellar approach was used for nailing of the tibia. The osteotomy site was compressed with the compression driver at the proximal end of the nail before being locked into place. Neither blocking nor stabilization screws were used in this case because there was felt to be a good end-osteal fit of the nail on both sides. If the osteotomy had been more metaphyseal in nature, then blocking screws would have been added. Overall anatomic alignment was achieved, and limb lengths were adequately equalized that he felt balanced with a simple shoe insert postoperatively (Fig. 13.4).

13.5.2 Case 2

The patient is a 56-year-old Haitian man with a history of a left tibia shaft fracture as the result of a gunshot wound 19 years ago. The patient has been symptomatic with medial knee pain that has become significant over the past few years and is also bothered by his limb length inequality. The patient was cared for with closed treatment at the time of the injury. He has no history of infection and no major medical comorbidities, and his endocrine workup was normal. The soft tissue envelope is generally benign apart from a couple small patches of skin that are adherent to bone.

The overall deformity is 12° varus, 9° apex posterior, 22 mm limb shortening, and no signifi-

Fig. 13.3 Intraoperative fluoroscopic series depicting the tension wire external fixator-assisted suprapatellar intramedullary nailing of the right tibia after completion of the osteotomy. The tension wire external fixator aids in maintaining reduction and alignment of the tibia after the osteotomy

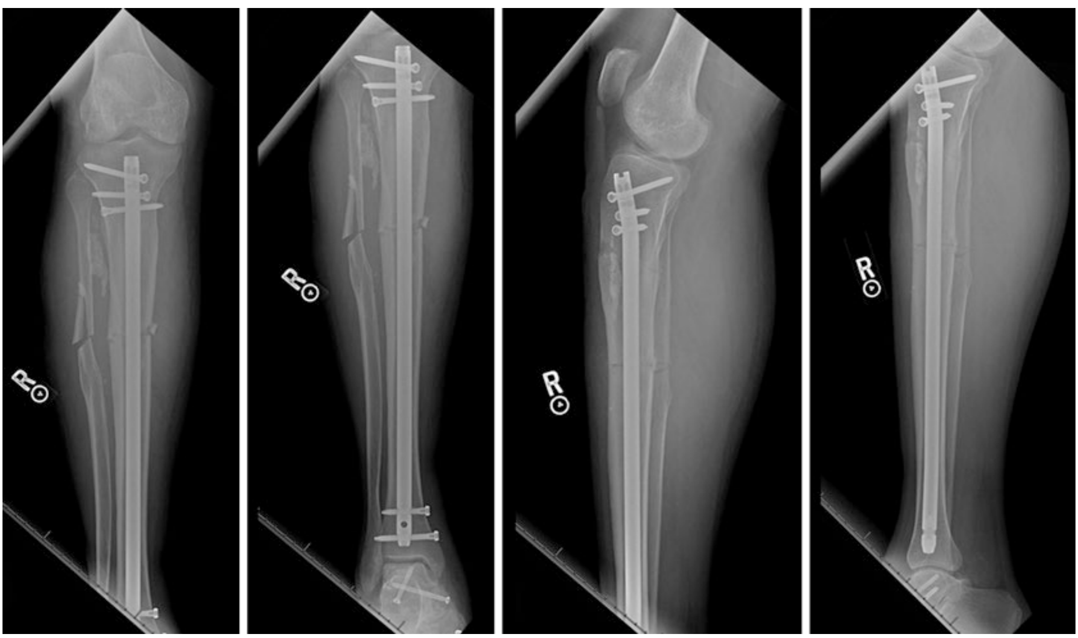


Fig. 13.4 Postoperative radiographs of the right tibia demonstrating restoration of anatomic alignment

cant rotational deformity (Fig. 13.5). It is notable that, although the mechanical axis can be corrected at one location, the anatomic axis is serpentine in nature. The complex nature of the shape of the midshaft makes intramedullary fixation impractical. Plate and lag screw fixation may be possible here, but it is difficult to accurately correct a difference of this magnitude with plating techniques and the skin is not ideal in some areas that would need to be accessed for this method. Therefore, external fixation is the most optimal solution to correcting this problem. It is possible to use an Ilizarov-type external fixator, a hexapod ring fixator, or a monolateral rail in this circumstance. However, the hexapod offers great flexibility in adjusting both alignment and height postoperatively, and in the authors' experience, it is the most reliable method to get an optimal result.

A TSF was applied with two wires and two half pins proximally and three 6 mm half pins spread over the distal segment (Fig. 13.6). The tibial osteotomy was performed with a multiple drill hole technique. The fibula was not captured because we desired to return the proximal tibia to its proper position relative to the proximal fibula. Performing distraction osteogenesis without capturing the fibula must be undertaken with great care and in most circumstances is not advised. However, circumstances such as tibial malunion after fracture and Blount's disease correction often benefit from the judicial use of this method to properly orient the proximal tibia relative to the fibula at the end of correction.

A Spatial Frame program was run postoperatively that returned the patient to an anatomical alignment plus 1–2° of valgus (Fig. 13.7). The extra couple degrees of valgus were introduced

Fig. 13.5 Anteroposterior and lateral radiographs of the left tibia demonstrating 12° varus, 9° apex posterior without significant rotational deformity. Limb length radiographs demonstrate a 22 mm limb shortening of the left lower extremity

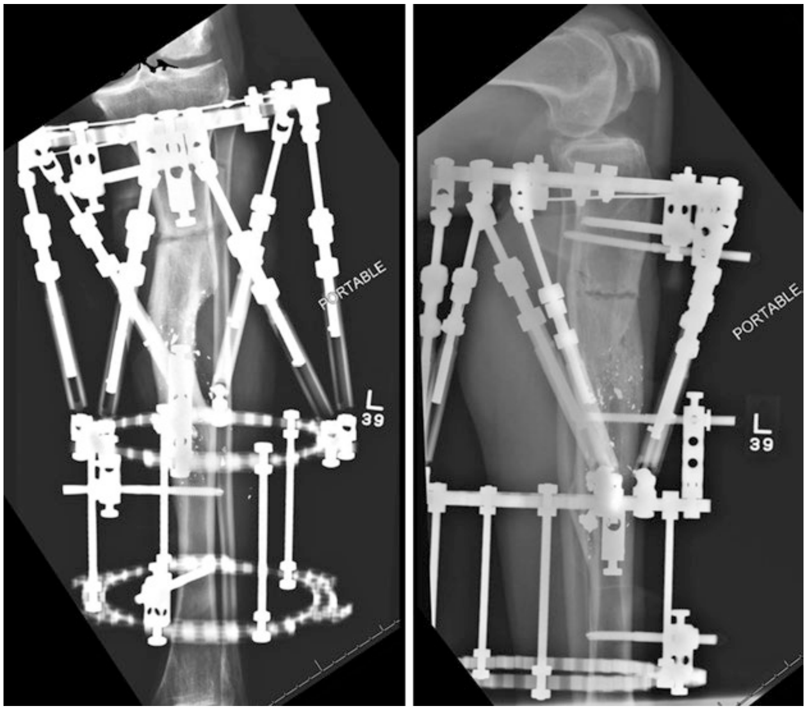


Fig. 13.6 Anteroposterior and lateral radiographs of the left tibia after a proximal tibia osteotomy via the multiple drill hole technique and application of a Taylor Spatial Frame prior to starting the distraction osteogenesis and multiangular correction protocol

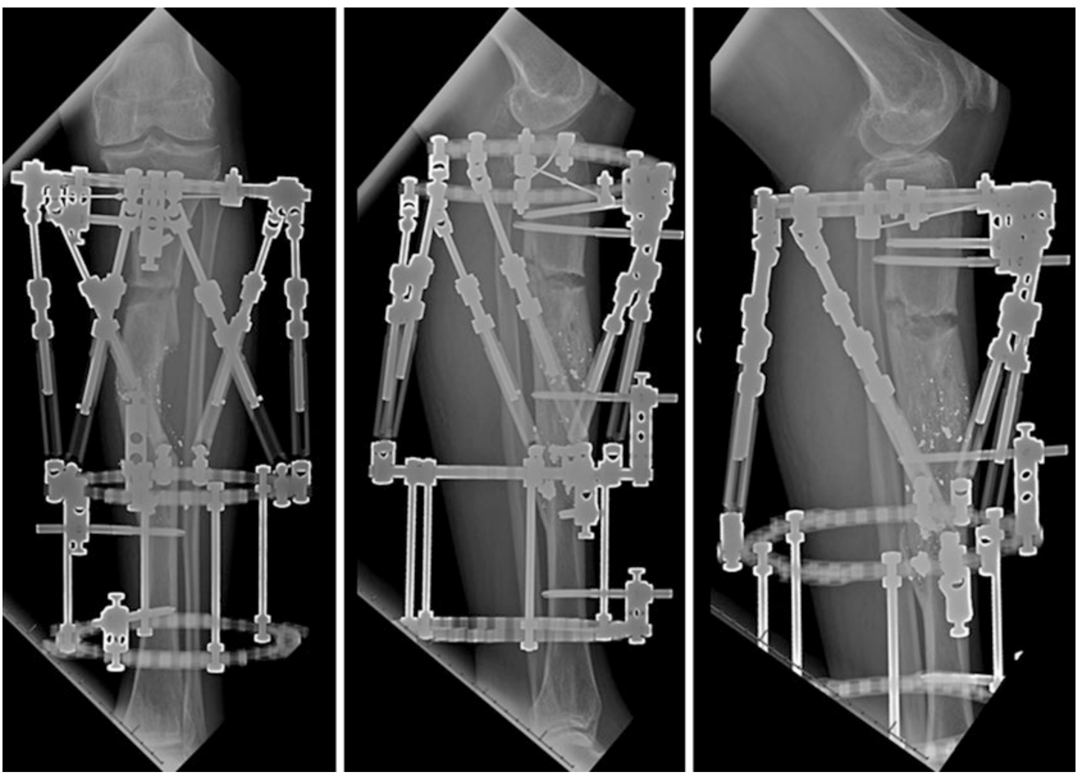


Fig. 13.7 Anteroposterior and lateral radiographs of the left tibia after completion of the Spatial Frame protocol demonstrating marked improvement in limb alignment with 1–2° of valgus to accommodate for the patient's medial compartment arthritis

Fig. 13.8 Limb length films demonstrating marked improvement in leg lengths compared to the image in Fig. 13.5

because of the medial arthritis that is present. The author is a proponent of recreation of essentially anatomical alignment and joint angles and believes this is almost always preferable to creating large compensatory deformities. A total residual program was used after achieving anatomic alignment in order to completely equalize the leg lengths (Fig. 13.8). Note also the improved position of the proximal fibula. Although the anatomic axis of the bone remains serpentine, a fully functional reconstruction has been achieved.

13.5.3 Case 3

The patient is a 45-year-old male construction worker who presented with a severe right grade IIIA open tibia and fibula fracture after falling from a 6-foot scaffold. The patient had a history of an open tibia fracture in the same leg treated nonoperatively in his home country when he was 11 years old. He has had obvious deformity of the right leg since that time but had managed to function reasonably well. Patient denied any history of tobacco use and has no other significant medical comorbidities.

The soft tissue injury was very severe, but flap coverage would only be required if internal fixation was used for stabilization. Radiographs revealed an acute fracture of the midshaft of the tibia with a deformity more distally that was in 14° of valgus and 18° of apex posterior deformity (Fig. 13.9). He also reported a known limb length inequality with a short right limb, but the magnitude was difficult to assess at the time of presentation.

He was initially taken for debridement of the fracture, stabilization with a spanning external fixator, and placement of antibiotic beads (Fig. 13.10). He returned for two staged debridements and then definitive care. The wound remained very marginal throughout this process and if internal fixation had been chosen, a flap would have been required. However, we chose to proceed with definitive care using a hexapod circular external fixator, specifically a TSF. We initially placed the frame with the limb in its original alignment in order to allow the soft tissues time to heal and callus for form (Fig. 13.11). It took almost 5 months for the soft tissues to heal adequately for us to return to the operating room to revise the frame and perform an osteotomy at the prior malunion site (Fig. 13.12). Initially the struts had been used to reduce the acute fracture, but the frame revised, they were now able to adjust the alignment of the osteotomy site and lengthen the leg while the original fracture was maintained to heal by the pins and wires

Fig. 13.9 Anteroposterior and lateral radiographs of the right tibia demonstrating an acute fracture of the midshaft with a distal deformity measuring 14° of valgus and 18° of apex posterior angulation

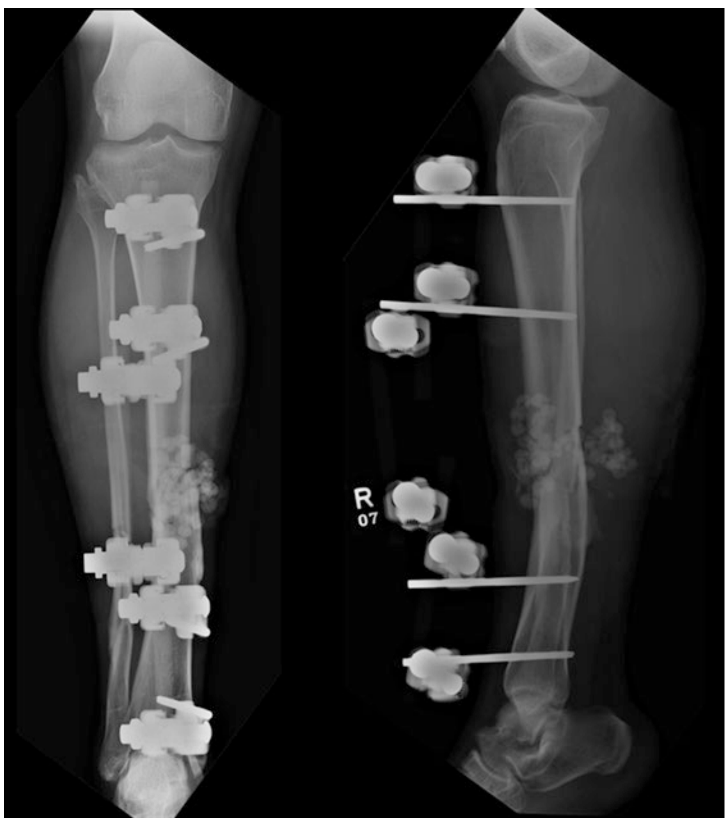


Fig. 13.10 Postoperative anteroposterior and lateral radiographs of the right tibia after application of a temporizing uniplanar external fixator and antibiotic cement beads

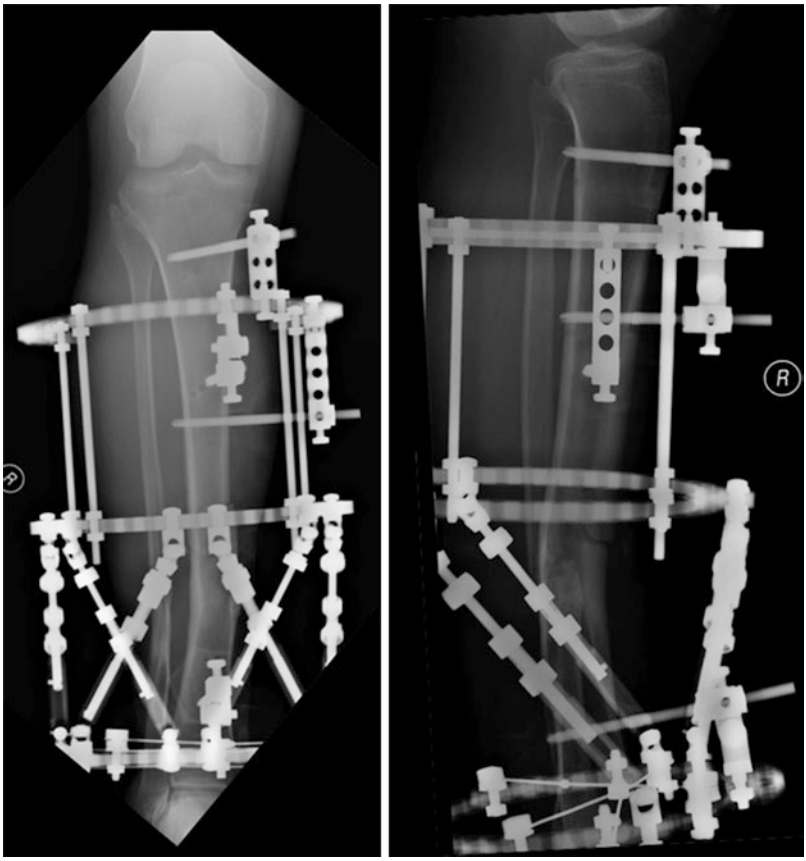


Fig. 13.11 Anteroposterior and lateral radiographs of the right tibia after removal of the temporizing uniplanar external fixator and application of a hexapod circular fixator (Taylor Spatial Frame) while keeping the original tibial deformity to allow the soft tissues to adequately heal

(Fig. 13.13). Eleven months after the index procedure, and 6 months after the osteotomy, the fracture and osteotomy healed with an anatomically aligned limb with equal leg lengths (Fig. 13.14).

13.5.4 Case 4

The patient is a 46-year-old man who initially presented with two open wounds overlying the tibia with a concern for underlying osteomyelitis in his left tibia. He reported having had a severe open left tibia fracture in Colombia over 20 years prior as the result of a high-speed motorcycle collision with a truck. At that time, he had over ten procedures to the left tibia including bone and skin grafting. Additionally, he reported that 5 years after the injury he was treated with IV antibiotics for osteomyelitis of the left tibia. At the time of presentation, the patient had several areas of deep ulcerations along the anterior tibia with very fragile appearing skin at the site of his previous skin grafts. He states that very minor trauma, such as hitting his leg against a coffee table, results in a nonhealing wound. However, these wounds arose spontaneously without precedent trauma. He also noted difficulty with ambulation secondary to his 5 cm limb length inequality, bony deformity, and acquired equinus contracture. Laboratory values demonstrated a mildly elevated ESR of 16 with normal CRP and WBC. Radiographs (Figs. 13.15 and 13.16) are concerning for sequestrum as well as a deformity

Fig. 13.12 Limb length radiographs demonstrating the right tibia after application of the Taylor Spatial Frame before any correction

with 15° apex and excess external rotation. MRI of the left tibia confirmed several cysts throughout the cancellous bone of the diaphysis and distal metaphysis.

At this point, we discussed with the patient that he had four main problems. The first was that he had an osteomyelitis of the tibia. The second was that he had a tibial malunion deformity and limb length inequality. The third was that his soft tissue quality was very poor and likely needed wound coverage. The fourth was the equinus contracture. We discussed the possibility of performing more limited procedures to address the current problem of the ulcerations without solving these other serious issues. However, the patient was strongly in favor of a more permanent solution that would address all of the above and so we proceeded with the reconstruction described below.

A debridement of the area of osteomyelitis was performed first. A segment was removed that included the sequential cuts were then made at 5 mm increments until there was a healthy normal appearing and bleeding bone end on each side (Fig. 13.17). An antibiotic cement spacer was fashioned in the standard fashion using the standard ratio of one pack of 40 grams of methyl methacrylate mixed with 2 g of vancomycin and 4.8 g of tobramycin. The spacer is formed over a Steinmann pin, which is placed within the medullary canal to keep the spacer in place. A spacer pouch was formed with this by covering the open wound with Ioban. The patient returned to the operating room after receiving 2 days of IV antibiotics. A free latissimus dorsi muscle transfer was performed for soft tissue coverage.

We waited approximately 6 weeks for the muscle flap to mature and then returned to the operating room for application of a cable transport circular external fixator and Spatial Frame struts to correct the ankle equinus contracture (Fig. 13.181a, b). The cable frame was constructed in the standard fashion for a balanced cable transport as described by Quinnan. Upon completion of the procedure, the patient was made weight-bearing as tolerated and began his transport on postoperative day 7 with lengthening at 1 mm per day. The patient was also given a program for correction of the equinus contracture.

Three months after the application of the cable transport frame, the patient completed the transport phase and was then converted to a lengthening frame. This conversion was performed by locking

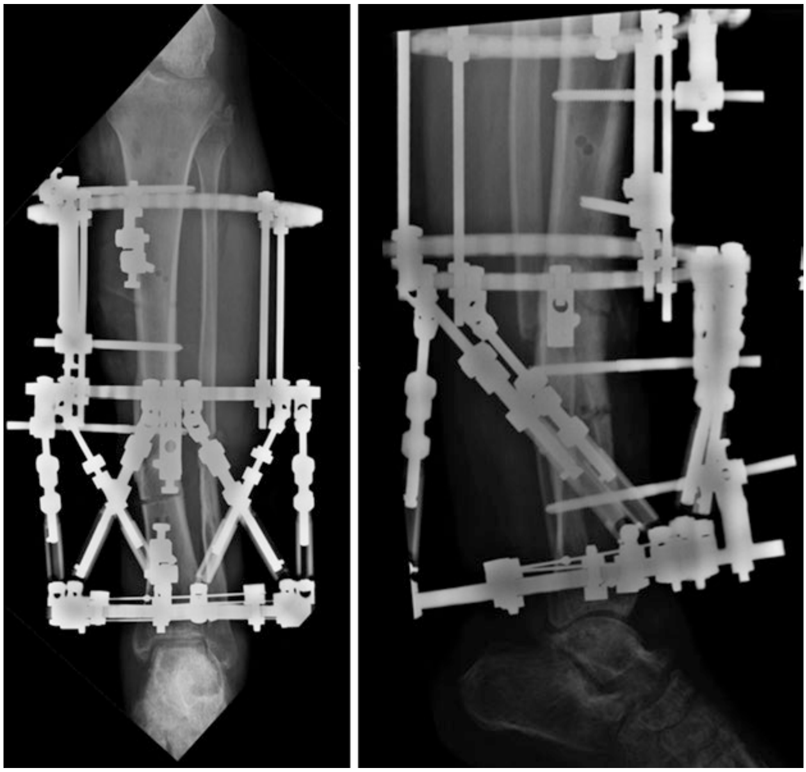


Fig. 13.13 Anteroposterior and lateral radiographs depicting the osteotomy of the malunion after the planned staged management of this patient's open injury and prior to initiation of the correction protocol

the cables to the middle ring while removing their attachment to the proximal ring (Fig. 13.19). The telescopic rods that were used as part of the original frame construction were then used as the motor. It is also notable that the toes had developed contractures during correction of the ankle contracture, so these were pinned and locked down to the foot ring. Lengthening progressed until the legs were of equal length (Fig. 13.20a, b), and then the frame was removed, and an antibiotic-coated intramedullary nail was placed (Fig. 13.21). He was made non-weight-bearing for 1 month and was then transitioned to weight-bearing as tolerated. Ultimately, the bony reconstruction created 16 cm of new bone. The patient spent a total of 6 months in the external fixator and clinically and radiographically 10 months after the start of the bony reconstruction (Fig. 13.22). The patient required an extensive course of physical therapy for rehabilitation. At his latest office visit, 2 years later, his infection is cured, his soft tissue coverage is much more durable, and he is ambulating independently and has returned to his activities of daily living (Fig. 13.23a, b).

Fig. 13.14 Anteroposterior and lateral radiographs demonstrating removal of the Taylor Spatial Frame with adequate healing of the osteotomy and restoration of anatomic alignment and length

Fig. 13.15 Anteroposterior and lateral radiographs of the left tibia concerning for sequestrum as well as a deformity with 15° apex and excess external rotation

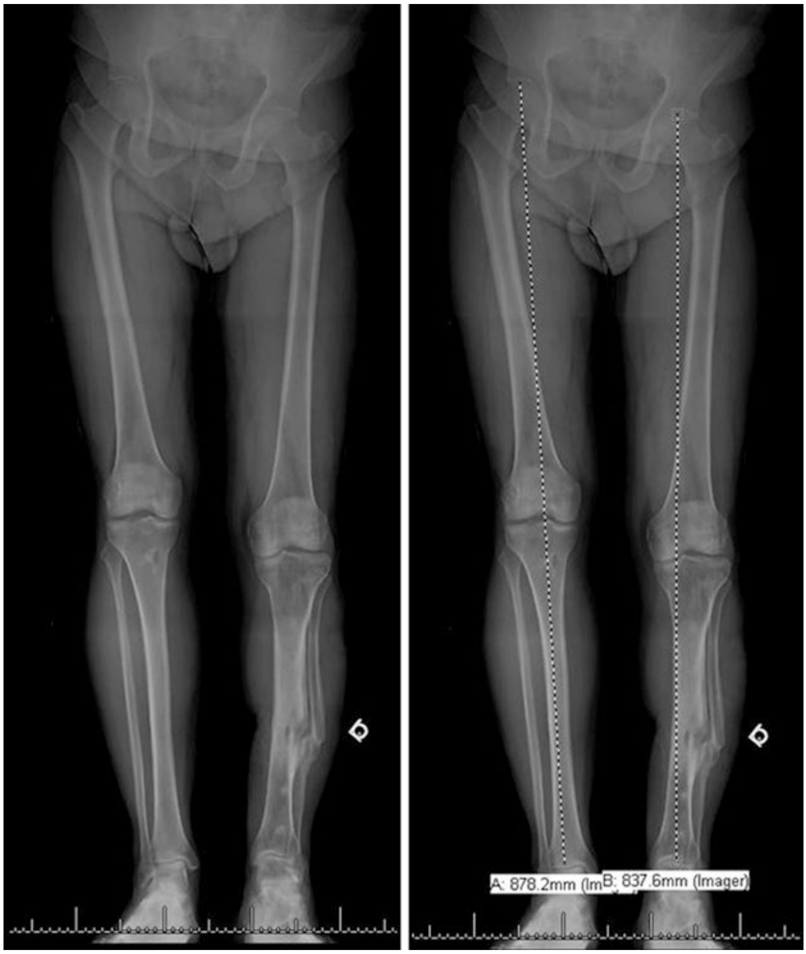


Fig. 13.16 Limb length radiographs demonstrating 40.6 mm of limb length discrepancy with the left shorter than the right

Fig. 13.17 Postoperative radiographs of the left tibia after debridement of the segment of tibia with osteomyelitis and application of a temporizing antibiotic cement spacer

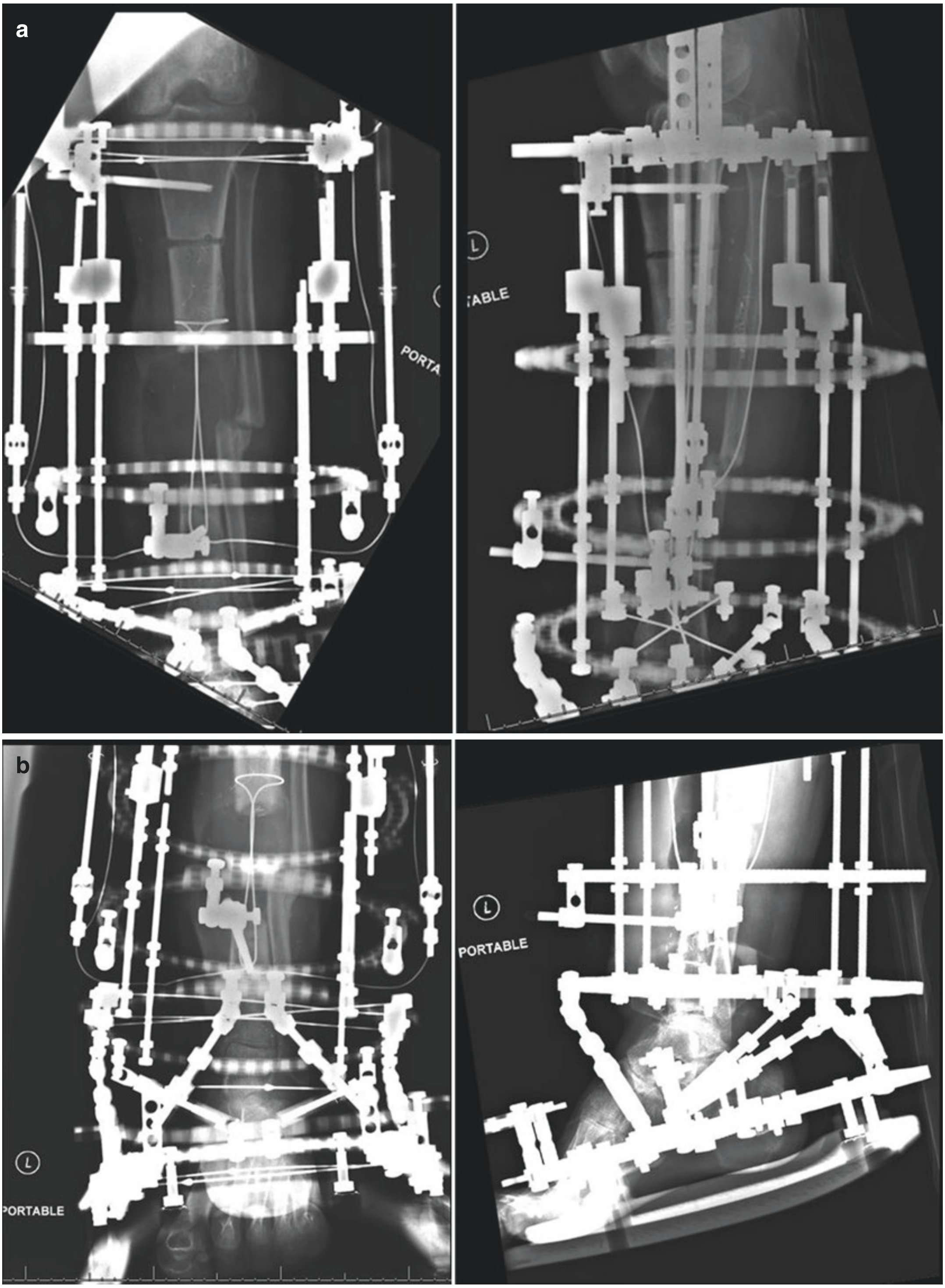


Fig. 13.18 (**a**, **b**) Anteroposterior and lateral radiographs of the left tibia and left ankle demonstrating the application of a Taylor Spatial Frame spanning the ankle to correct the ankle equinus contracture as well as allowing for placement of a cable transport system

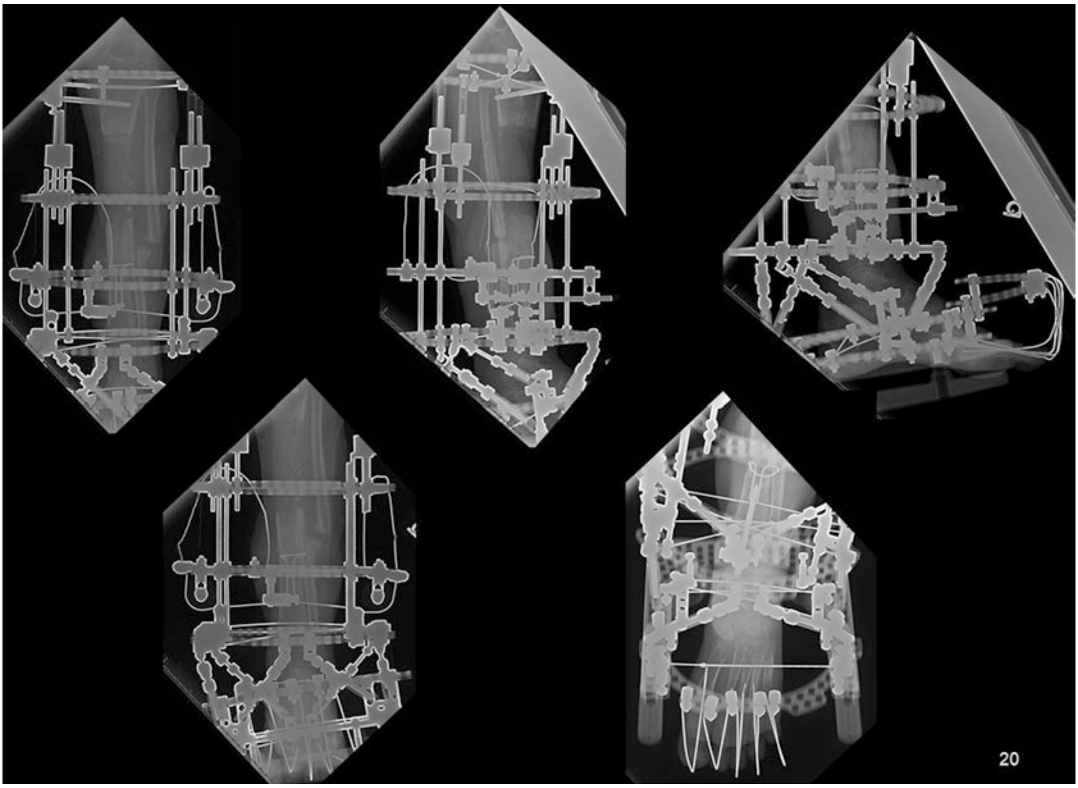


Fig. 13.19 Anteroposterior and lateral radiographs of the left tibia and left ankle after completion of the transport phase and conversion of the external fixator to a lengthening frame by locking the cables to the middle ring while removing their attachment to the proximal ring

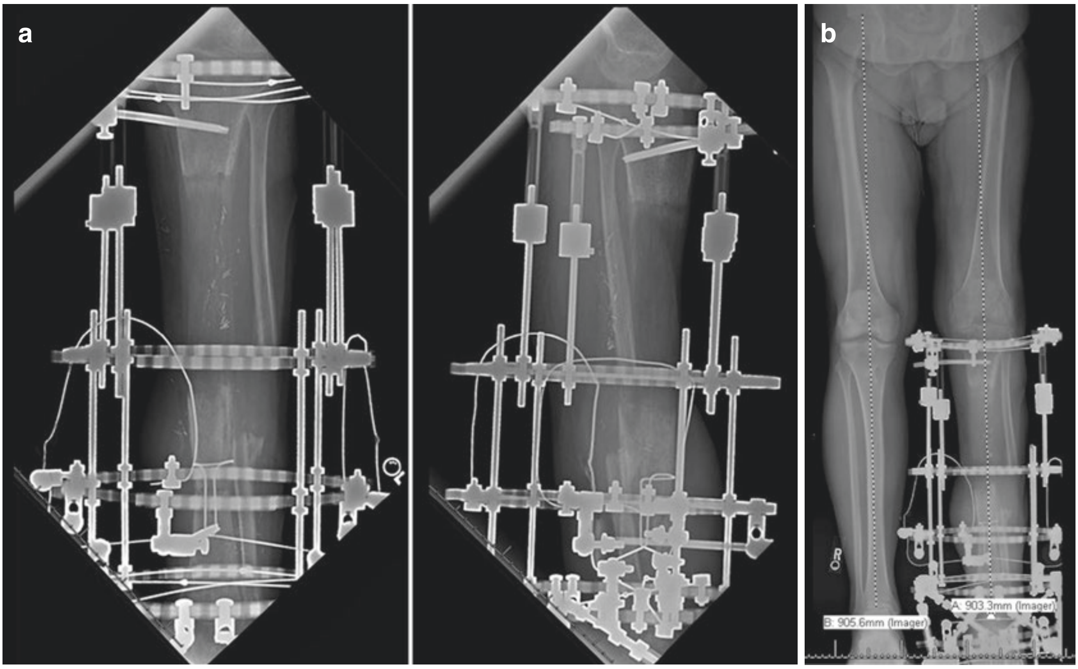


Fig. 13.20 (**a**, **b**) Anteroposterior, lateral, and limb length radiographs demonstrating the progressive lengthening process with the lengthening frame

Fig. 13.21 Anteroposterior and lateral radiographs of the left tibia after removal of the lengthening frame and application of an antibiotic-coated intramedullary nail

Fig. 13.22 Anteroposterior and lateral radiographs of the left tibia after healing and consolidation of the regenerate

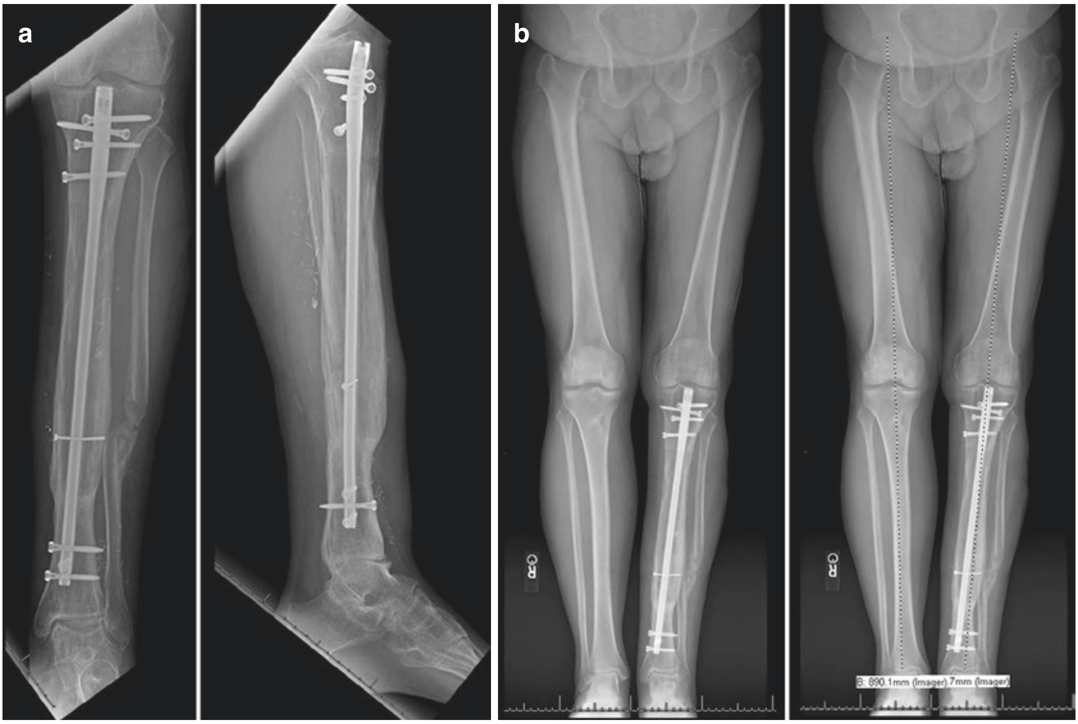


Fig. 13.23 (**a**, **b**) Final follow-up radiographs of the left tibia 2 years after his index reconstructive procedure demonstrating anatomic alignment and length

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Malunions of the Distal Tibia and Ankle

14

Kevin J. Pugh, B. Dale Sharpe Jr., and David B. Johnson Jr.

14.1 Introduction

14.1.1 What Is a Malunion?

Defining a malunion can be difficult. Is it a fracture or osteotomy that healed with residual deformity? Or is it a fracture which has healed with deformity leading to a functional loss or arthritis in an adjacent joint? A 30-degree residual varus deformity of the humerus in a patient with a sizable arm will have radiographic malalignment but may result in no cosmetic or functional abnormality. Contrast this to a patient who has a 15-degree varus malunion of the distal tibia where there may be significant cosmetic deformity and implications for arthritis in the adjacent ankle and subtalar joints. Thus, the magnitude of the residual deformity, the bone on which it is located, and its proximity to the weightbearing surface are the major determinants of which deformities are purely cosmetic and those which are true malunions requiring correction.

14.1.2 Goals of Management

In the upper extremity, where the skeleton is designed to maximize the positioning of the hand, malalignment may result in weakness and difficulty performing activities of daily living. In the lower extremity, residual deformity can lead not only to radiographic or cosmetic deformity but an alteration in the mechanical axis of the limb or the orientation of a joint to that axis [1]. This abnormal loading of the weightbearing skeleton can cause degradation of the articular cartilage over time leading to traumatic arthritis in adjacent joints. The goals of deformity correction in the lower extremity are to restore the mechanical axis of the limb and to maintain or restore the orientation of each joint to the mechanical axis, which ultimately prevents arthritis and restores function [2].

14.1.3 Deformity

Normal gait is dependent on the function and alignment of the ankle joint. When fractures occur, anatomic reduction and stable fixation of fractures about the ankle is required to restore function and obtain union. Disruption of the ankle mortise by a fracture of the plafond, malleoli, or syndesmotic injury may lead to ankle instability or lack of articular congruity; both of which can lead to degenerative arthritis. The ankle joint is unique in that it has several

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Table 14.1 Treatment suggestions: distal tibia and ankle malunions

Classification	Objective	Treatment	Suggestions	Problems
Meta-diaphyseal	Restore mechanical axis	Plate, external fixation, nail with polar screws		Small distal segment, inadequate stability
Meta-diaphyseal with length	Restore mechanical axis and length	Oblique plane osteotomy and plating, external fixation	Provide adequate fixation, build external fixator to foot if needed	
Lateral malleolus	Restore length and rotation	Plate	May require bone graft	Failure to restore syndesmosis and talar articulation
Posterior malleolus	Restore joint congruity and stability	AO techniques		Technically difficult to access
Medial malleolus	Restore joint congruity and stability	AO techniques		Small malleolar piece, inadequate fixation
Syndesmosis	Restore joint congruity and stability	AO techniques	Restore ankle mortise, stress views in OR	Failure to restore joint stability
Articular malunion	Restore articular surface and limb alignment	Intra-articular osteotomy, arthrodesis, arthroplasty	Arthrodesis if surface is not reconstructable	Cartilage injury, poor prognosis

AO Arbeitsgemeinschaft für Osteosynthesefragen (German for "Association for the Study of Internal Fixation"), *OR* operating room

structures that need to be accounted for when evaluating deformity. Coronal plane deformity in the meta-diaphyseal or metaphyseal regions of the bone leads to alterations in mechanical axis and subsequent degenerative joint disease of the tibiotalar joint and possible underlying compensatory deformity in the subtalar joint. The sagittal plane is the primary plane of motion of the lower extremity; thus, deformities to some degree are compensated for by the motion of the ankle. Flexion deformities, however, create a relatively dorsiflexed position of the ankle and limit overall ankle motion. Conversely, extension deformities of the distal tibia lead to an uncovered talus, abnormal loading, and a relative equinus deformity of the ankle. Structurally, malunions of the distal fibula, medial malleolus, or posterior malleolus may result in altered mechanics of the ankle mortise affecting joint stability and congruity. Deformity or malreduction of the distal syndesmosis or articular surface, both of which cause abnormal cartilage loading, will ultimately lead to post-traumatic arthritis.

There is no one method of treatment for malunions and deformity at the ankle. Instead, it is an analysis and correction of the cause of the malunion and the unique features of each specific case (Table 14.1). The fact that there is no one technique or implant to treat malunions is what makes them both challenging and satisfying to treat. The treatment plan, whether simple or involving several stages, is devised by following a set of principles as illustrated throughout this book. The principles of treating malunions about the ankle will be illustrated in this chapter.

14.2 Evaluating Malunions About the Ankle

The evaluation of a patient with a deformity, just as with an acute injury, requires a thorough look at more than just the fracture pattern and radiographs. One must determine the "personality of the fracture" as coined by Schatzker [3]. This involves a complete history of the events of the injury, the fracture, the host, the treating physician and the institution at which the treatment will occur. Only with this kind of analysis can one do proper preoperative planning and optimize the chance for success.

14.2.1 History

A comprehensive history is essential, as a complete picture of the fracture, and the host must be obtained [4]. Was the initial injury open or closed? Was there a high energy mechanism such as a motorcycle accident or a lower energy trip and fall? Were there any neurovascular issues at the time of initial injury or following treatment? A determination of the type and number of previous surgeries is essential, as is the presence and treatment of previous infection. If there is retained hardware at the fracture, old operative notes can be helpful in identifying the type and manufacturer for planned removal. Have previous fractures healed in a timely fashion? Patients with recreational drug habits or other substance abuse may have compliance issues, and this needs to be identified at the outset of treatment. Smokers are at risk because of the well-documented relationship between nicotine use and delayed healing, as are patients with comorbidities such as vascular disease, diabetes, and other chronic diseases [5]. Patients using nicotine gum are not immune to this problem. Adequate nutrition is essential to healing as is the normalization of vitamin D levels. The occupation of the patient is another factor to consider, as treatment that requires a non-weightbearing gait will affect a laborer differently than a patient with a sedentary job. The knowledge of the avocations and hobbies of your patient are also important, as it rounds out the level of activity to which the patient must return and sets an ultimate goal for treatment. Hospital discharge planning often begins before surgery. The patients' living situation, amount of support from family or friends, their financial resources, the location of their home, and what type of dwelling in which they reside are all helpful in planning successful aftercare.

14.2.2 Physical Examination

A thorough musculoskeletal examination is mandatory. Examination starts with the patient's other extremities, as this provides clues to other disabilities that may play a role in mobility and later rehabilitation. The malunited segment should then be inspected for gross deformity and overall limb alignment. Gross limb length can be checked, both radiographically and clinically, and if the patient is ambulatory, the gait pattern should also be examined. The fracture site should be checked for pain to manual stress, as well as for the presence of gross or subtle motion. The ligamentous stability and range of motion of adjacent joints should be examined, and soft tissue reconstruction may be required as part of the treatment plan. If there is joint contracture or subluxation present, it should be determined if it is due to soft tissue contracture, heterotopic ossification, joint ankylosis, or a combination thereof.

The skin should be inspected for the presence, location, and healing status of previous open wounds and incisions. Adherent skin, especially in areas with subcutaneous bone such as the medial face of the tibia, the distal fibula, and the calcaneus are important to note when planning treatment [6]. The presence or absence of lymphedema or venous stasis should be noted, as it may also influence the choice of surgical approach. If previous external fixators have been in place, the condition of the old pin sites should be examined for signs of previous infection. As with any injury, a complete neurovascular examination should be performed and documented prior to treatment. Existing nerve deficits can be examined by electromyography to determine the extent and likelihood of recovery. Patients with suspected dysvascular limbs should be sent for more thorough testing including transcutaneous oxygen tensions and ankle-brachial indices [7].

14.2.3 Radiographic Evaluation

Radiographic evaluation includes true anteroposterior and lateral films of the affected limb segment, orthogonal to the "normal" portion of the limb. If multiple limb segments or length issues are suspected, additional work-up is required. Standard full-length alignment films should be obtained, as well as alignment films centered on each area in question, i.e., tibia or ankle. Deformities must be fully characterized in all six axes using a general analysis of deformity as discussed in earlier chapters so that correction can be planned. Comparison films of the contralateral leg are helpful in determining the normal alignment of the patient, and population norms can be used if the problem is bilateral [8]. Nonunions must be ruled out. Radiographic signs of a nonunion, while sometimes subtle, include the absence of bridging trabeculae, sclerotic fracture edges, persistent fracture lines, and broken or displaced hardware [9]. Computed tomography (CT) scans with reconstructions can be helpful in analyzing subtle nonunions but can be hard to interpret with fracture fixation devices present. If infection is suspected, a combined bone scan and tagged white cell study can help to differentiate bone turnover from active infection. Magnetic resonance imaging (MRI) can be helpful in evaluation of bone for infection or identifying the integrity of ligamentous structures but are not commonly utilized in the evaluation of malunions or nonunions.

14.2.4 Laboratory Evaluation

Laboratory studies round out the clinical picture of the patient. In addition to routine preoperative chemistries and blood counts, patients suspected of infection should have erythrocyte sedimentation rate (ESR) and c-reactive protein (CRP) labs drawn. Patients suspected of malnutrition should have a complete nutritional panel performed including liver enzymes, total protein, albumin, calcium, phosphate, and vitamin D levels. Patients with diabetes should have optimization of their hemoglobin A1c levels (<7%), as tight control of blood sugar provides a more optimal healing environment [10, 11].

14.2.5 Facilities and Ancillaries

The last part of developing the personality of the fracture is a critical self-examination of the surgeon and the treating facility. Surgeons should honestly examine whether they have the training, skill, patience, and experience necessary to treat a complex malunion. Even the most gifted surgeon requires help, and the appropriate consultants must be available including plastic and vascular surgery, internal medicine, and infectious disease. The hospital is the final piece. Is the correct equipment in the facility or available to be brought in temporarily? Is there experienced nursing and surgical assistance available? Can the anesthesia staff care for the needs of a sick patient?

14.3 Treatment

14.3.1 Preoperative Planning

At the end of the evaluation, the surgeon should create a complete problem list in anticipation of preoperative planning. An attempt should be made to define the cause of the malunion in order to attempt to reverse it. Soft tissue defects, either existing or anticipated, must be covered. The consultants required should be listed and obtained. Infected fractures require debridement, treatment, and conversion to a non-infected bone with eventual staged reconstruction. Pre-existing hardware must be identified and a determination made as to whether it can be retained or must be removed. The location of the osteotomy and the desired method of fixation, along with the hardware required to carry it out, must be listed and should follow the osteotomy rules as espoused by Paley et al. [12]. The optimal mechanical site for an osteotomy may not be available due to soft tissue compromise or suboptimal bone quality. It is in these instances that the surgeon must think critically to devise a plan that is suitable for this particular patient and malunion (Table 14.2).

Table 14.2 Treatment strategy: Distal tibia and ankle malunions

Treatment method	Clinical indication
Plate and screw fixation	Metaphyseal, malleolar, or articular nonunion, no infection, adequate soft tissue
Intramedullary nail	Metaphyseal location, requires an acute correction, may require polar screws for stability, no infection
Multiplanar external fixation	Multi-axis deformity, leg length deficiency, infection, bone defect, poor soft tissue, joint subluxation
Acute correction	Small or no deformity, no lengthening, adequate soft tissues, nonunion requires open approach
Gradual correction	Larger deformity, leg length deficiency, infection, bone defect, poor soft tissue, joint subluxation

Using this problem list, a detailed preoperative plan should be drawn out in all but the simplest of conditions. Performing the case on paper, often with multiple methods or implants, allows one to foresee possible obstacles to success. One should define the sequential steps in the operation in detail, select the appropriate patient positioning, and ensure the availability of equipment and implants. Creating a detailed preoperative strategy allows the procedure in the operating room to be an execution of plan rather than a surgical adventure [13].

14.3.2 Selecting a Procedure

In general, a single-stage, acute correction with internal fixation can be done for simple deformities amenable to opening wedge, closing wedge, dome osteotomies (varus, valgus, flexion, extension), or transverse (rotational) osteotomies in limb segments with adequate soft tissues and bone available for fixation [14]. Gradual correction with distraction osteogenesis is best for deformities which have significant length issues and poor surrounding soft tissues or are in close proximity to the articular surface [15].

14.4 Malunions of the Meta-diaphyseal Tibia

14.4.1 Analysis of the Deformity

Malunions of the distal tibial shaft and meta-diaphyseal region of the tibia can be analyzed in the same manner as those of other long bones. This can be done with a general analysis of deformity as described by Paley and other authors. After appropriate radiographs are obtained, the malunion can be defined in all six axes: varus and valgus in the frontal plane, flexion and extension in the sagittal plane, and length and rotation in the axial plane [16–19].

14.4.2 Planning the Osteotomy

The center of rotation of angulation (CORA), as defined by Paley, is defined as the point at which the center axis of the proximal segment intersects the axis of the distal segment [20]. This line can be on either the anatomic or mechanical axis of the bone. The tibia is unique in that the mechanical and anatomic axis in the frontal plane are essentially congruent, making the preoperative planning of a tibial malunion simpler [21]. If the CORA and the apparent deformity are corresponding, the deformity is purely angular. If they are not, then there is translational deformity present that must be addressed [22].

In general, the obvious location for a planned osteotomy would be at the level of the apparent deformity. This would allow the simplest osteotomy to be carried out to correct the malunion. Unfortunately, this is not always possible due to poor soft tissue envelopes, inaccessibility of the site due to vital anatomic structures, poor bone quality, or its proximity to the articular cartilage. In these cases, an alternative osteotomy site must be selected.

14.4.3 Osteotomy Rules

When planning an osteotomy, one must consider the osteotomy rules described by Paley outlined below [12]. When correcting an angular deformity, the axis line around which the correction is done is called the angulation correction axis (ACA):

1. If the osteotomy line and the ACA pass through the CORA, then a pure angular correction will be achieved.
2. If the ACA is through the CORA but the osteotomy is done in a different location, then the axes will realign but introduce a translational deformity at the osteotomy site (Fig. 14.1).
3. If the ACA and osteotomy are not through the CORA, then the axes will become parallel but introduce a translational deformity to the limb segment [23].

14.4.4 Acute Correction Osteotomies

Simple deformities are very amenable to a well-planned osteotomy, acute correction, and stable internal fixation [24] (Fig. 14.2). An opening wedge osteotomy will either maintain or add to the length of the bone segment, while a closing wedge osteotomy will shorten it. The length of the contralateral limb must be considered and obtained from a scanogram during the preoperative evaluation. In order to obtain acute multiplanar correction, an oblique plane osteotomy must be created [25]. Transverse osteotomies are best for correcting pure rotational deformities. Bone grafting may be required if a significant defect is generated [26]. Malunions involving only length may be corrected with circular external fixators, uniplanar rail external devices, or lengthening nails [27].

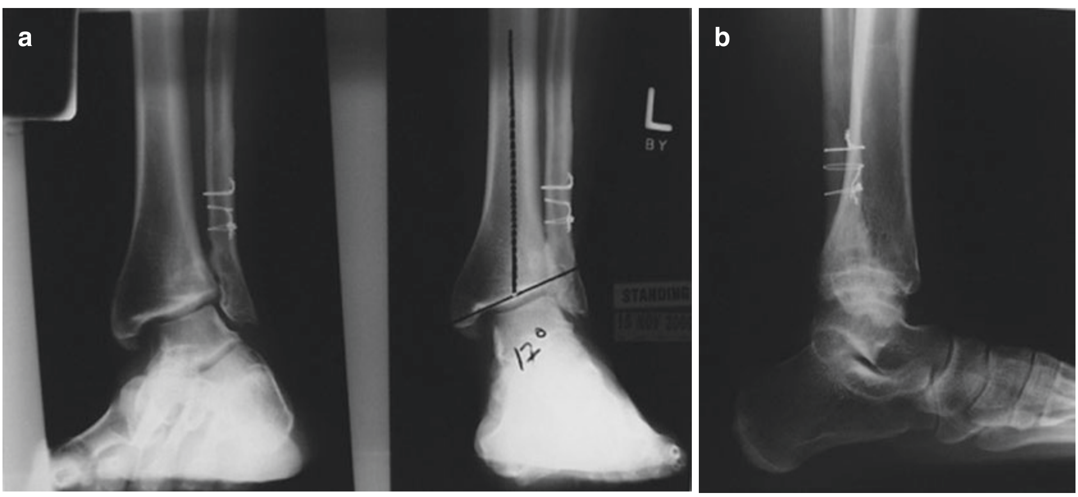

Fig. 14.1 A 27-year-old woman with malunited growth plate injury to plafond. (**a**) Anteroposterior (AP) and (**b**) lateral of the malunion with the center of rotation of angulation (CORA) at the joint line. (**c**) Scanogram of the deformity. (**d**) Osteotomy and application of a multiplanar external fixator. Osteotomy at a level above the CORA to allow fixation but introducing translation at the osteotomy. (**e, f**) AP and lateral of fracture union after frame removal. This demonstrates osteotomy rule 2

Fig. 14.1 (continued)

Fig. 14.2 A 30-year-old man after high velocity gunshot wound. (**a**) Anteroposterior (AP) and (**b**) lateral of a civilian gunshot wound to the medial distal tibia. (**c**) Initial fixation with medial plate. (**d**) AP after infection, plate removal, and flap coverage. (**e**) AP of malunion after external fixator removal. (**f**) AP after laterally based osteotomy, plate fixation, and bone grafting. (**g**) AP with union

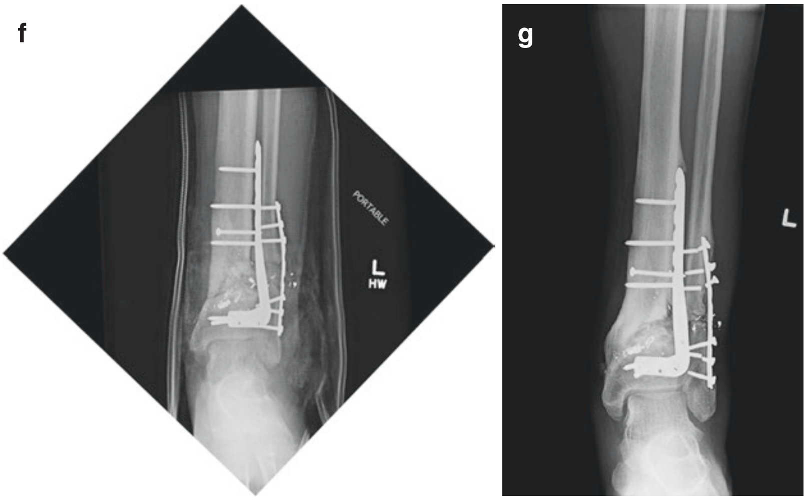

Fig. 14.2 (continued)

14.4.5 Gradual Correction

Multiplanar deformities, especially those involving length, can be successfully treated using distraction osteogenesis methods [28–35]. Traditional Ilizarov methods allow for the correction of a complex deformity in a sequential manner requiring frame modification at each stage. Newer hexapod external fixators, however, allow simultaneous correction of all six axes while utilizing a virtual hinge which requires little frame modification [36–41]. Circular external fixators can stabilize small periarticular joint segments. Additionally, spanning of the ankle joint increases the stability of the fixation construct and allows maintenance of neutral joint alignment [42, 43]. By placing multiple hinges in the external fixator, the surgeon may correct the deformity of the distal tibia ankle and/or foot simultaneously [44, 45]. The rate and magnitude of these complex corrections is limited by the position of related neurovascular structures, the skin, and the ability of the chosen osteotomy site to generate bone. Osteogenic potential depends upon the location that the osteotomy is created, local conditions including pre-existing hardware as well as soft tissue and vascular concerns, and the quality of the host. A detailed discussion of deformity planning, osteotomy techniques, and preoperative planning are beyond the scope of this chapter [46–48].

14.5 Malleolar Malunions

14.5.1 Lateral Malleolus

The fibula is most important near the ankle joint, as this is the origin of the lateral ankle ligament complex, the syndesmosis, and the fibular-talar articulation. Fibular deformity associated with tibial shaft fractures rarely causes problems, as the ankle structures are largely unaffected. However, as a deformity in the fibula approaches the ankle, it becomes a malunion of the lateral malleolus and has great implication on the overall integrity of the ankle joint including the syndesmosis and the talofibular articulation [49, 50]. The most common causes of lateral malleolar malunion are deficient length and inappropriate rotation during initial reduction [51–53]. In both cases, the malunion is treated with an osteotomy, adequate reduction, and internal fixation techniques [54–56]. Gaining length in a malunited fibula can be difficult; however employing indirect reduction techniques with the use of a pushing plate is reliable [57–59].

14.5.2 Posterior Malleolus

Fractures of the posterior malleolus generally signify disruption of the posterior inferior tibiafibular ligament (PITFL). Large fractures of the posterior malleolus, however, can lead to joint instability with posterior subluxation of the talus. Inadequate reduction of these fragments can lead to edge loading of the articular surface and post-traumatic arthritis of the ankle joint. In the sagittal plane, the anatomic axis of the tibia should intersect the lateral process of the talus. A significant posterior malleolus malunion will result in a posterior translation of the talus relative to this tibial axis [60]. This results in a relative shortening of the foot, altering soft tissue tension and compromising the biomechanics of motion and weightbearing. A CT scan should be performed to better evaluate the intra-articular reduction of the posterior malleolus. Correction of posterior malleolar malunions can be technically challenging and may require an intra-articular osteotomy and buttress plate fixation.

14.5.3 Medial Malleolus

Malunions of the medial malleolus are uncommon, about 4% when treated with open reduction internal fixation [61]. Deformity of the medial malleolus after fracture malreduction is clinically well tolerated as long as the deltoid ligament function is competent. Symptomatic malunions are those that compromise the position of the talus in the ankle mortise [62]. Malunions of the medial malleolus are best treated with a simple osteotomy and internal fixation [60].

14.6 Syndesmotic and Intra-articular Malunions

14.6.1 Syndesmotic Malunions

Syndesmotic injuries that have healed in improper position can lead to chronic pain, instability of the ankle mortise, and osteoarthritis over time due to altered loading of the articular surface [63]. Syndesmotic malunions can be difficult to diagnose, especially if there is residual fibular rotation or sagittal plane deformity. Diagnosis can be achieved through the abnormal appearance of a well-done ankle radiograph, ankle stress views, or a CT scan. It is often necessary to compare the anatomic structures of the injured side to those of the uninjured, contralateral side. Correction of these deformities may entail releasing the soft tissues about the syndesmosis, reduction, and internal fixation in the appropriate alignment. Due to the intimate relationship of the syndesmosis with the posterior and lateral malleoli, malunion correction of these structures may also be required [64, 65].

14.6.2 Intra-articular Malunions

Intra-articular malunions lead to abnormal cartilage loading and thus post-traumatic arthritis [66, 67] (Fig. 14.3). Simple articular malunions, such as those involving a simple vertical fracture line in the medial malleolus, are amenable to an intra-articular osteotomy with reduction and internal fixation. More complex intra-articular malunions, especially those involving articular depression, may require eventual arthrodesis of the ankle joint or an arthroplasty solution [68–70] (Fig. 14.4). Some articular malunions do not have a step-off in the articular surface, but represent the center of rotation of a more complex proximal malunion [71–73] (Fig. 14.5). Correction of these malunions requires addressing proximal deformity as well as the intra-articular malunion [26, 74–76].

14.7 Case Discussion

14.7.1 Case 1

This is a 27-year-old woman who presented to the office with complaints of chronic deformity and ankle pain (see Fig. 14.1). She gave a history of having broken her ankle as a child, and since that time she had progressive deformity and pain. She was able to give a history of having surgery

Fig. 14.3 A 70-year-old with remote bimalleolar fracture treated nonoperatively. (**a**) Anteroposterior (AP) and (**b**) lateral demonstrating bimalleolar malunion with arthritis. (**c**) AP after bimalleolar osteotomy to restore the mechanical axis with fusion. (**d**) Final union

Fig. 14.4 A 65-year-old man with malunited 43-C3 pilon fracture. (**a**) Anteriorposterior (AP) and (**b**) lateral of an originally non-united pilon fracture, now with a malunited metaphysis, ankle arthritis, and a mobile hindfoot. (**c**) AP and (**d**) lateral of a metaphyseal realignment osteotomy and ankle arthrodesis. (**e**) AP and (**f**) lateral at final union

on her ankle in her teenage years but was not able to give details.

Plain radiographs of the ankle show a valgus deformity at the distal tibia with a shortened fibula (see Fig. 14.1a, b). The ankle mortise and syndesmosis appear to be relatively well aligned. A scanogram (see Fig. 14.1c) was obtained to evaluate leg length and overall alignment. The length of the medial distal tibia was appropriate with all shortening occurring through a growth arrest in the lateral tibia and fibula.

In this case the center of the deformity, the CORA, is at the joint line. In order to gain appropriate space to mount a circular fixator on the distal tibia, the osteotomy had to be done at a level different from the CORA (see Fig. 14.1d). The preoperative planning can be seen by the pencil lines on the scanogram.

Fig. 14.5 A 35-year-old man with deformity after pilon fixation. (**a**) Anteroposterior (AP) and (**b**) lateral demonstrating malunited 43-C2 pilon fracture. (**c**) AP and (**d**) lateral intraoperative images demonstrating mechanical axis realignment with cervical allograft in the area of bone loss. (**e**) AP and (**f**) lateral at union

The final films (see Fig. 14.1e, f) show a correction of the overall limb alignment, with the introduction of translation of both the tibia and fibula. This illustrates osteotomy rule #2 which states that if the osteotomy is done at a level distant from the CORA, a translation is introduced into the correction. In this case, the osteotomy of the fibula was done at a level different than of the tibia in case of a nonunion in the tibia. This would have allowed a later tibia pro fibula to treat a tibial nonunion if that had occurred.

At final result, the patient was happy with the cosmetic alignment of her leg and the improvement in her ankle pain. She did note a fullness of the distal lateral leg but declined an offer to shave the bony prominence.

14.7.2 Case 2

This case involves a 30-year-old man with a civilian ballistic injury to the left distal tibia (see Fig. 14.2). AP and lateral radiographs were obtained of this injury by the original surgeon (see Fig. 14.2a, b). The wound over the anterolateral ankle is described as relatively small, and the patient was taken to the operating room initially for wound management and external fixation. After the soft tissues had calmed down, the patient was taken back to the operating room for open reduction and internal fixation utilizing a medially based plate (see Fig. 14.2c).

Unfortunately, the wound broke down in the postoperative period requiring plate removal, flap coverage, a repeated external fixator, and a period of intravenous antibiotics. The patient was referred for further care after removal of the second external fixator (see Fig. 14.2e).

On examination, the skin on the medial side of the distal tibia was relatively adherent. It was felt that avoiding dissection in this area would lead to a more successful soft tissue outcome. We planned an opening wedge osteotomy with the apex of the correction being on the medial cortex of the distal tibia. An anterolateral approach was undertaken which allowed an osteotome to be placed across the malunited distal tibia and the osteotomy opened with a lamina spreader. Once the desired correction had been achieved, both the tibia and the fibula were plated. Bone graft was placed in the osteotomy site to provide a scaffolding as well as encourage bone healing.

Unfortunately, the patient was not compliant with follow-up. He presented back several weeks later with a radiograph (see Fig. 14.2f) showing a union of the correction as well as broken hardware. The patient admits to walking on this construct almost immediately. His ankle symptoms were improved, and he was happy with his deformity correction. His soft tissue envelope had healed without issue.

14.7.3 Case 3

This patient (see Fig. 14.3) is a 70-year-old woman with a 4-year history of a bimalleolar ankle fracture treated, nonoperatively. She came in complaining of ankle pain, deformity, and an increasing difficulty with walking. Her ankle range of motion was minimal, and she did have pain with subtalar motion.

Initial radiographs (see Fig. 14.3a, b) show a malunited bimalleolar fracture with lateral shift of the talus, talar inclination, and wear on the lateral surface of the tibiotalar joint. In addition, the ankle is mildly subluxed posteriorly.

The patient desired one operation to correct her deformity and pain. With her age, bone quality, and deformity, our preoperative plan was to perform an osteotomy of both malleoli to shift the talus underneath the tibia and to treat the ankle arthritis with a intramedullary nail (see Fig. 14.3c).

Postoperative the patient was happy that she was able to bear weight early as well as with the correction of her cosmetic deformity (see Fig. 14.3d).

14.7.4 Case 4

This is a 65-year-old man who was originally treated for an open 43-C3 fracture (see Fig. 14.4). The meta-diaphyseal component of this injury was slow to heal, and it was treated with an intramedullary nail after union of the articular surface. Unfortunately, the alignment of the metaphysis was lost during treatment. Initially the patient was happy with his result, but presented back 3 years later with ankle pain, new complaints of deformity at the ankle, and a painless hindfoot (see Fig. 14.4a, b).

Because the patient's hindfoot was pain-free with motion, and all the arthritis seemed to be focused on the tibiotalar joint, the solution needed to preserve the subtalar joint. He was taken to the operating room for a realignment osteotomy of the metaphyseal region and a subtalar sparing ankle arthrodesis (see Fig. 14.4c, d).

Final radiographs show a nice correction of his alignment, and the patient reported resolution of most of his ankle symptoms (see Fig. 14.4e, f).

14.7.5 Case 5

This case (see Fig. 14.5) involves a 35-year-old man who was referred with ankle pain and swelling after treatment for an ankle fracture. His initial radiographs (see Fig. 14.5a, b) showed a pilon fracture which had gone on to union with valgus alignment and subluxation of the talus anteriorly on the tibia.

A preoperative CT scan, unfortunately not available, demonstrated an anterior and lateral tibial joint line which was not reconstructable. Our goals were to return the foot to its position underneath the tibia and to restore the anatomical axis of the lower extremity.

Intraoperative images (see Fig. 14.5c, d) demonstrate realignment of the mechanical axis on both AP and lateral views. The bone defect in the anterolateral tibia was filled with cortical allograft used in cervical arthrodesis.

Final films demonstrate a union with restored mechanical axis of the limb (see Fig. 14.5e, f).

14.8 Summary

Malunions of the distal tibia and ankle comprise a diverse group of clinical problems ranging from simple angular deformities to complex six-axis periarticular malunions requiring a multi-staged approach. In either case, a thorough analysis of the deformity based on standard radiographs and a detailed preoperative plan are essential for radiographic, cosmetic, and functional success.

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