26

PRINCIPLES OF MALUNIONS

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EVALUATION

Each malunited fracture presents a unique set of bony deformities. Deformities are described in terms of abnormalities of length, angulation, rotation, and translation. The location, magnitude, and direction of the deformity complete the characterization of the malunion. Proper evaluation allows the surgeon to determine an effective treatment plan for deformity correction.

Clinical

Evaluation begins with a medical history and a review of all available medical records, including the date and mechanism of injury of the initial fracture and all subsequent operative and nonoperative interventions. The history should also include descriptions of prior wound and bone infections, and prior culture reports should be obtained. All preinjury medical problems, disabilities, or associated injuries should be noted. The patient's current level of pain and functional limitations as well as medication use should be documented.

Following the history, a physical examination is performed. The skin and soft tissues in the injury zone should be inspected. The presence of active drainage or sinus formation should be noted.

The malunion site should be manually stressed to rule out motion and assess pain. In a solidly healed fracture with deformity, manual stressing should not elicit pain. If pain is elicited on manual stressing, the orthopaedic surgeon should consider the possibility that the patient has an ununited fracture.

A neurovascular examination of the limb and evaluation of active and passive motion of the joints proximal and distal to the malunion site should be performed. Reduced motion in a joint adjacent to a malunion site may alter both the treatment plan and the expectations for the ultimate functional outcome. Patients who have a periarticular malunion may also have a compensatory fixed deformity at an adjacent joint, which must be recognized to include its correction in the treatment plan. Correction of the malunion without addressing a compensatory joint deformity results in a straight bone with a maloriented joint, thus producing a disabled limb. The limb may appear aligned in these cases, but x-ray evaluation will reveal the joint deformity. If the patient cannot place the joint into the position that parallels the deformity at the malunion site (e.g., evert the subtalar joint into valgus in the presence of a tibial valgus malunion), the joint deformity is fixed and requires correction (Fig. 26-1).

Radiographic

The plain radiographs from the original fracture show the type and severity of the initial bony injury. Subsequent plain radiographs show the status of orthopaedic hardware (e.g., loose, broken, undersized) as well as document the timing of removal or insertion. The evolution of deformity—gradual versus sudden, for example—should be evaluated.

The current radiographs are evaluated next. Anteroposterior (AP) and lateral radiographs of the involved bone, including the proximal and distal joints, are used to evaluate the axes of the involved bone; manual measurement of standard radiographs or computer-assisted measurement of digital radiographs may be used with equivalent accuracy.[88,92,99] Bilateral

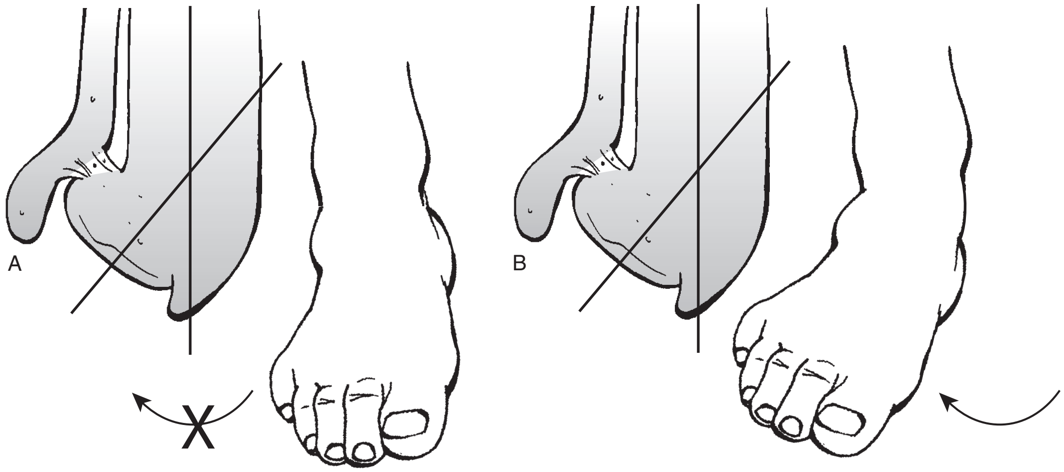


FIGURE 26-1 Angular deformity near a joint can result in a compensatory deformity through the joint. For example, frontal plane deformities of the distal tibia can result in a compensatory frontal plane deformity of the subtalar joint. The deformity of the subtalar joint is fixed **(A)** if the patient's foot cannot be positioned to parallel the deformity of the distal tibia or flexible **(B)** if the foot can be positioned parallel to the deformity of the distal tibia.

AP and lateral 51-inch alignment radiographs are obtained for lower extremity deformities to evaluate limb alignment (Fig. 26-2). Flexion/extension lateral radiographs may be useful to determine the arc of motion of the surrounding joints.

The current radiographs are used to describe the following characteristics: limb alignment, joint orientation, anatomic axes, mechanical axes, and center of rotation of angulation (CORA). Normative values for the relations among these various parameters[10,72] are used to assess deformities.

Limb Alignment

Evaluation of limb alignment involves assessment of the frontal plane mechanical axis of the entire limb rather than single bones.[35,45,47,77,78,90] In the lower extremity, the frontal plane mechanical axis of the entire limb is evaluated using the weight-bearing AP 51-inch alignment radiograph with the feet pointed forward (neutral rotation).[41,49,82] Mechanical axis deviation (MAD) is measured as the distance from the knee joint center to the line connecting the joint centers of the hip and ankle. The hip joint center is located at the center of the femoral head. The knee joint center is half the distance from the nadir between the tibial spines to the apex of the intercondylar notch on the femur. The ankle joint center is the center of the tibial plafond.

Normally, the mechanical axis of the lower extremity lies 1 mm to 15 mm medial to the knee joint center (Fig. 26-3). If the limb mechanical axis is outside this range, the deformity is described as MAD (see Fig. 26-3). MAD greater than 15 mm medial to the knee midpoint is varus malalignment; any MAD lateral to the knee midpoint is valgus malalignment.

Anatomic Axes

The anatomic and mechanical axes of each of the long bones are assessed in both the frontal plane (AP radiographs) and sagittal plane (lateral radiographs). The anatomic axes are defined as the line that passes through the center of the diaphysis along the length of the bone. To identify the anatomic axis of a long bone, the center of the transverse diameter of the diaphysis is identified at several points along the bone. The line that

FIGURE 26-2 A. Bilateral weight-bearing 51-inch AP alignment radiograph and **(B)** a 51-inch lateral alignment radiograph, which are used to evaluate lower extremity limb alignment.

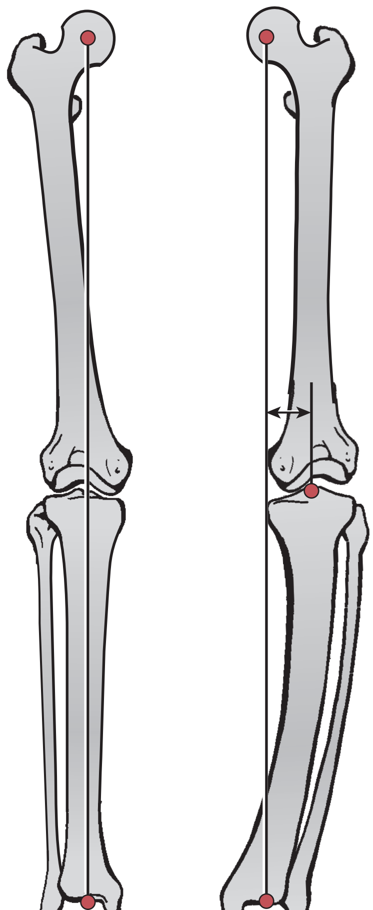


FIGURE 26-3 **A.** Mechanical axis of the lower extremity, which normally lies 1 mm to 15 mm medial to the knee joint center. **B.** Medial mechanical axis deviation, in which the mechanical axis of the lower extremity lies more than 15 mm medial to the knee joint center.

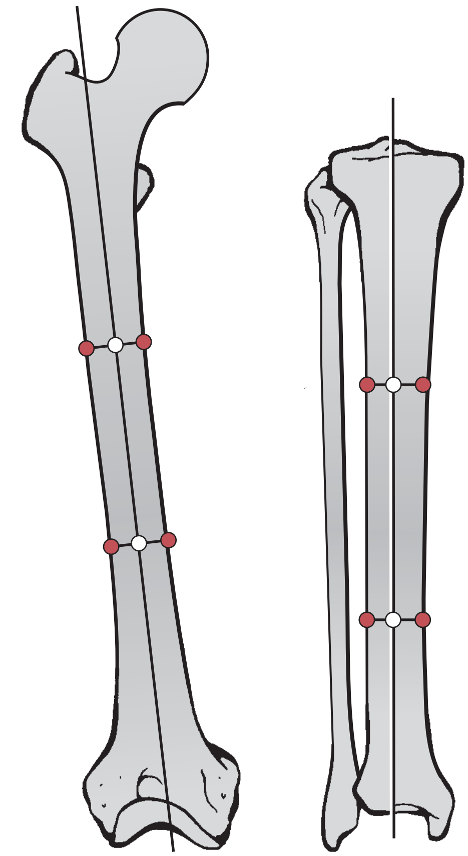


FIGURE 26-4 **A.** Anatomic axis of the femur. **B.** Anatomic axis of the tibia.

passes through these points represents the anatomic axis (Fig. 26-4).

In a normal bone, the anatomic axis is a single straight line. In a malunited bone with angulation, each bony segment can be defined by its own anatomic axis with a line through the center of the diameter of the diaphysis of each bone segment representing the respective anatomic axis for that segment (Fig. 26-5). In bones with multiapical or combined deformities, there may be multiple anatomic axes in the same plane (see Fig. 26-5).

Mechanical Axes

The mechanical axis of a long bone is defined as the line that passes through the joint centers of the proximal and distal joints. To identify the mechanical axis in a long bone, the joint centers are connected by a line (Fig. 26-6). The mechanical axis of the entire lower extremity was described above under the heading "Limb Alignment."

Joint Orientation Lines

Joint orientation describes the relation of a joint to the respective anatomic and mechanical axes of a long bone. Joint orientation lines are drawn on the AP and lateral radiographs in the frontal and sagittal planes, respectively.

Hip orientation may be assessed in two ways in the frontal plane. The trochanter-head line connects the tip of the greater trochanter with center of the hip joint (the center of the femoral head). The femoral neck line connects the hip joint center with a series of points which bisect the diameter of the femoral neck.

Knee orientation is represented in the frontal plane by joint orientation lines at the distal femur and the proximal tibia. The distal femur joint orientation line is drawn tangential to the most distal points of the femoral condyles. The proximal tibial joint orientation line is drawn tangential to the subchondral lines of the medial and lateral tibial plateaus. The angle between these two knee joint orientation lines is called the joint line congruence angle (JLCA), which normally varies from 0 degrees to 2 degrees medial JLCA (i.e., slight knee joint varus). A lateral JLCA represents valgus malorientation of the knee, and a medial JLCA of 3 degrees or greater represents varus malorientation of the knee.

Knee orientation is represented in the sagittal plane by joint orientation lines at the distal femur and the proximal tibia. The sagittal distal femur joint orientation line is drawn through the anterior and posterior junctions of the femoral condyles and the metaphysis. The sagittal proximal tibial joint orientation line is drawn tangential to the subchondral lines of the tibial plateaus.

Malorientation of the knee joint produces malalignment, but limb malalignment (MAD outside the normal range) is not necessarily due to knee joint malorientation.

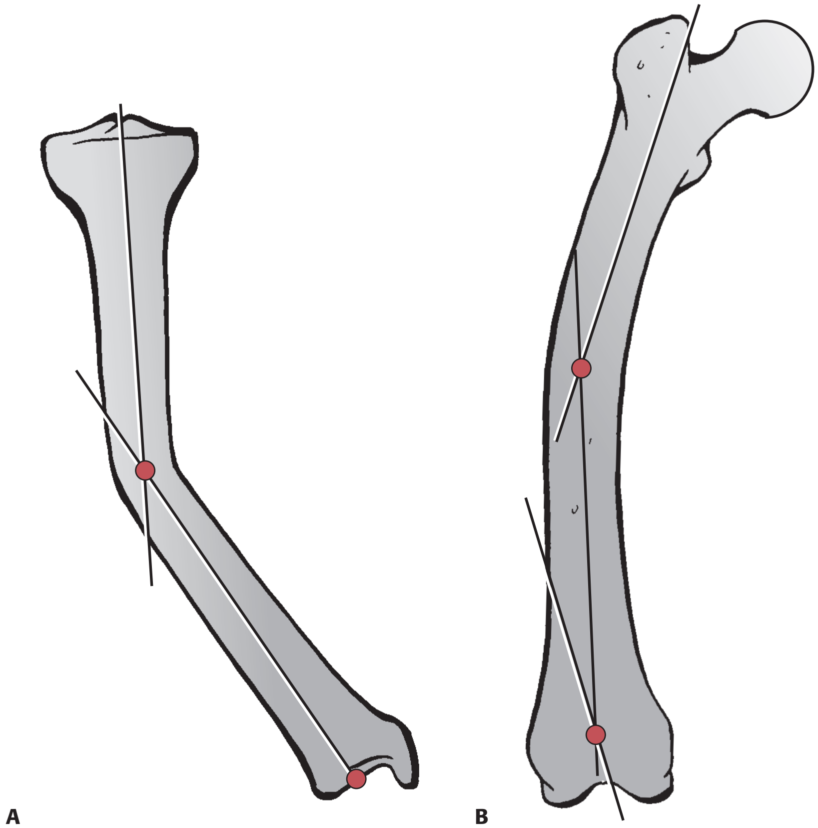


FIGURE 26-5 **A.** A malunited tibia fracture with angulation showing the anatomic axis for each bony segment as a line through the center of the diameter of the respective diaphyseal segments. **B.** A malunited femur fracture with a multiapical deformity, showing multiple anatomical axes in the same plane.

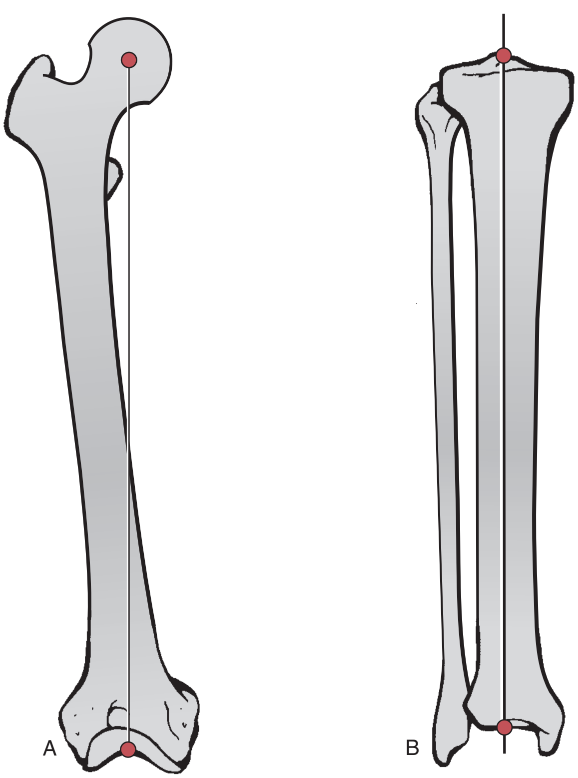


FIGURE 26-6 The mechanical axis of a long bone is defined as the line that passes through the joint centers of the proximal and distal joints. **A.** The mechanical axis of the femur. **B.** The mechanical axis of the tibia.

Ankle orientation is represented in the frontal plane by a line drawn through the subchondral line of the tibial plafond. Ankle orientation is represented in the sagittal plane by a line drawn through the most distal points of the anterior and posterior distal tibia.

Joint Orientation Angles

The relation between the anatomic axes or the mechanical axes and the joint orientation lines can be referred to as joint orientation angles described using standard nomenclature (Table 26-1 and Fig. 26-7).

In order to draw a joint orientation angle in the lower extremity, begin by drawing a joint orientation line. Next, identify the joint center, as the joint center will always lie on the mechanical axis and the joint orientation line. The mechanical axis line of the segment near the joint can be drawn using one of three methods: (1) using the population mean value for that particular joint orientation angle; (2) using the joint orientation angle of the contralateral extremity, assuming it is normal; or (3) by extending the mechanical axis of the neighboring bone.

For example, in order to draw the mechanical lateral distal femoral angle (mLDFA) in a femur with a frontal plane deformity, the steps would be as follows. Step 1: Draw the distal femoral joint orientation line. Step 2: Start at the joint center and draw an 88-degree mLDFA (population normal mean value), which will define the mechanical axis of the distal femoral segment, or draw the mLDFA which mimics the contralateral distal femur (if normal), or extend the mechanical axis of the tibia proximally (if normal) to define the distal femoral mechanical axis.

TABLE 26-1 Normal Values for Joint Orientation Angles in the Lower Extremity

Bone—Plane	Components		Mean Value (in degrees)	Normal Range (in degrees)
Femur—Frontal				
Anatomic medial proximal femoral angle	Anatomic axis	Trochanter-head line	84	80–89
Mechanical lateral proximal femoral angle	Mechanical axis	Trochanter-head line	90	85–95
Neck shaft angle	Anatomic axis	Femoral neck line	130	124–136
Anatomic lateral distal femoral angle	Anatomic axis	Distal femoral joint orientation line	81	79–83
Mechanical lateral distal femoral angle	Mechanical axis	Distal femoral joint orientation line	88	85–90
Femur—Sagittal				
Anatomic posterior distal femoral angle	Mid-diaphyseal line	Sagittal distal femoral joint orientation line	83	79–87
Tibial—Frontal				
Mechanical medial proximal tibial angle	Mechanical axis	Proximal tibial joint orientation line	87	85–90
Mechanical lateral distal tibial angle	Mechanical axis	Distal tibial joint orientation line	89	88–92
Tibial—Sagittal				
Anatomic posterior proximal tibial angle	Mid-diaphyseal line	Sagittal proximal tibial joint orientation line	81	77–84
Anatomic anterior distal tibial angle	Mid-diaphyseal line	Sagittal distal tibial joint orientation line	80	78–82

Center of Rotation of Angulation

The intersection of the proximal axis and distal axis of a deformed bone is called the CORA (Fig. 27-8), which is the point about which a deformity may be rotated to achieve correction.[22,30,34,46,72,73,76–78,89] The angle formed by the two axes at the CORA is a measure of angular deformity in that plane. Either the anatomic or mechanical axes may be used to identify the CORA, but these axes cannot be mixed. For diaphyseal malunions, the anatomic axes are most convenient. For juxta-articular (metaphyseal, epiphyseal) deformities, the axis line of the short segment is constructed using one of the three methods described above.

To define the CORA, the proximal axis and distal axis of the bone are identified, and then the orientations of the proximal and distal joints are assessed. If the intersection of the proximal and distal axes lies at the point of obvious deformity in the bone and the joint orientations are normal, the intersection point is the CORA and the deformity is uniapical (in the respective plane). If their intersection lies outside the point of obvious deformity or either joint orientation is abnormal, either a second CORA exists in that plane and the deformity is multiapical or a translational deformity exists in that plane, which is usually obvious on the radiograph.

The CORA is used to plan the operative correction of angular deformities. Correction of angulation by rotating the bone around a point on the line that bisects the angle of the CORA (the "bisector") ensures realignment of the anatomic and mechanical axes without introducing an iatrogenic translational deformity.[34] The bisector is a line that passes through the CORA and bisects the angle formed by the proximal and distal axes (see Fig. 26-8).[72] Angular correction along the bisector results in complete deformity correction without the introduction of a translational deformity.[10,73,75,77,78] All points which lie on the bisector can be considered to be CORAs because angulation about these points will result in realignment of the deformed bone (see Treatment—Osteotomies below).

Note that the proximal half of the mechanical axis for the femur normally lies outside the bone, so the CORA identified using the mechanical axis of the femur may lie outside the bone as well. By contrast, if the CORA identified using the anatomic axis of the femur or either axis of the tibia lies outside the bone, then a multiapical deformity exists (see Fig. 26-8).

Evaluation of the Various Deformity Types

Length

Deformities involving length include shortening and overdistraction and are characterized by their direction and magnitude. They are measured from joint center to joint center in centimeters on plain radiographs and compared to the contralateral normal extremity, using an x-ray marker to correct for magnification (Fig. 26-9).[91] Shortening after an injury may result from bone loss (from the injury or débridement) or overriding of the healed fracture fragments. Overdistraction at the time of fracture fixation may result in a healed fracture with overlengthening of the bone.

Angulation

Deformities involving angulation are characterized by their magnitude and the direction of the apex of angulation. Angulation deformity of the diaphysis is often associated with limb malalignment (MAD), as described above. Angulation deformities of the metaphysis and epiphysis (juxta-articular deformities) can be difficult to characterize. In particular, the angle formed by the intersection of a joint orientation line and the anatomic or mechanical axis of the deformed bone should be measured. When the angle formed differs markedly from the contralateral normal limb (or normal values when the contralateral limb is abnormal), a juxta-articular deformity is present.[10,75,78] The identification of the CORA is key in characterizing angular deformities and planning their correction.

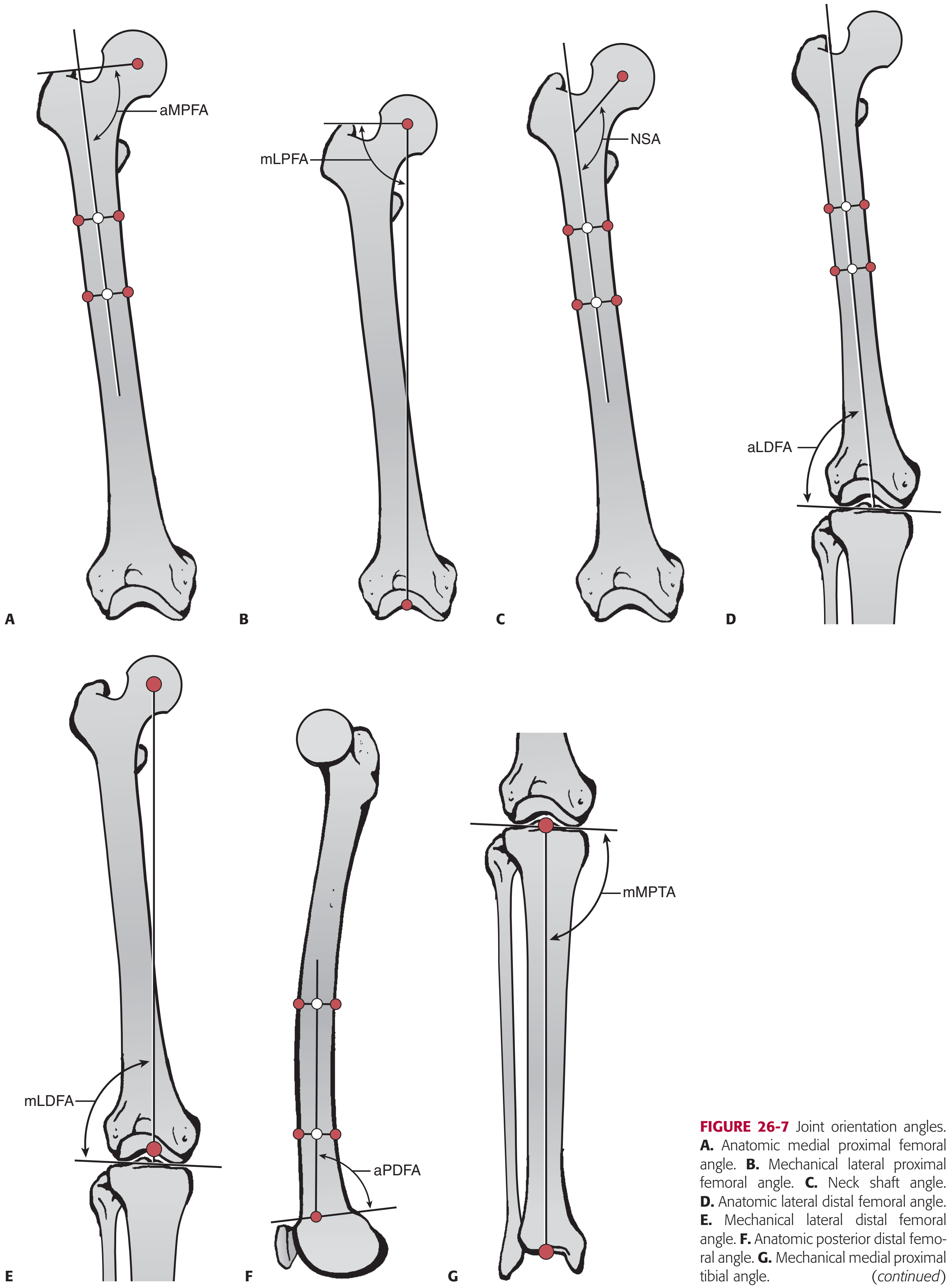


FIGURE 26-7 Joint orientation angles. **A.** Anatomic medial proximal femoral angle. **B.** Mechanical lateral proximal femoral angle. **C.** Neck shaft angle. **D.** Anatomic lateral distal femoral angle. **E.** Mechanical lateral distal femoral angle. **F.** Anatomic posterior distal femoral angle. **G.** Mechanical medial proximal tibial angle. (*continued*)

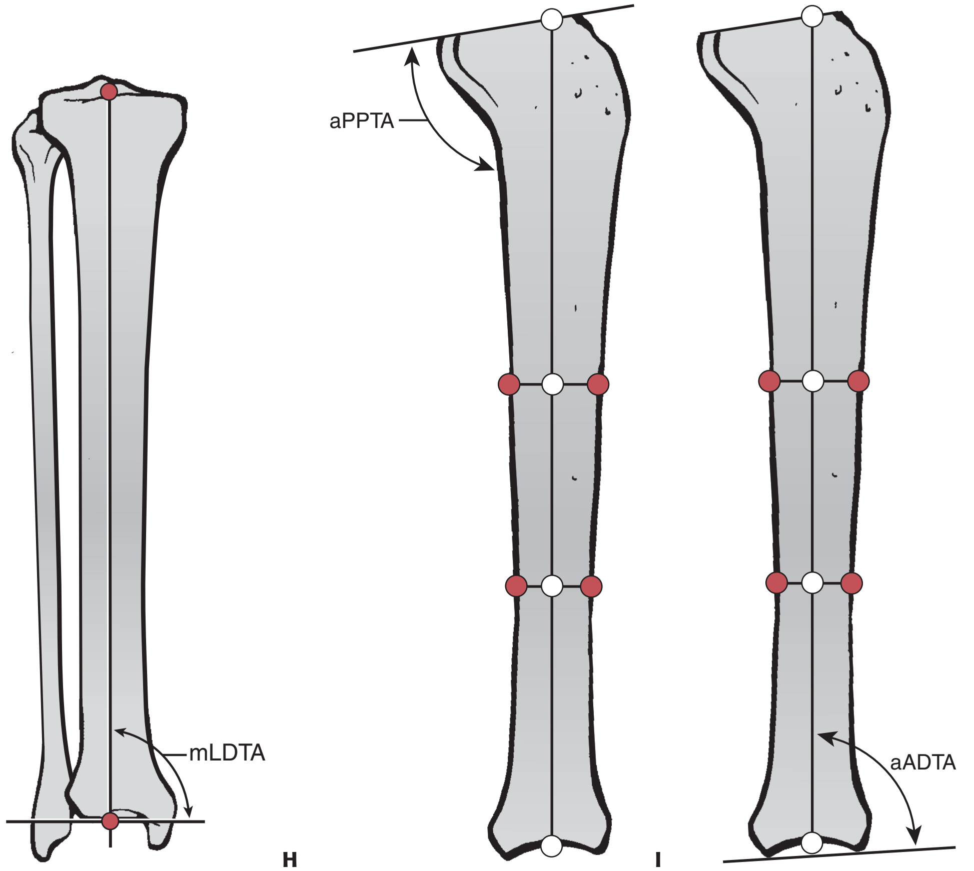


FIGURE 26-7 (*continued*) **H.** Mechanical lateral distal tibial angle. **I.** Anatomic posterior proximal tibial angle. **J.** Anatomic anterior distal tibial angle.

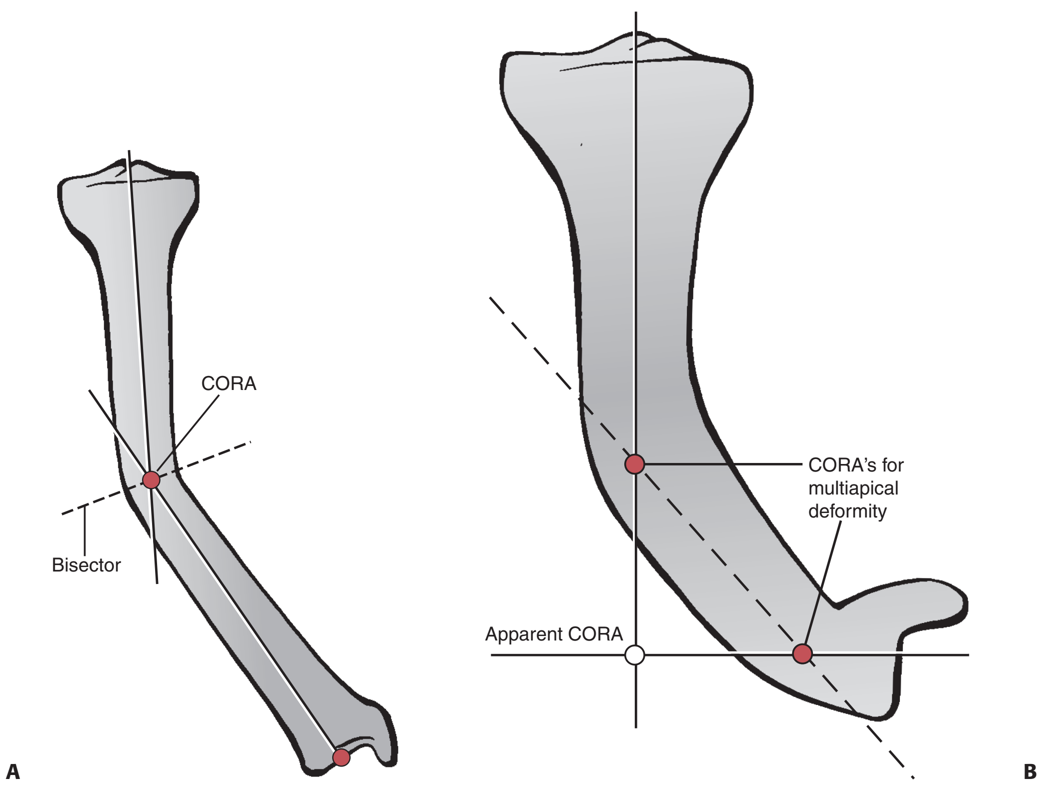


FIGURE 26-8 **A.** CORA and bisector for a varus angulation deformity of the tibia. **B.** Multiapical tibial deformity showing that the apparent CORA joining the proximal and distal anatomic axes (*solid lines*) lies outside of the bone. A third anatomic axis for the middle segment (*dashed line*) shows two CORAs for this multiapical deformity that both lie within the bone.

FIGURE 26-9 Bilateral standing 51-inch AP alignment radiograph reveals a 34 mm leg length inequality.

FIGURE 26-10 A 28-year-old woman presented with complaints of her leg "going out" and her knee hyperextending. **A.** 51-inch AP alignment radiograph reveals a 6-degree apex medial deformity with the CORA 6.5 cm distal to the proximal tibial joint orientation line. **B.** The lateral alignment radiograph shows a 17-degree apex posterior angulation with a CORA 6.5 cm distal to the proximal tibial joint orientation line. This patient has an oblique plane angular deformity without translation.

Pure frontal or sagittal plane deformities are simple to characterize; the angular deformity appears only on the AP or lateral radiograph, respectively. If, however, the AP and lateral radiographs both appear to have angulation with CORAs at the same level on both views, the orientation of the angulation deformity is in an oblique plane (Fig. 26-10). Characterization of the magnitude and direction of oblique plane deformities can be computed from the AP and lateral x-ray measures using either the trigonometric or graphic method.[18,37,72] Using the trigonometric method, the magnitude of an oblique plane angular deformity is:

$$\begin{matrix}\text{oblique}\\\text{magnitude}\end{matrix} = \tan^{-1}\sqrt{\tan^2\begin{pmatrix}\text{frontal}\\\text{magnitude}\end{pmatrix} + \tan^2\begin{pmatrix}\text{sagittal}\\\text{magnitude}\end{pmatrix}},$$

and the orientation (relative to the frontal plane) of an oblique plane deformity is:

$$\text{oblique orientation} = \tan^{-1}\left[\frac{\tan(\text{sagittal magnitude})}{\tan(\text{frontal magnitude})}\right].$$

Using the graphic method, the magnitude of an oblique plane angular deformity is:

$$\begin{matrix}\text{oblique}\\\text{magnitude}\end{matrix} = \sqrt{\begin{pmatrix}\text{frontal}\\\text{magnitude}\end{pmatrix}^2 + \begin{pmatrix}\text{sagittal}\\\text{magnitude}\end{pmatrix}^2},$$

and the orientation (relative to the frontal plane) of an oblique plane deformity is:

$$\text{oblique orientation} = \tan^{-1}\left(\frac{\text{sagittal magnitude}}{\text{frontal magnitude}}\right).$$

The graphic method, based on the Pythagorean Theorem, approximates the exact trigonometric method. The error of approximation for angular deformities using the graphic method is less than 4 degrees unless the frontal and sagittal plane magnitudes are both greater than 45 degrees.[10,46,72,75,77,78]

In the case that the CORA is at a different level on the AP and lateral radiographs, a translational deformity is present in addition to an angulation deformity (Fig. 26-11).

A multiapical deformity is defined by the presence of more than one CORA on either the AP or lateral radiograph (or both). In a multiapical deformity without translation, one of the joints will appear maloriented relative to the anatomic axis of the respective segment. For multiapical deformity, the anatomic

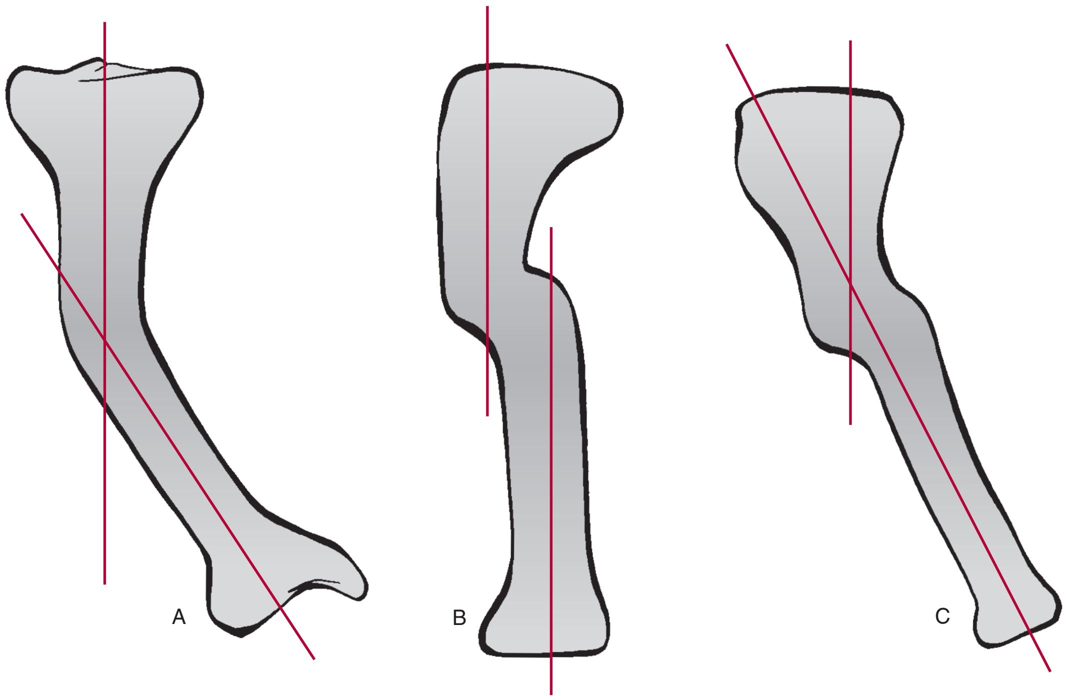


FIGURE 26-11 **(A)** Frontal and **(B)** sagittal views of a tibia with an angulation-translational deformity. Note that the angulation deformity is evident only on the frontal view and the translational deformity is evident only on the sagittal view. **C.** The oblique view showing both deformities.

axis of the segment that has the joint malorientation provides a third line that crosses both of the existing lines. These intersections are the sites of the multiple CORAs (see Fig. 8B).

Rotation

A rotational deformity occurs about the longitudinal axis of the bone. Rotational deformities are described in terms of their magnitude and the position (internal or external rotation) of the distal segment relative to the proximal segment. Identification of a rotational deformity and quantification of the magnitude can be done using clinical measurements,[101] axial computed tomography (Fig. 26-12),[12] or AP and lateral radiographs with either trigonometric calculation or graphical approximation.[72] While axial computed tomography and radiographic methods allow for more precise measurement of rotational deformities, clinical examination often results in measures of sufficient accuracy to allow for adequate correction.[101]

To measure tibial malrotation using clinical examination, the position of the foot axis, as indicated by a line running from the second toe through the center of the calcaneus, is compared to the projection of either the femoral or the tibial anatomic axis. To use the femoral axis, the patient is positioned prone or sits with the knee flexed to 90 degrees. The examiner measures the deviation of the foot axis from the line of the femoral axis; any deviation is considered to represent tibial malrotation. To use the tibial axis, the patient stands with the patella facing anteriorly (i.e., aligned in the frontal plane). To measure tibial malrotation, the examiner measures the deviation of the foot axis from the anterior projection of the tibial anatomic axis in the sagittal plane; any deviation of the foot axis from the tibial anatomic axis is considered to represent tibial malrotation.

To measure a femoral rotational deformity using clinical examination, the patient is positioned prone with the knee flexed to 90 degrees and the femoral condyles parallel to the examination table. The femur is passively rotated internally and externally by the examiner, and the respective angular excursions of the tibia are measured. Asymmetry of rotation in comparison to the opposite side indicates a femoral rotational deformity. If the patient also has a tibial angulation deformity, the tibia will not be perpendicular to the examination table when the femoral condyles are so positioned; tibial angulation deformity will cause an apparent asymmetry in femoral rotation. In this case, the rotational excursions of the tibia must be adjusted for the magnitude of the tibial angular deformity to avoid an incorrect assessment of femoral rotation.

Translation

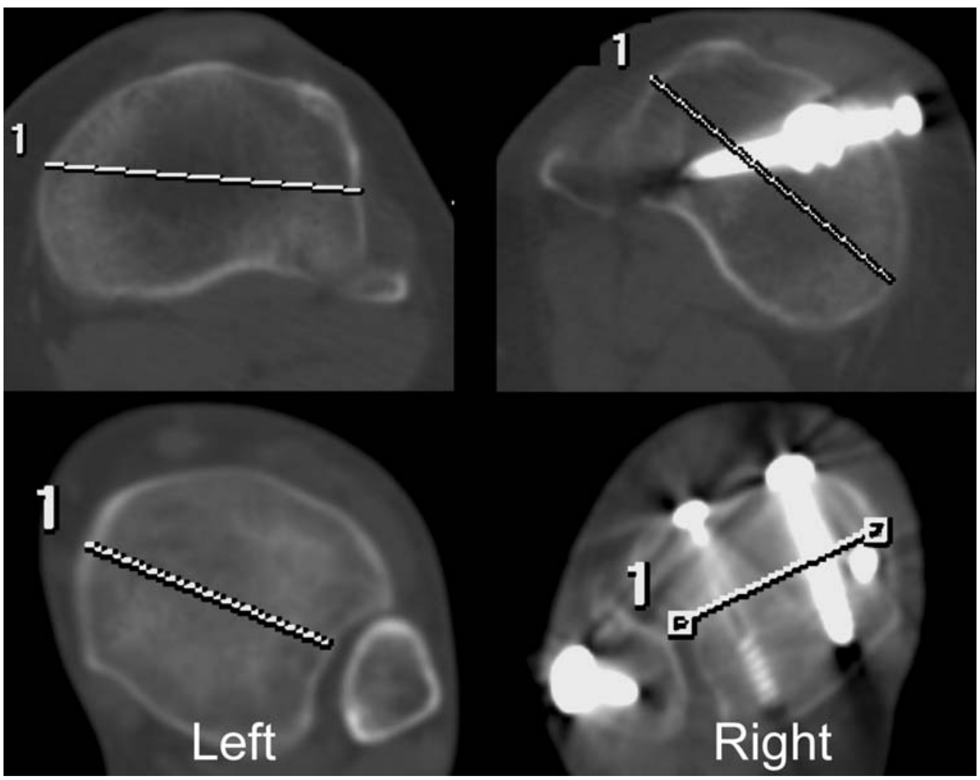
Translational deformities may result from malunion following either a fracture or an osteotomy. Translational deformities are characterized by their plane, direction, magnitude, and level. The direction of translational deformities is described in terms of the position of the distal segment relative to the proximal segment (medial, lateral, anterior, posterior), except for the femoral and humeral heads where the description is the position of the head relative to the shaft. Translational deformities may occur in an oblique plane, and trigonometric or graphical methods similar to those described for characterizing angulation deformities may be used to identify the plane and direction of the deformity.[18,37,72] Magnitude of translation is measured as the horizontal distance from the proximal segment's anatomic axis to the distal segment's anatomic axis at the level of the proximal end of the distal segment (Fig. 26-13).

TREATMENT

The clinical and radiographic evaluation of the deformity provides the information needed to develop a treatment plan. Fol-

A

B



C

FIGURE 26-12 A. Clinical photograph of a 38-year-old woman who presented 9 months after nail fixation of a tibial fracture. She complained of her right foot "pointing outward." **B.** Plain radiographs show what appears to be a healed fracture following tibial nailing. Comparison of the proximal and distal tibias bilaterally was consistent with malrotation of the right distal tibia. **C.** Computed tomography scans of both proximal and distal tibias show asymmetric external rotation of the right distal tibia which measures 42 degrees. The computed tomography scan also confirmed solid bony union at the fracture site.

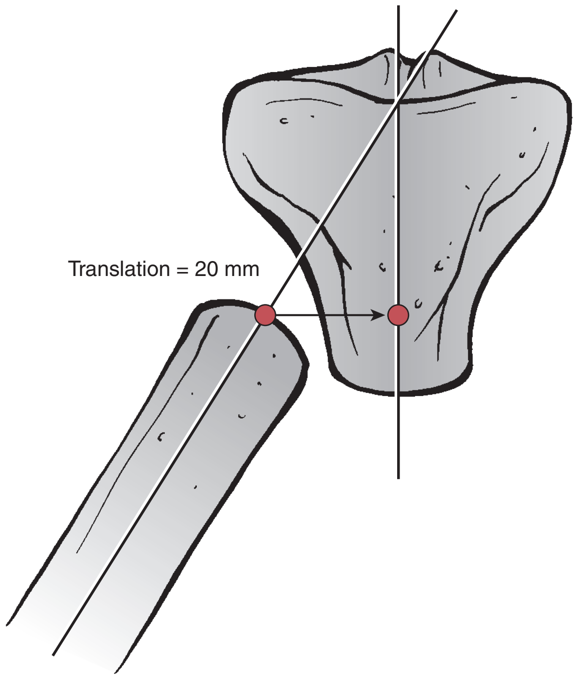


FIGURE 26-13 Method for measuring the magnitude of translational deformities. In this example, with both angulation and translation, the magnitude of the translational deformity is the horizontal distance from the proximal segment's anatomic axis to the distal segment's anatomic axis at the level of the proximal end of the distal segment.

lowing evaluation, the deformity is characterized by its type (length, angulation, rotational, translational, or combined), the direction of the apex (anterior, lateral, posterolateral, etc.), the orientation plane, its magnitude, and the level of the CORA.

The status of the soft tissues may impact the surgical treatment of a bony deformity. Preoperative planning should include an evaluation of overlying soft tissue free flaps and skin grafts. In addition, scarring, tethering of neurovascular bundles, and infection may require modifications to the treatment plan in order to address these concomitant conditions in addition to correcting the malunion. Furthermore, if neurovascular structures lie on the concave side of an angular deformity, acute correction may lead to a traction injury to them with temporary or permanent complications. In such cases, gradual deformity correction may be preferable and allow for gradual accommodation of the nerves or vasculature and thus avoid complications.

Osteotomies

An osteotomy is used to separate the deformed bone segments to allow realignment of the anatomic and mechanical axes. The ability of an osteotomy to restore alignment depends on the location of the CORA, the axis about which correction is performed (the correction axis), and the location of the osteotomy. While the CORA is defined by the type, direction, and magnitude of the deformity, the correction axis depends on the location and type of the osteotomy, the soft tissues, and the choice of fixation technique. The relation of these three factors to one another determines the final position of the bone segments. Reduction following osteotomy produces one of three possible results: (1) realignment through angulation alone; (2) realignment through angulation and translation; and (3) realignment through angulation and translation with an iatrogenic residual translational abnormality (Fig. 26-14).

When the CORA, correction axis, and osteotomy lie at the same location, the bone will realign through angulation alone, without translation. When the CORA and correction axis are at the same location but the osteotomy is made proximal or distal to that location, the bone will realign through both angulation and translation. When the CORA is at a location different than the correction axis and osteotomy, correction of angulation aligns the proximal and distal axes in parallel but excess translation occurs and results in an iatrogenic translational deformity (see Fig. 26-14).

Osteotomies can be classified by cut (straight or dome [understand that these osteotomies are not truly shaped like a dome, they are cylindrical]) and type (opening, closing, neutral). A straight cut, such as a transverse or wedge osteotomy, is made such that the opposing bone ends have flat surfaces. A dome osteotomy is made such that the opposing bone ends have congruent convex and concave cylindrical surfaces. The type describes the rotation of the bone segments relative to one another at the osteotomy site.

Selection of the osteotomy type depends on the type, magnitude, and direction of deformity, the proximity of the deformity to a joint, the location and its effect on the soft tissues, and the type of fixation selected. In certain cases, a small iatrogenic deformity may be acceptable if it is expected to have no effect on the patient's final functional outcome. This situation may be preferable to attempting an unfamiliar fixation method or using a fixation technique that the patient may tolerate poorly.

Wedge Osteotomy

The type of wedge osteotomy is determined by the location of the osteotomy relative to the locations of the CORA and the correction axis. When the CORA and correction axis are in the same location (to avoid translational deformity), they may lie on the cortex on the convex side of the deformity, on the cortex on the concave side of the deformity, or in the middle of the bone (Fig. 26-15).

When the CORA and correction axis lie on the convex cortex of the deformity, the correction will result in an opening wedge osteotomy (see Fig. 26-15). In an opening wedge osteotomy, the cortex on the concave side of the deformity is distracted to restore alignment, opening an empty wedge that traverses the diameter of the bone. An opening wedge osteotomy also increases bone length.

When the CORA and correction axis lie in the middle of the bone, the correction distracts the concave side cortex and compresses the convex side cortex. A bone wedge is removed from only the convex side to allow realignment. This neutral wedge osteotomy (see Fig. 26-15) has no effect on bone length.

When the CORA and correction axis lie on the concave cortex of the deformity, the correction will result in a closing wedge osteotomy (see Fig. 26-15). In a closing wedge osteotomy, the cortex on the convex side of the deformity is compressed to restore alignment; this requires removal of a bone wedge across the entire bone diameter. A closing wedge osteotomy also decreases bone length (resulting in shortening).

These principles of osteotomy also hold true when the osteotomy is located proximal or distal to the mutual site of the CORA and correction axis. As stated above, realignment in these

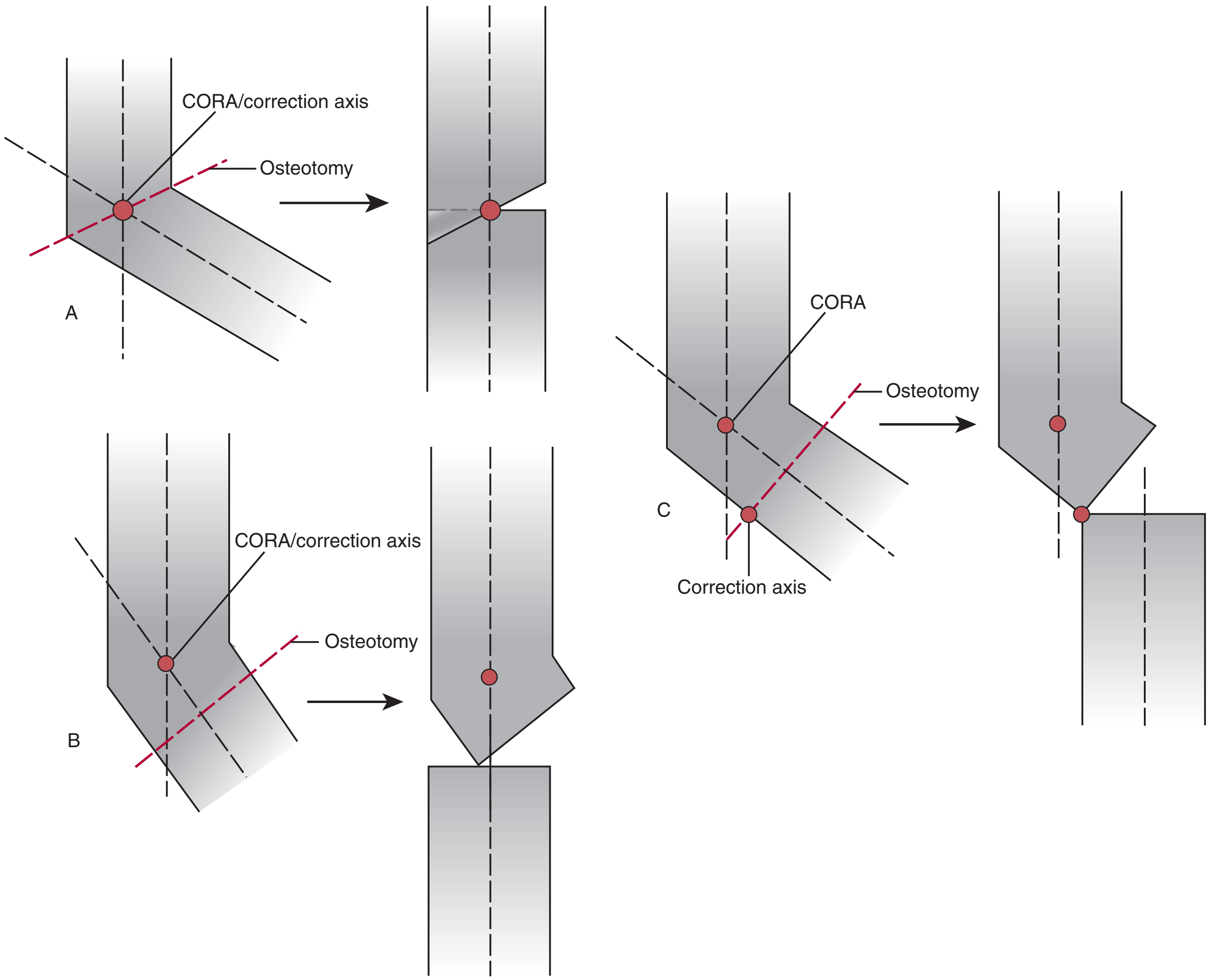


FIGURE 26-14 Possible results when using osteotomy for correction of deformity. **A.** The CORA, the correction axis, and the osteotomy all lie at the same location; the bone realigns through angulation alone, without translation. **B.** The CORA and the correction axis lie in the same location but the osteotomy is proximal or distal to that location; the bone realigns through both angulation and translation. **C.** The CORA lies at one location and the correction axis and the osteotomy lie in a different location; correction of angulation results in an iatrogenic translational deformity.

cases occurs via angulation and translation. When the CORA and correction axis are not at the same point and the osteotomy is proximal or distal to the CORA, the correction maneuver results in excess translation and an iatrogenic translational deformity.

Dome Osteotomy

The type of dome osteotomy is also determined by the location of the CORA and the correction axis relative to the osteotomy. In contrast to a wedge osteotomy, however, the osteotomy site can never pass through the mutual CORA-correction axis (Fig. 26-16). Thus, translation will always occur with deformity correction using a dome osteotomy.

Ideally, the CORA and correction axis are mutually located such that the angulation and obligatory translation that occurs at the osteotomy site results in realignment. Attempts at realignment when the CORA and correction axis are not mutually located results in a translational deformity (see Fig. 26-16). Similar to wedge osteotomy, the CORA and correction axis may lie on the cortex on the convex side of the deformity, on the cortex on the concave side of the deformity, or in the middle of the bone.

The principles guiding wedge osteotomies are also true for dome osteotomies. When the CORA and correction axis lie on the convex cortex of the deformity, the correction will result in an opening dome osteotomy (Fig. 26-17). The translation that occurs in an opening dome osteotomy increases final bone length. When the CORA and correction axis lie in the middle of the bone, the correction will result in a neutral dome osteotomy. A neutral dome osteotomy has no effect on bone length. When the CORA and correction axis lie on the concave cortex of the deformity, the correction will result in a closing dome osteotomy. The translation that occurs in a closing dome osteotomy decreases final bone length. Unlike wedge osteotomies, the movement of one bone segment on the other is rarely impeded, so removal of bone is not typically required unless the final

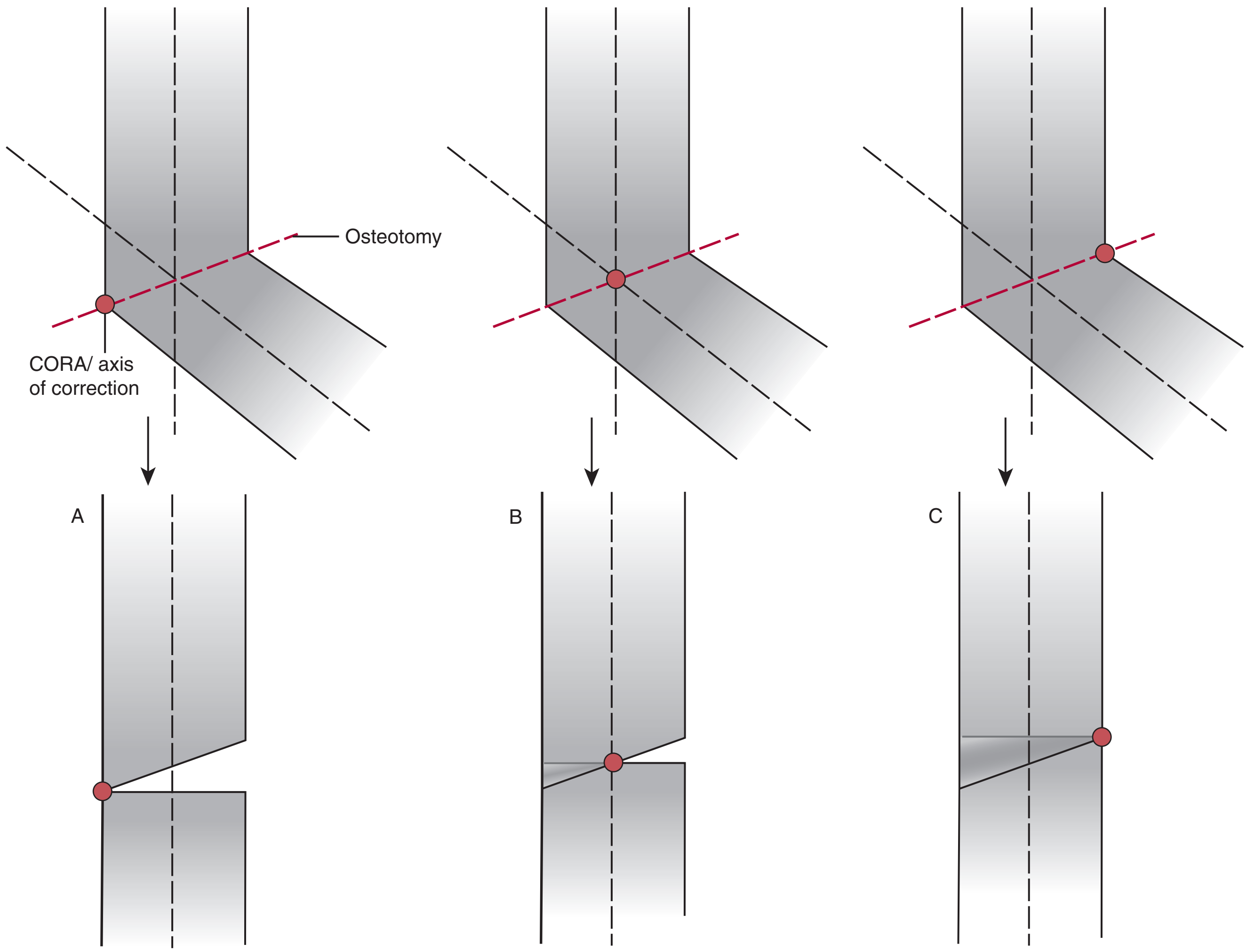


FIGURE 26-15 Wedge osteotomies; the osteotomy is made at the level of the CORA and correction axis in all of these examples. **A.** Opening wedge osteotomy. The CORA and correction axis lie on the cortex on the convex side of the deformity. The cortex on the concave side of the deformity is distracted to restore alignment, opening an empty wedge that traverses the diameter of the bone. Opening wedge osteotomy increases final bone length. **B.** Neutral wedge osteotomy. The CORA and correction axis lie in the middle of the bone. The concave side cortex is distracted and the convex side cortex is compressed. A bone wedge is removed from the convex side. Neutral wedge osteotomy has no effect on final bone length. **C.** Closing wedge osteotomy. The CORA and correction axis lie on the concave cortex of the deformity. The cortex on the convex side of the deformity is compressed to restore alignment, requiring removal of a bone wedge across the entire bone diameter. A closing wedge osteotomy decreases final bone length.

configuration results in significant overhang of the bone beyond the aligned bone column.

Treatment by Deformity Type

Length

Acute distraction or compression methods obtain immediate correction of limb length by acute lengthening with bone grafting or acute shortening, respectively. The extent of acute lengthening or shortening that is possible is limited by the soft tissues (soft tissue compliance, surgical and open wounds, and neurovascular structures).

Acute distraction treatment methods involve distracting the bone ends to the appropriate length, applying a bone graft, and stabilizing the construct to allow incorporation of the graft. Options for treating length deformities include the use of: (1) autogenous cancellous or cortical bone grafts; (2) vascularized autografts; (3) bulk or strut cortical allografts; (4) mesh cage-bone graft constructs; and (5) synostosis techniques. A variety of internal and external fixation treatment methods may be used to stabilize the construct during graft incorporation.[9] The amount of shortening that requires lengthening correction is uncertain.[38,65,102] In the upper extremity, up to 3 to 4 cm of shortening is generally well tolerated, and restoring length when shortening exceeds this value have been reported to improve function.[1,19,59,71,81,96,104,107] In the lower extremity, up to 2 cm of shortening may be treated with a shoe lift; tolerance for a 2 to 4 cm shoe lift is poor for most patients, and most patients with shortening of greater than 4 cm will benefit from restoration of length.[7,8,31,64,102,109]

Acute compression methods are used to correct overdistraction by first resecting the appropriate length of bone and then stabilizing the approximated bone ends under compression. For the paired bones of the forearm and leg, the unaffected bone

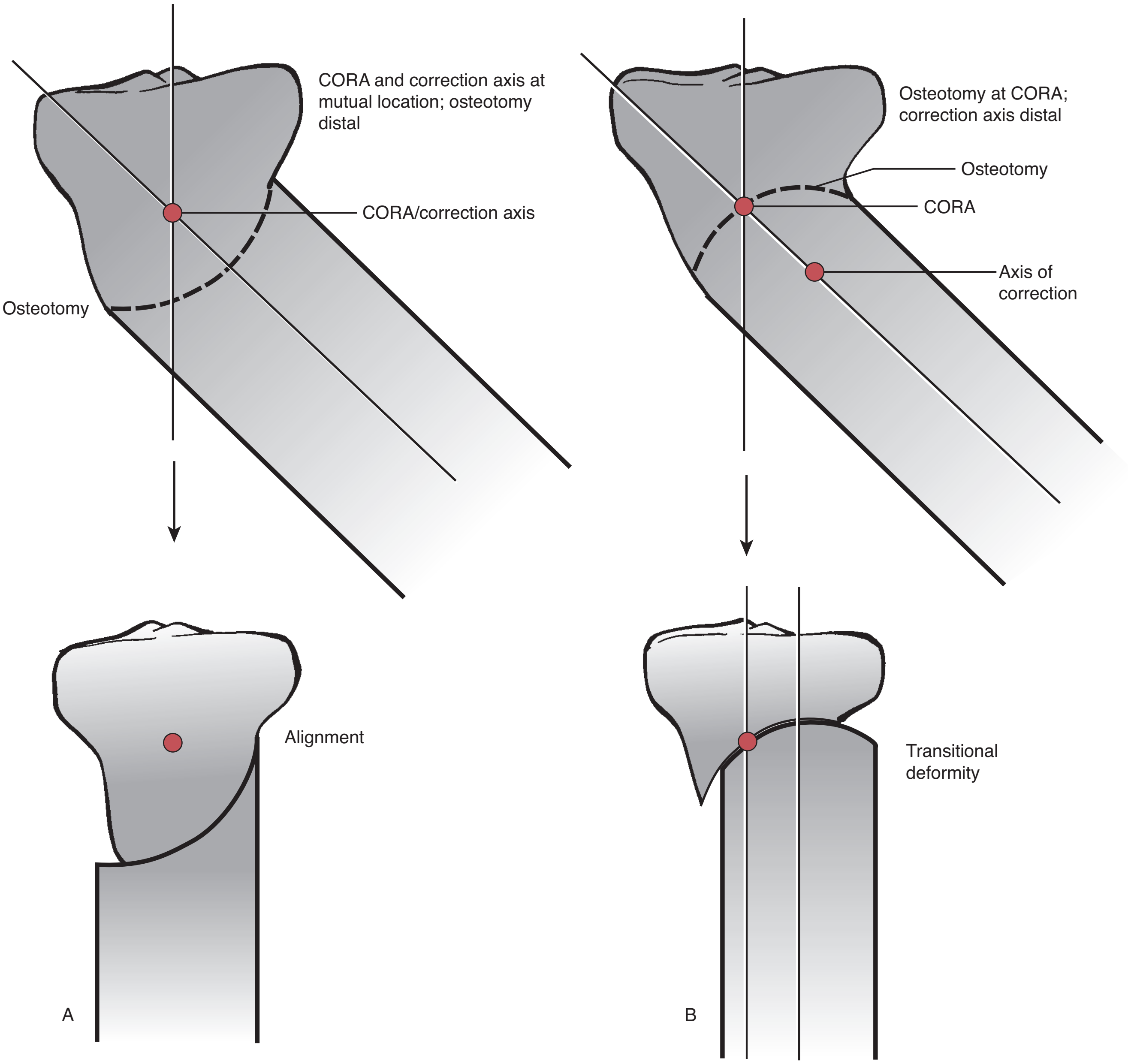


FIGURE 26-16 In a dome osteotomy, the osteotomy site cannot pass through both the CORA and the correction axis. Thus, translation will always occur when using a dome osteotomy. **A.** Ideally, the CORA and correction axis are mutually located with the osteotomy proximal or distal to that location such that the angulation and obligatory translation that occurs at the osteotomy site results in realignment of the bone axis. **B.** When the CORA and correction axis are not mutually located, a dome osteotomy through the CORA location results in a translational deformity.

requires partial excision to allow shortening and compression of the affected bone. For example, partial excision of the intact fibula is necessary to allow shortening and compression of the tibia.

Gradual correction techniques for length deformities typically use tensioned-wire (Ilizarov) external fixation,[3,16,50,59,60,62,74,102,104,107] although gradual lengthening using conventional monolateral external fixation has been described,[70,93,94] and an intramedullary nail that provides a continuous lengthening force has recently been developed.[17,43,44] The most common form of gradual correction is gradual distraction to correct limb shortening. Gradual correction methods for length deformities can also be used to correct associated angular, translational, or rotational deformities simultaneously while restoring length.

Gradual distraction involves the creation of a corticotomy (usually metaphyseal) and distraction of the bone segments at a rate of 1 mm per day using a rhythm of 0.25 mm of distraction repeated four times per day. The bone formed at the distraction site is formed through the process of distraction osteogenesis, as discussed below in the "Ilizarov Techniques" section.

Angulation

Correction of angulation deformities involves making an osteotomy, obtaining realignment of the bone segments, and securing

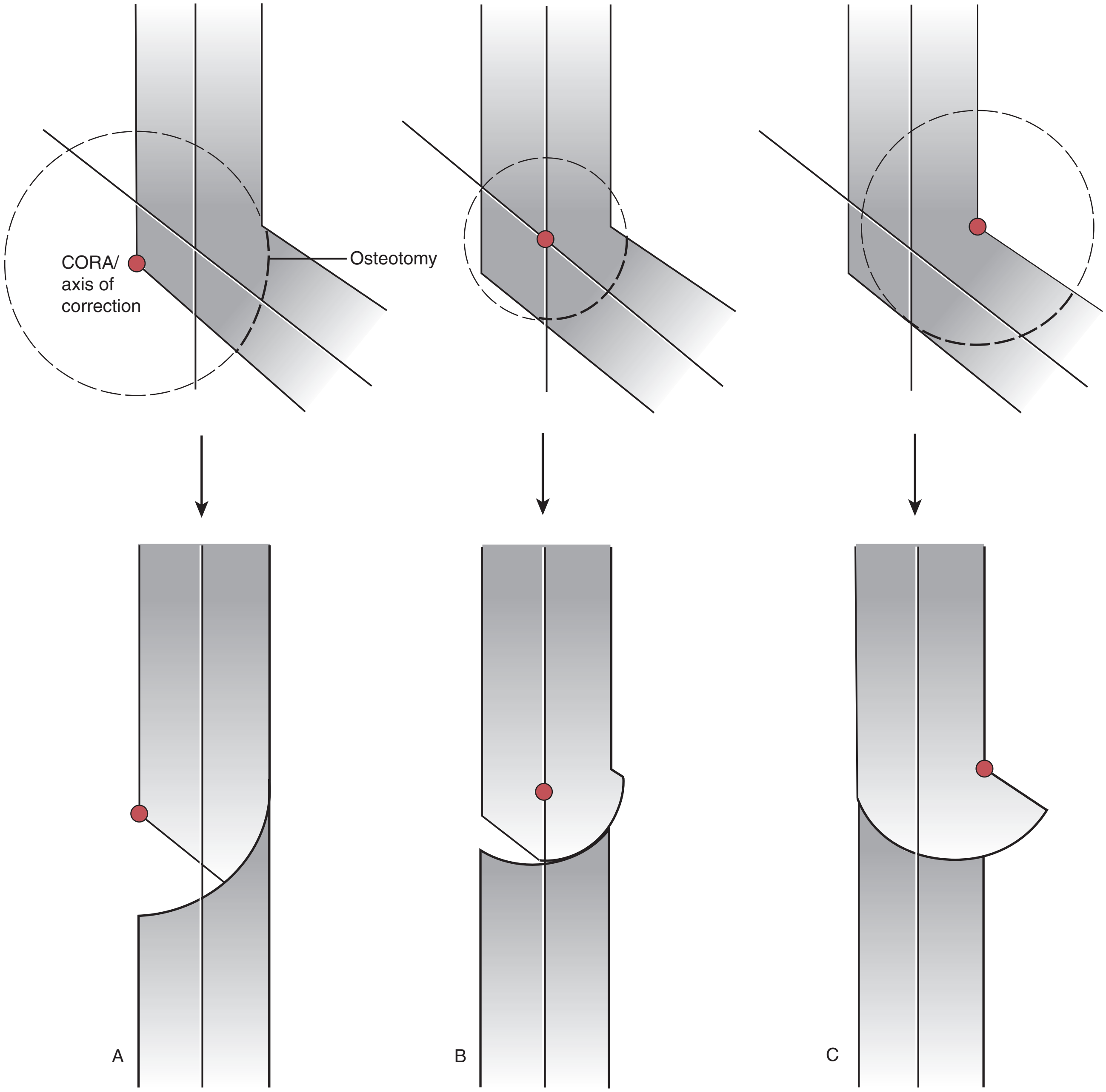


FIGURE 26-17 Dome osteotomies; the CORA and correction axis are mutually located with the osteotomy distal to that location in all of these examples. **A.** Opening dome osteotomy. The CORA and correction axis lie on the cortex on the convex side of the deformity. Opening dome osteotomy increases final bone length. **B.** Neutral dome osteotomy. The CORA and correction axis lie in the middle of the bone. Neutral dome osteotomy has no effect on final bone length. **C.** Closing dome osteotomy. The CORA and correction axis lie on the concave cortex of the deformity. A closing dome osteotomy decreases final bone length and can result in significant overhang of bone that may require resection.

fixation during healing. The correction may be made acutely and then stabilized using a number of internal or external fixation methods.[28,39] Alternatively, the correction may be made gradually using external fixation to both restore alignment and provide stabilization during healing.[28,105]

Angulation deformities in the diaphysis are most amenable to correction using a wedge osteotomy at the same level as the correction axis and the CORA. For juxta-articular angulation deformities, however, the correction axis and the CORA may be located too close to the respective joint to permit a wedge osteotomy. Thus, juxta-articular angulation deformities may require a dome osteotomy with location of the osteotomy proximal or distal to the level of the correction axis and the CORA.

Rotation

Correction of a rotational deformity requires an osteotomy and rotational realignment followed by stabilization. Stabilization may be accomplished using internal or external fixation following acute correction, or external fixation may be used to gradually correct the deformity. The level for the osteotomy, however, can be difficult to determine. While the level of the deformity is obvious in the case of an angulated malunion, the level of deformity in rotational limb deformities is often difficult to determine. Consequently, other factors, including muscle and tendon line of pull, neurovascular structures, and soft tissues, are usually considered to determine the level of deformity and level of osteotomy for correction of a rotational deformity.[32,56,57,72,80,100]

Translation

Translational deformities may be corrected in one of three ways. First, a single transverse osteotomy may be made to restore alignment through pure translation without angulation; the transverse osteotomy does not have to be made at the level of the deformity (Fig. 26-18). Second, a single oblique osteotomy may be made at the level of the deformity to restore alignment and gain length. Third, a translational deformity can be represented as two angulations with identical magnitudes but opposite directions. Therefore, two wedge osteotomies at the level of the respective CORAs and angular corrections of equal magnitudes in opposite directions may be used to correct a translational deformity. It should be noted that the osteotomy types used in this third method (opening, closing, or neutral) will affect final bone length. Internal or external fixation may be used to provide stabilization following acute correction of translational deformities, or gradual correction may be carried out using external fixation.

Combined Deformities

Combined deformities are characterized by the presence of two or more types of deformity in a single bone.[37,40] Treatment planning begins with identifying and characterizing each deformity independent from the other deformities. Once all deformities have been characterized, they are assessed to determine which require correction to restore function. Correction of all of the deformities may be unnecessary; for example, small translational deformities or angulation deformities in the sagittal plane may not interfere with limb function and may remain untreated. Once those deformities requiring correction are identified, the treatment plan outlines the order and method of correction for each deformity.

In many instances, a single osteotomy can be used to correct two deformities. For example, a combined angulation-translational deformity can be corrected using a single osteotomy at

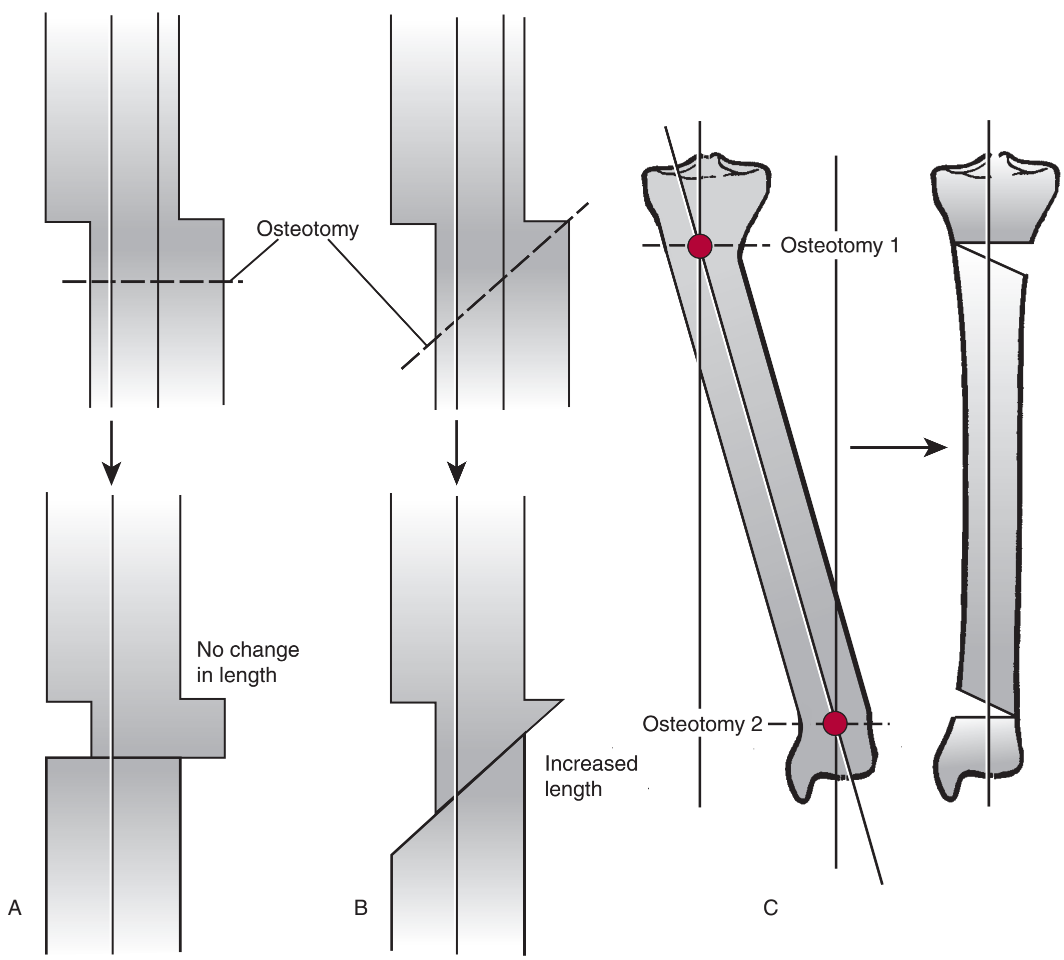


FIGURE 26-18 A. A single transverse osteotomy to restore alignment through pure translation without angulation. **B.** A single oblique osteotomy at the level of the deformity to restore alignment and gain length. **C.** A translational deformity represented as two angulations with identical magnitudes but opposite directions causing malalignment of the mechanical axis of the lower extremity. Two wedge osteotomies of equal magnitudes in opposite directions at the levels of the respective CORAs may be used to correct a translational deformity and restore alignment of the mechanical axis of the lower extremity.

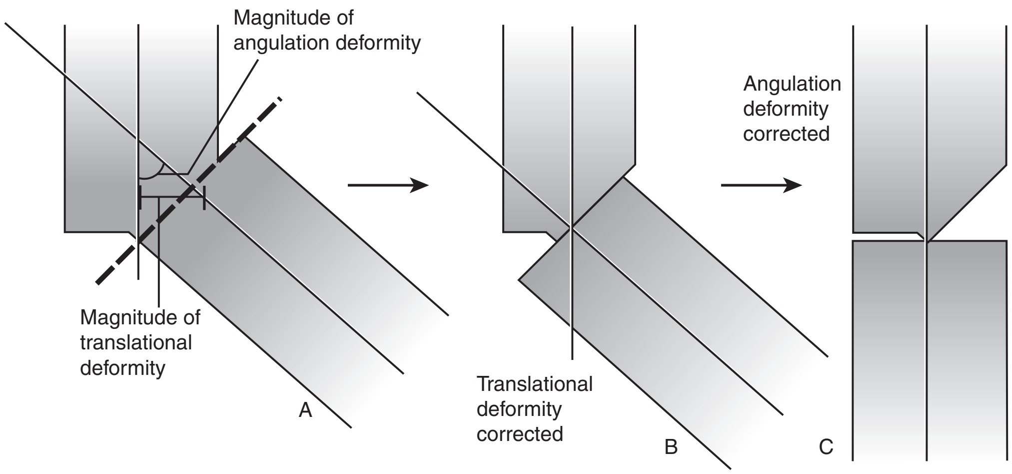


FIGURE 26-19 A single osteotomy to correct an angulation-translational deformity. **A.** A single osteotomy is made to allow correction of both deformities. **B.** Correction of the translational deformity, followed by **(C)** correction of the angulation deformity, resulting in realignment.

the level of the apex of the angulation deformity. This method restores alignment and congruency of the medullary canals and cortices of the respective bone segments (Fig. 26-19). The deformities are then reduced one at a time—reducing translation and then angulation, for instance. Consequently, stabilization can be achieved using an intramedullary nail, as well as a number of other internal fixation and external fixation methods.

Combined angulation-translation deformities can also be treated as multiapical angulation deformities with an osteotomy through either or both CORAs in the frontal and sagittal planes. While this method restores alignment of the bone's mechanical axis, it can also result in incomplete bone-to-bone contact and incongruence of the bone segments' medullary canals and cortices. As a result, stabilization cannot be achieved using an intramedullary nail and other internal fixation and external fixation methods are required to stabilize the bone segments.

A combined angulation-rotational deformity can be corrected by a single rotation of the distal segment around an oblique axis that represents the resolutions of both the component angulation axis and rotation axis (Fig. 26-20).[66] The direc-

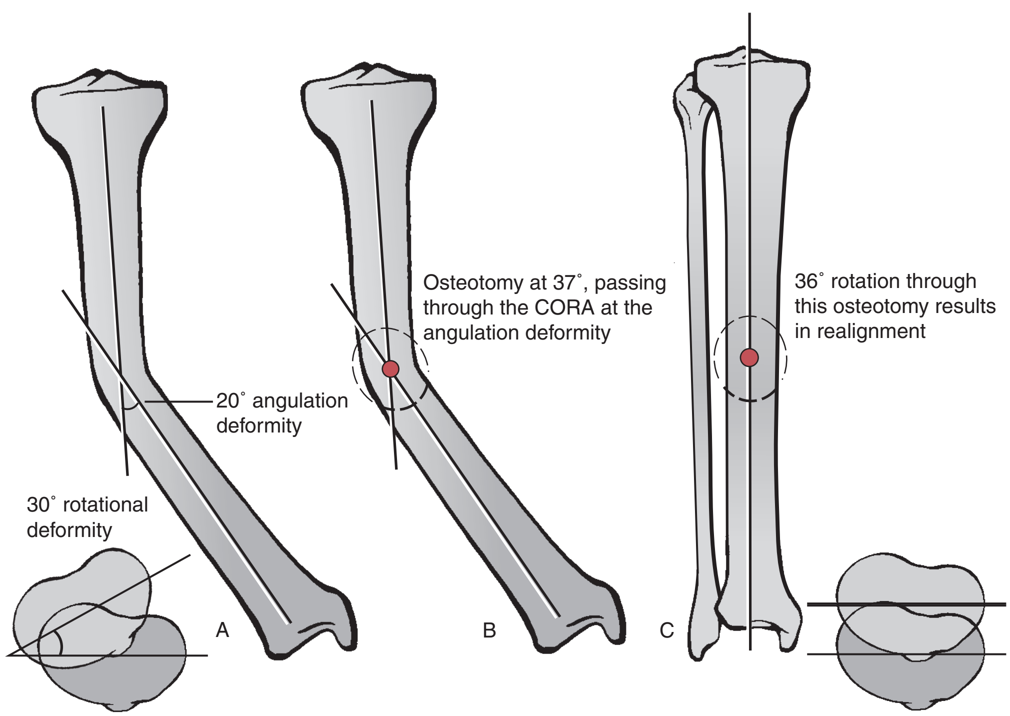


FIGURE 26-20 A. Combined angulation-rotational deformity with a 20-degree angulation deformity and a 30-degree rotational deformity. Calculations of the correction axis show an inclination of 56 degrees, which corresponds to an osteotomy inclination of 37 degrees. **B.** The 37-degree osteotomy is made such that it passes through the CORA of the angulation deformity. **C.** Rotation of 36 degrees about the correction axis in the plane of the osteotomy results in realignment by simultaneous correction of both deformities.

tion and magnitude of the combined angulation-rotational deformity are both characterized in this oblique axis. The angle of the oblique correction axis, which is perpendicular to the plane of the necessary osteotomy, can be approximated using trigonometry (axis angle = arctan[rotation/angulation]; orientation of plane of osteotomy = 90– axis angle).

This single osteotomy is made at a location such that it passes through the level of the CORA of the angulation deformity (i.e., the bisector of the axes of the proximal and distal segments). Rotation of the distal segment about this CORA in the plane of the osteotomy results in realignment; opening and closing wedge corrections can also be achieved by using the CORA located on the respective cortex. Rotation of the distal segment in the plane of the osteotomy but not about a CORA will lead to a secondary translational deformity. This secondary deformity can be corrected by reducing the translation after rotation is completed. Locating the level of the osteotomy distal to the level of the CORA and correcting the secondary translational deformity can be used to correct a combined deformity if locating the osteotomy at the level of the CORA is impractical, such as would occur if the osteotomy would violate a growth plate or place soft tissues or neurovascular structures at risk.

Treatment by Deformity Location

The bone involved and the specific bone region or regions (e.g., epiphysis, metaphysis, diaphysis) define the anatomic location. While a bone-by-bone discussion is beyond the scope of this chapter, we will address the influence of anatomic region on the treatment of malunions in general terms.

Shaft

Diaphyseal deformities involve primarily cortical bone in the central section of long bones. Characterizing deformities is straightforward, as angulation and translational deformities are usually obvious on plain radiographs. In addition, the use of wedge osteotomies through the CORA for deformity correction is generally achievable, thus allowing reduction of the deformity without concerns about inducing secondary translational deformities. By virtue of their relatively homogenous morphology, diaphyseal deformities are amenable to a wide array of fixation methods following correction. Intramedullary nail fixation is preferable when practical (Fig. 26-21).

Periarticular

Periarticular deformities located in the metaphysis and epiphysis are more difficult to identify, characterize, and treat. In addition to the juxta-articular deformities of length, angulation, rotation, and translation and the presence of joint malorientation, there may also be malreduction of articular surfaces and compensatory joint deformities, such as soft tissue contractures and fixed joint subluxation or dislocation. Identification, characterization, and prioritization of each component of the deformity are critical to forming a successful treatment plan.

Acute correction of periarticular deformities is most often accomplished using plate and screw fixation or external fixation. Gradual correction may be accomplished using external fixation (Fig. 26-22).

Treatment by Method

Plate and Screw Fixation

The advantages of plate and screw fixation include rigidity of fixation, versatility for various anatomic locations and situations (e.g., periarticular deformities), correction of deformities under direct visualization, and safety following failed or temporary external fixation. Disadvantages of the method include extensive soft tissue dissection, limitation of early weight bearing and

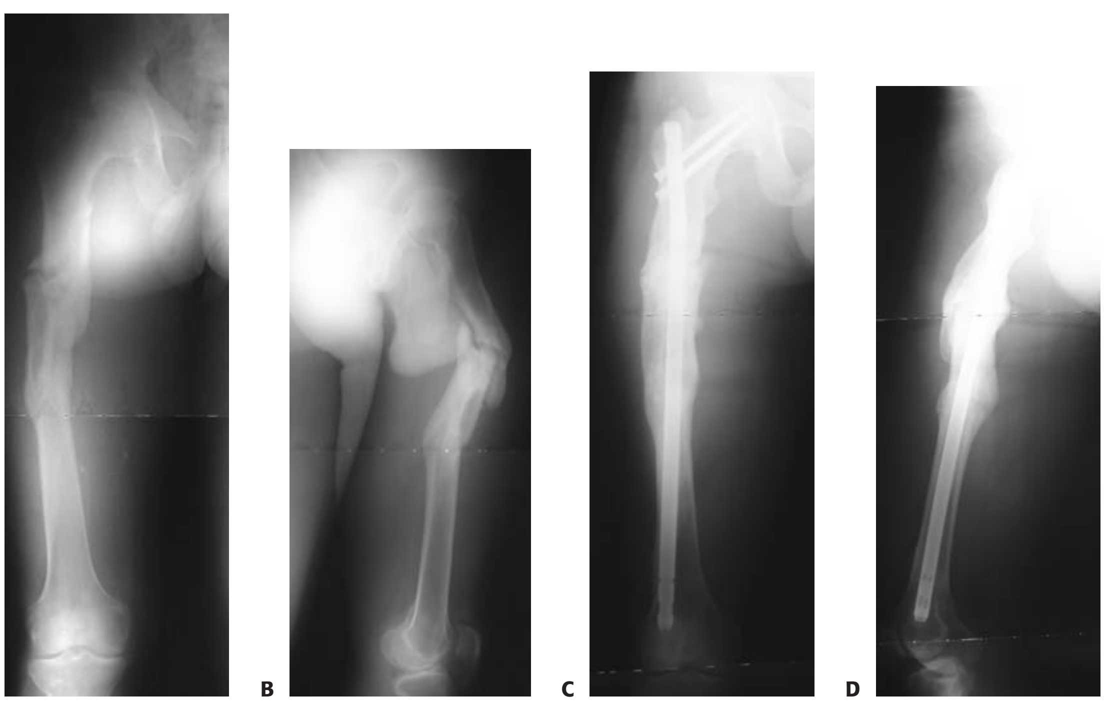
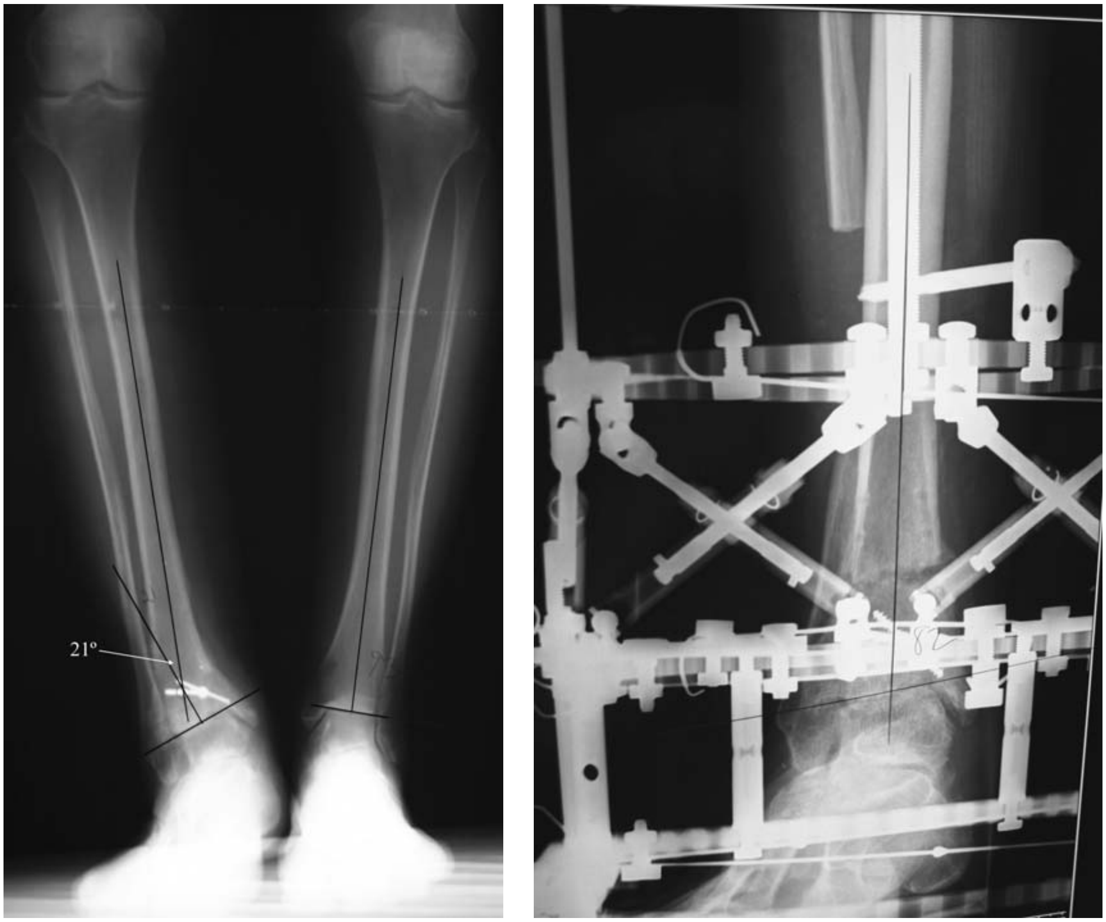

A B C D

FIGURE 26-21 A,B. AP and lateral radiographs on presentation. **C,D.** AP and lateral radiographs following deformity correction with closed antegrade femoral nailing.



A B

C

FIGURE 26-22 A. Presenting AP radiograph of a 45-year-old woman with a malunited distal tibial fracture. This pure frontal plane deformity measured 21 degrees of varus with a CORA located 21 mm proximal to the distal tibial joint orientation line. **B.** AP radiograph following transverse osteotomy during gradual deformity correction (differential lengthening) using a Taylor Spatial Frame. **C.** Final AP radiograph following deformity correction and bony consolidation.

A

FIGURE 26-23 **A,B.** AP and lateral 51-inch alignment radiographs of a 52-year-old woman with a painful total knee arthroplasty. This patient had severe arthrofibrosis, severe pain, and had failed revision total knee arthroplasty. She was referred for a knee fusion but was noted to have an oblique plane angular malunion of her proximal femur from a prior fracture, as indicated by the white lines superimposed on the femur. It was felt that without correction of this femoral malunion, passage of the knee fusion nail through the angled femoral diaphysis would have been difficult, and the final clinical and functional results would likely have been suboptimal due to malalignment of the mechanical axis of the lower extremity. **C,D.** Follow-up radiographs 5 months after operative treatment with resection of the total knee arthroplasty, percutaneous corticotomy of the proximal femur to correct the deformity, and percutaneous antegrade femoral nailing to stabilize the corticotomy site and stabilize the knee fusion site.

B

C

D

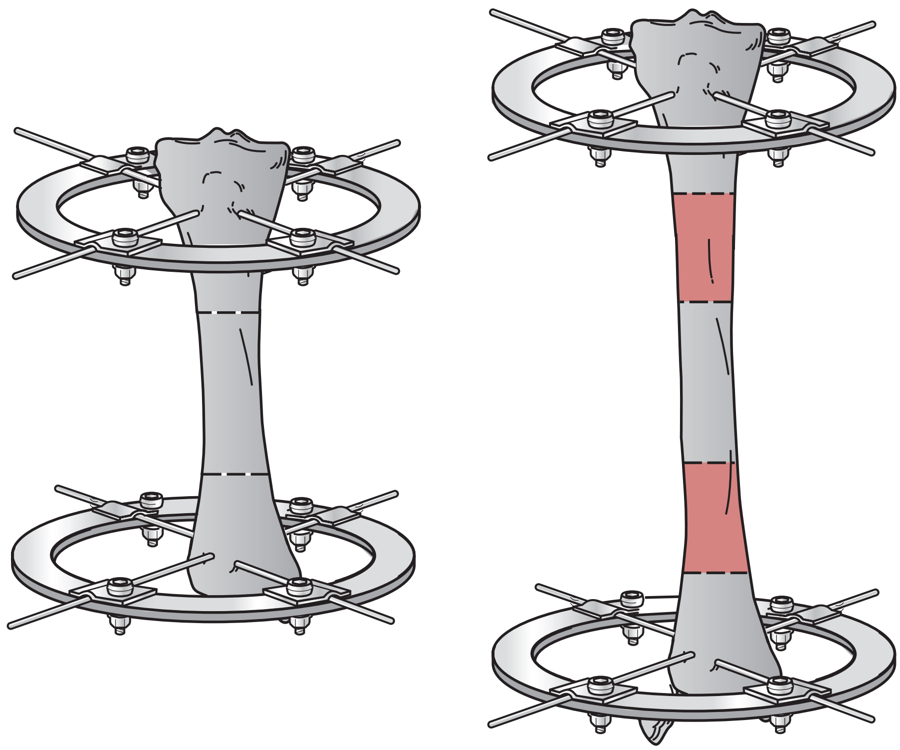


FIGURE 26-24 Bifocal lengthening. **A.** Tibia with length deformity showing two corticotomy sites. **B.** Tibia following distraction osteogenesis at both corticotomy sites showing restoration of length.

function, and inability to correct significant shortening deformity. A variety of plate types and techniques is available, and these are presented in the chapters covering specific fracture types. In cases of deformity correction with poor bone-to-bone contact following reduction, however, other methods of skeletal stabilization should be considered.

AQ1

Locking plates have screws with threads that lock into threaded holes on the corresponding plate. This locking effect creates a fixed-angle device, or "single-beam" construct, because no motion occurs between the screws and the plate.[15,24,42] 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.[24,42] As compared to compression plating where healing is by direct osteonal bridging, locked plating performed without compression results in healing via callus formation.[24,48,79,95,110] Due to the inherent axial and rotational stability with locked devices, obtaining contact between the plate and the bone is not necessary; the construct can be thought of as an external fixator placed within the body. Consequently, periosteal damage and microvascular compromise are minimal. Locking plates are considerably more expensive than traditional plates and should be used in deformity cases that are not amenable to traditional plate-and-screw fixation.[15]

Intramedullary Nail

Intramedullary nail fixation is particularly useful in the lower extremity because of the strength and load-sharing characteristics of intramedullary nails. This method of fixation is ideal for cases where diaphyseal deformities are being corrected (Fig. 26-23). The method may also be useful for deformities at the metaphyseal-diaphyseal junction. Intramedullary implants are excellent for osteopenic bone where screw purchase may be poor.

Ilizarov Techniques

Ilizarov techniques* have many advantages, including that they: (1) are primarily percutaneous, minimally invasive, and typically requires only minimal soft tissue dissection; (2) can promote the generation of osseous tissue; (3) are versatile; (4) can be used in the presence of acute or chronic infection; (5) allow for stabilization of small intra-articular or periarticular bone fragments; (6) allow simultaneous deformity correction and enhancement of bone healing[3–5,9,13,36,54,55]; (7) allow immediate weight bearing and early joint function; (8) allow augmentation or modification of the treatment as needed through frame adjustment; and (9) resist shear and rotational forces while the tensioned wires allow the "trampoline effect" (axial loading-unloading) during weight-bearing activities.

The Ilizarov external fixator can be used to reduce and stabilize virtually any type of deformity, including complex combined deformities, and restore limb length in cases of limb foreshortening. A variety of treatment modes can be employed using the Ilizarov external fixator, including distraction-lengthening, and multiple sites in a single bone can be treated simultaneously. Monofocal lengthening involves a single site undergoing distraction. Bifocal lengthening denotes that two lengthening sites exist (Fig. 26-24).

Distraction-Lengthening. The bone formed at the corticotomy site in distraction-lengthening Ilizarov treatment occurs by dis-

*References 3–6,11,12,14,21,23,26,33,36,39,46,50–54,61,73,74,81, 84,85,104,105.

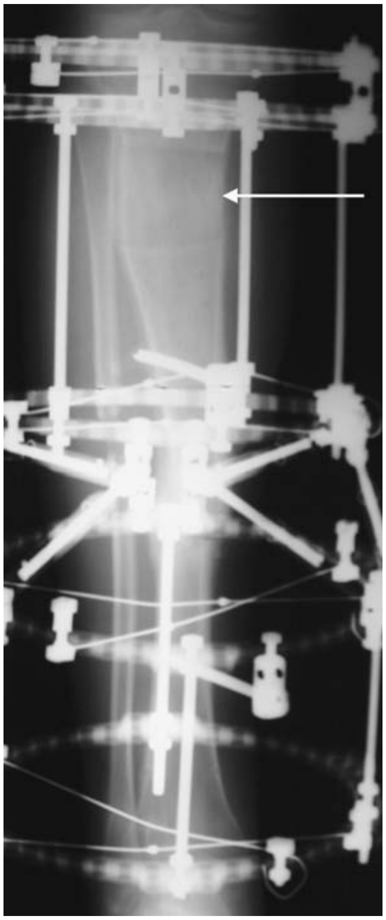


FIGURE 26-25 Regenerate bone (*arrow*) at the corticotomy site is formed via distraction osteogenesis.

traction osteogenesis (Fig. 26-25).[5,6,20,50,67] Distraction produces a tension-stress effect that causes neovascularity and cellular proliferation in many tissues, including bone regeneration primarily through intramembranous bone formation. Corticotomy and distraction osteogenesis result in profound biological stimulation, similar to bone grafting. For example, Aronson[4] reported a nearly ten-fold increase in blood flow following corticotomy and lengthening at the proximal tibia distraction site relative to the control limb in dogs as well as increased blood flow in the distal tibia.

A variety of mechanical and biologic factors affect distraction osteogenesis. First, the corticotomy or osteotomy must be performed using a low-energy technique to minimize necrosis. Second, distraction of the metaphyseal or metaphyseal-diaphyseal regions has superior potential for regenerate bone formation relative to diaphyseal sites. Third, the external fixator construct must be very stable. Fourth, a latency period of 7 to 14 days following the corticotomy and prior to beginning distraction is recommended. Fifth, since the formation of the bony regenerate is slower in some patients, the treating physician should monitor the progression of the regenerate on plain radiographs and adjust the rate and rhythm of distraction accordingly. Sixth, a consolidation phase in which external fixation continues in a static mode following restoration of length that generally lasts 2 to 3 times as long as the distraction phase is required to allow maturation and hypertrophy of the regenerate.

Complex Combined Deformities. All bone deformities can be characterized by describing the position of one bone segment relative to another in terms of angular rotations in each of three planes and linear displacements in each of three axes. Using the methods described above, complex deformities can be characterized using magnitudes for each of these six parameters. Directions of the rotations or displacements are defined as positive and negative relative to the anatomic position. Anterior, right, and superior displacements are defined as positive values. Positive rotation is defined by the right-hand rule: with the thumb pointed in the positive direction along the respective axis (defined identically to the displacement descriptions), the curled fingers indicate the direction of positive rotation (Fig. 26-26). For example, angulation in the frontal plane is rotation about an AP axis. With anterior defined as the positive direction for this axis, counterclockwise rotation (to an examiner who is face to face with the patient) is positive and clockwise rotation is negative.

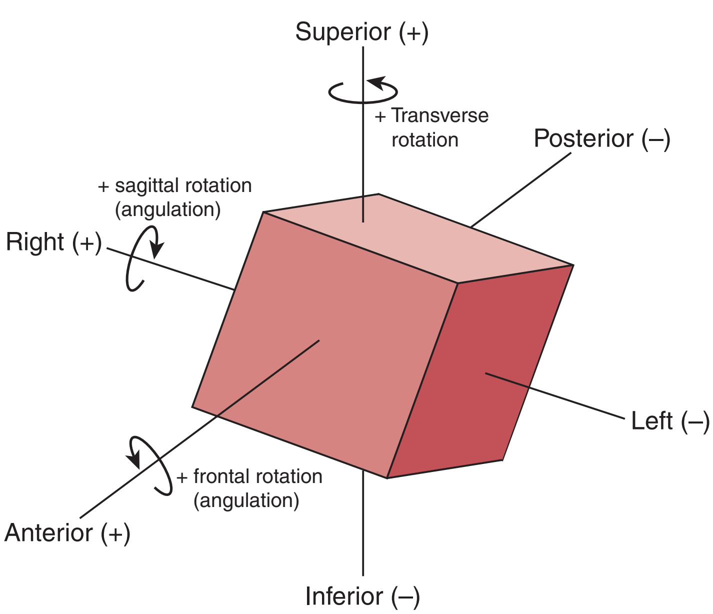
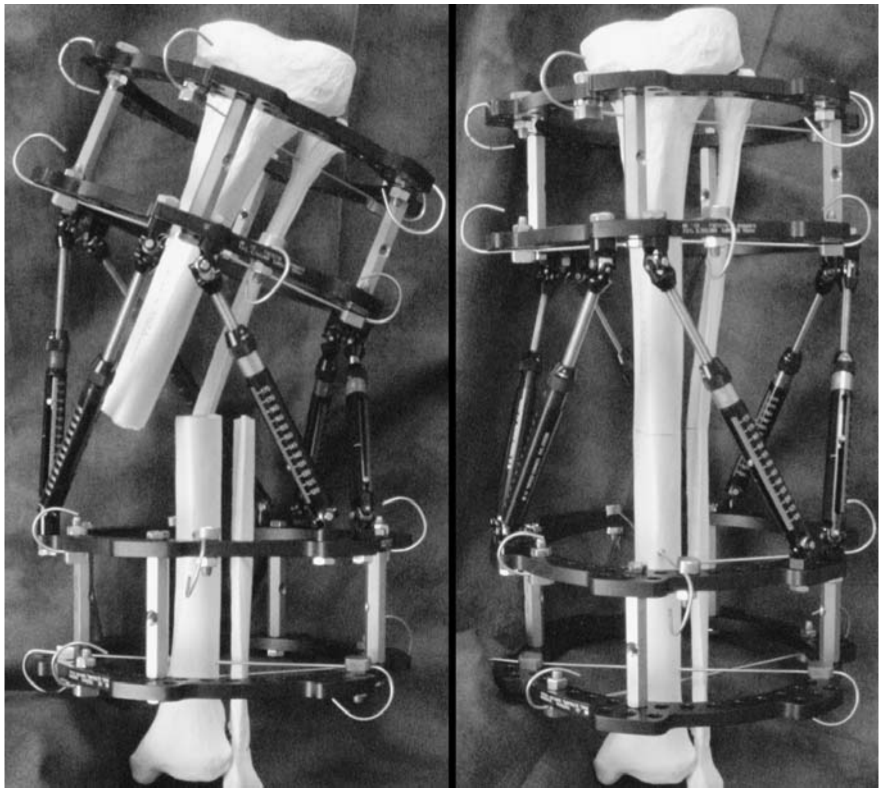


FIGURE 26-26 Definitions used to characterize complex deformities using three angular rotations and three linear displacements.



A B

FIGURE 26-27 A. Taylor Spatial Frame with rings placed obliquely to one another and in parallel with the position of the tibial angular-translation deformity. **B.** Taylor Spatial Frame following correction of the deformity by adjusting the six struts to attain neutral frame height (i.e., rings in parallel).

Complex combined deformities often require gradual correction to allow adaptation of not only the bone but also surrounding soft tissues and neurovascular structures. The modern Ilizarov hardware system uses different components (hinges, threaded rods, rotation-translation boxes) to achieve correction of multiple deformity types in a single bone. Alternatively, the Taylor Spatial Frame (Fig. 26-27), which uses six telescopic struts, can be used to correct complex combined deformities.[2,25–27,29,58,62,63,68,69,83–87,97,98,103,106,108,111,112] A computer program is used in treatment planning to determine strut lengths for the original frame construction. The rings of the external fixator frame are attached perpendicular to the respective bone segments and the struts are gradually adjusted to attain neutral frame height (i.e., rings in parallel). Any residual deformity is then corrected by further adjusting the struts.

Correction can be simultaneous, in which all deformities are corrected at the same time, or sequential, in which some deformities (e.g., angulation-rotation) are corrected before others (e.g., translations). The rate at which correction occurs must be determined on a patient-by-patient basis and depends on the type and magnitude of deformity, the potential effects on the soft tissues, the health and healing potential of the patient, and the balance between premature consolidation and inadequate regenerate formation.

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