Definition of Deformity

A limb deformity is a deviation from normal anatomy. The deformity may include abnormalities of length, rotation, translation, or angulation (Table 61-1). Several other components of limb deformity should also be considered in individual cases: deficiency, malformation, contour, circumference, and proportion.

To define a deformity, we need a concept of normal anatomy for comparison. In the lower limb, this usually is evaluated from long standing anteroposterior and lateral radiographs. The two considerations in evaluating the frontal plane mechanical axis of the lower extremity are joint alignment and joint orientation. The normal alignment of the hip, knee, and ankle joint centers is colinear. Frontal plane deformities lead to a mechanical axis deviation, which primarily affects the knee but also affects the subtalar, ankle, and hip joints. Normally the line of weight-bearing force from the ankle to the hip joint passes through the medial tibial spine in the center of the knee joint. In mechanical axis deviation, it passes medial or lateral to the center of the knee.

The second consideration is the orientation of each joint to the mechanical axis line. Each joint has a normal anatomical inclination to both the mechanical and anatomical axises of the limb segment (Fig. 61-1). In the tibia the mechanical and anatomical axes are the same, but in the femur they are different. The mechanical axis of the femur is defined as the line from the center of the hip to the center of the knee. This usually subtends a 6° angle to the anatomical axis of the femur, which runs from the psoas fossa to the center of the knee joint. The knee joint line has been measured to be about 3° off the perpendicular such that the distal femur is in slight valgus and the tibial diaphysis in slight varus. Krackow feels that the 3° inclination evolved to keep the knee joint horizontal (parallel to the ground) with walking. On walking the feet progress along the same line, with the leg inclined to the vertical at about 3°. Due to the 3° of varus attitude of the lower limbs, the knee joint maintains a parallel inclination to the ground during gait. In stance with the feet as wide apart as the pelvis and the
TABLE 61-2. Clinical Evaluation Algorithms for Lower Limb Deformity

<table>
<thead>
<tr>
<th>Position 1: Standing face forward</th>
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<tbody>
<tr>
<td>1. Frontal plane alignment</td>
</tr>
<tr>
<td>a. Pelvic tilt</td>
</tr>
<tr>
<td>b. Genu varum/valgum</td>
</tr>
<tr>
<td>c. Foot varus/valgus/abduction, adduction/supination/pronation</td>
</tr>
<tr>
<td>d. Obvious diaphyseal deformity</td>
</tr>
<tr>
<td>e. Trendelenburg sign (immediate; delayed)</td>
</tr>
<tr>
<td>2. Rotation alignment</td>
</tr>
<tr>
<td>a. Patellar orientation (forward, in, out)</td>
</tr>
<tr>
<td>b. Foot orientation (forward, in, out)</td>
</tr>
<tr>
<td>3. Length discrepancy</td>
</tr>
<tr>
<td>a. Pelvic tilt</td>
</tr>
<tr>
<td>b. Knee flexion long leg</td>
</tr>
<tr>
<td>c. Equinus stance short leg</td>
</tr>
<tr>
<td>d. Block for measurement</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Position 2: Standing Lateral Views</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sagittal plane alignment</td>
</tr>
<tr>
<td>a. Spine lordosis/kyphosis</td>
</tr>
<tr>
<td>b. Hips: flexion deformity</td>
</tr>
<tr>
<td>c. Knees: flexion or recurvatum deformity</td>
</tr>
<tr>
<td>d. Ankles: equinus or calcaneus</td>
</tr>
<tr>
<td>e. Foot arch: cavus or flat</td>
</tr>
<tr>
<td>f. Obvious diaphyseal deformity</td>
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<thead>
<tr>
<th>Position 3: Standing Posterior View</th>
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<tbody>
<tr>
<td>1. Frontal plane alignment</td>
</tr>
<tr>
<td>a. Scoliosis</td>
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<tr>
<td>b. Pelvic tilt</td>
</tr>
<tr>
<td>c. Genu varum/valgum</td>
</tr>
<tr>
<td>d. Heel varus, valgus, equinus</td>
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<table>
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<tr>
<th>Position 4: Walking</th>
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</thead>
<tbody>
<tr>
<td>1. Foot progression angle/patellar progression angle</td>
</tr>
<tr>
<td>2. Gait pattern (stance/swing), eg Trendelenburg, antalgic, short leg, lurch</td>
</tr>
</tbody>
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<tr>
<th>Position 5: Sitting</th>
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</thead>
<tbody>
<tr>
<td>1. Examination of the foot</td>
</tr>
<tr>
<td>a. Subtalar range of motion (ROM)</td>
</tr>
<tr>
<td>b. Ankle range of motion/stability</td>
</tr>
<tr>
<td>c. Forefoot and toes</td>
</tr>
<tr>
<td>d. Malleolar position (medial vs lateral)</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Position 6: Supine</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Knee ROM: flex/extension</td>
</tr>
<tr>
<td>2. Hip ROM</td>
</tr>
<tr>
<td>a. Abduction/adduction</td>
</tr>
<tr>
<td>b. Flexion</td>
</tr>
<tr>
<td>c. Thomas test for fixed flexion deformity</td>
</tr>
<tr>
<td>3. Patellar orientation relative to foot</td>
</tr>
<tr>
<td>4. Knee stability exam (tibiofemoral, patellofemoral)</td>
</tr>
<tr>
<td>5. Neurovascular exam</td>
</tr>
<tr>
<td>6. Limb length measurement</td>
</tr>
<tr>
<td>7. Femoral length (Galeazzi's sign)</td>
</tr>
<tr>
<td>8. Tibial length (knee heights)</td>
</tr>
<tr>
<td>9. Hamstring muscle length tests</td>
</tr>
<tr>
<td>a. Straight leg raising limit</td>
</tr>
<tr>
<td>b. Popliteal angle</td>
</tr>
<tr>
<td>10. Calf and thigh circumference</td>
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<tr>
<th>Position 7: Prone</th>
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<tbody>
<tr>
<td>1. Ely test</td>
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<tr>
<td>2. Hip rotation (internal/external)</td>
</tr>
<tr>
<td>3. Hip extension limit comparison</td>
</tr>
<tr>
<td>4. Tibial rotation (internal/external)</td>
</tr>
<tr>
<td>5. Thigh foot angle</td>
</tr>
<tr>
<td>6. Prone leg length, which includes tibia and foot height</td>
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<tr>
<td>7. Foot length, width</td>
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</table>

Indications for Correction of Lower Limb Deformities

Deformities of the lower limb may be symptomatic or asymptomatic. Deformity symptoms include pain and inflammation around joints, apparent or real joint restriction of motion, and gait dysfunction or alteration. Patients also present with aesthetic and psychosocial complaints regarding limb deformities.

In general, the goals in correcting a deformity are to relieve symptoms if present and to protect adjacent joints from development of osteoarthrosis secondary to the deformity. Without good data about the natural history of asymptomatic deformities and their contribution to later joint degeneration, it is difficult to specify exact indications for surgical treatment of asymptomatic deformities. Isolated rotational deformities should not be treated unless symptomatic. They should be corrected as part of a comprehensive approach to the treatment of lower limb alignment.

The following deformities should be considered for treatment, even in asymptomatic patients: distal femoral mechanical valgus greater than 5°, proximal tibial mechanical varus greater than 50°, and mechanical axis deviation greater than 15°. Other asymptomatic deformities should be considered for correction prophylactically if radiographic evidence of degenerative joint disease is seen or if only clinical signs are detected (eg, positive Trendelenburg sign in a dysplastic hip, lateral thrust in a varus knee). Other deformities that should be considered for treatment include procurvatum deformity of the distal tibia greater than 15°, recurvatum deformity of the distal tibia greater than 10°, and varus or valgus deformity of the distal tibia greater than 100°.
When subtalar joint motion is restricted. Although these guidelines for deformity correction are based on the available literature, each patient must be evaluated individually.

It is important to identify and treat the correct deformity and not create a deformity in an effort to treat a deformity. The best example is distal femoral valgus. Recommended treatment for genu valgum has included distal femoral osteotomy or proximal tibial osteotomy (Fig. 61.9).4,10,34 An isolated deformity in the femur should never be treated by a corrective osteotomy of a normal tibia. This will lead to persistent joint inclination and eventual subluxation. Cooke and colleagues demonstrated that for combined distal femoral and proximal tibial deformities, the best operation is a corrective osteotomy at both levels.4,5 The first step in deformity correction, therefore, is to assess the deformity by accurately defining and describing the deformity (see Tables 61-1 and 61-2); then preoperative planning begins.

Preoperative Planning

The apical level of diaphyseal deformities is obvious, while the apex of metaphyseal and especially juxta-articular deformities are subtle or less clear (Fig. 61-10). The first step is to determine the level of the apex of the angular deformity. With diaphyseal deformities, a line can be drawn down the concave or convex cortex proximal and distal to the apex. The intersection of these two cortical lines is the true apex of deformity. For juxta-articular and metaphyseal deformities a more complex system is necessary to accurately determine the level of the deformity's apex.

We have developed a "malalignment test" for frontal plane mechanical axis deviation (Fig. 61-11). Required materials are a standing radiograph with the patella pointing forward, knee in extension, from hips to ankles, of both lower limbs, and a pencil, a long straight edge, and a goniometer or protractor.

If a mechanical axis deviation is detected in step 0, then steps 1 to 3 will indicate whether the deviation is in the femur or tibia, respectively. If lines FC and TP are not parallel, then there is an intra-articular component to the mechanical axis deviation.
The lateral collateral ligament is lax (left). On single-leg stance during gait, the adductor moment arm leads to a varus deformity through the knee joint. The lateral joint line opens to the point that the lateral collateral ligament becomes tight (center). With descent of the fibular head, the lateral collateral ligament can be tightened to correct the articular varus deformity (right).

The medial collateral ligament is lax (left). Associated with a valgus deformity, the tibia subluxes laterally (middle). The medial collateral ligament can be retensioned by distraction of an osteotomy located proximal to its insertion (right). The distal end of the osteotomy runs distal to the tibial tubercle to avoid pulling the patellar tendon down.
PLANNING THE LEVEL OF OSTEOTOMY AND HINGE PLACEMENT

The optimal level for an osteotomy is usually at the apex of an angular deformity. The choice of level is influenced by the proximity to the joint, the type of fixation, skin coverage, bone quality, and, in children, the physis. A deformity apex within the bone's metaphysis or diaphysis is suitable for osteotomy and fixation. A juxta-articular deformity apex presents difficulties with both the osteotomy and fixation. In children, correcting a juxta-articular deformity would cause a transphyseal separation, whereas in adults such a correction would necessitate a peri-articular or intra-articular osteotomy. Therefore, the practical level for osteotomy is usually within the metaphysis in these deformities. For this reason, the metaphyseal and diaphyseal deformities will be grouped together under the name metadiaphyseal; the juxta-articular type of deformity will be considered separately.

After identifying the deformed and normal bone(s) using the above test, ascertain the apex of deformity. The osteotomy level can then be determined, taking into consideration the limitations imposed by the joint and physis and by the fixation method. Preoperative determination of tibial deformity with a normal femur is shown in Figures 61-12 and 61-13.

Preoperative planning for a deformity of the femur with a normal tibia is shown in Figures 61-14 through 61-17. When the apex of the deformity is metadiaphyseal, the osteotomy is done at the level of the apex, and the hinge is also placed at the level of the apex. The correction angulates the bone ends.

For a juxta-articular deformity apex, the osteotomy is performed in the metaphysis at a different level than the apex. The hinge is placed at the level of the apex. The correction causes translation and angulation of the bone ends.

OTHER FACTORS IN DETERMINING THE LEVEL OF THE OSTEOTOMY

Several other factors must be considered in determining the level of the osteotomy. The apex may not always be the optimal level or even a possible place to perform the osteotomy for several reasons. In developmental and congenital deformities, the deformity is often at the level of the growth plate or joint and, therefore, is inaccessible for fixation or osteotomy. Angular corrections performed as opening or closing wedges not at the level of the apex of the deformity create secondary translational deformities (Fig. 61-18). To avoid this, the bone ends should be translated either acutely or using a translation hinge. The translation needed can be minimized by performing the osteotomy as close as technically feasible to the true apex of deformity. An alternative technique uses a hinge at the level of the osteotomy, correcting angulation first, followed by translation by modifying the frame.

Other situations where the osteotomy is contraindicated at the apex include soft-tissue coverage problems or the presence of avascular, sclerotic, or previously infected bone (suboptimal for osteotomy). A translational correction of the osteotomy at a level above or below the apex is required.

If lengthening is a major consideration, the optimal level for lengthening is in the proximal or distal metaphysis. It may be preferable to perform a metaphyseal-level corticotomy followed by a translational correction to realign the mechanical axis for both angulation and translation or to perform two osteotomies, one for lengthening and one for deformity correction.

Malunions often present with combinations of angular and translational deformities. The translational component may either compensate or aggravate the mechanical axis deviation produced by the angular deformity. In the tibia, if translation is in the direction opposite of the angular deformity, then the translation will produce a compensatory effect on the
FIGURE 61-10. (A) Subtle deformity; juxta-articular and metaphyseal level deformities are relatively occult radiographically. This is particularly true when an isolated radiograph of a single bone is examined rather than an alignment x-ray of the entire lower limb. In this example the valgus of the distal femur is barely noticeable, even on the alignment x-ray. For clarification, cover up the tibia and look at the femur in isolation. The valgus of the distal femur is further hidden by this maneuver. (B) In contrast, this diaphyseal deformity is obvious. Arms of the deformity extend from either end of the apex. In the juxta-articular deformity there is no arm extending away from the deformity at the articular end.

mechanical axis deviation. While this translation may not completely realign the mechanical axis, it will reduce the amount of deviation (Fig. 61-19). On the other hand, if the translation is in the same direction as the angular deformity, the mechanical axis deviation will be aggravated. The apex of the deformity in these cases is not at the malunited level of the two bone segments. Because of the translation, the true apex of the deformity will be either proximal or distal, depending on whether the translation is aggravating or compensatory. In the tibia, compensatory deformities will have an apex distal to the level of the malunion, but aggravating translational angulation deformities will have a true apex proximal to the level of the malunion.

In the femur the opposite relationship exists (Fig. 61-20). By performing the osteotomy at the level of the true apex—the intersection point of the mechanical axis—the limb will realign both angulation and translation through a single hinge (Fig. 61-21). A translating hinge apex offers the added advantage of allowing an osteotomy through healthy bone rather than through a sclerotic, avascular, previously open, or infected region at the deformity's apex.

Most diaphyseal deformities can be corrected by an osteotomy at the level of the true apex. An osteotomy at the true apex corrects both angulation and translation of the malalignment simultaneously, but does not correct any contour deformity created by the translated bone ends (Fig. 61-22). If the contour deformity is significant, then the osteotomy should be done at the level of the malunion. Translation and angulation must be corrected separately.

DETERMINING THE TRUE PLANE OF THE DEFORMITY

Orthopaedic surgeons often describe angular deformities as varus; valgus, procurvatum, and recurvatum of the distal segment relative to the proximal segment. The terms varus and valgus describe angular deformities in the frontal plane; procurvatum and recurvatum describe angular deformities in the sagittal plane. Using this convention, a deformity with varus and recurvatum is described as a biplanar deformity. Careful analysis of most biplanar deformities reveals that they have but a single apex; moreover, the deformity lies in an oblique plane, somewhere between the frontal and sagittal planes (Fig. 61-23). We perceive the deformity as biplanar because the standard radiographic views are obtained in the anatomic reference planes, which may be different from the plane of angulation. Geometrically speaking, however, two lines can subtend only one plane. If we consider each bone segment as a line, these two lines can form an angle with each other only in one plane, irrespective of the presence of angulation, rotation, translation, or length deformities. A second plane of angulation can exist only if a second angular deformity at another level is introduced into these bone segments or lines.

Text continued on page 900
FIGURE 61-11. The malalignment test. This test determines the origin of frontal plane malalignment. Step 0. Draw HA, the mechanical axis line of the lower limb, from the center of the femoral head to the center of the ankle plafond. If this line passes medial to the medial tibial spine there is medial mechanical axis deviation (MAD). If it passes lateral to the center of the knee there is lateral MAD. Step 1. Draw HK, the mechanical axis of the femur, from the center of the femoral head to the center of the knee. Draw FC, the femoral condyle line. Measure the lateral angle HKF. This should be $5\degree \pm 2\degree$. Outside these limits the femur is contributing to the MAD. Step 2. Draw KA, the tibial mechanical axis line, from the center of the knee to the center of the ankle. Draw the tibial plateau line TP. Measure the medial angle AKP. This should be $3\degree \pm 2\degree$. Outside these limits the tibia is contributing to the MAD. Step 3: Compare the orientation of Fe to TP. These should be parallel to each other. If they diverge more than 1-2°, there is joint laxity contributing to MAD. (A) Femoral malalignment. (B) Tibial malalignment. (C) Joint laxity malalignment.
FIGURE 61-12. The apparatus for correction of this angular deformity is preconstructed with two levels of fixation on either side of the hinge. The hinge level, plane, magnitude, and direction are built into the apparatus. Tibial diaphyseal deformity with a normal femur. Step 0: Draw the mechanical axis line to demonstrate the degree of mechanical axis deviation created by the obvious tibial diaphyseal deformity. The mal alignment test was performed to confirm that the orientation of the distal femur is normal. Step 1: Since the femur is normal, draw the line from the center of the hip through the center of the knee and extend it distally. This is the mechanical axis of the proximal tibia. Step 2: Draw a line from the center of the plafond extending proximally in line with the anatomic axis of the tibia. This is the mechanical axis of the distal tibia. The center of rotation of angulation is at the intersection of the two mechanical axis lines. The angular deformity measures 26°. Step 2b: The alternative method is to draw a line down the convex cortices of the deformity. These lines intersect at the same level and also demonstrate a 26° deformity. Step 3a: The deformity correction is performed on paper at the level of the apex of the deformity for a total of 26°. This realigns and overlaps the mechanical axis lines to reestablish the colinearity of the hip-knee-ankle axis. Step 3b: After opening wedge correction, this osteotomy also realigns the diaphyseal line of the convex cortex so that it is colinear.
RIDGE FIXATION AND DISTRACTION TECHNIQUES

FIGURE 61-13. (A) Juxta-articular tibial deformity with a normal femur. Step 0: Draw the mechanical axis line from the center of the femoral head to the center of the ankle. The malalignment test was performed to confirm that the varus mechanical axis deviation is due only to the tibia and that the femur is normal. Step 1: Draw the mechanical axis line of the femur and extend it distally. This is the mechanical axis of the proximal tibia. Step 2: Draw the line from the center of the ankle plafond extending proximally parallel to the anatomic axis of the tibia. This is the mechanical axis of the distal tibia. Note the level of intersection of the two mechanical axis lines is at the level of the growth plate. The angular deformity measures 37°. Step 3a: The deformity may be corrected by a 37° opening wedge through the growth plate, thus realigning the mechanical axis and reestablishing normal joint orientation. Step 3b: Correction of the deformity at the level of the tibial metaphysis requires a 50° correction to realign the mechanical axis. This creates a malorientation of the knee and ankle. Notice that the mechanical axis now subtends a 96° orientation to the ankle joint instead of the normal 90°. Step 3c: If only 37° of deformity are corrected, there is persistent varus mechanical axis deviation. The knee and ankle are oriented correctly one to the other but the mechanical axis is deviated due to a persistent translational deformity (T). Step 3d: To realign the mechanical axis at the level of the metaphysis which is distal to the apex of the deformity, the correction should include both 37° of angular correction and lateral translation in the amount of T. The magnitude of T increases as the level of osteotomy moves farther away from the apex of the deformity. (B) Apparatus before and after open wedge correction with hinge at osteotomy level. The rings are parallel at the end of correction.

FIGURE 61-14. (A) Diaphyseal femoral deformity with a normal tibia. Step 0: Draw the line from the center of the femoral head to the center of the ankle, demonstrating a valgus mechanical axis displacement. The malalignment test confirms a normal tibial alignment. Step 1: Draw the mechanical axis line of the tibia from the center of the ankle to the center of the knee and extend it proximally. This is the mechanical axis of the distal femur. Step 2a: Draw the mechanical axis line of the femur on the opposite normal side. Draw the anatomic axis line of the normal side down the midshaft of the proximal femur. Measure the angle between the mechanical and anatomic axes (a). Draw the anatomic axis of the proximal femur on the deformed side. Draw a line from the center of the hip parallel to the anatomic axis. Step 2b: Draw a line from the center of the hip extending distally at a degrees to the last line. This is the mechanical axis of the proximal femur. This line intersects the distal mechanical axis line at the apex of the deformity, demonstrating a 15° angular deformation. Step 3: Correct the angular deformity through an osteotomy at the level of the apex of the deformity. The angular correction required to realign the mechanical axis is 15°. (B) Apparatus before and after open wedge correction with hinge at osteotomy level.
Ring Fixation and Distraction Techniques

Step 0: Draw the mechanical axis line from the center of the hip to the center of the ankle. This line passes lateral to the center of the knee, indicating a valgus mechanical axis deviation. The malalignment test confirms that the tibial alignment is normal. Step 1: Draw the mechanical axis line from the center of the ankle through the center of the knee and extend it proximally. This is the mechanical axis of the distal femur. Step 2a: Draw the mechanical axis line of the femur on the opposite normal side. Draw the anatomic axis line of the normal side down the midshaft of the proximal femur. Measure the angle between the mechanical and anatomic axes. Step 2b: Draw a line from the center of the hip extending distally at \( \theta \) degrees to the last line. This is the mechanical axis of the proximal femur. This line intersects the distal mechanical axis line at the knee joint, indicating a juxta-articular deformity measuring \( \theta \). Step 3a: Since it is not possible to do an osteotomy so distal, the osteotomy is performed at the level of the distal metaphysis. Correction of the mechanical axis alignment by a pure angular correction at this level requires \( \theta \) since the osteotomy is not at the level of the apex of the deformity. As in the tibial example, this produces a slight malorientation of the hip to knee joint lines. Step 3b: The correction of only \( \theta \) results in persistent valgus mechanical axis deviation. The deformity that remains is purely a translational one of amount T. Step 3c: The most accurate correction through a metaphyseal osteotomy is to combine \( \theta \) of angulation with lateral translation of amount T. T increases as the distance of the osteotomy to the true apex of the deformity increases. (B) Apparatus with hinge at juxta-articular center of rotation. Angulation and translation correction occur since the hinge is at a different level from the osteotomy.

FIGURE 61-15. (A) Juxta-articular femoral deformity with a normal tibia. Step 0: Draw the mechanical axis line from the center of the hip to the center of the ankle. This line passes lateral to the center of the knee, indicating a valgus mechanical axis deviation. The malalignment test confirms that the tibial alignment is normal. Step 1: Draw the mechanical axis line from the center of the ankle through the center of the knee and extend it proximally. This is the mechanical axis of the distal femur. Step 2a: Draw the mechanical axis line of the femur on the opposite normal side. Draw the anatomic axis line of the normal side down the midshaft of the proximal femur. Measure the angle between the mechanical and anatomic axes. Step 2b: Draw a line from the center of the hip extending distally at \( \theta \) degrees to the last line. This is the mechanical axis of the proximal femur. This line intersects the distal mechanical axis line at the knee joint, indicating a juxta-articular deformity measuring \( \theta \). Step 3a: Since it is not possible to do an osteotomy so distal, the osteotomy is performed at the level of the distal metaphysis. Correction of the mechanical axis alignment by a pure angular correction at this level requires \( \theta \) since the osteotomy is not at the level of the apex of the deformity. As in the tibial example, this produces a slight malorientation of the hip to knee joint lines. Step 3b: The correction of only \( \theta \) results in persistent valgus mechanical axis deviation. The deformity that remains is purely a translational one of amount T. Step 3c: The most accurate correction through a metaphyseal osteotomy is to combine \( \theta \) of angulation with lateral translation of amount T. T increases as the distance of the osteotomy to the true apex of the deformity increases. (B) Apparatus with hinge at juxta-articular center of rotation. Angulation and translation correction occur since the hinge is at a different level from the osteotomy.
FIGURE 61-16. Anatomic axis method of preoperative planning for femur. 

Step 0: There is a MAD due to a femoral deformity. Since there is a cup arthroplasty, the center of the femoral head, which is essential for mechanical axis planning, cannot be used. Therefore, anatomic planning is used. 

Step 1: Draw the anatomic axis line on the normal side down the midfemur and measure the lateral angle it subtends to the knee (83°). 

Step 2: Draw an 83° line from the center of the knee on the deformed side. This is the anatomic axis of the distal femur. 

Step 3: Draw the anatomic axis line of the proximal femur on the deformed side (midline proximal femur shaft). The intersection point of the two anatomic axis lines is the center of rotation of the angulation.

FIGURE 61-17. Combined femoral and tibial deformities in the absence of a normal opposite side. 

Step 0: Draw the mechanical axis line from the center of the hip to the center of the ankle. This line passes medial to the center of the knee, indicating a varus malalignment. 

Step 0: The malalignment test demonstrates a deformity in both tibia and femur. 

Step 1: Draw a line 87° to the knee orientation line. Extend this line both proximally and distally. 

Step 2: Draw a line perpendicular to the ankle plafond (or distal tibial shaft) and extend this line proximally. 

Step 3: Correct the tibial deformity, at the level of the apex of the deformity, realigning the tibial mechanical axis and reorienting the ankle and knee. 

Step 4: Draw the mechanical axis of the proximal femur. If there is a normal opposite femur to compare to, use the angle measured from the opposite side. If there is not a normal angle, use 90°. The intersection point indicates the apex of the deformity. 

Step 5a: The osteotomy may be performed at a lower level combined with translation in order to minimize the angulation in the shaft of the femur. 

Step 5b: The center of rotation of the second osteotomy (b) is still at level a.
Secondary translational deformities. (A) The so-called golf club deformity of the distal femur is a result of repeated closing wedge varus osteotomies in the supracondylar metaphyseal region of the femur for the treatment of a juxta-articular deformity of the distal femur. This produces a progressive medial translational deformity with each successive osteotomy. (B) Medial translational deformities of the tibia are the result of repeated valgus osteotomies at the metaphyseal diaphyseal junction for the treatment of these juxta-articular deformities of the tibia. In the right tibia, over-correction was carried out to realign the mechanical axis similar to that described in Figure 61-13, step 3b. On the left, the ankle and knee joints were reoriented but the mechanical axis was not fully corrected, leading to a persistent varus from the translational component of the deformity. (C) A varus deformity of the distal tibia due to a malunion was treated by a supramalleolar osteotomy in order to realign the ankle to the knee joint. This correction ignores the mechanical axis deviation created by the malunion. It demonstrates again that angular correction not at the level of the apex of an angular deformity leads to a translational deformity.
Angular malunions of the tibia lead to varying degrees of mechanical axis deviation, depending on the degree of angulation, the level of the malunion, and the magnitude and direction of any associated translational deformity. These three varus malunions differ only in the magnitude and direction of the translational component of the malunion. The center malunion has pure angulation without translation of the bone ends. The malunion to the left of center has the same degree of angulation combined with translation towards the convexity of the deformity. The malunion to the right of center has the same degree of angulation combined with translation towards the concavity of the deformity. Notice the amount of mechanical axis deviation in all three examples. The mechanical axis deviation is decreased when the translation is towards the convexity and increased when it is towards the concavity. The former is called compensatory translation, whereas the latter is called aggravating translation. Notice the point of intersection of the mechanical axis lines of the proximal and distal tibia. When there is no translation, the intersection is at the level of the malunion. When there is a compensatory translation the intersection point is distal to the malunion. When there is aggravating translation the intersection point is proximal to the malunion. The intersection point is considered to be the true apex of the angulation/translation deformity, while the malunion is considered to be the apparent apex.
RING FIXATION AND DISTRACTION TECHNIQUES

FIGURE 61-20. Varus malunions of the femur are illustrated with and without aggravating or compensatory translation. Notice that in the femur translation towards the convexity is aggravating while translation towards the concavity is compensatory. The reason for this is that by convention we refer to translation as the distal fragment relative to the proximal. If we think of the proximal fragment of the femur as the one that is translating, then the rules are similar to that described in the tibia (see Fig. 61-19). Notice that the translational deformity shifts the true apex of the deformity either proximal or distal to the apparent apex at the level of the malunion.

There are several ways to determine the magnitude and true plane of a deformity in a plane oblique to the frontal plane. The simplest method is to rotate the limb until it appears straight (Fig. 61-24). The true plane of deformity is the plane where the projection of a deformed limb appears straight. The plane 90° to this projection should demonstrate the maximum angulation profile of the deformity. Radiographs taken in these two planes can be used to determine the orientation of this plane and the magnitude of the true deformity.

The orientation of the oblique plane angular deformity can be calculated using trigonometric equations or a nomogram. The graphic method requires only a pencil and goniometer to calculate the magnitude and direction of the oblique plane deformity (Fig. 61-25). Bar and Breitfuss have published a nomogram to determine the true angular deformity and its oblique plane. Ilizarov plots the apical deviation from the axial midline on the anteroposterior and lateral views as x and y coordinates and determines the plane of deformity graphically (Fig. 61-26). The Ilizarov apparatus allows the surgeon to make use of these calculations. By determining the true plane of deformity the surgeon can also determine the axis of the deformity's apex. The axis of the deformity is always perpendicular to the plane of deformity (Fig. 61-27). By applying a hinge at the true apex of an oblique plane deformity perpendicular to the true plane...
FIGURE 61-21.
of this deformity, the surgeon can simultaneously correct the anteroposterior and lateral projections of this deformity (Fig. 61-28). Alternatively, the apparatus could be applied to correct the deformity in the anteroposterior plane; afterward, the hinges would be reoriented to correct the deformity in the lateral plane. This is more time-consuming and less efficient method, but it is accurate.

TRANSLATION DEFORMITIES

A translation deformity may also appear in both perpendicular planes (Fig. 61-29). The direction of the true translational deformity can be calculated using the methods described above (see Fig. 61-29). Since translation is a direct linear measurement and not an angular deviation, the Pythagorean or graphic methods described above are both accurate for the assessment of translation deformities in planes oblique to the frontal projection. Both the magnitude and the true plane of translation can be determined.

ANGULATION/TRANSLATION DEFORMITIES

When angulation and translation occur together, the plane of angulation may be the same or different than the plane of translation. If angulation and translation are in the same plane, they can be characterized as a single apex of angulation and translation (Fig. 61-31). If this is in one of the anatomic planes (frontal or sagittal), one view will show angulation and translation while the other shows no deformity. If both are in the same oblique plane, the center of rotation will be at the same level on both AP and lateral radiographs. If angulation and translation are in different planes 90° apart, there will be one plane with only angulation and one with only translation (Fig. 61-32). This is readily appreciated when the deformations correspond to the anatomic planes; translation only is seen on one view and angulation only on the other view. If they are in different oblique planes, then both angulation and translation are present, in both AP and lateral views. To differentiate this from angulation/translation in the same oblique plane, one must examine the levels of the center of rotation of the angulation on AP and lateral views. When both are in different planes, the center of rotation is at a different level on AP than on lateral views, usually one apex above and one below the fracture level. Angulation and translation may also be in different planes that are less than 90° apart (Fig. 61-32). The graphic method of oblique plane deformity assessment can be used to plot the plane of angulation and the plane of translation on the same graph (Fig. 61-24). The difference in planes between angulation and translation can then be measured off the graph.

The relationship between the plane of angulation and translation has ramifications on treatment. When both are in the same plane, there is a single center of rotation point that will correct both deformities by angulation alone. In nonunions the hinge can be placed at this angulation/translation point, and after distracting the ends apart the angulation and translation are corrected by angulation around this hinge. If there is a malunion, an osteotomy may be performed at this level with opening or closing wedge correction. This corrects both angulation and translation together (see Fig. 61-21).

If angulation and translation are in different planes, then several strategies may be pursued. Angulation may be corrected at the apical level on the AP, lateral, or oblique views (Fig. 61-24). Translation, if significant, will not correct with the angulation and requires a separate correction in the lateral, AP, or oblique planes, respectively (see Fig. 61-24). Alternatively, a double level osteotomy can be performed, correcting angulation and translation in the frontal plane with one osteotomy at the AP angulation/translation point and one osteotomy at the LAT angulation/translation point. This deformity is the only true "biplanar" deformity from a single fracture level.

Malrotation may also be a component of the deformity. Rotation is simply an angular deformity in the axial plane. Since all single-level angular deformities can be resolved into a single plane and a single axis of deformity, it should be possible to resolve the rotational component together with the angulation and translation. Sangeorzan and associates and other authors have demonstrated that combinations of angulation and rotation deformities can be resolved into a single axis of deformity using complex trigonometric computations and tables.

This geometric problem can also be solved in a simpler fashion. This x-y-z axis deformity can be computed as a
FIGURE 61-22. (A) Valgus malunion of the middiaphysis of the tibia with aggravating lateral translation. There was a significant contour deformity created by the malunion. Preoperative planning demonstrates that the true apex of the deformity is proximal to the level of the malunion. Angular correction at this level simultaneously corrects for the translational component of the deformity. (B) This leaves a persistent contour deformity which was unacceptable to the patient. (C) Therefore, the alternative is to perform the correction at the level of the malunion to correct separately the angulation, translation, and the contour deformities. The radiograph demonstrates the angular and translational correction which were performed acutely followed by distraction to lengthen the tibia. (D) The final radiograph demonstrates elimination of the angulation-translation and, as a result, of the contour deformity. The acute translational maneuver should be avoided because it contributes to delayed consolidation, by disrupting the periosteum. It is preferable to correct the angulation gradually, followed by distraction to lengthen the tibia, followed by gradual translation.
FIGURE 61-23. (A) Oblique plane deformity of the tibia. (B) The AP projection of this tibia demonstrates a valgus deformity. (C) The lateral projection of this tibia demonstrates a recurvatum deformity. The trigonometric exact formulae and graphic approximate formulae to calculate the magnitude (obi) and orientation of the oblique plane to the frontal plane (pin) are as follow:

- **Trigonometric:**
  \[ \text{obi} = \tan^{-1} \left( \frac{\tan^2 \text{ap} + \tan^2 \text{lat}}{\tan \text{pin}} \right) \]
  \[ \text{pin} = \tan^{-1} \left( \frac{\tan \text{lat}}{\tan \text{ap}} \right) \]

- **Graphic:**
  \[ \text{obi} = \text{varus} + \text{trel} \] (phythagorean Theorem)
  \[ \text{pin} = \tan^{-1} \left( \frac{\text{lat}}{\text{ap}} \right) \]

FIGURE 61-24. (A) Malunion of the tibia with 20° of varus and 13 mm lateral translation. (B) The lateral projection demonstrates 25° of procurvatum and 10 mm posterior translation. (C) Observation of the patient from the front demonstrates the varus deformity of the tibia. (D) When the patient turns his foot inwards, the varus deformity seems to disappear and the tibia appears straight. (E) Examination from the side demonstrates the procurvatum deformity of the tibia. (F) When the patient turns his foot inward again, the maximum angular profile of the deformity is seen. (G) The maximum angular profile is captured radiographically on this lateral oblique view of the tibia. It measures 32°. (H) An internal rotation AP oblique radiograph. In the plane of the deformity, the tibia appears straight. The translational component of the deformity can be appreciated on this view. (I) The measurement of 20° varus and 25° procurvatum were plotted on a graph. The vector obtained by the point 20-25 represents the magnitude 32° and true orientation 51.5° to frontal plane of the oblique plane angular deformity. Superimposed on this graph the magnitude of translation on the AP and LAT are plotted. The magnitude of the oblique plane translation is 16 mm oriented 35° to the frontal plane. The translation and angulation planes are 88° apart. This confirms the radiographic findings. (J) The malunion was split obliquely. (K) Notice the appearance of the apparatus in relationship to the left. The hinges have been placed relative to the apex of the oblique plane deformity. Notice that the distance of the hinge rods to the central bolts differs for the medial and the lateral hinge, demonstrating that the hinges are oriented obliquely to the anatomic planes. (L) A true lateral view of the deformity aligns the hinges with the apex in the oblique plane. (M) In this manner distradion
FIGURE 61-24. (Continued) of the concavity leads to realignment of the diaphysis on the lateral view of the tibia simultaneous with realignment on the AP view. (N) All that remains is to correct the translational deformity. (O) By applying translational rods, the tibia was narrowed, bringing the cortical ends together side to side. (P) Appearance of the callus at the time of the removal of the apparatus 23 weeks after application. Notice that there is no corticalization of the callus between the bone ends. The patient was, therefore, protected in a PTB cast. The final AP (Q) and lateral (R) radiographs demonstrate the recurrence of deformity that occurred due to premature removal of the apparatus prior to complete corticalization of the distraction callus. Notice in addition the ring sequestrum from one of the pin sites (arrow).
RING FIXATION AND DISTRACTION TECHNIQUES

FIGURE 61-24. (Continued)
FIGURE 61-24. (Continued)
Figure 61-25. (A) Mark direction of apex of angulation on axes of the graph (as if looking down at one's own feet). (B) Mark magnitude of AP and LAT angles (1 mm = 1°; AP, x axis, LAT, y axis). The resultant vector represents plane, magnitude, and apical direction.

Figure 61-26. Ilizarov's method for determination of the plane of the oblique deformity. A line is drawn from the center of the knee to the center of the ankle on both the AP and lateral views. The distance from this line to the apex of the deformity is measured on both views. These are plotted on a graph, and the orientation of the resultant vector from the AP or lateral plane is measured. This represents the plane of the apex of the deformity.

**Apical Direction Graphs**

**Anatomy**

**Ant (Procavatum)**

**Med (Valgus)**

**Post (Recurvatum)**

**LAT**

**AP**

**LAT**

**M**

**CONCAVE**

**CONVEX**

**plane of angulation**

**MULTI-APICAL ANGULAR DEFORMITIES**

A more complex situation exists when there is more than one level of angulation. Each level and each plane of deformity must be delineated for each apex. Sometimes a single osteotomy can be used to correct a multi-apical angular deformity, but usually more than one osteotomy is needed. Often one of the apices is obvious, while the other is subtle. This happens when one of the deformities is diaphyseal and...
FIGURE 61-27. Graphic preoperative planning of hinge placement in oblique plane deformities. Step 1: Measure the diameter of the tibia on the AP and LAT views and mark on the graph as shown. The lateral aspect of the tibia should be marked on the upper side of the y axis and the width on the AP should be marked to the minus or plus side on the x axis for right and left legs respectively. These markings should be to normal scale with 1 mm on the radiograph equal to 1 mm on the graph. The points on the x and y axes are connected with a line to form a triangle. This represents the cross section of the tibia at the level of the apex of angulation. If a different level or bone is chosen, the representative x section for that apical level should similarly be centered. Step 2: The hinge axis is always perpendicular to the plane of angulation. If an opening wedge hinge placement is chosen, it should be placed at the convex edge of the bone. The direction of the convexity is shown by the arrow. The hinge axis is therefore drawn perpendicular to the plane of angulation axis passing tangential to the convex cortex of the bone. Step 3: In order to determine the hinge holes a ring of the appropriate size for the limb should be placed on the graph. To center the ring the reference marks of the ring must be defined. The line connecting the central bolts represents the AP axis of the frame. Since the rings are normally centered over the lateral edge of the central bolts of the ring should be placed on the y axis. The ring is normally spaced 2 fingerbreadths from the anterior skin of the leg. This can be marked on the graph by noting the thickness of the anterior skin followed by a 2-fingerbreadth space anterior to that. The position of the ring on the y axis fixes it in place. The hinges are placed in the holes where the hinge line intersects the ring. The distraction rod on the concavity is places where the plane axis line intersects the ring on the concave side of the angulation.
RING FIXATION AND DISTRACTION TECHNIQUES

FIGURE 61-28. (A) Valgus malunion of the tibia with aggravating lateral translation. (B) The deformity measures 22° of valgus with an apex proximal to the level of the malunion. (C) On the lateral view there is an 11° deformity, indicating that this is an oblique planar deformity, with angulation and translation. (D) The maximum profile of deformity is demonstrated on this oblique lateral radiograph and measures 24°. (E) The radiograph in the plane of the deformity illustrates the translational component in the absence of angulation. (F) Graphic determination of the magnitude and plane of the oblique deformity on a left leg graph demonstrates a 24.5° deformity oriented 26.7° from the frontal plane. This is the same example shown in Figs. 61-23, 61-24, and 61-27. (G) The apparatus is applied so that the hinges are at the level of the true apex of the deformity which is proximal to the malunion. The corticotomy is performed at the same level. (H) An open wedge correction was carried out, realigning the mechanical axis of the lower limb. Note that all of the rings are parallel and the hinges are straight. (I) On the lateral view one can also appreciate the open wedge anteriorly with the correction of the recurvatum deformity. The rings are parallel on the lateral at the end of the correction. The follow-up AP (J) and lateral (K) radiographs demonstrate the restoration of AP and lateral alignment of the tibia.

the other is juxta-articular. Examples are anteromedial and posterolateral bows of the tibia (Fig. 61-35). Usually a varus or valgus diaphyseal deformity exists with a compensatory-juxta-articular angular deformity at the level of the proximal tibial physis. Correction requires two osteotomies: angulation-translation in the proximal tibia and angulation in the mid-diaphyseal region. These are called compensatory-bowing deformities because one deformity compensates for the other. There is usually little deviation of the mechanical axis.

True (noncompensatory) bowing is a continuous, multiaxial deformity that develops in soft bone such as in rickets, Paget’s, and osteogenesis imperfecta (Fig. 61-36 through 61-38). Whether due to remodeling or ongoing multiple stress fractures, these deformities demonstrate no single or double apex. While a bow can be considered as having a single apex, realignment through the apex corrects only the mechanical axis and does not improve the anatomical axis of the bone. It is preferable to perform at least two osteotomies to straighten a bowed bone. An alternative is to perform an osteotomy at a different level than the apex of the bow and combine this with a translational correction so as to eliminate some of the anatomical axis deformity.

The steps for preoperative planning of multi-apical angular deformities of the femur or tibia are shown in Figure 61-39. The clue that there is more than one apex of angulation is that the single center of rotation determined by the intersection of the proximal and distal mechanical axis lines is at a level where there is no "obvious" angulation (see Fig. 61-39, step 1). In multiapical deformities there is usually one obvious (diaphyseal, hip, or ankle) apex and one less obvious angulation apex. The obvious apex should be corrected first. The apex of this level may be chosen based on cortical or midbone lines, or, in the case of hip or ankle deformities, we know the apex is at the center of the joint. Once the first apex of angulation is corrected it will point to the second apex.
JOINT LAXITY DEFORMITIES OF THE KNEE

If lateral laxity of the knee is a cause of symptoms or malalignment, it should be corrected together with the tibial or femoral varus angulation. With conventional techniques, the head of the fibula can be osteotomized and moved distally. By the Ilizarov method, the proximal fibula is pulled down to tighten (even over-tighten) the lateral complex (see Figs. 61-8 and 61-36). The medial collateral ligament can also be tightened by distracting the tibia through an osteotomy proximal to the insertion of the medial collateral ligament. In order to tighten the medial collateral ligament, without pulling down the patellar tendon, the osteotomy of the tibia should be directed obliquely distally and laterally to exit below the tibial tuberosity (Fig. 61-8).

INDICATIONS FOR DISTRACTION OSTEOTOMY VERSUS CONVENTIONAL OSTEOTOMY

An angular deformity of a bone may be corrected by opening wedge, dome, closing wedge, or angular displacement osteotomies. Both distraction and conventional methods use all of these osteotomy types. With conventional osteotomy, the correction is achieved acutely in the operating room; stability is achieved with internal or external fixation. The closing wedge technique is preferred because of the good bone-to-bone contact possible. Conventional opening wedge methods are plagued with union problems and often require a bone graft. The dome osteotomy is a compromise between the opening and closing wedge, avoiding the length loss of the closing wedge method and offering some adjustability. The complications with these techniques include nonunion, osteomyelitis, compartment syndrome, nerve injury, and vascular injury. Accuracy of correction is often a problem, especially with the closing wedge technique. Even with meticulous planning, factors such as x-ray magnification, rotated x-rays, measurement error, the thickness of the saw blade, and the expertise of the surgeon all contribute to inaccuracy with conventional methods. After the operation there is no nonoperative way to adjust incomplete correction. Distraction osteotomies are less risky and more accurate. Since Ilizarov's technique is percutaneous, there is little risk of compartment syndrome, nerve injury, vessel injury, nonunion, or osteomyelitis. The correction is performed either acutely for small deformities or gradually for larger deformities. Gradual distraction prevents nerve stretch injuries, as can occur in the correction of a valgus tibial deformity. The distraction method is as accurate as one can measure on a radiograph, perhaps the greatest advantage of Ilizarov's technique. Even after acute corrections, adjustments can be made to fine-tune the correction until the exact alignment of the limb is achieved.

Text continued on page 923
FIGURE 61-30. (A) Frontal plane translation. Translation is seen on the AP only. There is no deformity on the lateral. (B) Oblique plane translation. Translation is seen on both AP and LAT. The axial view (floor) shows the orientation of the oblique plane of translation. The magnitude of the oblique plane translation is larger than that seen on either AP or LAT view.
FIGURE 61-31. Angulation-translation deformity, in the same plane. (A) Frontal plane angulation and translation. Angulation and translation are both in the frontal plane. No deformity is seen in the sagittal plane. Note that the center of rotation of the angulation is proximal to the fracture level. (B) Oblique plane angulation and translation: same plane. Angulation and translation are seen on both AP and LAT views. The center of rotation of the angulation is the same on both views. This indicates that both angulation and translation are in the same oblique plane (see axial). The apical direction of angulation is marked with an arrow A and the direction of translation marked T. This represents the same deformity shown in part A rotated into an oblique plane.
FIGURE 61-32. Angulation-translation deformity in different planes. (A) Frontal plane angulation with sagittal plane translation. The AP shows angulation without translation while the LAT shows translation without angulation. The axial view shows the direction of the apex of angulation A relative to translation T. In this example they are 90° apart. (B) Oblique plane angulation-translation: different planes 90° apart. Angulation and translation are seen on both AP and LAT views. Note that the center of rotation is at a different level on the AP than on the LAT. On the AP it is proximal to the osteotomy while on the LAT it is distal. This is the tipoff that the two are in different planes. On the axial view the direction of angulation A and of translation T are 90° apart. This represents the same deformity shown in A rotated into an oblique plane. (C) Oblique plane angulation-translation: different planes less than 90° apart. The AP and LAT projections are as before with angulation and translation seen on both views. The difference is that the plane of angulation A and translation T are different but less than 90° apart. This is one of the most common clinical situations.
If one adds rotation to the evaluation of angular deformity, then an XYZ graph can be used to determine the orientation of the axis and magnitude of the deformity. The oblique plane deformity is calculated first in the method described above. One then plots the oblique plane magnitude on the X axis and the rotational magnitude on the Z or axial axis. In the example illustrated there is a 25° varus angulation and 25° procurvatum angulation, producing a 35° oblique plane deformity, oriented 45° to the frontal plane. In addition, there is a 34° rotational deformity. This is plotted on the axial axis. The graph demonstrates a 39° angular deformity oriented at a 44.5° inclination to the transverse plane. This axis can be further qualified as oriented at 45° to the frontal plane on the transverse cut.

(A) Vertical inclined plane hinge. When the paper is folded with the tibia marked on it along a vertical oblique axis, the tibial diaphysis is both realigned as to its angular deformation and de-rotated. (B) This principle can be applied to the Ilizarov apparatus. By using universal hinges, two rings can be connected by hinges at different levels. The axis of rotation is no longer parallel to the plane of the rings, but rather is in a plane which is vertically oblique to the rings. (C) In this simulation the upper ring can be seen to pivot through the vertical oblique axis. Notice the position of the central bolt connecting the half rings on the moving ring relative to the central bolt on the stationary ring. In this reduced position the central bolts are properly aligned. In the flexed position the central bolts are rotated with respect to each other.
FIGURE 61-35.
FIGURE 61-35. Anteromedial tibial bow. (A) The frontal plane alignment of the tibia demonstrates an obvious varus deformity of the mid diaphysis and a subtle valgus deformity of the juxta-articular region of the tibia. There is also a very mild distal femoral valgus and a leg length discrepancy. (B) The osteotomies were performed in the proximal metaphysis and in the mid diaphysis. The distal osteotomy is for the correction of the varus and the procurvatum deformities; the proximal osteotomy is for the correction of the juxta-articular valgus deformity. Notice the pattern of the olive wires, which provide the necessary fulcrums and distraction points for this correction. (C) The apparatus is shown in the immediate postoperative period. Each ring is oriented perpendicular to its own bone segment. The mid diaphyseal hinge is properly located. The proximal tibial hinge was incorrectly located at the level of the osteotomy. This was one of the authors' earliest cases before complete understanding of the principles of angulation plus translation for juxta-articular deformities. (D) At the end of the correction, all of the rings are parallel and the hinges are straight. (E) The apparatus and lateral radiographs demonstrate the realignment of the tibia on both views as well as double level lengthening to equalize the limb length in equality. (F) The final radiograph demonstrates the realignment of the tibia with slight undercorrection of the distal angular deformity and slight overcorrection of the proximal angular deformity, which made up for the lack of translation at the proximal osteotomy. The preoperative planning of this case is illustrated in Figure 61-39.

FIGURE 61-36. (A) Back view of an 18-year-old woman with severe bowleggedness from hypophosphatemic rickets. (B) The radiographs demonstrate the severity of the preoperative deformity. Both legs do not fit on the width of a normal film, even when the legs are crossed. Notice the bowing in the femur. Notice that the bowing in the femur is diffusely distributed throughout the length of the femur, as is the bowing in the tibia. Notice also the lateral compartment joint laxity in the knee, which contributes the varus deformity. (C) The apparatus is shown during construction in the operating room. The femoral apparatus is applied first, followed by the tibial apparatus. The two devices need to be coordinated to allow at least 90° of free flexion of the knee. Care must be taken so that the most distal femoral and most proximal tibial rings do not collide. For this reason incomplete rings (Sjarings) open posteriorly are applied adjacent to the knee. (D) The tibial apparatus from the frontal view. The hinges are locked at the measured deformity. The incision for the distal corticotomy of the tibia is shown adjacent to the hinge. There are two levels of fixation within the proximal and distal segments. (E) At the completion of the realignment all of the rings of both the femur and the tibia are parallel. Notice the axial increase in length from realignment of these severely bowed bones. (F) After removal of the apparatus the patient was left with a 10-cm leg-length discrepancy. The realigned limb stands in marked contrast to the uncorrected side. (G) The second side was corrected after a 4-month hiatus. Notice that the left tibia was slightly overcorrected to try to compensate for the lateral knee joint laxity. On the right side the proximal fibula was pulled down 1 cm to tighten the lateral knee joint. Notice that even in bipedal stance the lateral knee joint is wider on the left than on the right leg. Notice also that the tibial head lies more distally on the right than on the left side. (H) The final clinical appearance of both legs shows normal alignment with an excellent cosmetic and functional result.
FIGURE 61-36.
FIGURE 61-37. (A) A lateral photograph of the marked anterior bow ("saber shin") deformity of the leg in a 75-year-old woman. (B) The lateral radiograph demonstrates monostotic Paget's disease with two levels of ununited stress fractures and an intact posterior fibular strut. (C) A push construct was applied to the tibia. Notice the single level of fixation in the proximal and distal tibia and three floating levels of fixation on opposite sides of the stress fractures. Anteriorly, a sliding plate suspends the three floating half rings. The threaded rods off this plate are used to push in the apex of the deformity. On the concave side there are two distraction rods, of which only one can be seen on the photograph. Both a knee and an ankle Dynasplint unit were used to help prevent joint contractures. (D) The apparatus is shown in situ at the beginning of the deformity correction. A fibular osteotomy was performed. The posterior aspect of the two non-unions can be seen to open slightly as the combined distraction and apical translation are carried out. (E) At the end of the deformity correction there is an opening wedge at both nonunion sites. The proximal and distal tibial rings as well as the three floating half rings are all parallel. (F) The apparatus was removed when a complete wall of cortical bone was seen posteriorly and when the fibula had united. This correction also equalized the patient's leg length. (G) The clinical appearance is excellent.
Oblique plane angular deformities are just as easy to correct as frontal or sagittal plane ones. More complex deformities including rotation, translation, and limb-length discrepancy can all be managed simultaneously. Multilevel and multibone corrections can be done since there is little blood loss and the apparatus can be applied to multiple levels and bones simultaneously. Lengthening is performed for small and large discrepancies, as needed, at one or more levels. Associated problems of nonunion, contracture, and osteomyelitis can be treated at the same time. The apparatus allows for unrestricted weight-bearing and personal hygiene; weight-bearing is usually restricted with internal fixation and bathing is difficult if a protective cast is used.

The main disadvantages of Ilizarov's method are those related to external fixation, including wearing a bulky apparatus for a prolonged period, pin infections, muscle transfixion, loss of joint range of motion, and pain. With proper application of the device, the latter three problems should be minimal. More recently with the use of half pins instead of transfixion wires these problems have been significantly reduced.

Obviously, the distraction osteotomy is most advantageous in treating complex deformities. Nevertheless, it still offers many advantages even for simple deformities that have a good conventional alternative, such as high tibial osteotomy. The decision to use Ilizarov's distraction method compared
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Basic Principles of Deformity Correction Using Circular External Fixation

There are two types of constructs for correcting deformity: focal hinges, and pull/push constructs.

FIGURE 61-39. (A) Multi-apical angular deformity of the tibia with a normal femur. Step 0: Draw the mechanical axis line from the center of the hip to the center of the ankle, demonstrating minimal varus mechanical axis deviation. The mal-alignment test was performed, demonstrating a normal distal femoral alignment. Step 1: Draw the proximal and distal tibial mechanical axis lines. Note that the intersection point is at a non-deformed level. The intersection of these two lines is not at the level of the obvious deformity. Notice that the proximal tibia also does not lie on this line. This indicates that there is a second apex of deformity. Step 2a: Draw the perpendicular to the middle segment of the tibia and extend this line proximally and distally. This should intersect the mechanical axis of the distal tibia at the level of the true apex of deformity. Step 2b: The same center of rotation is located by the convex cortex method. Step 3a: Correct the first deformity at the level of the obvious apex. Extend the corrected distal mechanical axis line proximally. This intersects the proximal tibial mechanical line at the growth plate. This is the second apex. The second osteotomy is of angulation and translation to realign the tibia. (B) The apparatus before and after correction.

Center of Rotation Hinge Technique

The basic construct for angular deformity correction using hinges consists of two levels of fixation proximal and two levels distal to the apex of deformity (Fig. 61-41). Each level of fixation is perpendicular to either the anatomical or mechanical axis of the bone fragment to which it is affixed. The hinge connects the proximal and distal blocks of fixation, articulating between them at the desired center of rotation for correcting the angular deformity.

If the hinge is placed at the apex of the deformity on the convex side, then distraction of the concavity will lead to...
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FIGURE 61-41. (A) Center of rotation hinge apparatus. There are two levels of fixation in each bone segment on opposite sides of the osteotomy. The rings are applied perpendicular to their respective bone segment. The hinge lies perpendicular to the ring. In this example the hinge is applied over the apex of the deformity, with the hinge rod overlying the medial convex cortex of the tibia. On the concave aspect there is a distraction rod connected by two twisted plates and a suspending post. The post connection to the twisted plate allows for self-adjustment of the distraction rod angle to that of the ring. (B) After the correction is completed all of the rings are parallel and the hinge rods are colinear. Notice the open wedge correction of the tibia and fibula and the change in angle between the distraction rod and the ring. (C) For a juxta-articular deformity of the tibia, the apparatus employs a translation hinge. Notice that the hinge is located over the level of the tibial physis. This is proximal to the upper ring. Two levels of fixation were achieved in each bone segment on opposite sides of the osteotomy. (D) At the end of the correction there is an angulation and translation of the bone segments at the level of the osteotomy. The rings are now parallel and the hinge rod is straight. Notice again the change in orientation of the distraction rod to the rings.
an opening wedge correction (see Figs. 61-28 and 61-42A). If the hinge is placed at a distance from the convex side of the apex of the deformity, then lengthening will occur together with correction of angular deformity (Figs. 61-42B and 61-43). Placing the hinge on the concave side of the deformity will lead to compression of the bone ends with angular correction (Figs. 61-42C and 61-44). If the hinge is placed either proximal or distal to the level of the osteotomy, then translation of the bone ends will occur with angular correction during distraction of the concavity (Figs. 61-42D and 61-45).

Therefore, it is important to keep the hinge at the level of the osteotomy to avoid any translation of the bone ends with respect to each other, unless translation is planned as part of the correction. Conversely, if translation of the bone ends is desired, then the proper level of the hinge should be selected. The level of the hinge is also governed by the bisector line of the angular deformity (Fig. 61-46).

To ensure that the desired correction is produced, the bone must be prevented from slipping along the wires (Fig. 61-47). The bone must be locked into the apparatus in such a way that the bone ends will follow the angular correction of the rings. To create such a constrained system, the appropriate fulcrum and distraction points must be built in. The positions of fulcrum and distraction points is best described as a four-point bending maneuver (Fig. 61-48). The "rule of thumbs" is used to determine the location of the fulcrum and distraction points for simple angular corrections without translation of the bone ends. In coronal plane deformities, olive wires in the frontal plane are inserted ac-
FIGURE 61-43. Application of distraction hinges for lengthening and correction of deformity. (A) A 5-year-old girl with bilateral genu varum and shortening due to meningococcemia septic emboli. She has skin grafts adherent to the bone and, therefore, distraction must be performed very gently. (B) Standing radiographs show the deformities and the preoperative planning markings for the placement of olive wires. (C) The apparatus has a hinge located lateral to the convex aspect of the osteotomy. To augment the stability of the fixation the distal hinge has a threaded rod applied through the center of the anterior and posterior hinge point. This can be performed only with distraction hinges. (D) Toward the end of the correction notice the increased length achieved through the distraction hinges without lengthening on the hinge rods. All of the lengthening is performed by distraction of the concavity. Notice that this method is gentle on the skin and there were no skin problems. (E) The final radiographs demonstrate 8 cm of lengthening of both tibias with realignment. Notice the bilateral triangular shaped tali. Both feet were plantigrade at the end of the correction. (F) The final appearance of both legs at the end of the lengthening and correction of deformities.
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**FIGURE 61-45.** (A) Application of translation hinge. Equinus malunion of ankle arthrodesis. (B) This was treated by a supramalleolar osteotomy with application of a translation hinge. The hinge was located at the level of the calcaneotibial fusion; the osteotomy was performed 3 cm proximal to that. (C) Simultaneous lengthening, angulation and translation were carried out. Notice the position of the tibia overlying the mid-foot. The entire foot has translated posteriorly to give this girl a heel and to shorten the stiff forefoot, improving her ambulation. Notice the translational pattern of the trabeculae.

**FIGURE 61-46.** Determination of hinge placement level by the bisector concept. A, distraction hinge; B, opening wedge hinge; C, compression hinge.

According to the four-point bending rule of thumbs (see Fig. 61-48). For sagittal plane deformities, transverse smooth wires in the frontal plane are used at all four levels of the rule of thumbs instead of olive wires (Fig. 61-49). Alternatively, threaded half-pins can serve as fulcrums for either sagittal or coronal plane deformities. It is preferable to use two olives counteropposed on the same side as the fulcrum or distraction point whenever possible. In the femur, threaded half-pins often substitute for olive wires.

For pure frontal plane translational correction, the olives are placed counteropposed between blocks but on the same side of the two levels of fixation within a block (Fig. 61-50). Therefore, the proximal two olive wires are on the same side and the distal two olive wires on the counteropposed side. In this pattern, the olives act to push the bone's distal segment from its translated position toward the properly aligned proximal segment.

For a combined angular and translational deformity correction using a hinge, the olive wires are placed in a modified rule of thumbs to effect both translation and angulation (Fig. 61-51). This requires the addition of a third olive wire on the side without the hinge. The third olive wire is the translation wire that forces the translational correction simultaneous with the angular correction. If half-pins are used they act to constrain the construct, thus replacing the need for olive wires.
DEFORMITY CORRECTION BY THE ILIZAROV TECHNIQUE

FIGURE 61-47. The principle of constraint of the apparatus to the bone. (A, B) If smooth wires only are used, distraction of the concavity of a deformity will lead to slippage on the smooth wires. The bone does not want to elongate with the correction but would rather move toward a part of the apparatus in which there is less elongation. Therefore, the bone moves from the convex side of the apparatus toward the concave side of the apparatus. This slippage leads to incomplete correction of the bone by the time the rings are in a corrected position, and it may lead to impingement of the skin against the ring on the convex side of the deformity. (C, D) Applying olives over the apex of the deformity prevents slipping. The concave bone and soft tissues are forced to elongate.
RING FIXATION AND DISTRACTION TECHNIQUES

The rule of thumbs. Four-point bending is the principle of correction in angular deformities. Olive wires are placed at the fulcrum point on opposite sides of the apex of the deformity and at the distraction points at either end of the bone. The location of the olive wires can be remembered by thinking of the four point bending rule of thumbs; the olive is located at the points where the thumbs press on the apex and the index fingers press on the ends of the bone.

In preoperative planning, first determine the level of osteotomy and identify the magnitude and true plane of the deformity. Construct an apparatus to correct the deformity. Two blocks of fixation are constructed, each with two levels of fixation. The spacing between levels is planned according to the strategy of correction. If only angular correction is required, then the blocks should be as wide as possible, with only a handbreadth separating the blocks at the level of the deformity. If significant lengthening is planned, the distance between blocks must be greater to avoid skin entrapment.

In this situation, the width of each block is narrower.

The hinge is placed in the axis of rotation of the angular deformity, perpendicular to the plane of deformity. In addition to the plane of the hinge axis, the level of the hinge and its function must be chosen. A hinge is placed either at the level of the osteotomy or at a different level. The latter will produce a translational effect during correction. Usually the hinge is placed at the level of the deformity's apex and

FIGURE 61-49. In sagittal plane deformities the transverse wires act to constrain the system in much the same way as olives do for frontal plane deformities.

The osteotomy is done as close to that level as other considerations permit. The function of the hinge as opening wedge or distraction will determine its distance from the center of the ring.

Once the hinge location is determined, the hinge is set at the calculated magnitude of angular deformity and locked in that position. A distraction rod is also placed between adjacent rings at a point halfway between the hinges on the

FIGURE 61-50. For translational deformities, the olives should be counteropposed.
The modified rule of thumbs helps to determine the location of the olives for combined angulation translational corrections. While one fragment is held as usual between the index and thumb, the other fragment is held with the thumb and index at the same level on opposite sides of the bone and the middle finger in the previous location of the index finger. The olive pattern is illustrated in Figure 61-42D.

**FIGURE 61-51.** The modified rule of thumbs helps determine the location of the olives for combined angulation translational corrections. While one fragment is held as usual between the index and thumb, the other fragment is held with the thumb and index at the same level on opposite sides of the bone and the middle finger in the previous location of the index finger. The olive pattern is illustrated in Figure 61-42D.

**FIGURE 61-52.** Push construct. (A) The push construct is shown applied to a procurvatum deformity of the tibia, similar to the example illustrated in Figure 61-37. The proximal and distal rings are perpendicular to their individual bone segments. The middle half-rings are suspended off an anterior plate. The plate, connected via buckles to a perpendicular shorter plate, pivots on the ring on a hinge. The buckles allow the horizontal plates to slide up and down while the hinges allow the horizontal plate to alter its orientation to the ring as the deformity gradually corrects. The half-rings are connected by threaded rods from posts on either side of the long plate. On the concavity there are two distraction rods connected by twisted plates and posts to allow auto adjustment at either end. Only a single wire is needed on each of the floating half rings, and two wires are used at either end on the full ring. (B) By coordinating the distraction on the concavity with the translation on the convexity, the deformity is gradually corrected. Notice that the buckles have moved toward each other on the long plate.

**PUSH/PULL CONSTRUCTS**

The push/pull construct uses one fixed level within each bone fragment and one floating level in each bone fragment. (Figs. 61-52 and 61-53). The proximal-most and distal-most levels are each affixed to a ring; distraction rods are applied on the frame’s concavity. On the convex side, the rings are articulated with a long plate. The articulation on the plate acts as both a pivot and a sliding joint. The apex of the deformity is either pushed or pulled into the concavity. A push construct uses smooth wires perpendicular to the plane of the deformity. The push wires are connected to a translational apparatus. The pull olive wires are connected using a slotted threaded rod translation apparatus. (see Fig. 61-52). A pull construct uses olive wires in the plane of deformity. The pull olive wires are connected using a slotted threaded rod translation apparatus. (see Fig. 61-53).

Because there is only one fixed level within each bone segment, this construct is less stable than the hinge construct. Therefore, this frame should be applied only to relatively stable pathologies such as stiff nonunions, bowing deformities with a large resistive tension band of soft tissue on the concavity (see Fig. 61-37), and bones that do not have great loads applied to them, such as the forearm.

The most stable configuration for angular deformity correction is constructed by a mix of push and hinged constructs. (Fig. 61-54). Two levels of fixation within each bone segment, articulated with hinges and a distraction rod on the concavity
RING FIXATION AND DISTRACTION TECHNIQUES

FIGURE 61-53. Pull construct. (A) The apparatus at the beginning of the correction, with olive wires on slotted threaded rods. The olive wires pull in the apex of the deformity, much like the way the push wires push in the apex of the deformity. In the minor deformity shown, conical washers are used at either end for distraction. Alternatively, a focal hinge or twisted plate at either end could be used. (B) The appearance of the construct at the end of correction. (C) Preoperative AP roentgenograph of CPT previously treated by a nail and onlay grafting. Note the valgus ankle and proximal migration of the fibula. (D) Distraction of the stiff pseudoarthrosis using a pull construct to correct the deformity. (E) Union, lengthening, and realignment were all achieved. The fibula was transported distally. It was transfixed with a screw to keep it from proximal migration and a bone graft applied to synostose it to the tibia. It remains united two years later. (C, D, E from Paley, D., Catagni, M., Argnani, F., et al: Treatment of Congenital Pseudoarthrosis of the Tibia. Using the Ilizarov Technique: Clin. Orthop. 280:91, 1992).
FIGURE 61-54. Combination hinge and push constructs. (A) The strongest construct of all combines the two levels of fixation of the hinge construct with the push construct. (B) This shows the construct at the end of deformity correction. (C) The construct shown in A and B was applied to a congenital pseudoarthrosis, which had malunited, in an effort to fracture the bone without an osteotomy. (D) Ilizarov calls this method metaphysealisis. It can be used to focus large concentrated forces on weak, narrow-diameter bone regions. Notice the fracture of the bone that has occurred. (E) The final result, showing union and correction of the deformity.
are augmented by a push construct on the apical two rings of the deformity to achieve augmented fixation and augmented constraints on the deformity.

CONSTRUCT CONSIDERATIONS. FOR ROTATIONAL DEFORMITIES

Most rotational deformities are corrected by rotational modifications of the basic hinge frame. The rotational vertical inclined plane hinge, while a theoretical possibility, is usually too complex to be readily applied (see Fig. 61-45). Two types of rotational corrections can be achieved with the circular frame: acute and gradual.

The rotational correction can be performed acutely by disconnecting the frame and rotating one section with respect to the other. This can be done at the time of surgery. Because acute correction is too painful in most outpatient situations, a controlled acute method is preferable. One of these methods is to angle the rods between one ring and the other and then tighten them. If all the rods are angled one or two holes over, then an acute derotation of one or two holes is achieved (Fig. 61-55A,B), resulting in 5° to 10° of derotation, depending on the ring diameter. This can be repeated every few days until the correction is completed, usually with minimal discomfort. An alternative method is to shift the wire on the ring (Fig. 61-55C,D) so as to bow each end of the wire in an opposite direction like a pinwheel; when the wires are tensioned, the bone rotates. This method is usually too complex, time-consuming, and painful, since all the wires need to be loosened and retensioned.

The gradual method can be applied in one of many constructs (Fig. 61-56A,B) at a set rate and rhythm determined by bone and soft-tissue considerations. The gradual method is the safest and involves the least amount of discomfort.

Since derotation occurs between adjacent rings, the configuration's center of the rotation is at the center of these rings. If the bone is located at the center of the ring, then the derotation will occur around the central axis of the bone. In most cases, however, the bone does not lie in the center of the ring; in both the thigh and the shank, the bone is eccentrically located within the soft-tissue mass. To center the bone within a ring, a ring of very large diameter would be needed, increasing the system's instability (Fig. 61-57).

As the derotation occurs around the center of a ring, an eccentrically placed bone will move sideways during rotation (Fig. 61-58). External rotation of the tibia leads to lateral
translation and internal rotation to medial translation. To a lesser extent, internal rotation is associated with posterior translation and external rotation with anterior translation. In the femur with its anterior location, the same relationships hold.

If significant translation occurs with derotation, a separate translational correction may be needed after derotation with either a translation device or a derotation-translation device. The former uses a translation frame modification to move the bone into the reduced position. The latter uses the translation-rotation point to reduce the fragments (Fig. 61-59).

The translation-rotation point is on the bisector of the center of each bone segment. Where this bisector crosses the ring is the location of the rotation center.

TRANSLATIONAL DEFORMITY CORRECTION

Translational deformity in combination with angulation was discussed earlier. Translation may also be corrected independently of angulation, either acutely or gradually. Acute translational correction may be achieved with olive wires and acute displacement using a wire tensioner (Fig. 61-60).
FIGURE 61-57. (A) The ring is normally centered around the leg so that there is a minimum of two fingerbreadths (3-4 cm) space between the inner edge of the ring and the skin. Notice that the center of the ring lies posterior and lateral to the center of the tibia. (B) To center the ring on the bone it would be necessary to use a much larger ring to allow a minimum of two fingerbreadths space between the ring and the skin. This leads to less stable fixation.

FIGURE 61-58. (A) Rotation of a ring that is centered on the leg and not on the bone leads to (B) lateral translation of the bone. (C) This malunion required a correction of varus and rotation. There was also a lateral translational deformity. Notice that there are two lateral translations and one medial translation of the united fragments. The net result is lateral translation. (D) A corticotomy at the junction of the proximal and middle thirds of the tibia was performed, and the angular deformity corrected at that level. The bone was then lengthened and derotated. Because the ring was centered on the leg and not on the bone, a medial translational deformity, which can be seen, occurred. In this particular case this was therapeutic because it realigned the translation of the tibia. Therefore, the translational effect of the derotation in some cases can be used to achieve a desired translational correction. Since the center of the ring is posterior to the tibia, internal rotation leads to medial translation while external rotation leads to lateral translation. This deformity must be factored into the realignment of the leg, especially in large derotations.
FIGURE 61-58. (Continued)

FIGURE 61-59. (A) To correct the translational deformity created by a derotation, one can use either conventional translational constructs or the more accurate translation rotation point. This point is located on the ring equidistant from the center of the two bone ends. The true plane of the translation must be identified, and then a point between on the line connecting the centers of the two bones is projected to the ring as the right bisector of that line. (B) A threaded rod is connected between the adjacent rings at that point and the rings are derotated around that threaded rod to rotate one bone fragment into the other. This leads to reduction in the translational deformity, without loss of the rotational correction.
Alternatively, acute correction will occur when tensioning an arced wire from both ends. Gradual translational correction can be achieved using gradual distraction on olive or arced wires using slotted threaded rods.

The most controlled way to correct translation is to use translational threaded rods articulating between parallel rings (Fig. 61-61). This allows very gradual translational movement in any direction. Unlike the rotational rods, which are oriented tangential to the ring, the translational rods are oriented parallel to each other in the direction of translation.

**ORDER OF CORRECTION FOR COMPLEX DEFORMITIES**

Complex deformities may have components of angulation, rotation, translation, and shortening. In correcting combi-
nations of deformity, the order of corrections is important. Complex deformities can be divided into two groups: those with and those without bone segments that must translate with respect to each other. Unlike lines on paper, segments of bone cannot slide past each other without colliding. Therefore, any manipulation that will lead to collision of one bone segment with another will cause obstruction and jamming of the system.

Therefore, the order of correction can be planned depending on the likelihood of potential segment collision and jamming (Fig. 61-62). Collision and jamming may occur when translation or rotation of bone fragments is required as part of the correction. The propensity for collision and jamming depends on the configuration of the bone fragments with respect to each other and the contour of their bone ends. Obviously, a transverse osteotomy through a bone with no overlap of the bone segment will allow movements of angulation, rotation, translation, and lengthening without collision and damage. On the other hand, if the two bone segments overlap, translation or angulation will be obstructed. In such a situation, the surgeon must first lengthen the limb and then correct angulation and translation together (see Figs. 61-62 and 61-63). When there is an oblique or spiral osteotomy and rotational correction is required, lengthening must be done first to avoid collision and jamming of the oblique bone segments, with each other.

The order of correction also depends on the expected rate of healing of the bone or the patient. In younger children, the expected rate of healing is faster than in adults. Open wedge angulation correction carries a risk of premature consolidation on the convex side; this would prevent subsequent lengthening. This risk is small in adults but significant in children. Therefore, the order of correction in adults and children may be different.

In patients with no risk of jamming and collision and in whom premature consolidation is not a concern, the order of correction is angulation, lengthening, rotation, and translation (see Fig. 61-63A).

In patients with no risk for jamming and collision but at risk for premature consolidation, the order is angulation and lengthening, rotation, and translation (see Fig. 61-63B). In these patients, the angulation and lengthening may be done simultaneously using a distraction hinge or lengthening on the hinged rods at differential rates from the distraction rods. In this situation, some of the length and some of the angulation are corrected simultaneously until the angular deformity or the length discrepancy is completely corrected, leaving either residual angular or length deformity to correct. This is followed by derotation and translation.

If jamming and collision are expected, the order of correction is lengthening, angulation, remaining lengthening, rotation, and translation (see Fig. 61-63C).

It is preferable to carry out both rotation and translation through long segments of regenerate new bone, where the shearing effect of these displacements can be distributed along the soft bone and blood vessels. There is far greater shear between bone ends of an undistracted osteotomy (leading to disruption of medullary and periosteal tissues during translation or rotation) than there is between bone ends that are separated several centimeters.

Translation should be carried out after rotation because a translational displacement may occur during derotation of an eccentrically located bone. This displacement may be used to the surgeon's advantage if both the translational deformity and the rotational deformity are in the same direction. In these cases, the bone ends can be rotated, thereby correcting translation and rotation simultaneously.

If the bone is rapidly consolidating, the rotational correc-
FIGURE 61-62. (A) When a translational correction is to be performed at the same time as an angular correction by means of a translational hinge, jamming of the bone ends may occur. (B) A valgus malunion of the distal tibia. A translational distraction hinge is in place to correct the length, angulation, and translation simultaneously. (C) Notice that the angulation was corrected but the translation was not correctable because of jamming of the bone ends. The deformity should have been distracted first to separate the bone ends, and then the hinge should have been activated.

RATIONALE OF CORRECTION

The accepted average rate of distraction for osteogenesis and soft-tissue neohistogenesis is 1 mm/day in 0.25-mm intervals. In limb lengthening, all the distraction rods can be lengthened at this rate to create a separation of the bone fragments of 1 mm/day. In angular correction, a calculation must be made to obtain a rate of distraction of 1 mm/day of the osteotomy site. We use the geometric rule of similar triangles (Fig. 61-64), which allows us to calculate the rate of distraction of the threaded rods that will produce a 1 mm/day distraction rate at the level of the bone. As the lengthening proceeds, the rule of similar triangles must be recalculated because the distraction rod approaches the concave aspect of the bone. For small deformities this is inconsequential, but with large deformities it is significant.

The deformity correction actually follows concentric circles (rather than triangles) that radiate around the hinge point. The calculation of the length of arc followed by the concentric circle at the radius R from the hinge is an approximation of the length of time needed to correct the deformity (Fig. 61-65).

The bone is not always the tissue that determines the rate of lengthening. For example, in a contracture of the knee, correction may be adjusted so that the sciatic nerve is dis-
FIGURE 61.63. Order of derormity correction. The order of correction depends on the risk of premature consolidation and the propensity for jamming of the bone ends. (A) Order I: 1) angulation; 2) lengthening; 3) derotation; 4) translation. (B) Order II: 1) simultaneous angular correction and lengthening; 2) derotation; 3) translation. (C) Order III: 1) partial lengthening; 2) angulation; 3) lengthening; 4) derotation; 5) translation.
Rule of similar triangles. The rate of distraction of the distraction rod $D$ that will produce 1 mm of opening wedge at the concave cortex of the tibia $T$ is calculated based on similar triangles. In the example shown the ratio is 4:1. Therefore, it takes 4 mm of distraction at the distraction rod to produce 1 mm of opening wedge of the tibia. In contrast, the fibula lies halfway between the distraction rod and the hinge. Therefore, at 4 mm/day distraction, the fibula will lengthen 2 mm/day. Because the peroneal nerve is at the level of the fibula, it may be preferable to open the wedge relative to a 1 mm rate of the fibula rather than the tibia.

Corrected at a maximum of 1 mm/day (Fig. 61-66). The calculation of the length $R$ is made from the center of the hinge to the sciatic nerve. Similarly, in valgus corrections of the tibia, the peroneal nerve may be the structure determining the rate of distraction.

Sometimes it is important to calculate not only the rate of distraction, but also the rate of compression on the bone’s opposite side. This can be done by the reciprocal rule of triangles (Fig. 61-67). In most cases, distracting one side at the rate of similar triangles and allowing the apparatus to self-adjust on the compression side avoids any errors of rate adjustment between the two sides.

Another method to calculate the time required for deformity correction is to measure the distance between the rings at the level of the hinge and the distance between the rings at the level of the distraction rod. The distance between rings at the hinge will change little before and after deformity correction if no distraction is carried out on the hinge rods. The difference between the hinge rod width and the distraction rod width divided by the rate of correction is an accurate approximation of the time needed for correction (see Fig. 61-67). At the end of correction, the rings should be parallel if the apparatus was properly applied. Therefore, the difference between the distraction rod width and the hinged rod width will eventually be zero.

The rate of correction is also important, for the push construct (Fig. 61-68). In the push construct, the apex of the deformity is being translated while the ends of the deformity are distracted. Correction of a pure translational deformity should be done at a rate of 0.5 to 1.0 mm/day. When translation is done through a lengthy distraction gap, 1 mm/day is used; 0.5 mm/day is used when translation is done through a narrow distraction gap or through an undistracted osteotomy.
FIGURE 61-65. The rule of concentric circles. Because the deformity correction is occurring around a hinge, the true pattern of correction follows the path of an arc of radius \( r \) where \( r \) is the width of the bone at the level of the osteotomy. Because the rate of correction is set to 1 mm/day at the concave cortex of the tibia, the length of the arc across the concave cortex is equal to the number of days it will take to correct the angular deformity. Arc length can be calculated as the number of degrees subtended by the arc divided by 360 times the circumference of the circle \((2\pi r)\). For a deformity of magnitude \( \theta \), the number of days to achieve correction of deformity is \( 2\pi r \theta / 360 \).

FIGURE 61-66. Reciprocal rule of triangles. It is sometimes necessary to distract on one side of a deformity and compress on the other side. For example, in this knee contracture the rate of distraction of the concave distraction rod is calculated by the rule of similar triangles. The rate of compression of the convex rod is a factor of \( r^2 \) to \( r^3 \); the rate of the distraction rod. In the example shown, the rate of distraction or compression are related to stretching of the most important tissue which in this case is the sciatic nerve. The sciatic nerve is located at a distance of \( r' \) from the center of rotation. The length \( r' \) is used in the calculation of similar triangles.
FIGURE 61-67. Alternate method for calculating the treatment time for angular correction. A quick and simple method for calculating the total number of days of distraction until the rings become parallel is to subtract the length of the distraction rod between its connection point on the ring from the length of the hinge rods. (A) When the hinge lies on the ring, the space between the rings is used as the length $d'$. (B) When the hinge lies between the rings, the limb above and below the hinge are added ($d' + d^2$) and then $d^4$ is subtracted from the sum of the other two. The difference $d^4$ is then divided by the rate of distraction of rod $d^3$ to calculate the total treatment time.

FIGURE 61-68. Coordinate the rate of apical translation with that of concavity distraction. Step 1: Use the rule of similar triangles to calculate the rate of distraction at the distraction rod. Step 2: Use the $211/360$ calculation to determine the number of days until complete deformity correction. Step 3: Measure the distance for complete apical translation from the center of the bone at the level of the apex to the line connecting the center of the joint above with the center of the joint below. Step 4: Divide the total distance to be translated ($T$) by the number of days of correction. This will be the rate for apical translation.
The rate of correction for a rotational deformity is about 1 mm/day at the surface of the bone. The number of degrees of rotation to keep the surface rotation rate to 1 mm/day depends on the diameter of the bone: 12° for a 1-cm-diameter bone, 6° for a 2-cm-diameter bone, 4° for a 3-cm-diameter bone, and 3° for a 4-cm-diameter bone. The rate should be adjusted for small and large bones.

The rate of rotational correction using the gradual technique depends on the ring size. The number of degrees between adjacent holes is equal to 360° divided by the total number of holes. (The count should include the solid portion of the rings adjacent to the flare.) Dividing the number of millimeters per hole by the number of degrees per hole gives the number of millimeters per degree of arc. Multiply this by the number of degrees permissible for different diameter bones to get the rate of correction. Divide this number by three or four times per day to split the rate into a dosed rhythm of correction. In most cases this works out to be 1 mm three to five times per day.

It is important not to exceed these guidelines except when above-average bone formation is seen. These guidelines serve to optimize the new bone formation according to the basic biological principles of Ilizarov. They must be altered in situations of hypotrophic and hypertrophic bone formation. In the former the rate may be cut by 25% to 50% as needed, while in the latter the rate may be increased by similar amounts.

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REFERENCES