Biomechanics of spinal deformity

Richard P. Schlenk, M.D., Robert J. Kowalski, M.D., M.S., P.E., and Edward C. Benzel, M.D.

Department of Neurosurgery, Cleveland Clinic Foundation, Cleveland, Ohio

The correction of spinal deformity may be achieved by a variety of methods, each of which has advantages and disadvantages. The goals of spinal deformity surgery include reasonable correction of the curvature, prevention of further deformation, improvement of sagittal and coronal balance, optimization of cosmetic issues, and restoration/preservation of function. The failure to consider all these factors appropriately may result in a suboptimal outcome. Understanding fundamental biomechanical principles involved in the formation, progression, and treatment of spinal deformities is essential in the clinical decision-making process.

Key Words • spinal deformity • biomechanics

Pathological spinal deformation, either in an acute or chronic form, is usually a result of at least one unstable motion segment. For the deformity to progress, pathological stressors must be applied to the spine, although non-pathological stressors applied to an already deformed spine may also cause further deformity. The spine surgeon is faced with significant challenges in formulating treatment strategies for both spinal deformities and deformity progression. Objectives including curvature correction, prevention of further deformity, restoration of sagittal and coronal balance, cosmetic optimization, and improvement and preservation of neurological function must be simultaneously considered during treatment planning to optimize successful outcomes. Spinal deformities are complex entities, often composed of more than one deformation type with more than one attendant problem. A complex solution can be achieved by combining component strategies for each aspect of the complex problem. Awareness of the complexities of deformation development and progression is critical to the design of an appropriate management scheme. The surgeon must try to understand the forces at play in creating the deformity, which is necessary because during the correction the forces must be countered or reversed, thereby neutralizing the pathological forces. Complete deformity correction is often the goal, but it is not necessarily required to alleviate symptoms and prevent further deformity or neurological deficit. The goal of surgery, hence, should be the attainment and maintenance of a nonpathological relationship between the neural elements and their supporting and surrounding osseous and soft-tissue structures.

Spinal Deformities

Physical Principles and Kinematics

Forces applied to the spine can be broken down into component vectors. A vector is defined as a force oriented in a fixed and well-defined direction in three-dimensional space. A force vector may act on a lever (moment arm), creating a bending moment. The bending moment applied to a point in space causes rotation, or a tendency to rotate, around an axis. This axis is termed the IAR. The IAR acts as a pivot point or fulcrum around which flexion or extension occur.

The moment arm is a lever that extends from the IAR to the position of application of force to the spine (Fig. 1). The bending moment (M) is defined as the product of the force (F) applied to the lever arm and length of the lever arm (D) in the following formula: \( M = F \times D \). The bending moment is effectively the torque applied by a circular force. The magnitude of a circular force is the torque. Around each of the three axes of the cartesian coordinate system, translation or rotation can occur.

Therefore, six fundamental segmental movements of the spine along or around the IAR can occur: 1) rotation or translation around the long axis; 2) rotation or transla-
tion around the coronal axis; 3) rotation or translation around the sagittal axis of the spine; 4) translation along the long axis of the spine; 5) translation along the coronal axis; and 6) translation along the sagittal axis of the spine (Fig. 2). Each movement may result in deformation in one of two directions involving one or many spinal segments as a result of acute or chronically applied loads.

Rotational Deformation

A bending moment affects a spinal segment by the application of an eccentrically placed load (that is, eccentric to the IAR). Angular deformation of the spinal segment may result along one or both of the axially oriented axes following the application of a bending moment. Such rotation can take the form of kyphosis (flexion rotation deformation), lordosis (extension rotation deformation), scoliosis (lateral bending rotation deformation), or a combination of these. Rotational deformations are manifestations of an asymmetrical load or a rotatory load (torque) applied to a spinal segment. Rotational deformations around an axially oriented axis (coronal or sagittal) can occur at the level of the VB or intervertebral disc space. Segmental spinal rotatory deformation can also occur around the long axis of the spine (Fig. 3). The application of a rotatory or torsional load to the spine (either acutely due to trauma or chronically due to gradual deformity progression) can cause the spinal segments above the unstable segment to rotate in a direction in opposition to that below the unstable segment.

Translational Deformation

Shearing, compression, or distraction of the spinal segments may result in translational deformation, which occurs along an axis defined by the direction of the deformation-creating force vector. Translational deformation may occur in any plane. Burst fractures are caused by oppositional translational forces of the upper and lower endplates of a VB. Axially oriented translational deformities occur secondary to two parallel but noncoincident opposed force vectors resulting in fracture dislocation or spondylolisthesis. Distraction deformation is uncommon and usually accompanies a significant flexion component in the acute form. Distraction forces may be applied using spinal traction or by excessive implant-induced distraction. Most spinal deformities, however, are a result of more than one type of deformation.

Categories of Spinal Deformity

Spinal deformities may be divided into three fundamental categories: 1) sagittal plane; 2) coronal plane; and 3) axial plane. Many deformities are composed of a combination of sagittal-, coronal-, and axial-plane components (Fig. 4). Degenerative lumbar scoliosis is a common deformity resulting in both a rotational and a kyphotic component.

Prevention of Deformity Progression

Excessive forces affecting the spine and/or nonpathological stressors affecting an already deformed spine are
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required to create a deformation or for it to propagate. A working understanding of the neutral axis, Cobb angle, and the radius of the curvature is important in the decision-making process when managing cases of spinal deformity.

Prevention of kyphotic deformity progression requires knowledge of the neutral axis (load-bearing axis). Placement of strut grafts well ventral to the neutral axis helps prevent further kyphotic deformity (Fig. 5). This may, however, require the use of longer struts. Likewise, dorsal constructs must be placed well behind the neutral axis to prevent the progression of kyphosis.

The Cobb angle is measured from rostral and caudal neutral vertebrae associated with a curve. A neutral vertebra is located in the transition zone between two curves. As the Cobb angle increases, an increased moment arm is applied to the spine. The radius of the curve is important to consider when measuring the Cobb angle. Segmental angulations, when acute, may have similar angular measurements compared with less acutely segmental angulations. The radius of acute angular deformities is inherently shorter than that of the same curve over more spinal segments.

**Principles of Deformity Correction**

Many factors must be considered when attempting to correct a spinal deformity. The deformities are frequently multisegmental. Thus, strategies must be applied to multiple spinal segments. A deformity that occurs along or around an axis of the cartesian coordinate system often produces another motion along or around another axis (that is, coupling phenomenon).

The load-bearing axis in both the sagittal and coronal planes must also be considered. The load-bearing axis in the healthy cervical and lumbar regions is located in the dorsal region of the VBs. Conversely, in the normal thoracic spine, it is located in the ventral region. The load bearing neutral axis is usually in the region of the middle column (Fig. 6). The neutral axis is shifted ventrally with flexion and dorsally in extension.

Sagittal balance of the spine must be considered. In the standing position, a plumb line dropped from the mid-C-7 VB should fall in the region of the dorsal L5–S1 interspace. A negative 2 to 4-cm space behind this region is normal. As an individual ages, this line can usually be seen to move forward. A loss of balance may occur, with the sagittal vertebral axis falling quite ventral to S-1 (Fig. 7). The CSL is used to assess balance in the coronal plane and as well as in the assessment of scoliosis. The CSL is one that is perpendicular to a line passing through both iliac crests, ascending rostrally in the line with the sacral spinous processes. The vertebrae bisected by this line are termed stable vertebrae.

The length and location of the stabilizing construct are critical. On one hand, implant length must be sufficient to apply the necessary bending moment to the spine. On the other hand, it must not be so long that it creates excessive spinal stiffness.

The apical and neutral vertebrae in the coronal and sagittal planes must be assessed. Compared with all other intervertebral disc spaces in the curve, the apical vertebrae are those associated with the greatest segmental angulation at both its rostral and caudal disc interspaces (Fig. 8). The apical vertebra is typically located in the midpoint and horizon of the curve. The neutral vertebra usually has little or no angulation at its rostral and caudal disc spaces and is the vertebra located between curves (Fig. 8). The apical and neutral vertebrae should be established on radiographs in the coronal and sagittal planes. An implant should not terminate at or near an apical vertebra, and should, in general, be long enough to extend to the neutral vertebra. If a long moment arm is extended to, but not above, an apical vertebra, there exists a significant

*Fig. 3. A twisting of the spine around its long axis (A) can result in a rotatory deformation around the axis (B). Curved arrow depicts applied bending moment.*

*Fig. 4. Sagittal- (A), coronal- (B) and axial-plane (C) deformities are the three fundamental deformations that contribute to all spinal deformities, either individually or in combination.*
risk for deformation progression (Fig. 9). The determination of the apical vertebra is therefore a critical component of the decision-making process.

The cervicothoracic and thoracolumbar regions are prone to deformity and deformity progression if the implants are placed to, but not beyond, these levels. Disc spaces adjacent at the junctional zones are usually not parallel to the ground in the standing position, thus applying angular forces to the spine.

Several clinically relevant deformity classification schemes have been developed. King, et al.,20 divided coronal-plane deformities into five categories for classification of idiopathic scoliosis: Type I, a double concave curve in which the lumbar curve is larger and more rigid than the thoracic curve; Type II, a double concave curve in the thoracic curve is more rigid than the lumbar curve; Type III, a thoracic curve; Type IV, a long thoracic curve that tilts into the curve; and Type V, a double thoracic curve that tilts into the concavity (Fig. 10). The management of these deformities depends on curvature type and other patient-specific characteristics. In the scheme described by Lenke, et al.,23 the position of the lumbar apical vertebra with respect to the center sacral line is strongly emphasized (Fig. 11). The compensatory curve forms in response to the primary curve’s reflexive attempt to achieve balance.

**COMPONENT STRATEGIES FOR DEFORMITY PREVENTION AND CORRECTION**

Complex deformities can be corrected using spinal implant–induced forces along one axis or a combination of the three axes of the cartesian coordinate system, by which the spine is brought to the implant (Fig. 12). Bending moments applied in the sagittal plane are of three- or
Three- or Four-Point Bending Force Application

Three-point bending force application consists of a fulcrum that directs a force vector contralateral to the direction of the terminal force vectors (Fig. 13 upper left and right). In Harrington rod or universal spinal instrumentation application, techniques involve three-point bending force application over multiple spinal segments. Dorsally directed forces are applied at the upper and lower termini of the construct and a ventrally directed force is applied at the fulcrum. This is equal to the sum of the dorsally directed forces. Three-point bending fixation may also be used to correct a deformity near the termini of the construct, as opposed to the midportion (Fig. 13 lower left and right). These techniques may be used to correct deformities as well as to prevent them.

Four-point bending force applications involve the loading of a long spinal segment with two transverse forces on one side and two on the other. The bending moment is constant between the two intermediate points of force application. The bending moment peaks at the intermediate point of force application with three-point bending and two intermediate points of force application with four-point bending constructs.

Correction of Crossed-Rod Deformity

An established technique for the correction of thoracic and lumbar kyphotic deformities is the crossed-rod technique (Fig. 14), which was first performed in the Harrington rod distraction. With the subsequent use of Luque sublaminar wires, however, gradual reduction of kyphosis can be achieved by sequentially bringing the spine toward the rod (Fig. 15). With sequential hook insertion, universal spinal instrumentation systems may also facilitate application of the crossed-rod technique.

IN VIVO ALTERATION OF IMPLANT CONFIGURATION

Applied Moment Arm Cantilever Beam Force Application

For short-segment fixation, applied moment arm cantilever beam constructs may be placed to reduce the curvature. Commonly applied in the thoracolumbar and lumbar regions for deformity correction in cases involving burst and wedge compression fractures, these constructs require significant loads to be placed at the time of corrective surgery. Sagittal-plane applied moment arm cantilever beam forces may be applied in either flexion or extension. An applied moment arm cantilever involving distraction and extension may be prone to failure if the...
Implant is excessively loaded. Because interbody strut loading (for example, compression) significantly unloads the axial forces through the spinal implant, the risk of hardware failure and progressive deformity is reduced. The procedure involving the sequential application of distraction forces (load bearing), decompression of the dural sac, placement of an interbody strut, and finally compression of the strut is deemed a load-bearing-to-load-sharing force application.

Reduction of Short-Segment Parallelogram Deformity

Lateral translational deformities may be surgically treated using the technique of short-segment parallelogram reduction. This technique is used when treating lateral translational deformities.
eral translational deformities. In it, a rigid cantilever beam pedicle fixation is performed in the thoracic and lumbar regions (Fig. 16). Pedicle screws are first placed and rods are applied to friction–glide tightness. Rod holders are subsequently placed and a torque applied to both rods simultaneously until fraction reduction is achieved. Rigid cross-rod fixation maintains the achieved reduction. Placement of structural bone graft is then followed by placing screws in compression mode to achieve load sharing.

Crossed-Screw Fixation

The crossed-screw fixation technique requires an extracavitary approach. It can be used to alter sagittal- or coronal-plane abnormalities as an alternative to other short-segment fixation techniques. It requires two large VB screws that bear axial loads and two ipsilateral smaller pedicle screws that attain reduction and prevent flexion or extension deformities. The near 90° screw toe–in angle provides rigid cross-fixation (Fig. 17). Compression or distraction of the pedicle screw addresses sagittal-plane deformities. Coronal-plane angles may be changed by manipulating VB screw relationships. This technique in the purest sense is seldom used. Its underlying principles, however, may often find utility.

In Vivo Implant Contouring

To achieve reduction of a spinal deformity, in vivo implant contouring to alter segmental relationships is often effective. After the placement of pedicle screws or hooks, the rods are fit to the shape of the spine. Subsequent in vivo contouring of the rods, with the attached spine, may be used to reduce the deformity. This technique applies unknown and perhaps excessive forces to the spine. Alteration of the relationship between the spine and the implant may occur, such that the screw or hook is overtightened or becomes loosened and then migrates. Sublaminar hooks may be inadvertently forced ventrally, impinging the thecal sac and spinal cord.
Spinal Derotation

Spinal derotation is performed by careful rotation of two rods that have been attached to the spine in its deformed scoliotic state. The 90° rotation of the rods can be used to convert a scoliotic to a kyphotic curve (Fig. 18). If the resultant kyphotic deformity is unacceptable, it may be corrected by contouring the rod. Biconcave curves may also be corrected in this manner. These maneuvers must be performed gradually to allow for continuous assessment of the implant–bone and component–component relationships. If the hooks do not rotate with the rod, significant stress at the hook–bone interface may occur. Suboptimally placed pedicle screws may cut out during rod rotation.

Intrinsic Implant Bending Moment Application in the Sagittal or Coronal Plane

After placement of screws and loosely connected rods, correction of a scoliotic curvature may be achieved by dis-

Fig. 12. In “bringing the spine to the implant” forces that are oriented along any axis or plane may be used (for example, the long axis [A], the sagittal plane [B], and the coronal plane [C]). Arrows depict forces applied by the implant.

Fig. 13. Bending moments are applied in the sagittal plane by a three-point bending mechanism (upper left) and an applied moment arm cantilever beam mechanism (upper right). Straight arrows depict forces; curved arrows depict bending moments. Lower Left: The three-point bending construct brings the spine to the implant. Lower Right: The terminal three-point bending constructs simply have one long and one short moment arm. Straight arrows depict forces applied.

Fig. 14. The crossed-rod technique for correcting thoracic and lumbar kyphotic deformities involving the Harrington distraction rod (A), Luque sublaminar wiring (B), and universal spinal instrumentation (C). The latter technique is facilitated by the use of sequential hook insertion (from E.C.B.). The crossed-rod technique strategy can be used for coronal-plane (scoliotic) deformities as well (D). Two rod translation force application strategies can similarly be used. In this case, a small rod may be applied to the spine and brought to a longer rod that spans the concave side of the deformity, thus partially correcting the deformity (E).
traction on the concave side of the curve with simultaneous distraction on the convex side (Fig. 19 upper left and right). Cross-fixation is usually used to help maintain the correction. This technique may be performed to correct both coronal- and sagittal-plane deformities (Fig. 19 lower left and right). Care should be taken to achieve friction–glide tightness at the interface prior to distraction so that the screws maintain their angular relationship with the rod during distraction.

Maintenance of Deformity Correction

Cross-fixation of bilaterally placed rods substantially augments the integrity of the construct. If the maintenance of deformity correction depends on cross-connection, as in cases of short-segment parallelogram deformity reduction, the use of cross-fixation in short constructs is essential. Longer constructs involving cross-fixation provide a quadrilateral frame construct that offers increased rotatory and torsional stability. Cross-fixation also enables maintenance of the desired interrod width, which may prevent hook migration or screw dislodgment.

Screw triangulation plays an integral role in the prevention of lateral translational deformation. Screw toe–in may be used in conjunction with cross-fixation to allow, in a “belt and suspenders–like” manner, the corrected curvature to be maintained.

REGION-SPECIFIC STRATEGIES

The various regions of the spine have unique anatomic and biomechanical properties. Thus, it is appropriate to consider correction-related strategies based on the spinal region. The CCJ, upper cervical spine, lower cervical spine, cervicothoracic junction, thoracic spine, thoracolumbar junction, lumbar spine, and the lumbosacral region are each discussed.

Craniocervical Junction and Upper Cervical Spine

The high degree of mobility of the CCJ and upper cervical spine leave it vulnerable to deformities in the coronal, sagittal, and axial planes. Although many cases may be corrected by nonoperative means, deformity reduction and occipitocervical fusion are occasionally required.
Angular bending moment application, which resists rotation of this region, may be required. This may be addressed by the techniques of occipitocervical fusion or transarticular C1–2 screw fixation.

Lower Cervical Spine

Deformity correction in the lower cervical spine presents unique regional challenges. The ease of ventral and dorsal exposure is offset by relatively poor availability of adequate fixation points, especially dorsally.

Coronal-Plane Deformities. Cervical scoliosis is an uncommon entity. The application of concave distraction and convex compression, as well as the use of the derotation maneuver, may be used to correct such curves. The recent introduction of rod-and-screw constructs to cervical spine surgery has facilitated the use of these techniques.

Sagittal-Plane Deformities. Sagittal-plane deformities are relatively common and consist of kyphosis, subsidence, and spondylolisthesis.

The degenerative changes of the cervical spine frequently alter normal cervical lordosis. This usually begins with loss of disc space height and follows with subsidence of the cervical VBs. The moment arm substantially increases as kyphosis worsens, and this promotes further deformity. Progression of the deformity may be further complicated by progressive myelopathy.

Ventral, dorsal, or combined approaches can all be used in cervical kyphosis. A ventral approach provides direct decompression of ventral lesions, while allowing kyphosis to be corrected by placing a strut graft. A ventral approach can be performed to release the anterior cervical spine to decrease forces placed during second-stage correction of the dorsal deformity.

Several dorsal techniques, originally developed for the thoracic and lumbar spine, may also be performed to
reduce cervical kyphotic deformities. The crossed-rod technique, enhanced by ventral release, may be conducted (Fig. 20). This can be applied via lateral mass screw fixation. Weakening or disrupting the dorsal tension band tends to exaggerate sagittal-plane deformations. Fusion may be indicated in selected patients at risk for postlaminectomy kyphosis. Laminoplasty may decrease the risks of postoperative deformity by minimally disrupting the dorsal tension band.

Cervical translational deformities are not uncommon. Trauma-induced cervical subluxation may result from flexion/distraction force applications, which may result in facet dislocation. Closed or open surgical reduction may be associated with the risk of disrupted disc retropulsion into the spinal canal and associated neurological sequelae. Many surgeons, therefore, prefer to undertake ventral decompressive surgery followed by reduction.8,27 Distraction of the disc interspace may disengage the locked facet joints, allowing for stabilization and fusion in a single-stage procedure (Fig. 21). Caspar pins may be used to apply rotational forces, to reduce ventrally a unilateral jumped facet. Dorsal reduction and fusion must often begin with a partial resection of the facet joint. This iatrogenic destabilization, by removal of the facet joint, may obligate the incorporation of an additional motion segment into the fusion. Reduction of the deformity and internal fixation complete the procedure. Occasionally, deformity correction cannot be attained via a dorsal approach alone. If neural decompression has been achieved, instrumentation-assisted fusion in the nonreduced position may be performed.

In certain cases, a failed initial attempt at ventral reduction may require a combined ventral-dorsal-ventral approach (540°), which provides ventral decompression and both ventral and dorsal stabilization (Fig. 22).

Cervicothoracic Junction

Biomechanically, the transition from a normal cervical lordosis to thoracic kyphosis makes this region challenging to manage. This is a unique region of the spine. The shift from the mobile cervical spine to the far less mobile thoracic spine represents a major transition in kinematics. Biomechanical considerations are further complicated by geometrical, implant–bone interface integrity, and ventral surgical exposure problems. Decompression of this junction via a dorsal approach may often necessitate dorsal fusion to prevent the development of deformity. Long implants should not terminate at this junction but should extent through the transitional zone (Fig. 23).

Thoracic Spine

The thoracic spine is characterized by larger VBs that are protected by the rib cage and a relatively smooth bend at each segmental level. Deformities often have elements in each of the three fundamental planes. Scoliosis is a complex deformation that is nearly always associated with the phenomenon of coupling. This occurs when one deformation along or around an axis obligates a second deformation along or around another axis, such as lateral bending and rotation around the long axis of the spine. Thoracic scoliotic deformities rotate the spinous processes toward the concave side of the curve, resulting in axial load forces transmitted on the concave facet joints. This is usually associated with loss of thoracic kyphosis. Correction of the curvature may often require a ventral release to achieve adequate correction. Surgical release procedures are usually combined with ventral interbody fusions.

Coronal-Plane Deformities

Coronal-plane abnormalities may be corrected via ventral, dorsal, or combined approaches. In the pediatric population, skeletal maturation must be appreciated. In the skeletally immature patient a stand-alone dorsal approach may result in unopposed ventral growth (crank-shaft phenomenon). Ventral strategies typically use involve segmental screws and rods placed on the convex side of the scoliotic curve from neutral vertebra to neutral vertebra. The result is typically a shorter construct than that achieved dorsally. Compression and distraction, derotation, or a combination of strategies are conducted to reduce thoracic deformities via a ventral approach (Fig. 24). Ventral procedures tend to promote kyphosis more than dorsal procedures involving constructs.

Dorsal strategies involve similar maneuvers to achieve correction. Scoliosis correction achieved using dorsal de-rotation methods requires longer constructs and is usually supplemented by concave distraction and convex compression.9 Longer constructs often lead to a higher incidence of rod fracture and acceleration of end-fusion de-
generative changes. Strategies to combat these include cross-fixation, larger-diameter rods, and external immobilization. The use of pedicle screw fixation may limit the length the construct required.

**Sagittal Plane Deformities.** The first step in correcting a kyphotic deformity is its objective assessment. This may be accomplished by measuring the angle from the superior endplate of the VB one level above the involved VB to the inferior endplate of the VB one level below. The correction itself begins by undertaking the crossed-rod procedure, which is supplemented with ventral interbody fusion. Fig. 21. The management of a cervical dislocation with locked facet joint(s) via a ventral approach. After a decompressive discectomy (A) to release/relax the spine, distraction can be performed using a disc interspace spreader (B). This disengages the locked facet joints. Dorsal rotation and relaxation of the applied forces (after the facets have been “unlocked”) results in the resumption of the normal spine posture (C and D). Fixation and fusion in normal alignment may then be achieved (E). Caspar pins and distractors can also be used. Pins placed in an angular orientation can be used to exaggerate a kyphosis to disengage the facet joints (F), thus permitting reduction (G). Removal of the distractor and pins then restores normal alignment. Rotational deformity, such as that which occurs with a unilateral locked facet, can be reduced by placing Caspar pins out of the midsagittal plane (H).

Fig. 22. A 540° operation is occasionally indicated. Ventral decompression (A), followed by a dorsal reduction (B), and ventral stabilization and fusion (C) may be used to decompress, reduce, and stabilize the spine, respectively.

Fig. 23. A: A long implant should perhaps not terminate at the cervicothoracic junction. B: Should this occur, the deformity may become exaggerated at the terminus of the implant.
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Fig. 24. Coronal-plane deformities may be reduced using compression and distraction (A), the crossed-rod technique (B), the derotation maneuver (C), or a combination of these techniques.

and the curves are associated with a loss of lumbar lordosis. The aging spine with concurrent osteoporosis may significantly limit surgical options. Predictors of deformity progression include lateral spondylosis of the apical vertebra, a Cobb angle of 30° or more, the number of vertebrae in the curve, degree of disc wedging within the curve (disc index), lateral vertebral translation of 6 mm or more, and the prominence of L-5 in relation to the intercrest line.

Lumbar Spine

The aforementioned strategies for the thoracic and thoracolumbar spine are likewise applicable to the lumbar spine. The majority of deformities have a significant translation component that requires careful consideration of sagittal-plane balance. An important factor in the attainment and maintenance of lordosis is intraoperative positioning. Surgical beds or frames that facilitate lordosis by encouraging extension of the spine and hips are optimal. Intraoperative pelvic flexion can result in inadequate lordosis with a resultant flat back. The sagittal vertebral axis should be brought back to the dorsal L5–S2 joint, which may require aggressive osteotomy and/or ventral load-bearing adjuncts.
The lumbosacral junction poses unique and complex biomechanical challenges. Instability may be assessed by examining flexion and extension radiographs. Whereas they are commonly obtained while the patient is standing, the lateral decubitus position off-loads the spine, thus minimizing pain and allowing a more accurate assessment. Spinal instability may require aggressive surgical strategies and accompanying lumbar, sacral, and pelvic fixation. The likelihood of deformity progression must be known. Patients in whom the degenerative process has begun are less likely to slip further than those in whom it has yet to begin. Partial correction is often obtained after positioning. Three-point bending force application may facilitate reduction by pulling back the intermediate (L-5) screw of a three-screw construct. Long moment arms that pass ventral or caudal to the lumbosacral pivot point are often required to achieve adequate correctional bending moments (Fig. 25 upper). Although complete deformity correction is the goal, it is often difficult and unnecessary, even when decompression is performed.

In cases of L5–S1 spondylolisthesis, the L-5 VB may have to be removed and L-4 fused to the sacrum by using an intervening strut graft that bears axial loads. The use of interbody morselized bone graft may be associated with a higher incidence of pseudarthrosis. Dorsal instrumentation maintains reduction (Fig. 25 center and lower).

**Ventral and Dorsal Osteotomy**

A variety of ventral and dorsal osteotomy types may help to achieve deformity correction. The risks of neural injury must be weighed against the potential benefits of the osteotomy-induced correction. When considering the usefulness of osteotomy, two factors are important: extent of correction required and degree of ankylosis. The axis around which the correction is to be achieved must be considered (Fig. 26). The goal of deformity correction via osteotomy is to shift the sagittal vertebral axis dorsally, bringing the spine into balance.

Regardless of the type of osteotomy performed, it is most effective when performed at the apex of a curve. Dorsal osteotomy is most safely performed in the lumbar spine, whereby the disc interspace and pedicles have been removed. The axis of rotation is around the anterior longitudinal ligament (Fig. 27 left). The egg-shell osteotomy is a variant of the dorsal osteotomy. This technique involves resection of the pedicle via a dorsal approach and subcortical resection of VB medullary (cancellous) bone. This facilitates collapse of the VB in a wedgelike manner (Fig. 27 center and right).

**CONCLUSIONS**

The correction of deformity may be achieved by a variety of methods, each with advantages and disadvantages. Understanding the biomechanical principles involved facilitates the clinical decision-making process, thus enabling the surgeon to optimize patient outcome. The ultimate goal is to ensure a biomechanically sound environment, and facilitate a nonpathological relationship between the neural elements and the surrounding osseous and soft tissue confines.

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Fig. 26. The axis for sagittal-plane correction is perpendicular to the long axis of the spinal axis (dot in the lateral view). This axis may be located in the region of the spinal canal (A). It may also be located ventrally, in the region of the anterior longitudinal ligament (for example, for dorsal wedge osteotomies [B] or in the middle column region [C]).

Fig. 27. **Left:** Dorsal osteotomy. **Center and Right:** Egg-shell osteotomy.
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Manuscript received November 29, 2002. Accepted in final form December 11, 2002.

Address reprint requests to: Edward C. Benzel, M.D., Director, Spinal Disorders, Cleveland Clinic Foundation, Department of Neurosurgery/S80, 9500 Euclid Avenue, Cleveland, Ohio 44195.