Chapter 35
Decompression, Arthrodesis, and Arthroplasty: Decision Making in the Surgical Treatment of Lumbar Disc Disease

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What was once a simple lumbar disc herniation treated with laminotomy and partial discectomy, with typically excellent results (25, 46), has evolved into a surprisingly complex clinical problem with a dazzling array of therapeutic alternatives. Much of this, of course, is based on clinical studies emphasizing the heterogeneity of disc disorders. Advances in biomechanics research focusing on the lumbar disc have provided valuable insights into the consequences of disc herniation and progressive degeneration in the lumbar spine complex. But in the end, what has this work meant to our patients?

RESULTS OF CLINICAL TREATMENT OF LUMBAR DISC DISEASE

Standard discectomy has been used to treat lumbar disc herniation for over five decades, since the seminal description by Mixter and Barr (25). Despite the fact that recent advances in minimally invasive techniques have gained attention, standard (including microdiscectomy) discectomy is still the preferred management technique among most surgeons for treatment of lumbar disc herniation (46). Reports of long-term outcome after lumbar discectomy describe success rates between 76 and 93% (although evaluation methods vary) with approximately 10% of patients undergoing revision surgery for recurrent disc herniation (46). The success rates for redo discectomy for recurrent disc herniation are lower (60–80% good or excellent results) than for initial discectomy (5).

PATHOPHYSIOLOGY AND BIOMECHANICS OF LUMBAR DISC HERNIATION

The pathophysiology of lumbar disc herniation involves biomechanical and biochemical processes. The temporal profiling and ordering of these processes is the subject of investigation and may, in part, be situation-specific. It is unclear if discs fail mechanically because they are weakened by biochemical changes or whether the biochemical changes represent a cellular response to mechanical failure (1). It is clear, however, that disc function deteriorates along with its structure (1).

Water represents 65 to 80% of the disc's total weight through its association with glycosaminoglycan chains attached to proteoglycans, which are produced by fibroblasts in the disc nucleus (8). The glycosaminoglycan chains bind water and swell to the point at which they are limited by resistance from the collagen matrix in the nucleus (8). The equilibrium between these two major components of the disc gives the disc its load-bearing, compression-resisting qualities. Although the exact mechanism has not been elucidated, loss of glycosaminoglycans has been associated with disc degeneration. As glycosaminoglycan concentrations decrease, less water is bound, and disc turgor decreases; therefore, the same load on the disc causes increasing deformation of its extracellular matrix and fibroblasts (8). Fibroblast deformation transfers through the cytoskeleton to cause altered synthetic mechanisms via mechanotransduction. This altered synthesis can lead to the production of degenerative enzymes, such as matrix metalloproteinases, causing further loss of proteoglycans (34). Hence, once the cycle that the disc degeneration begins, it may become self-perpetuating.

These biomechanical phenomena have been shown to alter disc morphology. Endplate damage from moderate repetitive loading in cadaveric lumbar motion segments causes reduced pressure in the adjacent nucleus pulposus and generates peaks of compressive stress in the annulus (usually posteriorly). These stress concentrations in the annulus result in complete radial fissures, extreme outward bulging of the annulus, and inward collapse of the annulus (1). Additionally, vertebral endplate microtrauma is associated with lower stiffness, load, and energy-absorbing capacities for injured specimens compared with intact specimens (43).

Studies have suggested that endplate failure precedes disc failure (43). Although disruption of the disc may seem important, degeneration of the disc as a function of repetitive loading may be a more significant phenomenon. Studies have shown that the disc is at its stiffest during physiologic elastic loading (43, 41). As loads increase, disc trauma occurs gradually, with microfailure (indiscernible on radiography) leading to subsequent yielding of the disc (Fig. 41.1). With continued loading, stiffness decreases, and gross disc failure occurs. Recognizing that initiation of disc trauma occurs without visible changes is clinically important. This may represent the stage at which mechanical pain and osteophyte formation begin. Also, disc microtrauma may lead to increased facet joint loading and subsequent facet degeneration, even if the disc appears normal. As intervertebral discs degenerate and desiccate, intradiscal pressure decreases and shifts the loading of the intervertebral joint to the annulus fibrosus. With subsequent disc height loss, loads are also transmitted to the facet joints, resulting in vertebral osteophytosis and facet arthropathy. These changes occur along a continuum and can be associated with degenerative instability as the disc fails (19).

INSTABILITY

Knowledge of normal spinal function is critical when defining abnormal spinal motion. The range and direction of spinal motion is limited by articular process orientation and characteristics of the spinal ligaments and intervertebral discs. Normal motion is always symmetrical and coupled. Specifically, motion about one axis is always accompanied by motion about at least one other axis. Primary and coupled motions are limited by anatomical constraints (i.e., the ligaments, joint capsules, and intervertebral discs) under normal functioning. The vertical orientation of the articular surfaces of the zygapophyseal joints permits flexion, extension, and lateral bending but limits axial rotation. As in the cervical spine, rotation and lateral bending are coupled. Translation occurs in association with flexion but is normally less than 3 mm (33) because of the resistance to shear by the intervertebral disc and the coronally oriented anterior portion of the superior articular processes (21).

The vertebral column is both stationary and mobile; hence, a definition of stability and instability should incorporate both features (21). The stable spinal column is symmetrical in movement, and its configuration, whether normal or abnormal, does not change with time. The unstable spinal column may be asymmetrical in movement, its configuration may change with time, or both may occur. Three different types of asymmetrical movement may occur: asymmetrical angular motion without abnormal coupling (Fig. 41.2), asymmetrical motion with abnormal coupling (Fig. 41.3), or abnormal coupling without asymmetrical angular movement (Fig. 41.4A) (21). The limits of normal translation were established by experiments where restriction of flexion and extension was not a factor (33). Because coupling is proportional to the primary movement, the translation associated with flexion or extension may be within normal limits if these movements are restricted by pain. Hence, translational movement at a motion segment that is greater than that at adjacent segments can be considered evidence of instability, even if it falls within established values for normal. Even if asymmetrical translational movement cannot be demonstrated on bending films, it can be implied from the development of traction spurs (Fig. 41.4B) (21).

Disc degeneration and facet joint osteoarthritis have been implicated in segmental instability (12). Studies have demonstrated that disc degeneration may increase the flexibility of lumbar motion segments (12). Fujiwara et al. (12) studied the effects of disc degeneration and facet osteoarthritis on segmental flexibility of the lumbar spine. They found that axial rotational motion was most affected by disc degeneration. Segmental motion increased with increasing disc degeneration up to grade IV but decreased when disc degeneration advanced to grade V. These results support the concept of the three stages of spinal degeneration described by Kirkaldy-Willis and Farfan (19), namely, dysfunction, instability, and stabilization. Segmental axial rotational motion was found to increase with cartilage degeneration of the facet joints (12). From a clinical perspective, instability manifests with back pain, usually provoked with spinal motion, and, to the extent that there is neural element compromise, with varying degrees of numbness, weakness, and bowel or bladder dysfunction.

EFFECTS OF SURGICAL ALTERATIONS ON SPINAL STABILITY

Cusick et al. (6) studied the biomechanical effects of progressive surgical alterations (bilateral facetectomies—medial, total, and total with posterior ligament section) in the lumbar spine. Their data suggest that until all posterior ligaments are violated, the effects of progressive surgical alterations on the lumbar facet joints are controllable in a preparation undergoing acute compression-flexion loads (6). Yoganandan et al. (44) studied the biomechanical effects of two-level laminectomy on thoracic stability (ribs removed). Biomechanical responses of the laminectomized specimens were significantly different ($P < 0.05$) from those in the control group (intact spine) at deformations from the physiological to the failure range. Failure forces for the laminectomized specimens were significantly decreased ($P < 0.001$) than those for the control group. The stiffness and energy-absorbing capacities were significantly reduced ($P < 0.05$) for the laminectomized group (44).

Internal fixation is an important adjunct to facilitate arthrodesis. The biomechanical effects of lumbar nonsegmental instrumentation in trauma have been evaluated. Yoganandan et al. (45), in a cadaveric study, found that there was a reduction of motion between fixated levels, increasing the rigidity of the column at levels proximal and distal to fixation motion increased, indicating added flexibility. They noted that these alterations in motion, observed during single-cycle loading, might be further accentuated in vivo, leading to hypermobility and spine degeneration (45). Other groups have corroborated these results (16). The biomechanical effect of spinal fusion on adjacent segments has been modeled with finite element analysis (23). Interbody fusion without or with instrumentation induces higher stresses at adjacent levels, which may enhance degeneration subsequent to surgery. Oda et al. (31) studied the types of spinal instability that require interbody support in posterior lumbar reconstruction in the calf spine. Their data suggests that for spinal instability with preserved anterior load sharing, pedicle screw fixation alone is biomechanically adequate, and interbody cages should not be used because they further increase segmental motion at the adjacent segment. They noted that pedicle screw fixation alone provides insufficient stability and high implant strain in the case of a damaged anterior column. In such cases, additional inter-body cages significantly increase construct stiffness and decrease hardware strain. However, they increase range of motion at the adjacent segment as well (31).

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CLINICAL DECISION MAKING

Who gets surgery and why? Furthermore, why fuse for disc pathology if the results for simple laminotomy and discectomy are so good? Knowing the biomechanical consequences of instrumented fusion, can we justify fusion for incipient instability? The situation of posterolateral disc herniation with concomitant radiculopathy (in the expected distribution) without or with back pain has been managed for the last half century with discectomy. Regular and microdiscectomy are achieved by performing a laminotomy or medial facetectomy to obtain adequate exposure of the disc space. The supra- and interspinous ligaments are preserved, and less than half of the medial facet joint is resected. Yorimitsu et al. (46) reported that 74.6% of patients after a discectomy had residual low back pain, 12.7% of whom had severe low back pain at 10-year follow-up. Residual low back pain and recurrent disc herniation can occur after a discectomy because the remaining disc is subjected to physiologic loading. In the situation of the postoperative disc with decreased disc space height, loads can be transferred disproportionately to the facets and disc annulus promoting facet arthropathy and vertebral body osteophyte formation. There may be a greater risk of recurrent disc herniation in patients with maintained disc height after discectomy (46). Yorimitsu et al. (46) reported a 4% rate (3 of 72 patients) of instability after discectomy at 10-year follow-up. Instability was defined as a difference in angles of both endplates between flexion and extension films at final follow-up of more than 10 degrees. They also noted unstable discs in five patients stabilized after surgery caused by progression of degeneration (46). When considering the short-term biomechanical effects of discectomy, recall that Cusick et al. (6) reported that the effects of progressive surgical alterations on the lumbar facet joints are controllable in a preparation undergoing acute compression-flexion loads until the supraspinous and interspinous ligaments are violated.

There is a difference of opinion regarding the extent of disc removal in discectomy. Removal of the extruded fragment and readily identifiable additional loose pieces of disc seems to be adequate. Vigorous curettage and attempts at interspace evacuation are not associated with a less frequent incidence of recurrent disc herniation (2). Retention of as much disc as possible preserves some of the biomechanical functions of the disc (21). It has been shown that the biomechanical properties of the lumbar motion segment are more adversely affected by total as opposed to partial discectomy (15).

When does a discectomy get turned into a fusion? Recurrent disc herniation with evidence of progressive disc degeneration and failure, upon radiography (static and dynamic) and magnetic resonance imaging, certainly can be an indication. Redo discectomy is also an option, with the proviso that success rates are lower than for first discectomy (60–80%) (5). The decision to recommend subtotal discectomy and fusion versus redo discectomy should be made on a case-by-case basis. In the case of recurrent disc herniation with radiographic instability, fusion is optimal. Redo discectomy with posterolateral fusion (PLF) or posterior lumbar interbody fusion (PLIF) are both plausible options. In multilevel fusion with single-level recurrent herniation, the biomechanical changes at the level of the diseased disc make interbody fusion also necessary. Broad-based central disc herniation requiring bilateral discectomy to obtain adequate decompression is another indication for fusion because of the destabilizing effects of bilateral discectomy. This can be accomplished via bilateral discectomy and PLF or PLIF. We recently reviewed our results with instrumented PLF (55 patients) versus PLIF with noninstrumented PLF (45 patients) (submitted) with a mean follow-up of 24 months. PLIF was superior to PLF in disc space height maintenance and demonstrated a tendency toward higher fusion rates, but clinical outcome was similar for both. Fritzell et al. (11) prospectively studied 222 patients with chronic back pain and disc degeneration who were randomized into one of three fusion procedures: PLF with transpedicular fixation, PLF without instrumentation, and PLIF combined with instrumented PLF. After 2-year follow-up, they reported fusion rates of 91% for PLIF, 87% for instrumented PLF, and 72% for noninstrumented PLF. No significant differences in clinical outcome were observed at the end of the follow-up period. The authors recommended fusing patients with the least demanding procedure (i.e., transverse process bony fusion alone). We tend to favor redo posterior discectomy with instrumented PLF in this patient population.

Overt instability, as evidenced by abnormal motion on dynamic radiography, in the symptomatic individual is an indication for arthrodesis. Recall, however, the previously described definition of instability per Larson and Maiman (21) that evaluates angular motion and associated coupling to assess for instability. The unstable spinal column demonstrates asymmetrical motion, which can manifest as asymmetrical angular motion (i.e., asymmetrical hypermobility at an interspace with flexion/extension), asymmetrical coupling (i.e., listhesis at an interspace with flexion/extension), or both. Symptomatic degenerative spondylolisthesis can be associated with disc failure and may be an indication for arthrodesis. Arthrodesis augmented by internal fixation has been shown to improve fusion rates (13). A discussion of the history of spinal internal fixation is beyond the scope of this text; however, suffice it to say, transpedicular instrumentation is widely used for internal fixation of the lumbar spine (13). Madan and Boeree (22) compared the outcome of PLF versus PLIF combined with instrumented PLF in patients with grade I and II spondylolisthesis. Disc space height changes were not significant between the two groups. Fusion rates were better for the PLIF group. However, clinical outcome was better for the PLF group. Christensen et al. (4) compared the outcome of instrumented PLF versus circumferential fusion with the anterior lumbar interbody fusion (ALIF) cage plus posterior instrumentation in a prospective, randomized clinical study of 146 patients. Dorsal neural decompression was performed in both groups as indicated. All patients had chronic low back pain and leg pain with isthmic spondylolisthesis or degenerative instability. There was less leg pain at 1-year follow-up ($P < 0.03$) and less peak back pain at 2 years ($P < 0.04$) in the circumferential fusion group. The circumferential fusion patients showed a higher PLF rate (92%) than the PLF group (80%) ($P < 0.04$). The value of the ALIF in their population, then, may have been to promote posterior fusion. In the setting of degenerative spondylolisthesis with clear disc failure, we tend to favor PLIF with instrumented PLF if the disc space is of adequate height to accept an interbody device. If disc space height precludes a PLIF, we favor instrumented PLF.

BACK PAIN WITH RESPECT TO THE INTERVERTEBRAL DISC AND ZYGAPOPHYSEAL JOINTS

The disc may be a source of back pain. In disc surgery under local anesthesia, palpation of the disc was associated with local back pain (40). Degenerative changes in the joints are closely connected with degenerative changes in the discs of the same motion segment (21). The “facet syndrome” was first described by Ghormley (14), who considered the pain to be secondary to degenerative changes in the joints and in some instances to pressure by hypertrophic joints on neural elements. Although the existence of a facet syndrome has been questioned, the posterior intervertebral joints are recognized as a source of pain (36). Mooney and Robertson (28) found that injection of hypertonic saline into the joints produced pain in the back, thigh, and sometimes into the leg. However, the distribution of pain was not specific. The production of pain by injection of hypertonic saline could be blocked by the introduction of local anesthetic into the joints.

In patients whose symptoms of back pain are precipitated by standing, flexion, and applied loads and relieved by lying down, the major factor in their low back pain seems to be mechanical (21). Loss of the normal biomechanical properties of the disc is followed by greater stress on the annulus, as previously described. The annulus is not well suited to withstand vertical loads (30), and an applied stress may excite the nerve endings of the sinuvertebral nerve in the periphery of the annulus with or without the development of fissures. Pressure on the articular surfaces of the zygapophyseal joints is increased by extension and with narrowing of the disc and can be associated with back pain (42).

Because both disc degeneration and back pain are common, a correlation between anatomical change and symptoms can be difficult to elucidate. Discography has been used for this purpose. Discography is, at best, controversial and has been considered both useful (39) and useless (29). Many currently use discography to ascertain whether the pain associated with contrast medium injection is similar or dissimilar to the patient's symptoms. Similar, or concordant, pain was produced in a series of patients in whom pain was considered sufficiently severe to warrant surgery. For those who had concordant pain with only a degenerative disc, 50% improved as compared with 75% of those where annular tears were demonstrated (27). These observations suggest that reproduction of pain by discography alone is not reliable. We never use the technique, recognizing the lack of correlation between results of discography and clinical outcome.

SURGERY FOR DEGENERATIVE DISC DISEASE AND BACK PAIN

The role of fusion for the treatment of degenerative disc disease in the absence of disc herniation, lumbar stenosis, instability, spondylolisthesis, or neural element compromise is controversial. Parker et al. (32) studied the outcome of posterolateral fusion in highly selected patients with discogenic low back pain. Twenty-three patients underwent posterolateral fusion with autogenous iliac crest bone graft (all were instrumented except isolated L5-S1 fusions) for mechanical back pain. All questionable levels based on magnetic resonance imaging and at least one radiographically normal disc level were studied by discography. Only levels with concordant pain were selected for fusion. Overall, 39% had a good or excellent result, 13% had a fair result, and 48% had a poor result. Fritzell et al. (11) performed a prospective, multicenter, randomized study to compare three different surgical fusion techniques among 222 patients with chronic low back pain and disc degeneration. Patients were randomized into one of three fusion procedures: PLF with transpedicular fixation, PLF without instrumentation, and PLIF combined with instrumented PLF. After 2-year follow-up, they reported fusion rates of 91% for PLIF, 87% for instrumented PLF, and 72% for noninstrumented PLF. No significant differences in clinical outcome were observed at the end of the follow-up period. The authors recommended fusing patients with the least demanding procedure (i.e., transverse process bony fusion alone). When the nonsurgical arm of this study was compared with the above surgical arm at 2-year follow-up, back pain was reduced in the surgical group by 33%, compared with 7% in the nonsurgical group ($P < 0.0002$). Disability according to Oswestry was reduced by 25% compared with 6% among nonsurgical patients ($P < 0.015$). The "net back to work rate" was slightly in favor of surgical treatment, or 36 versus 13%. The early complication rate in the surgical group was 17%. They concluded that lumbar fusion in a well informed and selected group of patients with severe chronic low back pain can diminish pain and decrease disability more efficiently than frequently used nonsurgical treatment (10).

Knox and Chapman (20) reported on 22 patients undergoing ALIF for discogram concordant pain. Results were poor in all two-level fusions. Among single-level fusions, there were 35% good, 18% fair, and 47% poor results. Patients with previous surgery or workmen's compensation did poorly as a group, despite positive discography.

We do not operate on black discs. Discogenic pain, as traditionally diagnosed, responds poorly to fusion. Progressive disc degeneration is not necessarily associated with instability. Disc herniation (i.e., recurrent or central) or instability in the symptomatic patient who has failed nonsurgical therapy may be an indication for fusion. We advocate aggressive nonsurgical treatment using physical and occupational therapy for all patients.

Disc Arthroplasty

The reality and incidence of disc degeneration and its attendant consequences has been the impetus for investigation into disc replacement strategies. Research into disc replacement has focused on two main areas: nucleus replacement and total disc arthroplasty. There is a relative paucity of published literature regarding the biomechanics, material properties, and basic science of intervertebral disc replacement. Zollner et al. (48) performed a three-dimensional biomechanical study of a polymethyl siloxane (PMSO) polymer artificial lumbar nucleus implant in calf cadavers. They performed measurements on intact specimens, specimens after nucleotomy, and specimens after introduction of the PMSO implant. There was a statistically significant ($P = 0.0313$) increase in segmental mobility in all directions after nucleotomy with an increased mobility of the segment up to 30% for rotation and 50% for translation. After introduction of the PMSO implant, segmental mobility for all movement directions was restored with no statistically significant difference from the intact situation before nucleotomy (48). Dooris et al. (7) performed a finite element analysis of load sharing between anterior and posterior elements in a lumbar motion segment implanted with an artificial disc. They determined that by altering placement of the artificial disc in the anteroposterior direction, a surgeon could modulate motion segment flexural stiffness and posterior load sharing, even though the disc replacement design tested had no inherent rotational stiffness. Huang et al. (17) reported on the implications of constraint in lumbar total disc replacement. Unconstrained designs are more likely to provide a physiologic, mobile instantaneous axis of rotation (IAR), which may explain why they display greater range of motion in vivo. This lack of constraint may prevent excessive facet loads in the extremes of flexion and extension. Because of their mobile IAR, they may be less sensitive to small errors in placement. Constrained designs seem to be advantageous in protecting the posterior elements from shear loading (17). Ingrowth characteristics of total disc replacement implants have been evaluated. McAfee et al. (24) analyzed porous ingrowth in intervertebral disc prostheses in a baboon model. They used the hydroxyapatite-coated SB Charite prosthesis, recently approved by the FDA. The mean bony ingrowth was ~48%, which was reportedly more favorable than for cementless total joint replacements in the appendicular skeleton. Radiography revealed no lucency or loosening of any prostheses. Histochemical assays showed no evidence of wear debris or cytokines (24). Seguin et al. (37) studied tissue engineered nucleus pulposus tissue formed on a porous calcium polyphosphate substrate. The nucleus pulposus-like tissue formed in vitro resembled the native tissue in terms of proteoglycan content and compressive mechanical properties. Other groups have performed similar investigations (26).

The PDN prosthetic disc nucleus (Raymedica, Minneapolis, MN) is an example of a nucleus replacement device. The PDN prosthetic disc nucleus has a rectangular morphology and is composed of a polymeric hydrogel core wrapped in a woven polyethylene jacket, which allows the device to absorb fluid. Fluid absorption exerts a swelling pressure similar to the intact nucleus (9). After laminotomy and nucleotomy, a subtotal discectomy is performed. The PDN is then placed. In most adults, two implants are placed. They are loosely sutured to each other end-to-end (to decrease the risk of extrusion) and placed in succession, both parallel to each other and in the coronal plane. Shim et al. (38) reported good or excellent outcomes in 78% according to MacNab's criteria with an average increase in disc height of

9.4% at 1-year follow-up. Retrograde migration and extrusion into the spinal canal have been the major complications with placement of the PDN, occurring in 8 to 12% of cases, which have kept it from being widely used and accepted (38).

Total disc arthroplasty or intervertebral disc replacement is intended to restore normal motion to the affected functional spinal unit. It is hypothesized that restoration of physiologic motion will decrease the risk of adjacent segment degeneration. Intervertebral disc replacement involves an anterior approach to perform a total discectomy. Blumenthal et al. (3) reported statistically significant improvements in mean pain scores as assessed by the visual analog scale (VAS) and Oswestry scores for all follow-up intervals (from 6 wk to 12 mo), which correlated to 63% and 88.9% success, respectively. Clinical success was reported as an improvement of >20 points in the VAS score and an improvement of at least 10 points in the Oswestry score (3). Reported complications include implant malposition, implant dislodgement, vertebral body fracture, great vessel injury, retrograde ejaculation, and persistent radicular pain without radiographically evident neural compression (47). Continued narcotic use was common. There is also preliminary evidence that disc replacement may be beneficial in the setting of adjacent segment degeneration after spinal fusion (18). However, there are no noncorporate, long-term randomized, controlled trials of disc arthroplasty versus fusion in the published literature. Is disc arthroplasty better than anterior or posterior fusion? Currently, there is no evidence to support this assertion. Is disc arthroplasty better than aggressive nonsurgical therapy? To our knowledge, there are no randomized, controlled trials comparing aggressive nonsurgical therapy with disc arthroplasty.

WHAT IS ON THE HORIZON?

Recent trends involve the use of more metal in spinal surgery. Robertson (35) reported on the rapid increase in the diagnosis of spinal disorders, partially related to retirement and disability. He documented that in 1983, per million people, 15 lumbar fusions were performed in Sweden versus 52 to 99 lumbar fusions in the United States. In 1998, per million people, 97 to 144 lumbar fusions were performed in the United States (35). Robertson concluded that there was no evidence that the increased fusion rate had increased the rate of good results from back surgery. Although this is not quite true (10), it is close. Recent Scandinavian studies (10) suggest that outcome is better and costs are cheaper with less metal, recognizing the importance of the material properties of spinal implants. The future of spinal surgery will, in part, involve advances in diagnosis and evidence-based, non-operative care. It will also, likely, involve less implant use and use of nonmetallic implants that are less stiff and bioabsorbable.

HOW DO WE IMPROVE OUTCOMES IN DECISION MAKING?

A poorly conceived operation is destined for failure. Knowledge of applied biomechanics is required to construct cogent operative treatments for surgical problems. Questions can be answered in the biomechanics laboratory and aid clinical decision making for our patients. In addition to basic research, the importance of clinical research cannot be understated. Clinical research is the forum for critical evaluation of the efficacy, complications, and outcomes of surgical procedures. However, applying new techniques without adequate investigation in the basic science laboratory is dubious, especially when results of experimental treatments are marginal when compared with accepted treatment methods. It is only through thoughtful study and research that the science of spinal surgery and reconstruction can be advanced to the benefit of our patients.

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FIG. 41.1 The continuum concept as described by Yoganandan et al. (43). This idealized force-deformation curve demonstrates four phases of loading. During the physiological zone, load/deformation behavior is almost linear. The critical phase is the traumatic zone or the area of microtrauma. Here, although not grossly pathologic, injury to components of the column occurs, often not visible on radiography (*from*, Biomechanics of the spine, in Larson SJ, Maiman DJ (eds), *Surgery of the Lumbar Spine*. New York, Thieme, 1999, p 17. Reprinted by permission [33]).

FIG. 41.2 Films during flexion, *A*, and extension, *B*, demonstrate greater angular motion at L4-5 than at L3-4 or L5-S1 (*from*, Instability of the vertebral column, in Larson SJ, Maiman DJ (eds), *Surgery of the Lumbar Spine*. New York, Thieme, 1999, p 37. Reprinted by permission [33]).

FIG. 41.3 Films during flexion, *A*, and extension, *B*, showing retrolisthesis in extension at L4-5 with greater angular motion at L4-5 than at L3-4 or L5-S1 (*from*, Instability of the vertebral column, in Larson SJ, Maiman DJ (eds), *Surgery of the Lumbar Spine*. New York, Thieme, 1999, p 38. Reprinted by permission [33]).

FIG. 41.4 *A*, Films during flexion (*left*) and extension (*right*) demonstrating anterolisthesis at L4-5. *B*, Traction spurs (*arrows*) on L4 and L5 before (*left*) and 6 months after (*right*) fusion. The L4 spur is no longer present, and that on L5 is smaller (*from*, Instability of the vertebral column, in Larson SJ, Maiman DJ (eds), *Surgery of the Lumbar Spine*. New York, Thieme, 1999, p 39. Reprinted by permission [33]).