

Biomechanical Consequences of Spinal Decompression Procedures: Implications for Stability, Fusion, and Surgical Decision-Making

Raed H. Ogaili¹, Lames H. Almanseekanaa²

¹College of Veterinary Medicine, University of Kerbala, Iraq

¹College of Medicine, National University of Malaysia, Malaysia

²College of Applied Medical Sciences, University of Karbala, Iraq

raedogaili@uokerbala.edu.iq

<https://orcid.org/0000-0001-7092-4936>

Article Info.

Article history:

Received 4 February 2026

Revised 19 February 2026

Accepted 10 March 2026

Published 9 April 2026

Keywords:

Spinal Decompression; Spinal Biomechanics; Lumbar Spinal Stenosis; Cervical Myelopathy; Laminotomy.

How to cite:

Raed H. Ogaili, Lames H. Almanseekanaa. Biomechanical Consequences of Spinal Decompression Procedures: Implications for Stability, Fusion, and Surgical Decision-Making. Aca. Intl. J. Med. U. 2026;4(1) 18-28.

DOI:

<https://doi.org/10.59675/U413>

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Abstract

Degenerative spinal disease in adults is one of the most common reasons for surgical intervention, and lumbar spinal stenosis alone affects about 11% of the general population. The biomechanical effects of spinal decompression procedures, including both unilateral and multilevel laminectomy, are highly variable and depend on the type of surgery performed. As the mainstay of surgical management, understanding each procedure's effects is essential to maximize surgical outcomes.

Objectives: Review available evidence for the biomechanical effects of lumbar and cervical spinal decompression surgeries, understand instrumented fusion's contribution to post-decompression stability, and consider novel interspinous process decompression (IPD) devices regarding spinal mechanics.

Methods: Cadaveric biomechanical studies, finite element analyses (FEA), randomized controlled trials, and patent literature informed this narrative review. Unilateral laminotomy, midline decompression, nucleotomy, laminectomy, laminoplasty, posterior and anterior cervical fusion, and IPD implantation procedures are examined.

Results: Unilateral laminotomy yields a modest increase in Range of Motion (ROM) of about 10%. ROM increases are progressive in midline decompression (destabilization around 20%) and nucleotomy (around 50%). Pedicle screw fixation decreases segment ROM by

around 80% in bending. For a kyphotic spine, cervical laminectomy and laminoplasty increase disc stress and facet forces, potentially requiring concomitant fusion. Adjacent segment disease (ASD) remains a

major long-term complication of instrumented fusion. IPD devices show similar functional results to conventional decompression but feature increased reoperation rates.

Conclusion: The extent of decompression required must be balanced with expected biomechanical consequences when making surgical decisions. Minimally invasive procedures avoid mandatory fusion in appropriate patients, while extensive resections usually need instrumented stabilization. Understanding the biomechanical gradient of decompression surgeries is crucial to minimizing iatrogenic instability and improving long-term surgical outcomes..

Introduction

Degenerative Spinal Disease is one of the most common and costly musculoskeletal diseases in the world. The prevalence of LSS is around 11% of the general adult population with a prevalence of 25–39% of those attending primary or secondary care [1]. In the U.S., more than 135 surgical decompression procedures are performed per 100,000 Medicare beneficiaries each year, which costs more than USD 1.65 billion in hospitals [2]. With the world's population aging, the need for spinal decompressive surgery is only expected to continue to rise and an in-depth knowledge of the biomechanical implications is clinically essential.

The basic goal of spinal decompression is to remove abnormal pressure on any nerve structures – such as the spinal cord, nerve roots or cauda equina – that is caused by bony or soft tissue impingement. This is accomplished through a variety of procedures which vary significantly in the amount of posterior element, disc material and ligamentous tissue removed. Each resection will have a biomechanical consequence that is more than just a theoretical concept – disruption of the posterior osteoligamentous complex, intervertebral disc or facet joints will affect load distribution and can lead to segmental instability, adjacent segment disease (ASD) or progressive deformity [3].

Today, a spectrum of approaches can be used that vary from microsurgical unilateral laminotomy with unilateral canal decompression (sparing most of the posterior tension band) to extensive multilevel laminectomy, involving the sacrifice of most of the supraspinous and interspinous ligaments, as well as the laminar arch. If a decompression-induced instability is greater than the physiological compensating ability, however, instrumented posterior fusion using pedicle screw-rod constructs is necessary to regain segmental stability; this will also lead to an increased risk of accelerated ASD at the neighbouring motion segments, as will be discussed [4].

The cervical spine has some added complexities. Cervical stenosis causing myelopathy or radiculopathy can be treated with an operation to decompress the back of the neck (laminectomy or laminoplasty), or an operation to decompress the front of the neck and fuse the bones (anterior decompression with fusion). The method of approach will have significant biomechanical consequences, especially in patients with a preexisting kyphotic deformity, where an approach through the back may not be sufficient to relieve the mechanical cause of neural injury and not prevent further instability [5].

The introduction of technological innovation has also led to the creation of a group of indirect decompression devices, such as interspinous process decompression (IPD) implants, which maintain foraminal dimension and decompress the nerve by distracting adjacent spinous processes without a formal bone and/or ligament resection [6]. Such devices have been thoroughly studied in the clinical and biomechanical sense for their mechanical effectiveness and life.

This review examines the biomechanics of the available and emerging spinal decompression techniques, in an extensive biomechanical review. Based on cadaveric experimental studies, finite element modelling, randomized clinical trial evidence, and more current literature of surgical devices, the aim is to provide clinicians and biomedical engineers with a framework that provides evidence on how each of

the different decompression techniques alters the spinal mechanics and how this information should guide surgical planning and selection of implants.

Methods

A narrative review was carried out via PubMed/MEDLINE, Scopus and Google Scholar search. The following search terms were used in the MeSH and/or free text: "spinal decompression biomechanics", "laminectomy range of motion", "lumbar stenosis cadaveric study", "cervical decompression finite element analysis", "interspinous process device randomized trial", and "adjacent segment disease lumbar fusion. The literature search was made without any language restriction, from 1990 to April 2026. Other sources were U.S. patents related to the methodology of interspinous implant devices. A hand search of reference lists was also performed of included articles for additional relevant references. Studies included original research articles, systematic reviews, meta-analysis and patent publications that were peer reviewed and relevant to the topic. Studies with no quantitative biomechanical data and studies that only included clinical outcome measurement, but not biomechanical assessment were excluded. 20 references were found to be most relevant to this review.

2. Spinal Biomechanics: Anatomical and Mechanical Foundations

2.1 The Functional Spinal Unit

The spine is made up of functional spinal units (FSUs), which consist of two adjacent vertebrae, a disc between them, two facet joints and the ligaments connecting them. The three main rotational planes of motion in the FSU are flexion/extension (FE), lateral bending (LB) and axial rotation (AR) and the three translational directions are anterior shear (AS), lateral shear (LS) and axial compression/distraction (AC). Under the standardized 7.5 Nm pure moment loading, the median values of the native ROM of the lumbar segments in cadaveric studies are around 6.8° in FE, 5.6° in LB and 1.7° in AR. These are the biomechanical baseline values that are used to measure the changes in ROM being achieved during decompression.

2.2 The Posterior Osteoligamentous Complex

The posterior osteoligamentous complex (laminae, spinous process, supraspinous ligament (SSL), interspinous ligament (ISL) and facet joint capsule) is the major posterior tension band of the spine. This structure helps protect against excessive flexion, restricts anterior translation and helps share compressive and shear forces with the anterior disc-body complex. Even when clinically indicated, disruption of these elements by surgery alters the load distribution and can cause a shift that can be beyond physiological tolerances [8]. Interestingly, ISL resection does not lead to statistically significant differences in FSU ROM in any direction, while SSL resection significantly increases FE ROM in both operated and neighboring level [8]. This imbalance of ISL vs. SSL contributions has significant implications on surgical targeting of ligament preserving techniques.

2.3 Intervertebral Disc Mechanics

The intervertebral disc behaves as a pressurized hydraulic cushion: the compression acts radially in the nucleus pulposus and the annulus fibrosus resists hoop stresses due to its multi-directional lamellar structure. This load-transmitting mechanism is seriously affected by nucleotomy. The results of

biomechanical studies of cadaver ACs have shown that nucleotomy can improve AC-ROM by up to 153% for a single step of decompression. Some models of FEA have also reported a rise in pressure in the anterior annulus to 130% following nucleotomy, highlighting the need for conservative disc resection in surgical decompression.

2.4 Biomechanical Assessment Methodology

There are two main approaches in biomechanics studies of spinal decompression: cadaveric studies and finite element analysis (FEA). Cadaveric studies allow direct measurement of the ROM and structural failure properties under controlled loading, but suffer from inter-specimen variability, lack of consideration of physiological muscle forces and lack of the ability to model long-term responses of remodeling. FEA can be used for parametric study of stress distribution, intradiscal pressures and facet forces for a variety of loading conditions and anatomical configurations, but validations using experimental data are required due to the model assumptions and simplifications [9]. Both methods are complementary, and the strongest conclusions are obtained when results from both methodologies are integrated.

3. Lumbar decompression procedures have been shown to have biomechanical effects.

3.1 Unilateral Laminotomy

Lumbar canal stenosis has been considered the least destabilising surgery by many and is performed with unilateral laminotomy with ipsilateral or bilateral undercutting decompression. This technique maintains the majority of the posterior tension band, by preserving the contralateral facet joint, and the SSL, and ISL. Cadaveric data show that the ROM changes by around 6% in the FE, 3% in the LB, 12% in the AR, 11% in the AS, and 8% in the LS when compared to their native state [7]. To compare the biomechanical advantage of the minimally invasive (MI) with the conventional bilateral decompression (BC), a direct comparison was made between the two techniques, and the biomechanical advantage of the MI technique was found to be significant in FE ($p < 0.005$) and AR ($p < 0.05$) [10].

The cadaveric studies and the FEA studies showed a consistent finding that laminotomy always resulted in a decrease in the degree of post-procedural instability when compared to laminectomy, while bilateral procedures resulted in a larger increase in ROM than unilateral procedures [9]. In addition, medial facet resection >45-50% was determined as a threshold value, at which spinal stability is drastically reduced [9]. Such a ROM increase following unilateral laminotomy is a normal part of physiological compensation and is not routinely a requirement for additional fusion in patients with intact disc height and facet integrity.

3.2 Midline Decompression

Full laminar resection and bilateral sacrifice of SSL and ISL (midline decompression) results in greater biomechanical disruption. Approximate spine ROM increases are reported for FE of 15%, for LB of 5%, for AR of 21%, for AS of 20% and for LS of 19% compared to the intact spine 7. This greater elevation of FE ROM is most determined by the detachment of the SSL: Gercek et al. cadaveric data confirmed that SSL detachment significantly elevated FE ROM in both the decompressed and adjacent segments, which was not seen with ISL resection alone.

Frontal plane biomechanics are also disrupted by laminectomy. In the cadaveric study of degenerative lumbar scoliosis, laminectomy was found to cause a significant reduction in the shear stiffness of 24%,

shear yield force of 41%, and shear force to failure of 44% [11], and in the female specimens, relatively low failure thresholds of 11%. The effects of this are exacerbated with multilevel laminectomy and are more commonly seen in patients who have pre-existing sagittal imbalance, who will usually need an instrumented fusion.

3.3 Nucleotomy and Discectomy

In nucleotomy, which is the biomechanically most significant individual decompression step, 153% more AC ROM was achieved than with any of the posterior resection procedures [7]. FEA modelling also demonstrates that the increases in intradiscal pressure (IDP) following nucleus removal are large and that the increases in ROM in the FE, LB and AR increase significantly following the posterior decompression steps alone [9]. These data reinforce the concept of conservative disc resection surgery at operation: only as much nucleus should be removed as is needed to get sufficient neural decompression and fusion should be strongly considered when the nucleus is removed while doing extensive posterior resection.

3.4 How the Instrumented Posterior Fusion Works.

The reductions of ROM following pedicle screw-rod fixation are significant: ~82% FE, ~72% LB, ~42% AR, ~31% AS and ~17% LS with respect to the native spine. Most importantly, if instrumentation is used, further ROM changes due to additional decompression procedures such as unilateral laminotomy and midline decompression or nucleotomy are only marginal, thus demonstrating that the mechanical behaviour of the instrument segment [7] is dominated by the implant-bone construct. The surgeon can therefore choose to perform the amount of decompression necessary without worrying that more tissue would significantly affect the fusion construct.

Table 1. Biomechanical Gradient, ROM Alterations, Stabilization Requirements, and Supporting References of Spinal Decompression Procedures

Surgical Procedure	Lumbar ROM / Mechanical Alterations	Cervical Spine Biomechanical Impact	Structural Stability & Fusion Requirement	Reference
Unilateral Laminotomy	Modest increase in ROM (~6–12% across FE, LB, AR, AS, and LS).	—	Highly stable; preserves contralateral facets and most posterior tension band. Routine fusion is generally not required.	[7], [10]
Midline Decompression	Moderate increase in ROM (FE ~15%, LB ~5%, AR ~21%, AS ~20%, LS ~19%).	Increased annular, nuclear, and facet stresses in kyphotic alignment.	Conditionally stable; SSL detachment increases instability and fusion may be required in patients with sagittal imbalance.	[7], [8], [11]
Nucleotomy / Discectomy	Severe reduction in axial compression stiffness; AC-ROM increases up to 153%; increased intradiscal pressure.	—	Biomechanically unstable; fusion should be considered when combined with extensive posterior decompression.	[7], [9]
Interspinous Process Decompression (IPD)	Reduces extension ROM and facet loading through indirect distraction.	—	Motion-preserving alternative; avoids extensive tissue resection but is associated with higher reoperation rates.	[16], [18], [19], [20]

Surgical Procedure	Lumbar ROM / Mechanical Alterations	Cervical Spine Biomechanical Impact	Structural Stability & Fusion Requirement	Reference
Instrumented Posterior Fusion (Pedicle Screws)	Marked reduction in segmental ROM (~82% FE, ~72% LB, ~42% AR).	Reduces global cervical ROM by approximately 40% compared with non-fusion techniques.	Provides rigid stabilization and allows extensive decompression; however, may accelerate adjacent segment degeneration (ASD).	[5], [7], [12], [13], [14]

Abbreviations: FE = Flexion–Extension; LB = Lateral Bending; AR = Axial Rotation; AS = Anterior Shear; LS = Lateral Shear; AC = Axial Compression; ROM = Range of Motion; ASD = Adjacent Segment Disease.

4. Adjacent Segment Disease Following Intraoperative Foraminotomy and Osseous Alteration (IFOA)

Although spinal fusion is an effective procedure in providing long-term post-decompression stability, there is a well-defined long-term risk associated with this procedure: ASD. Fusion-related biomechanical changes, such as greater intradiscal pressure, higher loading on the facet joints, and augmented mobility in adjacent motion segments have been directly attributed to the increased degeneration of neighboring motion segments [12]. The incidence of radiographic ASD after lumbar fusion is reported to range from 5.2% to 100%, depending on the definition of ASD and the duration of the follow up. In clinical ASD patients who underwent subsequent surgery, the incidence of further ASD was about 11.7% at a mean follow-up of 28.6 months [13], and previous studies suggest that incidence of ASD in instrumented lumbar surgery is as high as 30% [14].

Risk factors for ASD include older age, female sex, osteoporosis, preoperative disc degeneration at the adjacent level and high BMI [15]. Other surgery-related factors such as multilevel fusion, sagittal imbalance, facet joint violation near the fusion construct and decompression away from the fusion area are also blamed [13]. These data collectively highlight the need to use fusion in the operated segment, but only when standalone decompression is not enough to achieve a stable physiology, and when a biological and mechanical cascade is likely to lead to subsequent ASD, to minimize such subsequent ASD.

5. Biomechanical Analysis of Cervical Decompression

5.1 Posterior Cervical Decompression: Laminectomy and Laminoplasty

The biomechanical characteristics of cervical myelopathy or radiculopathy decompression surgery differ significantly from those seen in lumbosacral decompression surgery and are related to both the small size of the cervical spine, its mobility and the close proximity of the spinal cord. FEA of the kyphotic cervical spine (C2–C7) shows no significant difference in the global ROMs between the pre- and post-operational states with posterior decompression alone (laminectomy or laminoplasty), and that there is an increase in the stress on the annulus, nucleus, and facet contact forces at the operated levels [5]. This is a mechanical environment which is hostile to progressive kyphotic deformity, especially in those with pre-existing malalignment.

Post-laminectomy kyphosis is a recognized complication caused by the redistribution of mechanical forces not being done properly after posterior element removal, while the spinal cord and nerve roots are decompressed, which causes anterior loading of the vertebrae and neurological deterioration despite a satisfactory initial decompression. FEA confirms that there is a higher risk in kyphotically aligned spines where the spine is already under tension pre-operatively, and where there will be no remaining posterior column stabilizers after removal of the lamina and ligamentum flavum conventional surgery [5].

5.2 Fusion-Based Cervical Procedures

The instrumented fusion for posterior decompression (PDF) and anterior decompression with fusion (ADF) techniques were both found to have about 40% less global ROM at C2–C7 compared to non-fusion decompression techniques in FEA modelling [5]. Both procedures effectively reduce stress at the surgical levels at the annulus, nucleus and facet contacts, and are sufficient to provide mechanical stability for good results in kyphotic cervical spines. But it is interesting that there are certain differences between the two approaches in terms of consequences to adjacent segments. A 20% increase in annular stresses occurs in the adjacent cranial segment (C2–C3) when ADF is applied; and a 20% increase in nucleus stresses occurs in the adjacent caudal segment (C5–C6) when PDF is applied. Clinically, it has implications for surgical planning in that the decision between ante- or posterior fusion should be made based on the deformity correction requirement as well as the type of adjacent segment which is most mechanically vulnerable in the specific patient's sagittal alignment profile.

6. Interspinous Process Decompression Devices

6.1 Biomechanical Rationale and Mechanism of Action

Interspinous Process Decompression (IPD) devices are posterior spinal implants that are used to maintain a relative flexed posture of the spinal canal at the stenosed level without cutting bone. The devices are placed between the spinous processes and serve as indirect spacers which increase foraminal height and decrease posterior annular and facet joint loading [6]. The biomechanical mechanism of the efficacy of the IPDs is the known flexion-dependence of LSS symptoms: patients typically feel better flexed than when they are upright, and the IPDs mimic this effect of flexion when they are in the upright position and during walking [16].

FEA analysis of several IPD designs showed that for the devices tested, extension ROM and facet contact forces at the device level were significantly decreased while facet contact forces at neighboring levels varied depending on the stiffness of the IPD and the distance of interspinous gap distraction. Increased stress at neighboring levels may occur paradoxically with too much distraction, which is why sizing during the operation is crucial to obtain a biomechanically optimal implantation.

6.2 Surgical Device Technology

New surgical engineering has given rise to IPD surgical devices that can be inserted through percutaneous or minimally invasive access, significantly decreasing the operative morbidity in comparison with the classic decompression. In one such system (US Patent No. 11,712,253 B2, 2023), a method for interspinous implant insertion is described, which comprises sequentially performing the following steps: a decompression knife is used to prepare (facia and soft tissue), a broach cutter is used to resection the interspinous ligaments, an intraoperative sizing tool is used to assess the gap, an insertion tool is used to insert the interspinous implant, and a compressor-lock mechanism is used to secure the implant to (bilateral spinous processes). An intraoperative sizing step is another feature of this new generation of devices which resolved one of the weaknesses of previous devices that were linked to higher revision rates due to insufficient sizing of the implant. Bilateral compression design principle maximizes the number of contacts between spinous process with minimum risk of migration.

6.3 Analysis of clinical and biomechanical evidence

Evidence from randomized controlled trials comparing interspinous process decompression (IPD) with conventional decompressive surgery for lumbar spinal stenosis (LSS) has demonstrated similar functional outcomes during short- and intermediate-term follow-up. In the landmark double-blind FELIX trial, treatment success at 18 months was reported in 63% of patients treated with IPD compared with 72% of patients undergoing conventional decompression, with no statistically significant difference between groups. Similarly, no significant differences in clinical outcomes were observed at two years. However, the IPD group exhibited a significantly higher reoperation rate (18%). Five-year follow-up data further demonstrated comparable long-term functional outcomes, although reoperations remained more frequent among IPD-treated patients, particularly during the first two postoperative years [19]. Despite this limitation, FDA trial data reported sustained quality-of-life improvements, including a 49% increase in the Physical Component Summary score from baseline at five years [20].

These data suggest that IPD devices are a biomechanically viable and mechanically less extensive decompression alternative than traditional decompression. Selection of patients is the most important factor for success: candidates must have extension dependent neurogenic claudication at 1-2 levels, preserved disc height, no spondylolisthesis, and good spinous process bone quality for contact forces of the implant.

Discussion

Biomechanical evidence reviewed in this review supports a hierarchical conceptualization of spinal destabilisation that occurs as a consequence of decompression. The level of ROM gained for each incremental step of posterior resection (ISL excision, midline laminectomy, discectomy) is measurable for the treated segment. The gradient has direct surgical implications: surgical interventions that restrict the laminotomy to unilateral surgery cause destabilisation within the range of physiological compensation, while surgical procedures that involve midline decompression and nucleotomy result in combined elevation of the range of motion which could require additional fixation for structurally vulnerable patients.

Based on cadaver studies, it has been determined that the following increase in ROM can be expected after performing unilateral laminotomy, midline decompression, and nucleotomy, respectively, of 10%, 20%, and 50% [7]. These findings may be used to make decisions intra-operatively as to the necessity of fusion, especially when pre-operative imaging shows pre-existing spondylolisthesis, decreased disc height, and/or multilevel disc degeneration that may limit the structural reserve to accommodate an iatrogenic instability.

These numerical benchmarks need to be set within a proper context. The percentages in the ROMs presented from different studies are based on cadaveric specimens tested under standardized loading conditions and are only approximate comparative benchmarks and not precisely generalizable thresholds. The differences in the results from one study to another are caused by the use of different specimens of varying age and degenerative status, testing of different spinal levels, size of the specimen sample, magnitude of the loading applied, and the presence or absence of preload conditions. The review of Levy et al. confirms that post-decompression instability increase is generally smaller in degenerative specimens than in non-degenerative specimens, due to the fact that the majority of the pre-existing motion restriction in the former is pre-existing osteophytes or disc desiccation [9], and "suggests that direct numerical extrapolation from cadaveric non-degenerative data to a typical surgical patient should be approached with caution."

In the fixed instrument, since the dominant motion of this construct is the implant-bone construct, further decompression does not make a biomechanical difference [7]. This establishes a surgical paradox: On one hand, instrumentation allows for a wide decompression without worries of iatrogenic instability at the decompressed level, but on the other hand, the biomechanical chain reaction of increased adjacent-segment loading that might require additional surgery begins at the time of instrumentation. It is not a theoretical risk as illustrated in the ASD literature, which reports that at medium-term follow-up, 4.7–11.7% of patients with symptomatic ASD that required reoperation, and up to 30% or more of patients presented with radiographic ASD over longer period of follow-up [13,14]. Such a compromise needs to be carefully considered during pre-operative planning.

The neck (cervical spine) is particularly important. It is noteworthy that the kyphotic cervical spine has increased disc stress and facet forces with laminectomy and laminoplasty that indicate this population to be appropriate for instrumented fusion. Thus, pre-operative sagittal alignment evaluation should be deemed essential when planning a cervical decompression. The different adjacent-segment stresses experienced by ADF and PDF adds a new stress dimension to the operative decision-making process, and the anatomy and condition of every adjacent segment should be considered on a case-by-case basis in choosing the approach.

IPD devices fit into a significant, but well-defined place within this continuum. However, they have a biomechanical disadvantage (indirect decompression without resection of the posterior elements) with a higher reoperation rate than conventional surgery [18,19]. Further device evolution, such as the introduction of an intra-operative sizing system and bilateral compression locking systems [6], may help narrow this gap in future cohorts, but most evidence available thus far suggests that these devices should only be used in carefully-selected patients with mild-to-moderate extension dependent stenosis and normal spinal architecture.

In the future, patient-specific FEA combined with pre-operative imaging could be used to provide patient-specific biomechanical risk assessment. Computational models can be validated with cadaver data to simulate ROM and stress effects of planned decompression extents for the patient's specific anatomy and degenerative profile and giving personalized surgical planning that goes beyond current group-level empirical benchmarks. This type of strategies are natural combinations of the biomechanical and clinical evidence streams presented above [17].

Conclusion

There is a definite continuum to the biomechanics of the spinal decompression procedures and the evidence reviewed here enables meaningful quantification of the destabilising effect of each procedure. Biomechanically unilateral laminotomy is compatible with stand-alone decompression in most patients with good structural integrity. Like the other two procedures, midline decompression and nucleotomy combine to significantly increase the segmental ROM and may require instrumented fusion in cases with compromised structures. Surgery for posterior cervical decompression in the kyphotic spine (backward curve) is often insufficient. The instrumented fusion is effective in stabilizing the fusion site but produces biomechanical alterations at adjacent segments that are known to have a documented risk for reoperation in the long-term. However, IPD devices offer a mechanically useful alternative to conventional decompression in patients with stenosis that is likely to change with extension but do have an increased rate of revision surgery.

The use of expected biomechanical implications and patient-specific variables such as sagittal alignment, disc integrity, bone quality and the number of stenotic levels is required for optimal surgical decision making. Further studies are needed to validate these biomechanical to outcome relationships in the future, and to create patient-specific computational models to enhance the accuracy of pre-operative planning.

Declarations

Funding: The authors received no specific funding for this work.

Competing interests: The authors declare no competing interests.

Ethics approval: Not applicable. This is a narrative review article and did not involve primary data collection from human participants or animals.

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