Risk factors and treatment strategies for adjacent segment disease following spinal fusion (Review)

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Abstract. Adjacent segment disease (ASD) is a significant clinical complication following cervical and lumbar spinal fusion surgery, characterized by the degeneration of spinal segments adjacent to the fused area. The present literature review aimed to elucidate the risk factors contributing to ASD and to evaluate current and emerging treatment strategies. Epidemiological data indicate that patient-related factors such as age, pre-existing spinal degeneration and comorbidities, along with surgical factors including the type of fusion, instrumentation and alignment correction, play pivotal roles in ASD development. Biomechanical alterations post-fusion further exacerbate the risk. The underlying mechanisms of ASD involve changes in spinal kinematics and disc degeneration, driven by inflammatory and degenerative processes. Diagnostic modalities, such as magnetic resonance imaging and computed tomography scans, are essential for early detection and accurate diagnosis. Preventive strategies emphasize meticulous preoperative planning, advanced surgical techniques and postoperative rehabilitation. Treatment approaches range from conservative methods such as physical therapy and pharmacological interventions to surgical solutions, including revision surgeries and the use of motion-preserving technologies. Emerging therapies, particularly in regenerative medicine, show promise in mitigating ASD. The present review underscored the necessity of a multidisciplinary approach to optimize patient outcomes and highlighted the need for ongoing research to address gaps in the current understanding of ASD in both cervical and lumbar regions.

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Contents

1. Introduction

Spinal fusion (SF) involves the surgically joining of two or more vertebrae to eliminate motion between them and provide stability. This procedure typically uses bone grafts alongside hardware such as screws, rods, or plates to aid the fusion process (1-3). A well-known complication of SF is adjacent segment disease (ASD), where degeneration occurs in the spinal segments next to the fused vertebrae. This can present as disc herniation, spinal stenosis, or facet joint arthritis, resulting in pain, neurological issues and potentially further surgeries (1). ASD often arises due to altered spinal biomechanics following fusion (2). The fused segments cease to bear mechanical loads, shifting increased stress onto adjacent, unfused segments, which accelerates degenerative changes in these areas (3). A number of studies have confirmed that these mechanical alterations post-fusion contribute to the degeneration of intervertebral discs and facet joints adjacent to the fusion site. The increased range of motion and mechanical load on these segments intensifies degeneration, particularly in longer fusion constructs (4,5). In cervical spine surgeries such as anterior cervical discectomy and fusion (ACDF), altered cervical mechanics influence adjacent segment degeneration, while lumbar fusion affects spinal alignment and load distribution (6).

Epidemiological studies report a broad range of ASD incidence rates, typically between 2-36%, depending on the spinal region involved (such as lumbar or cervical), the duration of postoperative follow-up and the surgical technique used (6). Clinically, ASD may manifest as chronic back pain, radiculopathy, or myelopathy in severe cases, especially if degeneration results in nerve compression or spinal canal narrowing (1). Diagnostic imaging, including magnetic resonance imaging (MRI) and computed tomography (CT),

is commonly employed to identify degenerative changes in adjacent segments. While spinal fusion remains an effective treatment for conditions such as degenerative disc disease, scoliosis and spinal instability, the increasing prevalence of ASD is a significant concern, particularly as spinal fusion procedures continue to rise globally (7). In the U.S. alone, >500,000 fusion surgeries are performed annually, with millions worldwide (8), emphasizing ASD as a critical postoperative issue (9).

Several factors contribute to the development of ASD, which can generally be categorized into patient-related and surgical factors. Patient-related factors include age, body mass index (BMI), bone mineral density (BMD) and pre-existing spinal conditions (4,7,10). Surgical factors, such as the length of the fusion and the instrumentation used, also play a role. Longer fusion constructs, for instance, can impose excessive mechanical stress on the adjacent segments, accelerating degeneration (4,5). Moreover, studies have investigated the correlation among genetic predisposition, inflammatory mediators and the local biochemical environment in the development of ASD-associated adjacent segment degeneration (7,10). Therefore, understanding these risk factors is vital for developing strategies to reduce ASD incidence.

Addressing ASD requires a multifaceted approach involving both preventive and therapeutic strategies. Surgical innovations, such as dynamic stabilization devices and total disc arthroplasty, aim to preserve spinal motion and reduce ASD risk, though more research is needed to confirm their efficacy (11). Minimally invasive surgical techniques (MIS), which minimize tissue damage and scar formation, are associated with lower ASD rates (12). However, the optimal treatment for ASD remains debated. While conservative management (such as physical therapy, medications) may relieve symptoms, surgical intervention may be required for patients with significant neurological deficits or instability (13).

In summary, the present review specifically focused on ASD associated with cervical and lumbar spine surgeries, as these are the most commonly performed fusion procedures (6). ASD continues to present challenges in the management of patients undergoing spinal fusion. A deeper understanding of its risk factors, along with advancements in both surgical techniques and emerging therapies, is essential for improving patient outcomes and minimizing the need for subsequent interventions.

2. Risk factors for ASD

Patient-related factors

Age. Age is a risk factor for ASD following SF surgery, though findings vary, leading to continuing debate. A 16-year cohort study reveals that younger patients, particularly those under 40, who underwent primary ACDF, were more probably to require subsequent ASD surgery (12). Other studies, however, report consistent ASD rates across all age groups (4,14). Similar results were noted in lumbar fusion cases, with advanced age being emphasized as a risk factor (15). The overall reoperation rate due to symptomatic ASD following cervical fusion is 6.57%, peaking at 8.12% in individuals aged 30-39 and decreasing with age. Additionally, those under 50 have a higher likelihood of requiring ASD reoperation (4). Conversely, for posterior lumbar fusion, patients younger than 45 have a lower risk of ASD compared with those over 60 (5). Although a meta-analysis revealed a slight age difference in ASD patients, it was not statistically significant (16). While age-related spinal degeneration is well known, it does not fully explain the higher reoperation rates in younger patients (3). A study has shown that older individuals exhibit more rapid radiological signs of degeneration post-fusion (17). This discrepancy may be linked to differences in physical activity levels and underlying health conditions. The mixed research findings suggest that age alone is not the sole risk factor for ASD, necessitating caution in future studies and clinical care, especially for younger patients.

BMI. Biomechanically, obesity can overload intervertebral discs, accelerate cervical disc degeneration and lead to abnormal stress on surrounding small joints, spinal ligaments and muscles, causing ASD (14). However, the relationship between BMI and the development of ASD following fusion surgery remains debated. Studies by Wei *et al* (14) and Zhong *et al* (18) demonstrate that elevated BMI is a risk factor for ASD in patients undergoing cervical ACDF and minimally invasive lumbar interbody fusion for degenerative lumbar conditions. Additionally, some investigations have suggested that a BMI >34 is associated with increased risk following lumbar fusion procedures (19). Conversely, certain studies have reported no correlation between BMI and the risk of ASD following both cervical ACDF (20) and adult lumbar spondylolisthesis fusion procedures (21). Notably, this discrepancy is more pronounced in the studies addressing cervical fusion, without accounting for the potential effect of postoperative changes in BMI. Therefore, in clinical practice, in addition to emphasizing preoperative BMI control, it is also crucial to focus on maintaining BMI within a reasonable range following fusion surgery for different anatomical regions, which warrants further in-depth investigation.

BMD. Osteoporosis reduces vertebral hardness, alters stress distribution and induces significant biomechanical changes in adjacent segments (22). After fusion surgery, the BMD of adjacent segments decreases compared with preoperative levels (23). Biomechanical studies demonstrate that in lumbar posterior interbody fusion models with osteoporosis, there is reduced pressure within adjacent intervertebral discs, decreased shear stress on fibrous rings and limited range of motion, which negatively influences ASD progression (24). Studies indicate a higher prevalence of ASD in postmenopausal women (25), suggesting that osteoporosis is a risk factor and a predictor of reoperation (19,22). Patients with low BMD undergoing SF surgery may experience implant failure, resulting in poor fusion and heightened stress on nearby vertebrae, worsening ASD onset (26). Studies have demonstrated that osteoporosis (T-score <-2.5) is associated with the development of ASD following ACDF (27). Among patients undergoing fusion for lumbar degenerative conditions, those with osteoporosis show a higher incidence of ASD (28). However, the reoperation rate in osteoporotic patients is lower compared with non-osteoporotic patients (7.4 vs. 13.1%) (28). Additionally, animal experiments illustrate the effectiveness of anti-osteoporotic drug therapy in mitigating intervertebral disc degeneration (IDD) near the lumbar fusion site in rats (29). However, some studies indicate no direct association between osteoporosis and ASD, possibly due to significant BMD variations before and after studies or measurement

inaccuracies (19,30). These conflicting findings underscore the importance of monitoring vertebral BMD pre-fusion, implementing timely postoperative anti-osteoporosis treatments and adopting precise BMD measurement methods, including CT scans alongside the potentially less accurate Dual X-ray Absorptiometry (DXA) (23).

Diabetes. Research indicates that diabetes alters the composition and biomechanical properties of intervertebral disc, contributing to degenerative changes and increased spinal instability (10). Beyond microvascular complications, diabetes affects osteoclast and osteoblast function, leading to the release of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin (IL) 6 and IL-18, which impair bone graft vascularization, formation and remodeling (10,31). Diabetic patients undergoing multilevel fusion surgery face higher complication rates, including non-union and pseudoarthrosis, compared with non-diabetic individuals (10). Consequently, the risk of revision surgery for ASD following pseudoarthrosis exceeds the risk of the initial procedure (10,31). However, the literature indicates that diabetes is not a risk factor for the development of ASD in patients undergoing ACDF (20). While diabetes has no effect on fusion rates in lumbar fusion surgeries using cellular bone allografts (32), other findings reveal that diabetes is a significant factor for reoperation following lumbar fusion due to ASD, with a 44% higher revision rate compared with non-diabetic patients (10). Therefore, it is important to note that current literature lacks comprehensive studies on diabetic patients, particularly regarding preoperative blood glucose levels and postoperative glycemic control. Further clinical and animal studies are needed to confirm these findings.

Pre-existing spinal degeneration. Patients with pre-existing degenerative changes in the spine, such as disc degeneration, facet joint arthritis, vertebral slippage and spinal stenosis, face a higher risk of developing ASD before fusion surgery (33). These degenerative changes reduce disc height, alter biomechanical and increase pressure on neighboring segments (34). Research by Kim *et al* (35) found that MRI-detected disc degeneration was a significant predictor of ASD development. Similarly, one study has suggested that patients with pre-existing degeneration in adjacent disc segments are more prone to ASD following SF (2). Degenerative changes in adjacent facet joints also affect spinal mobility, stability and ASD progression (2). Research stresses that preoperative facet joint degeneration is a risk factor for the development of ASD (2). A study by Tan *et al* (36) further supports this, demonstrating a strong association between facet joint degeneration and an increased incidence of ASD following lumbar fusion surgery. Patients with grade III degeneration [according to the Weishaupt classification (37)] showed a markedly higher risk of developing ASD compared with those with grade I or II degeneration (38). Vertebral slippage can also lead to instability and heightened pressure on neighboring segments (39). Research indicates that preoperative vertebral slippage (spondylolisthesis) and spinal stenosis increase the risk of developing ASD following lumbar fusion and ACDF (40). Moreover, as the severity of postoperative spinal stenosis worsens, patients with ASD show significantly higher Visual Analog Scale scores (41) for back pain and Oswestry Disability Index scores (42) during follow-up compared with those without ASD (43). The current absence of comparative clinical studies leaves uncertainty regarding whether degenerative-related ASD results from fusion surgery or natural degeneration, necessitating further confirmation through animal experimental studies.

Spinopelvic sagittal imbalance. Spinal and pelvic sagittal parameter imbalance can result in lumbar spine instability, widely recognized as a risk factor for postoperative ASD (44). Proper alignment of the spine and pelvis ensures that the load distribution across the spine is balanced, minimizing excessive stress on individual segments. When there is an imbalance in spinopelvic parameters, such as pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS) and lumbar lordosis (LL), this balance is disrupted, leading to abnormal biomechanical forces on the adjacent segments, which accelerates their degeneration (45). A mismatch between PI and LL-especially when the difference exceeds 10˚-forces adjacent spinal segments to compensate by altering their alignment. This compensation increases shear forces and mechanical stress on the adjacent discs and facet joints, leading to premature degeneration and, ultimately, ASD (44,45). One study has shown that degenerative changes in neighboring intervertebral discs are associated with elevated PT and persistent pelvic tilt mismatch with the PI-LL change, particularly in lower lumbar fusions (L4-S1) (44). SS is crucial for sagittal alignment as a compensatory mechanism (45). Postoperative PI-LL mismatch increases the risk of ASD 10-fold compared with controls (34). As PT increases, the center of gravity shifts forward, raising the spine axis deviation (SVA) and increasing stress on adjacent segments (46). After posterior lumbar interbody fusion (PLIF) at L4/5, higher preoperative vertical SVA, vertical PT angle, reduced LL and PI-LL mismatch are closely associated with ASD (45). Maintaining a sacral tilt angle >20˚ at L4/5 is vital for postoperative ASD prevention (34,45). Longer fusion segments in patients with Cobb angle >25˚ (47) are more effective in correcting spinal issues, but higher preoperative Cobb angle may contribute to postoperative ASD (34). Moreover, individuals with a greater C2-C7 SVA following ACDF are at an increased risk of ASD (20). Despite conflicting evidence, orthopedic surgeons should carefully consider these parameters during surgery, especially when feasible intraoperative CT scanning and measurements are available.

Surgical factors

Length of fusion construct. The length of the fusion construct is a critical in the development of ASD due to the biomechanical stresses placed on adjacent segments. Longer fusion constructs, which often span multiple vertebral levels, restrict spinal mobility and increase mechanical loads on unfused adjacent segments (34). Mechanistically, this increased rigidity alters the distribution of forces along the spine, leading to hypermobility and accelerated degeneration in adjacent segments (48). Biomechanical models have shown that the longer the fusion construct, the greater the stress on adjacent segments, especially in regions near the thoracolumbar junction, where the transition between mobile and immobile segments occurs. This change in biomechanics promotes microdamage in adjacent intervertebral discs and facet joints, leading to their progressive degeneration (49). Okuda *et al* (48) found ASD rates of 8.6% over 4.6 years post single-segment lumbar PLIF surgery and 16.4% over 6.0 years post double-segment

surgery. Park *et al* (46) showed a 2.7 times higher ASD risk in three-segment fusion patients compared with those with single or two-segment fusions. The key mechanism here is that long constructs redistribute the load across a smaller number of remaining mobile segments, leading to biomechanical overload and subsequent degeneration. These findings emphasize the need for careful consideration of fusion construct length in preoperative planning for optimal clinical outcomes.

Type of surgical approach. The incidence of ASD following spinal surgery varies depending on the surgical approach; however, there is ongoing debate regarding which technique is most effective in minimizing postoperative ASD. PLIF, due to its increased rigidity, places greater mechanical stress on adjacent segments, resulting in a higher incidence of ASD compared with posterolateral fusion (PLF) (50). A retrospective study revealed that the incidence of ASD in PLIF patients is 3.4 times higher than in PLF patients, with the 10-year ASD-free survival rate being significantly lower in the PLIF group (51). By contrast, transforaminal lumbar interbody fusion (TLIF) causes less disruption to posterior spinal structures, reducing ASD occurrence compared with PLIF (52). Anterior lumbar interbody fusion, which accesses the spine through the abdomen, avoids posterior disruption and has been linked to a lower incidence of ASD compared with both PLIF and TLIF (53). Furthermore, minimally invasive approaches, such as percutaneous fixation, cause less damage and significantly reduce ASD risk (16). Total disc arthroplasty was developed as an alternative to fusion, aiming to preserve segmental motion and potentially delay or prevent adjacent-level degeneration (54). Studies suggest that patients undergoing ACDF with anterior revision surgeries have higher rates of recurrent radiculopathy and ASD compared with those undergoing posterior revisions (55). Additionally, patients who undergo posterior cervical fusion tend to exhibit higher rates of early ASD compared with those who opt for anterior approaches (56). While the literature presents mixed findings regarding the risk of ASD with different surgical techniques, numerous uncontrollable variables, such as the severity of the condition, complicate the conclusions. Therefore, careful consideration of the surgical approach is crucial in planning SF surgeries to minimize the risk of ASD.

Tissue disruption during surgery. Tissue disruption during surgery, particularly damage to the paraspinal musculature, ligaments and facet joints, plays a critical role in ASD development. Surgical techniques that cause extensive damage to the paraspinal muscles, ligaments and joints significantly alter spinal biomechanics, thereby increasing stress on adjacent segments (57). One study has demonstrated a strong correlation between extensive joint resection and a higher incidence of ASD (57). Moreover, ASD is more commonly observed in the intervertebral disc above the fused segment rather than the segment below, probably due to the biomechanical changes that increase stress on the superior adjacent segment (3). This stresses the importance of preserving the superior facet joint capsule during the initial surgery, as it plays a key role in maintaining the stability and biomechanics of the adjacent upper segment, potentially preventing the development of ASD. Additionally, damage to the spinous processes and surrounding muscles during open surgery can lead to scar formation and alterations in spinal mechanics, further contributing to the ASD development (58). Comparative studies have shown that traditional open surgeries, which involve extensive muscle dissection, result in higher rates of ASD compared with minimally invasive surgeries, which improve the preservation of the integrity of surrounding tissues (57). Furthermore, research has indicated that minimally invasive surgeries, which cause less disruption to the paraspinal muscles and ligaments, are associated with a lower incidence of ASD (59).

Different fixation methods. It is well known that the primary goal of fusion is to alleviate pain and prevent further spinal deformity by stabilizing the affected vertebral segments. Therefore, different fixation methods aim to achieve physiological spinal motion and a higher fusion rate, improving biomechanical compatibility and reducing ASD (60). One study has shown that the more rigid the instrumentation used, the earlier ASD tends to develop after fusion (61). Varol *et al* (60) and Hsiao *et al* (62) found that, compared with traditional rigid systems, the Dynesys dynamic system induced less range of motion in adjacent joints and preserved the intervertebral disc structure of adjacent segments, thereby reducing the incidence of ASD. Further biomechanical studies have shown that the hybrid Dynesys-Transition-Optima system, composed of both dynamic (flexible and non-fusion) and static (rigid and fusion) components, can significantly reduce the range of motion at the fusion level (L4-L5), while improve the preservation of the mobility of stable segments. This results in a reduced range of motion at the transitional segments, which may help prevent the occurrence of adjacent segment degeneration (62). Similarly, research by Guan *et al* (63) revealed that non-fusion techniques incorporating dynamic stabilization not only reduced the incidence of ASD but also maintained spinal stability.

Biological factors

Genetic predisposition. Although no direct studies have established a connection between ASD and genetic predisposition, evidence suggests a link between genetic factors and IDD, offering insights into ASD risk factors. A study of 205 Japanese volunteers and patients aged 20-29 found that the Tt genotype of the Taq I polymorphism in the vitamin D receptor was more frequently associated with multilevel disc disease, severe degeneration and disc herniation compared with the TT genotype, probably due to changes in the extracellular matrix (ECM) structure of the disc (7). Research indicates that cartilage intermediate layer protein (CILP) expression increases as disc degeneration progresses (64). A recent case-control study identified an association between degenerative disc disease in a Japanese cohort and the SNP +1184T→C in exon 8 of CILP. Given that CILP can bind to transforming growth factor-β or insulin-like growth factor-1, it may regulate ECM synthesis in the intervertebral disc, altering the extracellular microenvironment and promoting IDD (64). Furthermore, Research has highlighted that gene variations associated with inflammatory pathways, such as the functional SNP (+3954C→T) in exon 5 of the IL-1β gene, are linked to IDD and lower back pain (65).

Inflammatory mediators. Inflammatory cytokines, such as TNF-α and IL-1β, are also associated with the progression of the IDD (66). These mediators exacerbate degeneration by promoting catabolic processes within spinal tissues (66). One study suggested that targeting these inflammatory pathways

may be a viable strategy for preventing ASD (66). Elevated levels of IL-1β, IL-6, IL-8 and TNF-α have been observed in patients with degenerative disc disease (66,67). Chen *et al* (67) demonstrate in an animal model of SF associated with ASD that TNF-α and IL-1β expression in adjacent segment discs significantly increases over time. Additionally, research indicates that patients receiving TNF-α inhibitors preoperatively experienced a markedly higher rate of reoperation within 1 year due to issues such as fusion failure and ASD (68). Additionally, macrophage migration inhibitory factor (MIF) has been identified as a key factor in spinal degeneration. Research indicates that MIF may contribute to the hypertrophy of the lumbar ligamentum flavum in patients with type 2 diabetes mellitus, which is closely associated with the development of ASD (69). Furthermore, MIF can directly affect the vertebral endplates, modulating inflammation and matrix metabolism in degenerated cartilage endplate chondrocytes through the activation of the ERK1/2 pathway (70). Thus, more clinical and animal studies focusing on inflammatory factors could provide new insights into ASD prevention.

Biochemical environment. The alteration of the local biochemical environment in the spine is closely associated with IDD, particularly concerning nutrient supply, oxygen tension and pH levels (71). Adequate nutrient supply is crucial for maintaining disc cell activity and preventing degeneration (72). Disruptions in these factors accelerate disc degeneration, with aging leading to diminished nutrient supply, reduced oxygen, lower pH and impaired extracellular matrix synthesis (71). Research indicates that the functionality of nucleus pulposus cells is affected by the transport characteristics of the cartilaginous endplate. Degenerated endplates hinder nutrient transport, worsening IDD (72,73). Gilbert *et al* (74) demonstrate that increased acidity (lower pH) reduces disc cells vitality and enhances pro-inflammatory cytokines expression. Inhibiting acid-sensing ion channel-3 may offer therapeutic potential. Recent advances in understanding the biochemical environment of the spine have prompted the exploration of novel therapeutic approaches. For instance, the use of bioactive scaffolds and hydrogels has been investigated to enhance postoperative nutrient delivery and maintain intervertebral disc hydration (71,72). The alterations in the local biochemical environment of the spine, along with emerging therapeutic strategies, warrant further exploration for the prevention and management of ASD following SF surgery.

In addition to patient-related, surgical and biological factors, other variables such as postoperative rehabilitation and lifestyle factors play a critical role in the development and progression of ASD following SF.

Other factors

Patient education, compliance and psychological factors. Education provided by healthcare professionals on postoperative health and pain management significantly affects patient adherence and understanding of their condition (75). Thys *et al* (75) found that surgeons often impose stricter postoperative restrictions compared with physical therapists, some of whom advocate for no restrictions. Mental health conditions, including anxiety and depression, are risk factors for ASD following SF surgery (12,76). Studies found that preoperative and early postoperative fear of movement significantly influences postoperative pain and functional rehabilitation in patients undergoing SF (77,78). Therefore, combining exercise rehabilitation programs with cognitive behavioral therapy and patient-centered goal-directed therapies may enhance patient recovery and help prevent postoperative ASD.

Smoking and alcohol. Alcohol consumption and smoking are potential risk factors for ASD following SF surgery, though the relationship remains debated. Smoking has been shown to reduced blood flow, lower oxygen levels and impair nutrient supply to spinal tissues. Additionally, smoking can decrease estrogen levels, increasing the risk of osteoporosis and spinal fractures, as well as the likelihood of pseudarthrosis in fusion surgery patients (8). One study advocated for mandatory smoking cessation for at least four weeks postoperatively (8). Evidence shows that smokers have a significantly higher incidence of ASD following SF compared with non-smokers (79). While the direct effect of alcohol on ASD is less studied, it is known to lower bone density, increase fracture risk and impair bone healing and regeneration, all of which may indirectly elevate the risk of ASD (80). However, one study argued that alcohol consumption and smoking are not risk factors for ASD, highlighting the limitations of retrospective research (20). Addressing lifestyle factors, such as smoking and alcohol consumption, is crucial in the management of patients undergoing SF surgery. Healthcare providers should emphasize smoking cessation and reducing alcohol intake to mitigate the risk of ASD and improve overall surgical outcomes.

In summary, while the role of these factors (patient education, compliance, psychological health, smoking and alcohol use) may be under-researched specifically in the context of ASD, their influence on broader spinal surgery outcomes is well-established. Thus, they are highlighted as significant contributors to postoperative success and further investigation is encouraged to solidify these associations in the context of ASD.

3. Treatment strategies for ASD

Diagnosing ASD requires a comprehensive approach, combining clinical evaluation, imaging studies and patient history. Clinically, symptoms such as pain and recurrent neurological deficits are assessed, while imaging (especially MRI and CT) help detect degenerative changes in adjacent segments, such as disc herniation and facet joint arthritis. One study indicated that symptomatic ASD occur in 16.5% of patients at five years and 36.1% at ten years post-fusion (81), highlighting the importance of vigilant postoperative monitoring. Management strategies for ASD include conservative treatments and surgical interventions. Treatment recommendations should be individually based on symptom severity, degree of degeneration, overall health status and patient preferences.

Conservative treatment. Conservative treatments are often the first line of defense in managing patients with ASD, particularly in those with mild to moderate symptoms. These treatments aim to relieve symptoms, improve functional capacity and delay the need for surgical intervention by addressing the mechanical and inflammatory aspects of ASD.

Postoperative rehabilitation therapy. Following SF surgery for degenerative spinal diseases, patients often experience a

protective state in the spine, making it challenging to full return to normal function quickly (82). Appropriate postoperative rehabilitation therapy not only improves functional capacity but also strengthens the muscles supporting the spine, helping distribute mechanical loads more evenly and reducing stress on adjacent segments (83). Although there is no consensus on the optimal timing, intensity and duration of rehabilitation after fusion surgery (83), early endurance and muscle strengthening exercises to restore core balance significantly enhance back strength, alleviate pain and reduce disability (83). Changes in paravertebral muscle size following cervical, lumbar and thoracolumbar fusion surgeries are significant risk factors for ASD (58,84,85). For instance, research by Xu *et al* (58) demonstrate a reduction in the functional area of the multifidus and erector spinae muscles, along with an increase in the functional area of the psoas major muscle following L4-S1 PLIF. Furthermore, Zhou *et al* (82) reveal that gait alterations (such as stride length, speed and cadence) and post-minimally invasive transforaminal interbody fusion may affect spinal-pelvic and lower limb joint parameters, underscoring the importance of postoperative rehabilitation in preventing ASD. Research indicates that physical therapy methods such as flexion-distraction techniques, high-velocity low-amplitude adjustments and thermotherapy may effectively relieve pain following fusion surgery (9,86). Additionally, therapies such as myofascial release and acupuncture, commonly used by chiropractors, benefit postoperative care following lumbar fusion surgery (9). Gliedt *et al* (87) report that stimulating multiple acupuncture points and auricular therapy effectively reduces postoperative pain. Compared with traditional rehabilitation, electroacupuncture demonstrates significant improvements in functional recovery following lumbar fusion surgery (88). To address ASD risk factors, it is essential to develop a detailed postoperative rehabilitation treatment plan that involves collaboration orthopedic and rehabilitation physicians.

Pharmacological treatment. Similar to the initial treatment for degenerative disc disease and radiculopathy, ASD can be managed with physical therapy, rehabilitation therapies such as early back bracing and lifestyle modifications such as avoiding excessive weight and bending (89). Medication, including non-steroidal anti-inflammatory drugs, steroids and muscle relaxants, can relieve clinical symptoms (90). Recently, small molecule drugs such as naringin have shown promise in preventing further degeneration of disc cells and enhancing regeneration, but most are still in early stages and have not been applied in clinical studies (91). Non-surgical treatment should be the first choice for ASD, as long as significant clinical improvement is observed, regardless of imaging findings (89). However, research comparing non-surgical and surgical treatments for ASD is lacking, highlighting the need for more in-depth studies.

Epidural steroid injections (ESIs). Research indicates that ~20% of patients experience pain following surgeries for spinal stenosis or herniated discs, necessitating additional measures to alleviate this pain (92). When conservative treatments such as rehabilitation techniques and pharmacotherapy prove ineffective, ESIs may be used. Corticosteroids reduce inflammatory and edema by inhibiting inflammatory mediators, resulting in pain relief (93). Interventional treatments via different approaches, such as interlaminar, transforaminal and caudal, demonstrate promising outcomes for various types of chronic back pain (93). For instance, Song *et al* demonstrated that both transforaminal and caudal ESIs effectively alleviated chronic pain and improved function following spinal surgery (92). Additionally, Park *et al* showed that nerve root blocks and interlaminar epidural steroid injections were effective in relieving cervical radicular pain and enhancing function (94). While the relief provided by nerve root blocks is typically temporary, they can be used as a diagnostic tool to confirm the source of a patient's symptoms and guide further treatment decisions. However, the efficacy of ESIs in the treatment of ASD warrants further clinical investigation to establish its benefits conclusively.

Facet joint interventions. ASD following SF surgery often involves degeneration of the facet joints, which can cause referred or radicular pain (95). Direct injection of medications into affected facet joints or thermal ablation to target pain-transmitting nerve fibers are viable treatment options (95). Evidence-based guidelines for managing chronic spinal pain recommends various facet joint interventions, including corticosteroid injections, saline injections, facet joint nerve blocks and radiofrequency ablation, depending on the specific spinal segment involved (96). Recently, procedures guided by ultrasound or CT improved the accuracy, safety and efficacy of these interventions (97). For example, Wong and Rajarathinam (97) demonstrate that the accuracy of ultrasound-guided injections into the cervical facet joints and their innervating nerves ranged from 78-100%, while the accuracy for lumbar facet intra-articular injections was between 86-100%. Compared with fluoroscopy or CT-guided methods, ultrasound guidance resulted in shorter procedure times with comparable pain relief outcomes (97). Similarly, research by Suputtitada *et al* (98) demonstrate that intra-articular injections of saline, corticosteroids and anesthetics provide favorable long-term clinical outcomes for patients with chronic low back pain. For patients who do not achieve long-term relief from facet joint injections, radiofrequency ablation (RFA) is a minimally invasive procedure that targets the nerve fibers transmitting pain signals from the degenerated facet joints (99). By using heat to ablate these nerve fibers, RFA provides longer-lasting pain relief compared with injections alone (99). A study has shown that RFA can significantly reduce pain and improve function in patients with chronic low back pain-related facet joint degeneration, making it a valuable tool in the interventional management of ASD (99). However, these treatment modalities are insufficiently emphasized in the management of ASD, with limited related literature available. Orthopedic surgeons should not focus solely on surgical interventions for ASD.

Surgical interventions. In cases of ASD following SF, only 6% of patients with significant clinical symptoms require additional surgical intervention (90). Surgical interventions are a crucial treatment option for patients with ASD, especially when conservative therapies fail to provide adequate symptom relief or when significant spinal instability and neurological deficits are present (16). Spinal instability or structural deformities, such as kyphosis or spondylolisthesis, often require surgical correction to prevent further degeneration and potential damage to the spinal cord or nerve

Table I. Treatment strategies for adjacent segment disease.

Treatment strategies	Treatment method	(Refs.)
Conservative treatment	Postoperative rehabilitation therapy	(9,57,83-89)
	Pharmacological treatment	(91,92)
	Epidural steroid injections	(93-95)
	Facet joint interventions	(97-100)
Surgical interventions	Total disc replacement	(101,102)
	Extension of fusion	(105-107)
	Decompression surgery	(108-110)
	Minimally invasive surgery	(111-115)
	Oblique lateral interbody fusion	(116-118)
	Zero-profile interbody fusion	(120,121)
Emerging treatments	Stem cell and exosome therapies	(123,124)
	Annulus fibrosus repair	(124)
	Tissue engineering	(123)
	Nanoparticle drug delivery systems	(126)
	Growth factor injections	(126)
	3D-printed interbody cages and PEEK cage	(127,128)

PEEK, polyetheretherketone.

roots (16). However, as with any surgical procedure, there are risks involved, including the potential for further degeneration at other levels of the spine. Careful preoperative planning and postoperative rehabilitation are essential to optimize outcomes and minimize complications. The choice of surgical procedure depends on the specific pathology and the patient's overall health status.

Total disc replacement (TDR). TDR is an alternative to fusion that involves replacing the degenerated disc with an artificial disc. TDR has emerged as a significant alternative to traditional fusion techniques for the treatment of degenerative disc disease and ASD. The primary advantage of TDR is its ability to preserve motion at the affected segment, which is in contrast to fusion, where the vertebrae are permanently immobilized (100). By maintaining the natural biomechanics of the spine, TDR reduces the mechanical stress placed on adjacent segments, potentially decreasing the risk of degeneration at these levels (100). TDR shows favorable outcomes in selected patients, with improvements in pain, function and range of motion (100). Rajakumar *et al* (100) demonstrate that cervical TDR surgery effectively alleviates nerve compression-related symptoms caused by ASD following ACDF. Additionally, none of the patients required further surgery at the same vertebral level during the three-year follow-up period. A study demonstrated that in the treatment of ASD, TDR provided an improved range of motion at C2-C7 over a follow-up period of more than one year compared with ACDF (40.2 vs. 35.1˚; P=0.001) (101). Additionally, TDR shows comparable outcomes in terms of improvement in the neck disability index, neck visual analog scale and upper limb function (101). However, TDR is not suitable for all patients, particularly those with pre-existing joint degeneration. One study showed no difference in the incidence of ASD between TDR and fusion surgery (102). This finding necessitates more rigorous evaluation of the efficacy of TDR for treating ASD post-fusion surgery, including larger sample sizes and longer follow-up periods. Therefore, careful patient selection is crucial to ensure the success of the procedure.

Extension of fusion. Extended fusion surgery has been extensively studied and widely applied as an effective intervention for treating ASD following SF. This approach aims to reduce degeneration caused by biomechanical stress transfer by extending the fusion to include affected adjacent segments (103). It is particularly suitable for patients with significant ASD and accompanying clinical symptoms, such as spinal instability (90). This method involves the addition of instrumentation and performing fusion at the affected segments to stabilize the spine (104). Research indicates that combining extended fusion with decompression surgery alleviates symptoms and reduces the need for subsequent surgeries during long-term follow-up (104). However, compared with traditional surgeries, extended fusion is associated with greater trauma, longer operative times and potential complications (105). To address these drawbacks, recent advancements introduced modified techniques, such as using connectors to extend fixation without removing the existing hardware, which was showed to significantly reduce surgical trauma and costs (106). Nonetheless, further randomized controlled trials are essential to determine the long-term outcomes of various surgical strategies, particularly in the context of advancing minimally invasive techniques.

Decompression surgery. Decompression surgery is recommended for patients with significant nerve root compression, leading to radiculopathy or myelopathy following SF. However, it is not ideal for patients with pre-existing spinal kyphosis or instability (90,107). Procedures, such as laminectomy, laminoplasty and foraminotomy, aim to relieve the spinal cord or nerve roots pressure, alleviating pain and improving

neurological function (107). Yang *et al* (107) found that laminectomy with instrumentation effectively improves symptoms and function in ASD patients following anterior cervical corpectomy and fusion (ACCF), though lordosis gradually declined. He *et al* (108) report that in ASD patients following ACCF or ACDF, laminoplasty provides satisfactory clinical outcomes when cervical lordosis was <10˚ and spinal canal encroachment occupied <50% of the canal's cross-sectional area. Früh *et al* (109) showed that microscopic decompression reduced operative time and trauma in lumbar ASD. However, microscopic surgery significantly reduced operative time and surgical trauma.

Minimally invasive surgery (MIS). MIS has become an essential approach in the management of ASD due to its numerous benefits over traditional open surgery (59). MIS techniques, such as endoscopic decompression, minimally invasive fusion and robot-assisted cortical bone trajectory (CBT) screw fixation, aim to minimize the damage to paraspinal muscles, ligaments and other soft tissues, which are often compromised in open procedures. The preservation of these structures is critical for maintaining spinal stability and reducing the risk of further degeneration in adjacent segments (59). Han *et al* (110) demonstrate that percutaneous endoscopic lumbar foraminotomy and interlaminar decompression effectively alleviate ASD symptoms following lumbar decompression surgery. Feng *et al* (111) report that for elderly patients with ASD following lumbar fusion, presenting with unilateral radiculopathy or intermittent claudication and showing radiographic stability, percutaneous full-endoscopic lumbar discectomy is a viable alternative. Additionally, one study showed favorable outcomes with the unilateral biportal endoscopic approach (112). Furthermore, minimally invasive discectomy, without fusion, proves effective in treating new-onset cervical disc herniation in patients with previous multilevel fusion (113). Robot-assisted CBT screw fixation is identified as an effective salvage strategy for ASD after lumbar fusion (114). Moreover, MIS techniques can be combined depending on the disease characteristics, such as integrating percutaneous spinal endoscopy with fusion techniques and CBT screw placement (59). However, no standardized criteria currently exist for selecting surgical methods and further studies with larger sample sizes and longer follow-up periods are needed to evaluate the efficacy of these revision surgeries.

OLIF (Oblique lateral interbody fusion) technique. The OLIF technique accesses the intervertebral disc via the natural corridor between the peritoneum and the psoas muscle, minimizing trauma to posterior muscles, ligaments and other structures (115). This approach reduces the risks of vascular and nerve plexus injuries, as well as postoperative low back pain (116). OLIF also facilitates the removal of substantial disc tissue, increasing the fusion surface area, which enhances fusion rates (115,116). OLIF alone is an effective option for symptomatic adult ASD (115). Compared with PLIF, OLIF demonstrates superior outcomes in terms of the operative time, blood loss, postoperative complications and restoration of disc height (116). However, OLIF provides only indirect decompression, which may be inadequate for patients with large disc herniations, ossifications, or spinal stenosis (115). One study indicated that complication rates after lateral approaches (lateral lumbar interbody fusion, LLIF or OLIF) and posterior approaches (PLIF or TLIF) are similar when treating ASD. Lateral approaches may increase the risk of radicular pain due to manipulation of the psoas muscle (117). Therefore, surgical decisions must be carefully tailored to the specific characteristics of the patient's ASD.

Zero-profile (Zero-P) interbody fusion for cervical ASD. With the increasing clinical application of ACDF and ACCF and longer follow-up periods, ASD has gained attention from spine surgeons, with a number of cases requiring surgical treatment. Scar tissue and prior anterior fixation devices limit the space for revision surgeries, often necessitating hardware removal, which prolongs operative time and increases blood loss (118). The Zero-P system, a stand-alone device developed for ACDF, reduces complications such as dysphagia and esophageal injury while providing the benefits of fusion and anterior plating (119). However, one study suggested that the Zero-P system is not recommended for single-segment ASD cases with severe ossification of the posterior longitudinal ligament, osteoporosis, or vertebral fractures (120). Moreover, there is a lack of prospective studies and long-term follow-up observations on its use in ASD surgeries, raising concerns about its long-term efficacy and safety in these specific patient populations.

4. Emerging treatments and future directions

Compared with primary lumbar fusion surgery, revision lumbar fusion is linked to higher rates of reoperation and subsequent revision surgeries (121). This can lead to a vicious cycle, particularly in younger patients undergoing SF. Therefore, innovative treatments for IDD are urgently needed. Recent advances in biological therapies offer potential solutions in this area, providing new hope for more effective interventions. Techniques or materials such as stem cell and exosome therapies, growth factor injections, annulus fibrosus repair, tissue engineering, biocompatible interbody cages made from polyetheretherketone (PEEK), 3D-printed implants and nanoparticle drug delivery systems were designed to promote the regeneration and repair of intervertebral discs (122-127). Yu *et al* (122) demonstrate that transplanting of menstrual blood-derived stem cells embedded in collagen I gel into annulus fibrosus defects after discectomy in rats preserves disc structure and prevents post-discectomy disc degeneration. Jia *et al* (123) found that injecting acellular/drug hydrogels with nucleus pulposus-matched viscoelasticity maintains the viability of nucleus pulposus cells under pathological loading conditions, showing potential for post-discectomy repair. In a study of patients 12 weeks post-discectomy, autologous disc chondrocyte transplantation provided long-term pain relief over a two-year follow-up period, although it did not alter disc height (124). Meng *et al* (125) developed a high-strength smart microneedle capable of locally penetrating annulus fibrosus tissue, with near-infrared remote-controlled drug release to restore the biomechanical properties of the disc. The studies of Dou *et al* (126) and Wang *et al* (127) demonstrate that posterior lumbar decompression, fixation and fusion effectively reconstructs lumbar stability, with fusion rates for 3D-printed interbody cages and PEEK cage groups

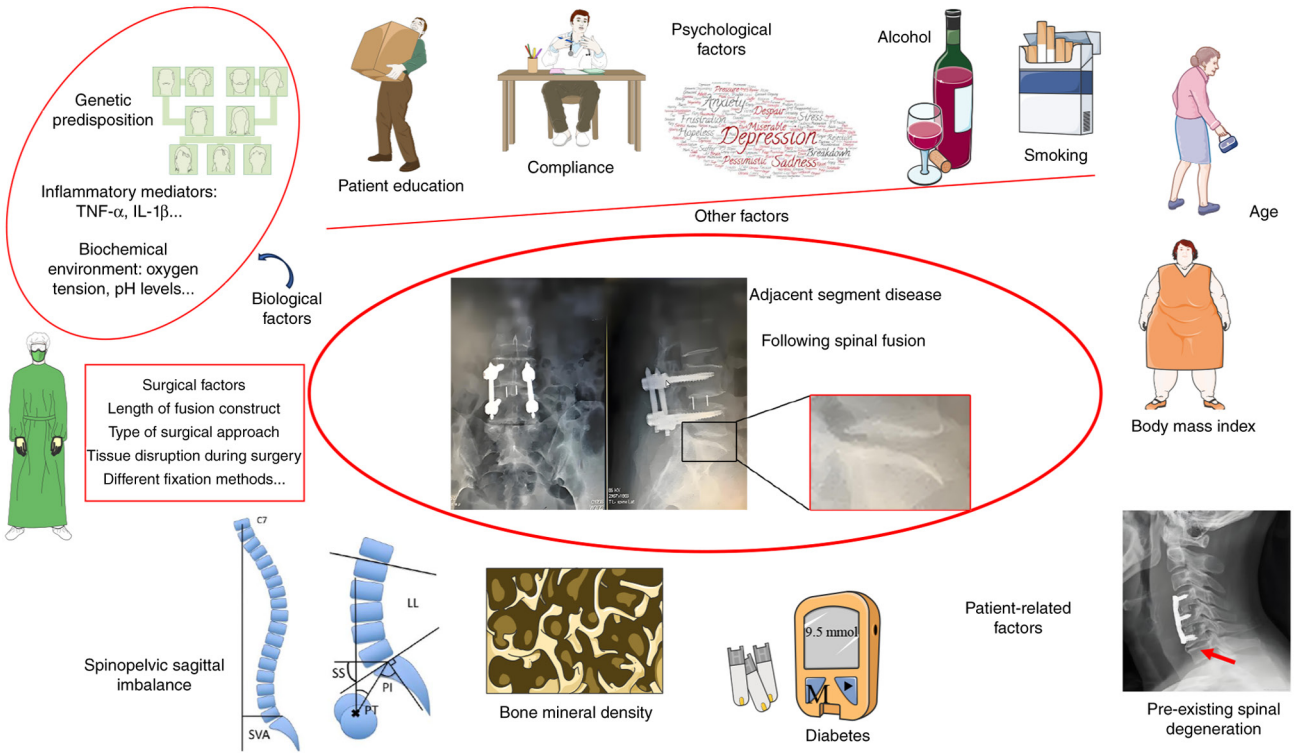

Figure 1. Risk factors for adjacent segment disease. SS, sacral slope; SVA, spine axis deviation, PT, pelvic tilt; LL, reduced lordosis; PI, pelvic incidence; TNF-α, tumor necrosis factor-α; IL-1β, interleukin-1β.

reaching 89.13 and 90.91%, respectively. Notably, excellent interbody fusion can be achieved without the need for bone grafting (126,127). Encouragingly, a number of other biological therapies such as gene editing technologies were currently under investigation. However, since most of these therapies remain in the experimental stage (Table I), further research is necessary to establish their efficacy and safety in clinical practice.

5. Conclusion and future perspectives

While fusion itself may exacerbate the degeneration of adjacent spinal levels, the question of whether ASD results from the natural progression of the disease or the fusion surgery itself remains contentious (128). The present review identified several potential risk factors for ASD following SF, including patient-related variables such as age, BMI, BMD, diabetes and overall health, as well as surgical factors such as the length of the fusion segment, the surgical approach and specific technical choices (Fig. 1).

In conclusion, ASD remains a challenging complication of spinal fusion surgery, with both mechanical and biological factors contributing to its development. Current treatment strategies, including conservative management, interventional procedures and surgical interventions, provide varying levels of relief, but the risk of further degeneration persists. Emerging treatments, such as stem cell therapy, exosome-based treatments and gene therapy, offer promising new avenues for addressing the underlying causes of ASD. These therapies aim to restore the biomechanical and biochemical environment of the intervertebral disc, potentially reducing the need for revision surgeries. MIS techniques also show potential in reducing tissue damage and promoting faster recovery, further contributing to improved long-term outcomes for ASD patients.

Future research should focus on large-scale clinical trials to validate the safety and efficacy of these emerging therapies. Additionally, multidisciplinary approaches that integrate biological, mechanical and patient-specific factors will be essential for optimizing treatment strategies and improving patient outcomes.

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XH was responsible for reviewing the concept design, article writing and proofreading. YC, KC, QR, BH, GW, YW and JL participated in the literature collection, analysis and summary. JZ was involved in drafting the manuscript and revising it critically for important intellectual content. Data authentication is not applicable. All authors read and approved the final manuscript.

Ethics approval and consent to participate

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Competing interests

The authors declare that they have no competing interests.

References

1. Wang K, Wang X, Li Z, Xie T, Wang L, Luo C, Huang S and Zeng J: The influence of screw positioning on cage subsidence in patients with oblique lumbar interbody fusion combined with anterolateral fixation. Orthop Surg 15: 3263-3271, 2023.
2. Nakajima H, Watanabe S, Honjoh K, Kubota A and Matsumine A: Risk factors for early-onset adjacent segment degeneration after one-segment posterior lumbar interbody fusion. Sci Rep 14: 9145, 2024.
3. Hilibrand AS and Robbins M: Adjacent segment degeneration and adjacent segment disease: The consequences of spinal fusion? Spine J 4 (Suppl 6): 190S-194S, 2004.
4. Shahzad H, Alvarez PM, Pallumeera M, Bhatti N, Yu E, Phillips FM, Khan SN and Singh VK: Exploring the incidence and risk factors of reoperation for symptomatic adjacent segment disease following cervical decompression and fusion. N Am Spine Soc J 17: 100305, 2023.
5. Sears WR, Sergides IG, Kazemi N, Smith M, White GJ and Osburg B: Incidence and prevalence of surgery at segments adjacent to a previous posterior lumbar arthrodesis. Spine J 11: 11-20, 2011.
6. Helgeson MD, Bevevino AJ and Hilibrand AS: Update on the evidence for adjacent segment degeneration and disease. Spine J 13: 342-351, 2013.
7. Pinto EM, Teixeria A, Frada R, Oliveira F, Atilano P, Veigas T and Miranda A: Patient-related risk factors for the development of lumbar spine adjacent segment pathology. Orthop Rev (Pavia) 13: 24915, 2021.
8. Berman D, Oren JH, Bendo J and Spivak J: The effect of smoking on spinal fusion. Int J Spine Surg 11: 29, 2017.
9. Daniels CJ, Wakefield PJ, Bub GA and Toombs JD: A narrative review of lumbar fusion surgery with relevance to chiropractic practice. J Chiropr Med 15: 259-271, 2016.
10. Wilson C, Czernik PJ, Elgafy H, Khuder S, Serdahely K, Rowland A and Lecka-Czernik B: Diabetes increases risk of lumbar spinal fusion complications: association with altered structure of newly formed bone at the fusion site. JBMR Plus 8: ziae053, 2024.
11. Saghebdous S, Zare R, Chaurasia B, Vakilzadeh MM, Yousefi O and Boustani MR: Dynamic rod constructs as the preventive strategy against adjacent segment disease in degenerative lumbar spinal disorders: A retrospective comparative cohort study. Arch Bone Jt Surg 11: 404-413, 2023.
12. Wu JC, Chang HK, Huang WC and Chen YC: Risk factors of second surgery for adjacent segment disease following anterior cervical discectomy and fusion: A 16-year cohort study. Int J Surg 68: 48-55, 2019.
13. Tobert DG, Antoci V, Patel SP, Saadat E and Bono CM: Adjacent segment disease in the cervical and lumbar spine. Clin Spine Surg 30: 94-101, 2017.
14. Wei Z, Yang S, Zhang Y, Ye J and Chu T: Prevalence and risk factors for cervical adjacent segment disease and analysis of the clinical effect of revision surgery: A minimum of 5 years' follow-up. Global Spine J: Jul 8, 2023 (Epub ahead of print).
15. Mesregah MK, Yoshida B, Lashkari N, Abedi A, Meisel HJ, Diwan A, Hsieh P, Wang JC, Buser Z and Yoon ST; AO Spine Knowledge Forum Degenerative: Demographic, clinical, and operative risk factors associated with postoperative adjacent segment disease in patients undergoing lumbar spine fusions: A systematic review and meta-analysis. Spine J 22: 1038-1069, 2022.
16. Cannizzaro D, Anania CD, Safa A, Zaed I, Morenghi M, Riva M, Tomei M, Pessina F, Servadei F, Ortolina A and Fornari M: Lumbar adjacent segment degeneration after spinal fusion surgery: A systematic review and meta-analysis. J Neurosurg Sci 67: 740-749, 2023.
17. Tomé-Bermejo F, Moreno-Mateo F, Piñera-Parrilla Á, Cervera-Irimia J, Mengis-Palleck CL, Gallego-Bustos J, Garzón-Márquez F, Rodríguez-Arguisjuela MG, Sanz-Aguilera S, de la Rosa-Zabala KL, *et al*: Instrumented lumbar fusion in patients over 75 years of age: is it worthwhile?-A comparative study of the improvement in quality of life between elderly and young patients. J Spine Surg 9: 247-258, 2023.
18. Zhong ZM, Deviren V, Tay B, Burch S and Berven SH: Adjacent segment disease after instrumented fusion for adult lumbar spondylolisthesis: Incidence and risk factors. Clin Neurol Neurosurg 156: 29-34, 2017.
19. Ankrah NK, Eli IM, Magge SN, Whitmore RG and Yew AY: Age, body mass index, and osteoporosis are more predictive than imaging for adjacent-segment reoperation after lumbar fusion. Surg Neurol Int 12: 453, 2021.
20. Broida SE, Murakami K, Abedi A, Meisel HJ, Hsieh P, Wang J, Jain A, Buser Z and Yoon ST; AO Spine Knowledge Forum Degenerative: Clinical risk factors associated with the development of adjacent segment disease in patients undergoing ACDF: A systematic review. Spine J 23: 146-156, 2023.
21. Wang F, Hou HT, Wang P, Zhang JT and Shen Y: Symptomatic adjacent segment disease after single-lever anterior cervical discectomy and fusion: Incidence and risk factors. Medicine (Baltimore) 96: e8663, 2017.
22. Yuan C, Zhou J, Wang L and Deng Z: Adjacent segment disease after minimally invasive transforaminal lumbar interbody fusion for degenerative lumbar diseases: Incidence and risk factors. BMC Musculoskelet Disord 23: 982, 2022.
23. Demir Ö, Öksüz E, Deniz FE and Demir O: Assessing the effects of lumbar posterior stabilization and fusion to vertebral bone density in stabilized and adjacent segments by using Hounsfield unit. J Spine Surg 3: 548-553, 2017.
24. Zhang C, Chang M, Zhang R and Tang S: Biomechanical effects of osteoporosis on adjacent segments after posterior lumbar interbody fusion: A finite element study. Pak J Med Sci 37: 403-408, 2021.
25. Dash AS, Billings E, Vlastaris K, Kim HJ, Cunningham ME, Raphael J, Lovecchio F, Carrino JA, Lebl D, McMahon D and Stein EM: Pre-operative bone quality deficits and risk of complications following spine fusion surgery among postmenopausal women. Osteoporos Int 35: 551-560, 2024.
26. Wang SK, Wang P, Li XY, Kong C, Niu JY and Lu SB: Incidence and risk factors for early and late reoperation following lumbar fusion surgery. J Orthop Surg Res 17: 385, 2022.
27. Gong DC, Baumann AN, Muralidharan A, Piche JD, Anderson PA and Aleem I: The association of preoperative bone mineral density and outcomes after anterior cervical discectomy and fusion: A systematic review. Clin Spine Surg: Jul 23, 2024 (Epub ahead of print).
28. Lechtholz-Zey EA, Ayad M, Gettleman BS, Mills ES, Shelby H, Ton AT, Shah I, Wang JC, Hah RJ and Alluri RK: Systematic review and meta-analysis of the effect of osteoporosis on reoperation rates and complications after surgical management of lumbar degenerative disease. J Bone Metab 31: 114-131, 2024.
29. Zhou Z, Tian FM, Wang P, Gou Y, Zhang H, Song HP, Wang WY and Zhang L: Alendronate prevents intervertebral disc degeneration adjacent to a lumbar fusion in ovariectomized rats. Spine (Phila Pa 1976) 40: E1073-E1083, 2015.
30. Bagheri SR, Alimohammadi E, Zamani Froushani A and Abdi A: Adjacent segment disease after posterior lumbar instrumentation surgery for degenerative disease: Incidence and risk factors. J Orthop Surg (Hong Kong) 27: 2309499019842378, 2019.
31. Thever Y, Han Lincoln LM, Gatot C and Chee Cheong RS: Do diabetic patients have poorer clinical and radiological outcomes following minimally invasive transforaminal lumbar interbody fusion? Int J Spine Surg 17: 708-714, 2023.
32. Russo A, Park DK, Lansford T, Nunley P, Peppers TA, Wind JJ, Hassanzadeh H, Sembrano J, Yoo J and Sales J: Impact of surgical risk factors for non-union on lumbar spinal fusion outcomes using cellular bone allograft at 24-months follow-up. BMC Musculoskelet Disord 25: 351, 2024.
33. Lee CS, Hwang CJ, Lee SW, Ahn YJ, Kim YT, Lee DH and Lee MY: Risk factors for adjacent segment disease after lumbar fusion. Eur Spine J 18: 1637-1643, 2009.
34. Pang L, Gao Z, Ma L, Li Y, Lu Z, Zhang L, Li P and Wu L: Comparison of short-segment and long-segment fixation in treatment of degenerative scoliosis and analysis of factors associated with adjacent spondylolisthesis. Open Med (Wars) 19: 20240983, 2024.

35. Kim JY, Ryu DS, Paik HK, Ahn SS, Kang MS, Kim KH, Park JY, Chin DK, Kim KS, Cho YE and Kuh SU: Paraspinal muscle, facet joint, and disc problems: Risk factors for adjacent segment degeneration after lumbar fusion. Spine J 16: 867-875, 2016.
36. Tan L, Du X, Tang R, Rong L and Zhang L: Preoperative adjacent facet joint osteoarthritis is associated with the incidence of adjacent segment degeneration and low back pain after lumbar interbody fusion. Asian Spine J 18: 21-31, 2024.
37. Weishaupt D, Zanetti M, Boos N and Hodler J: MR imaging and CT in osteoarthritis of the lumbar facet joints. Skeletal Radiol 28: 215-219, 1999.
38. Mu YZ, Chen X and Zhao B: Effect of adjacent segmental facet joint degeneration on adjacent segment disease after lumbar fusion and fixation. Zhongguo Gu Shang 36: 428-431, 2023 (In Chinese).
39. Ekman P, Möller H, Shalabi A, Yu YX and Hedlund R: A prospective randomised study on the long-term effect of lumbar fusion on adjacent disc degeneration. Eur Spine J 18: 1175-1186, 2009.
40. Zhu Q, Li N, Ding Y, Zhang Z, Jiang W, Jiang T, Qiao Q, Qian Y and Cheng H: Incidence of adjacent segment degeneration and its associated risk factors following anterior cervical discectomy and fusion: A meta-analysis. World Neurosurg 183: e153-e172, 2024.
41. Todd KH, Funk KG, Funk JP and Bonacci R: Clinical significance of reported changes in pain severity. Ann Emerg Med 27: 485-489, 1996.
42. Fairbank JC, Couper J, Davies JB and O'Brien JP: The Oswestry low back pain disability questionnaire. Physiotherapy 66: 271-273, 1980.
43. Sun Z, Li W, Guo Y, Zhou S, Xu F, Chen Z, Qi Q, Guo Z, Zeng Y and Sun C: Effect of pre-existing adjacent segment degeneration on short-term effectiveness after lumbar fusion surgery. Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi 33: 837-844, 2019 (In Chinese).
44. Matsumoto T, Okuda S, Nagamoto Y, Takahashi Y, Furuya M and Iwasaki M: Spinopelvic sagittal realignment and incidence of adjacent segment disease after single-segment posterior lumbar inter-body fusion using 12° lordotic cages-a 2-year prospective cohort study. J Spine Surg 9: 269-277, 2023.
45. Tartara F, Garbossa D, Armocida D, Di Perna G, Ajello M, Marengo N, Bozzaro M, Petrone S, Giorgi PD, Schirò GR, *et al*: Relationship between lumbar lordosis, pelvic parameters, PI-LL mismatch and outcome after short fusion surgery for lumbar degenerative disease. Literature review, rational and presentation of public study protocol: RELApSE study (registry for evaluation of lumbar artrodesis sagittal alignEment). World Neurosurg X 18: 100162, 2023.
46. Park JS, Shim KD, Song YS and Park YS: Risk factor analysis of adjacent segment disease requiring surgery after short lumbar fusion: The influence of rheumatoid arthritis. Spine J 18: 1578-1583, 2018.
47. Loder RT, Urquhart A, Steen H, Graziano G, Hensinger RN, Schlesinger A, Schork MA and Shyr Y: Variability in Cobb angle measurements in children with congenital scoliosis. J Bone Joint Surg Br 77: 768-770, 1995.
48. Okuda S, Yamashita T, Matsumoto T, Nagamoto Y, Sugiura T, Takahashi Y, Maeno T and Iwasaki M: Adjacent segment disease after posterior lumbar interbody fusion: A case series of 1000 patients. Global Spine J 8: 722-727, 2018.
49. Burch MB, Wiegers NW, Patil S and Nourbakhsh A: Incidence and risk factors of reoperation in patients with adjacent segment disease: A meta-analysis. J Craniovertebr Junction Spine 11: 9-16, 2020.
50. Zhang C, Berven SH, Fortin M and Weber MH: Adjacent segment degeneration versus disease after lumbar spine fusion for degenerative pathology: A systematic review with meta-analysis of the literature. Clin Spine Surg 29: 21-29, 2016.
51. Alentado VJ, Lubelski D, Healy AT, Orr RD, Steinmetz MP, Benzel EC and Mroz TE: Predisposing characteristics of adjacent segment disease after lumbar fusion. Spine (Phila Pa 1976) 41: 1167-1172, 2016.
52. Wang T and Ding W: Risk factors for adjacent segment degeneration after posterior lumbar fusion surgery in treatment for degenerative lumbar disorders: A meta-analysis. J Orthop Surg Res 15: 582, 2020.
53. Ke W, Chen C, Wang B, Hua W, Lu S, Song Y, Luo R, Liao Z, Li G, Ma L, *et al*: Biomechanical evaluation of different surgical approaches for the treatment of adjacent segment diseases after primary anterior cervical discectomy and fusion: A finite element analysis. Front Bioeng Biotechnol 9: 718996, 2021.
54. Epstein NE and Agulnick MA: Cervical disc arthroplasty (CDA)/total disc replacement (TDR) vs. anterior cervical diskectomy/fusion (ACDF): A review. Surg Neurol Int 13: 565, 2022.
55. Bydon M, Xu R, De la Garza-Ramos R, Macki M, Sciubba DM, Wolinsky JP, Witham TF, Gokaslan ZL and Bydon A: Adjacent segment disease after anterior cervical discectomy and fusion: Incidence and clinical outcomes of patients requiring anterior versus posterior repeat cervical fusion. Surg Neurol Int 5 (Suppl 3): S74-S78, 2014.
56. Liu WJ, Hu L, Chou PH, Wang JW and Kan WS: Comparison of anterior cervical discectomy and fusion versus posterior cervical foraminotomy in the treatment of cervical radiculopathy: A systematic review. Orthop Surg 8: 425-431, 2016.
57. Jeong TS, Son S, Lee SG, Ahn Y, Jung JM and Yoo BR: Comparison of adjacent segment disease after minimally invasive versus open lumbar fusion: A minimum 10-year follow-up. J Neurosurg Spine 36: 525-533, 2022.
58. Xu F, Zhou S, Sun Z, Jiang S, Han G and Li W: Relationship between the postoperative variations of paraspinal muscles and adjacent-segment degeneration in patients with degenerative lumbar spinal stenosis after posterior instrumented lumbar fusion. J Neurosurg Spine 40: 551-561, 2024.
59. Liu DS, Wang YX and Rexiti P: Progress in minimally invasive surgery for adjacent segment disease after lumbar fusion. Zhonghua Wai Ke Za Zhi 61: 722-727, 2023 (In Chinese).
60. Varol E, Etli MU, Avci F, Yaltirik CK, Ramazanoglu AF, Onen MR and Naderi S: Comparison of clinical and radiological results of dynamic and rigid instrumentation in degenerative lumbar spinal stenosis. J Craniovertebr Junction Spine 13: 350-356, 2022.
61. Kim CH, Chung CK and Jahng TA: Comparisons of outcomes after single or multilevel dynamic stabilization: Effects on adjacent segment. J Spinal Disord Tech 24: 60-67, 2011.
62. Hsiao CK, Tsai YJ, Yen CY, Li YC, Hsiao HY and Tu YK: Biomechanical effect of hybrid dynamic stabilization implant on the segmental motion and intradiscal pressure in human lumbar spine. Bioengineering (Basel) 10: 31, 2022.
63. Guan J, Liu T, Yu X, Li W, Feng N, Jiang G, Zhao H and Yang Y: Biomechanical and clinical research of Isobar semi-rigid stabilization devices for lumbar degenerative diseases: A systematic review. Biomed Eng Online 22: 95, 2023.
64. Liu L, He J, Liu C, Yang M, Fu J, Yi J, Ai X, Liu M, Zhuang Y, Zhang Y, *et al*: Cartilage intermediate layer protein affects the progression of intervertebral disc degeneration by regulating the extracellular microenvironment (review). Int J Mol Med 47: 475-484, 2021.
65. Chan D, Song Y, Sham P and Cheung KMC: Genetics of disc degeneration. Eur Spine J 15 (Suppl 3): S317-S325, 2006.
66. Johnson ZI, Schoepflin ZR, Choi H, Shapiro IM and Risbud MV: Disc in flames: Roles of TNF-α and IL-1β in intervertebral disc degeneration. Eur Cell Mater 30: 104-117, 2015.
67. Chen S, Suo S, Xie Z, He J, Li J, Duan D, Qiao G and Zhang W: Establishment of an animal model of adjacent segment degeneration after interbody fusion and related experimental studies. J Orthop Surg Res 18: 666, 2023.
68. Gaudiani MA, Winkelman RD, Ravishankar P, Rabah NM, Mroz TE and Coughlin DJ: The association of preoperative TNF-alpha inhibitor use and reoperation rates in spinal fusion surgery. Spine J 21: 972-979, 2021.
69. Lu QL, Wang XZ, Xie W, Chen XW, Zhu YL and Li XG: Macrophage migration inhibitory factor may contribute to hypertrophy of lumbar ligamentum flavum in type 2 diabetes mellitus. Chin Med J (Engl) 133: 623-625, 2020.
70. Xiong C, Huang Y, Kang H, Zhang T, Xu F and Cai X: Macrophage inhibition factor-mediated CD74 signal modulate inflammation and matrix metabolism in the degenerated cartilage endplate chondrocytes by activating extracellular signal regulated kinase 1/2. Spine (Phila Pa 1976) 42: E61-E70, 2017.
71. Ying Y, Cai K, Cai X, Zhang K, Qiu R, Jiang G and Luo K: Recent advances in the repair of degenerative intervertebral disc for preclinical applications. Front Bioeng Biotechnol 11: 1259731, 2023.
72. Wong J, Sampson SL, Bell-Briones H, Ouyang A, Lazar AA, Lotz JC and Fields AJ: Nutrient supply and nucleus pulposus cell function: Effects of the transport properties of the cartilage endplate and potential implications for intradiscal biologic therapy. Osteoarthritis Cartilage 27: 956-964, 2019.
73. Xiang P, Luo ZP and Che YJ: Insights into the mechanical microenvironment within the cartilaginous endplate: An emerging role in maintaining disc homeostasis and normal function. Heliyon 10: e31162, 2024.

74. Gilbert HTJ, Hodson N, Baird P, Richardson SM and Hoyland JA: Acidic pH promotes intervertebral disc degeneration: Acid-sensing ion channel-3 as a potential therapeutic target. Sci Rep 6: 37360, 2016.
75. Thys T, Bogaert L, Dankaerts W, Depreitere B, Van Wambeke P, Brumangne S, Bultheel M, Vanden Abeele V, Moke L, Spriet A, *et al*: Qualitative study exploring the views of patients and healthcare providers on current rehabilitation practices after lumbar fusion surgery. BMJ Open 14: e077786, 2024.
76. Adogwa O, Verla T, Thompson P, Penumaka A, Kudyba K, Johnson K, Fulchiero E, Miller T Jr, Hoang KB, Cheng J and Bagley CA: Affective disorders influence clinical outcomes after revision lumbar surgery in elderly patients with symptomatic adjacent-segment disease, recurrent stenosis, or pseudarthrosis: Clinical article. J Neurosurg Spine 21: 153-159, 2014.
77. Archer KR, Seebach CL, Mathis SL, Riley LH and Wegener ST: Early postoperative fear of movement predicts pain, disability, and physical health six months after spinal surgery for degenerative conditions. Spine J 14: 759-767, 2014.
78. Jakobsson M, Hagströmer M, Lotzke H, von Rosen P and Lundberg M: Fear of movement was associated with sedentary behaviour 12 months after lumbar fusion surgery in patients with low back pain and degenerative disc disorder. BMC Musculoskelet Disord 24: 874, 2023.
79. Glassman SD, Anagnost SC, Parker A, Burke D, Johnson JR and Dimar JR: The effect of cigarette smoking and smoking cessation on spinal fusion. Spine (Phila Pa 1976) 25: 2608-2615, 2000.
80. Maurel DB, Boisseau N, Benhamou CL and Jaffre C: Alcohol and bone: Review of dose effects and mechanisms. Osteoporos Int 23: 1-16, 2012.
81. Chou PH, Lin HH, An HS, Liu KY, Su WR and Lin CL: Could the topping-off technique be the preventive strategy against adjacent segment disease after pedicle screw-based fusion in lumbar degenerative diseases? A systematic review. Biomed Res Int 2017: 4385620, 2017.
82. Zhou C, Zhou N, Zheng Y, Si H, Wang Y and Yin J: The efficacy of 3D gait analysis to evaluate surgical (and rehabilitation) outcome after degenerative lumbar surgery. BMC Surg 24: 197, 2024.
83. Barbosa TP, Raposo AR, Cunha PD, Cruz Oliveira N, Lobarinhas A, Varanda P and Direito-Santos B: Rehabilitation after cervical and lumbar spine surgery. EFORT Open Rev 8: 626-638, 2023.
84. Pennington Z, Cottrill E, Ahmed AK, Passias P, Protopsaltis T, Neuman B, Kebaish KM, Ehresman J, Westbroek EM, Goodwin ML and Sciubba DM: Paraspinal muscle size as an independent risk factor for proximal junctional kyphosis in patients undergoing thoracolumbar fusion. J Neurosurg Spine 31: 380-388, 2019.
85. Kwok WCH, Wong CYY, Law JHW, Tsang VWT, Tong LWL, Samartzis D, An HS and Wong AYL: Risk factors for adjacent segment disease following anterior cervical discectomy and fusion with plate fixation: A systematic review and meta-analysis. J Bone Joint Surg Am 104: 1915-1945, 2022.
86. Beyerman KL, Palmerino MB, Zohn LE, Kane GM and Foster KA: Efficacy of treating low back pain and dysfunction secondary to osteoarthritis: Chiropractic care compared with moist heat alone. J Manipulative Physiol Ther 29: 107-114, 2006.
87. Gliedt JA, Daniels CJ and Wuollet A: Narrative review of perioperative acupuncture for clinicians. J Acupunct Meridian Stud 8: 264-269, 2015.
88. Zhao B, Wang K, Zhao JX, Wang C, Huang X, Shu-qiang M and Qiang H: Clinical effects of acupuncture after surgical operation in patients with prolapse of the lumbar intervertebral disc. J Tradit Chin Med 28: 250-254, 2008.
89. Chou D, Dekutoski M, Hermsmeyer J and Norvell DC: The treatment of lumbar adjacent segment pathology after a previous lumbar surgery: A systematic review. Spine (Phila Pa 1976) 37 (22 Suppl): S180-S188, 2012.
90. McDonald CL, Alsoof D, Glueck J, Osorio C, Stone B, McCluskey L, Diebo BG, Daniels AH and Basques BA: Adjacent segment disease after spinal fusion. JBJS Rev 11, 2023.
91. Kamali A, Ziadlou R, Lang G, Pfannkuche J, Cui S, Li Z, Richards RG, Alini M and Grad S: Small molecule-based treatment approaches for intervertebral disc degeneration: Current options and future directions. Theranostics 11: 27-47, 2021.
92. Song JH, Lee WY, Cho KR, Nam SH, Park KD and Park Y: Fluoroscopy-guided transforaminal versus caudal epidural steroid injection for chronic pain after spinal surgery: A retrospective mid-term comparative study. J Pain Res 14: 2129-2138, 2021.
93. Kvasnitskyi M: Epidural injections in the treatment of radicular syndrome and chronic lower back pain in degenerative-dystrophic spine damage. Georgian Med News: 109-115, 2022.
94. Park KD, Lee WY, Nam SH, Kim M and Park Y: Ultrasound-guided selective nerve root block versus fluoroscopy-guided interlaminar epidural block for the treatment of radicular pain in the lower cervical spine: A retrospective comparative study. J Ultrasound 22: 167-177, 2019.
95. Yoo YM and Kim KH: Facet joint disorders: From diagnosis to treatment. Korean J Pain 37: 3-12, 2024.
96. Manchikanti L, Kaye AD, Soin A, Albers SL, Beall D, Latchaw R, Sanapati MR, Shah S, Atluri S, Abd-Elsayed A, *et al*: Comprehensive evidence-based guidelines for facet joint interventions in the management of chronic spinal pain: American society of interventional pain physicians (ASIPP) guidelines facet joint interventions 2020 guidelines. Pain Physician 23 (Suppl 3): S1-S127, 2020.
97. Wong MJ and Rajarathinam M: Ultrasound-guided axial facet joint interventions for chronic spinal pain: A narrative review. Can J Pain 7: 2193617, 2023.
98. Suputtitada A, Nopsopon T, Rittiphairoj T and Pongpirul K: Intra-articular facet joint injection of normal saline for chronic low back pain: A systematic review and meta-analysis. Medicina (Kaunas) 59: 1038, 2023.
99. Láinez Ramos-Bossini AJ, Jiménez Gutiérrez PM and Ruiz Santiago F: Efficacy of radiofrequency in lumbar facet joint pain: A systematic review and meta-analysis of placebo-controlled randomized controlled trials. Radiol Med 129: 794-806, 2024.
100. Rajakumar DV, Hari A, Krishna M, Konar S and Sharma A: Adjacent-level arthroplasty following cervical fusion. Neurosurg Focus 42: E5, 2017.
101. Lu VM, Mobbs RJ and Phan K: Clinical outcomes of treating cervical adjacent segment disease by anterior cervical discectomy and fusion versus total disc replacement: A systematic review and meta-analysis. Global Spine J 9: 559-567, 2019.
102. Parish JM, Asher AM and Coric D: Adjacent-segment disease following spinal arthroplasty. Neurosurg Clin N Am 32: 505-510, 2021.
103. Drysch A, Ajiboye RM, Sharma A, Li J, Reza T, Harley D, Park DY and Pourtaheri S: Effectiveness of reoperations for adjacent segment disease following lumbar spinal fusion. Orthopedics 41: e161-e167, 2018.
104. Chen WJ, Lai PL, Niu CC, Chen LH, Fu TS and Wong CB: Surgical treatment of adjacent instability after lumbar spine fusion. Spine (Phila Pa 1976) 26: E519-E524, 2001.
105. Louie PK, Haws BE, Khan JM, Markowitz J, Movassaghi K, Ferguson J, Lopez GD, An HS and Phillips FM: Comparison of stand-alone lateral lumbar interbody fusion versus open laminectomy and posterolateral instrumented fusion in the treatment of adjacent segment disease following previous lumbar fusion surgery. Spine (Phila Pa 1976) 44: E1461-E1469, 2019.
106. Turel MK, Kerolus MG, David BT and Fessler RG: Minimally invasive options for surgical management of adjacent segment disease of the lumbar spine. Neurol India 66: 755-762, 2018.
107. Yang S, Yang D, Ma L, Wang H and Ding W: Clinical efficacy of laminectomy with instrumented fixation in treatment of adjacent segmental disease following ACCF surgery: A retrospective observational study of 48 patients. Sci Rep 9: 6551, 2019.
108. He W, He D, Wang QL, Tian W, Liu B, Liu YJ, Sun YQ, Xing YG, Yuan N, Yuan Q, *et al*: Longitudinal spinous-splitting laminoplasty with coral bone for the treatment of cervical adjacent segment degenerative disease: A 5-year follow-up study. Orthop Surg 14: 435-442, 2022.
109. Früh A, Leißa P, Tkatschenko D, Truckenmüller P, Wessels L, Vajkoczy P and Bayerl S: Decompression with or without fusion in degenerative adjacent segment stenosis after lumbar fusions. Neurosurg Rev 45: 3739-3748, 2022.
110. Han J, Tang W, Li G, Ji X, Wu X, Zhu K, Zhang G, Zhou C, Ma X and Guo J: Comparison of percutaneous endoscopic transforaminal and interlaminar approaches in treating adjacent segment disease following lumbar decompression surgery: A clinical retrospective study. Pain Physician 26: E833-E842, 2023.
111. Feng P, Kong Q, Zhang B, Liu J, Ma J and Hu Y: Percutaneous full endoscopic lumbar discectomy for symptomatic adjacent segment disease after lumbar fusion in elderly patients. Orthop Surg 15: 1749-1755, 2023.
112. Sakhrekar R, Ha JS, Han HD, Kim DH, Kim CW and Kulkarni S: Unilateral biportal endoscopic approach for symptomatic adjacent segment disease: Case report and technical note. J Orthop Case Rep 13: 172-177, 2023.

113. Jacobson RE, Granville M and Berti A: Minimally invasive anterior cervical discectomy without fusion to treat cervical disc herniations in patients with previous cervical fusions. Cureus 9: e1131, 2017.
114. Han J, Guo J, Ma X, Zhang G, Han S, Zhang H, Liu H, Chen M and Wang Y: The cortical bone trajectory screw technique assisted by the mazor renaissance robotic system as a salvage strategy for failed lumbar spine surgery: Technical note and case series. J Pain Res 16: 2971-2980, 2023.
115. Zhang B, Hu Y, Kong Q, Feng P, Liu J and Ma J: Comparison of oblique lumbar interbody fusion combined with posterior decompression (OLIF-PD) and posterior lumbar interbody fusion (PLIF) in the treatment of adjacent segmental disease (ASD). J Pers Med 13: 368, 2023.
116. Miscusi M, Trungu S, Ricciardi L, Forcato S, Piazza A, Ramieri A and Raco A: Stand-alone oblique lumbar interbody fusion (OLIF) for the treatment of adjacent segment disease (ASD) after previous posterior lumbar fusion: Clinical and radiological outcomes and comparison with posterior revision surgery. J Clin Med 12: 2985, 2023.
117. Rajan PV, Megerian M, Desai A, Halkiadakis PN, Rabah N, Shost MD, Butt B, Showery JE, Grabel Z, Pelle DW and Savage JW: Transforaminal versus lateral interbody fusions for treatment of adjacent segment disease in the lumbar spine. Clin Spine Surg: Sep 12, 2024 (Epub ahead of print).
118. Shen Y, Du W, Wang LF, Dong Z and Wang F: Comparison of zero-profile device versus plate-and-cage implant in the treatment of symptomatic adjacent segment disease after anterior cervical discectomy and fusion: A minimum 2-year follow-up study. World Neurosurg 115: e226-e232, 2018.
119. Wang F, Wang P, Miao DC, Du W and Shen Y: Different surgical approaches for the treatment of adjacent segment diseases after anterior cervical fusion: A retrospective study of 49 patients. Medicine (Baltimore) 96: e7042, 2017.
120. Tu Q, Sun H, Chen H and Zhu C: The surgical treatment strategy for adjacent segment disease after anterior cervical discectomy and fusion of multi-segments. Chin J Clin Anat 41: 218-223, 2023.
121. Lambrechts MJ, Toci GR, Siegel N, Karamian BA, Canseco JA, Hilibrand AS, Schroeder GD, Vaccaro AR and Kepler CK: Revision lumbar fusions have higher rates of reoperation and result in worse clinical outcomes compared to primary lumbar fusions. Spine J 23: 105-115, 2023.
122. Yu L, Wu H, Zeng S, Hu X, Wu Y, Zhou J, Yuan L, Zhang Q, Xiang C and Feng Z: Menstrual blood-derived mesenchymal stem cells combined with collagen I gel as a regenerative therapeutic strategy for degenerated disc after discectomy in rats. Stem Cell Res Ther 15: 75, 2024.
123. Jia H, Lin X, Wang D, Wang J, Shang Q, He X, Wu K, Zhao B, Peng P, Wang H, *et al*: Injectable hydrogel with nucleus pulposus-matched viscoelastic property prevents intervertebral disc degeneration. J Orthop Translat 33: 162-173, 2022.
124. Krut Z, Pelled G, Gazit D and Gazit Z: Stem cells and exosomes: New therapies for intervertebral disc degeneration. Cells 10: 2241, 2021.
125. Meng Q, Xie E, Sun H, Wang H, Li J, Liu Z, Li K, Hu J, Chen Q, Liu C, *et al*: High-strength smart microneedles with 'offensive and defensive' effects for intervertebral disc repair. Adv Mater 36: e2305468, 2024.
126. Dou X, Liu X, Liu Y, Wang L, Jia F, Shen F, Ma Y, Liang C, Jin G, Wang M, *et al*: Biomimetic porous Ti6Al4V implants: A novel interbody fusion cage via gel-casting technique to promote spine fusion. Adv Healthc Mater 13: e2400550, 2024.
127. Wang Z, Zhang D, Zhang Z and Miao J: The postoperative clinical effects of utilizing 3D printed (Ti6Al4V) interbody fusion cages in posterior lumbar fusion: A retrospective cohort study. Medicine (Baltimore) 103: e38431, 2024.
128. Song KJ, Choi BW, Jeon TS, Lee KB and Chang H: Adjacent segment degenerative disease: is it due to disease progression or a fusion-associated phenomenon? Comparison between segments adjacent to the fused and non-fused segments. Eur Spine J 20: 1940-1945, 2011.