

Reviews

Spondylolisthesis

Nathan Li¹ ^a, John Scofield², Payton Mangham², Joshua Cooper², William Sherman³, Alan D. Kaye²

¹ Medical College of Wisconsin, ² Louisiana State University Shreveport, ³ Tulane University Department of Orthopaedic Surgery

Keywords: Spondylolisthesis, Spondylolysis, Back pain, Vertebra

<https://doi.org/10.52965/001c.36917>

Orthopedic Reviews

Vol. 14, Issue 3, 2022

Spondylolisthesis refers to the anterior, lateral, or posterior slippage of a superior vertebral disc over the adjacent inferior disc, and is often separated into categories based on the causative etiology. Spondylolisthesis is often asymptomatic but may present with low back pain and neurogenic claudication which is worsened with spinal extension and activity. A detailed history and physical exam, along with appropriate imaging tests are useful in making the diagnosis. Conservative therapy is first-line and includes pain management with physical therapy. Patients who fail conservative therapy may consider surgical decompression, stabilization, and fusion. This review aims to discuss the epidemiology, pathophysiology, presentation, and treatment options of spondylolisthesis.

INTRODUCTION

Spondylolisthesis is a broad term used to describe the anterior, lateral, or posterior slippage of one vertebral body over another. Isthmic spondylolisthesis occurs when anterior displacement of the vertebra is caused by a defect in the pars interarticularis, commonly due to previous spondylolysis at the L5-S1 joint.¹⁻⁴ While isthmic spondylolisthesis is the most common form of spondylolisthesis in children, degenerative spondylolisthesis predominates in adults, which can occur independent of pars interarticularis injury and has a tendency to present in female patients.^{1,2,5} The presentation of spondylolisthesis can vary widely, including but not limited to compressive neurologic defects (i.e. spinal stenosis), mild-to-severe back pain, a cosmetic defect, and as an incidental finding.¹ The standard classification of spondylolisthesis is the Meyerding system (graded I through V), which correlates with the percentage of superior disc translocation over the inferior disc. The degree of Meyerding grading is generally associated with symptom severity.^{1,3,6} Grade IV and V spondylolisthesis indicates severe disc translation and is usually due to isthmic spondylolisthesis since significant damage to the pars interarticularis is generally required for impressive degrees of translation.³ While many patients respond to conservative management (NSAIDs, injections, bracing), many cases of-

ten require decompression, fusion, reduction, fixation, among other surgical interventions.^{2,3} Surgical treatment for spondylolisthesis should be considered in patients with persisting, debilitating symptoms that have not responded to conservative management.⁷

EPIDEMIOLOGY/RISK FACTORS

Spondylolisthesis is typically categorized into isthmic and degenerative spondylolisthesis. Isthmic (i.e. spondylolytic) spondylolisthesis is classically precipitated by progression of previous spondylolysis. Spondylolysis is exceedingly rare in individuals who do not bear weight (i.e. infants, children with disabilities), with incidence and risk of progression to spondylolisthesis continually increasing from birth until age 18, with relatively stable incidence rates thereafter.⁴ The incidence of spondylolysis in adults has been estimated to be between 3-8% with a prevalence of 11.5%.⁸⁻¹⁰ Spondylolisthesis is less prevalent than spondylolysis, with an estimated prevalence of 3.1%.^{11,12} Interestingly, most patients with these conditions are asymptomatic, with only 23% of patients reporting clinical complaints prior to the age of 20. In fact, studies have estimated that between 2.5-3.5% of children undergoing CT scans or MRI for unrelated abdominal or pelvic pathologies discover spondylolysis and isthmic spondylolisthesis as incidental findings.¹³

^a Corresponding author:

Nathan Li
Medical College of Wisconsin – Milwaukee
8701 W Watertown Plank Rd
Wauwatosa, WI, 53226
Phone: (920) 277-8327
linathan006@gmail.com

Additionally, the extent of disc slippage in spondylolisthesis has not been strongly correlated with symptomatic severity. Both progression from spondylolysis to isthmic spondylolisthesis, as well as symptomatic onset are often correlated with periods of rapid pubertal bone growth in adolescents between 10-15 years old.⁸

Young athletes have been well-documented to have increased risk for developing spondylolysis and subsequently progressing to spondylolisthesis. These patients typically present with unilateral low back pain that is relieved by rest, and interestingly usually do not exhibit neurologic deficits.¹⁴ Athletes participating in sports with high torsion in their lumbar spine are at particularly increased risk of developing spondylolysis due to either unilateral or bilateral damage to the lumbar pars interarticularis.^{4,15} Harvey et al. reported a spondylolysis incidence rate of between 23-63% of young athletes participating in high risk sports, which include football, gymnastics, hockey, diving, wrestling, pole vaulting, racquet sports, and body building.^{14,16} Medical conditions may also predispose to development of spondylolysis. Inherent spinal disease such as scoliosis, kyphosis, and spina bifida occulta have been correlated with increased risk of development of spondylolysis.^{4,8,17} Additionally, studies suggest an element of heritability, with 15-70% of patients with spondylolysis also possessing first-degree relatives who have spondylolysis.¹⁸ Additional genetic risk factors include Native Alaskan heritage.^{9,14}

In contrast to isthmic spondylolisthesis, degenerative spondylolisthesis is most commonly seen in adults, with increased risk associated with progression of age. Degenerative spondylolisthesis is almost six times more common in females than males.^{5,19} In a prospective study of 142 women, Aono et al. reported that 12.7% of previously healthy women developed degenerative spondylolisthesis over a period of 8 years. Retrospective analysis of baseline radiographs suggested that the pelvic incidence, vertebral inclination angle, degree of lumbar lordosis, as well as baseline vertebral sizes were all additional risk factors for development of degenerative spondylolisthesis.^{5,20}

PATHOPHYSIOLOGY

Spondylolisthesis is the anterior, lateral, or posterior translation of a superior vertebral segment over the adjacent inferior vertebra.³ Spondylolisthesis may progress from spondylolysis, which is the degeneration of the pars interarticularis. In fact, up to 70% of patients with bilateral pars defects progress to isthmic spondylolisthesis. This slippage most commonly occurs during periods of rapid growth.¹¹ Disc slippage most often occurs at the L5-S1 joint.¹⁻⁴ Severity of disc slippage is often quantified with the Meyerding grading system and is graded from I through V.^{1,3,6} High grade spondylolisthesis with greater than 50% disc slippage corresponds to Meyerding grade III or higher and presents with higher risk of neurological complications due to spinal cord and neural compression. High grade spondylolisthesis is most often due to isthmic rather than degen-

erative spondylolisthesis, as severe translation is enabled by pars interarticularis fracture.³

Degenerative spondylolisthesis is considered a disease of aging with a predilection for females, hypothetically due to both the increased laxity in female ligaments as well as other hormonal factors.⁵ Most cases of degenerative spondylolisthesis are low grade and classified as either Meyerding grade I or II.⁵ Low back and lower extremity pain may be observed due to focal disc slippage and degeneration as well as nerve impingement and ensuing spinal stenosis.

There exist numerous other etiologies of spondylolisthesis in addition to the isthmic and degenerative subtypes. A rarer etiology of spondylolisthesis includes dysplastic (i.e. congenital) spondylolisthesis, and is due to a congenital anomaly of the pars interarticularis which subsequently results in early anterior disc translocation, most commonly at L5-S1.²¹ Early disc slippage can also result in spondylolysis due to increased stress on the pars interarticularis. Congenital disease is often multifactorial and made worse by repetitive movements of the lower back. Traumatic spondylolisthesis is caused by trauma that fractures a part of the posterior column of the spine besides the pars, and usually coexists with other injuries.⁸ Pathologic spondylolisthesis is similar to traumatic, but is however due to infection, neoplasm, autoimmunity, or another pathology unrelated to trauma.⁸ Iatrogenic spondylolisthesis can cause all of the aforementioned variants of the disease, and usually occurs following a large spinal decompression (laminectomy). This procedure can cause destabilization of the vertebrae, with subsequent disc slippage.⁸

CLASSIFICATION AND GRADING

The symptomatic severity of spondylolisthesis has been weakly correlated with the degree of vertebral slippage.²²⁻²⁴ The most common grading scale to describe the degree of vertebral slippage in spondylolisthesis patients was proposed by Meyerding.^{23,25-28} Specifically, this scale correlates the degree of anterior displacement of a vertebral body to a numerical score.²⁵ The grading scale of the Meyerding scale is as follows: Grade I is equivalent to a <25% slippage of the vertebral body, grade II is equivalent to a 25% to 50% slippage of the vertebral body, grade III is equivalent to a 50% to 75% slippage of the vertebral body, grade IV is equivalent to a 75% to 100% slippage of the vertebral body, and grade V equivalent to a complete slippage of the vertebral body.^{23,25,26} The majority of cases usually fall into either grade I or grade II.²⁵ This grading system is invaluable for continual assessment of both the current degree of disc slippage as well as the progression of the displacement of the vertebrae, thus providing valuable prognostic information and assisting in determination of the most appropriate future management.^{23,29} However, studies have suggested that additional factors including etiology, lumbopelvic measurements, sacral structure, and global spinal alignment are also important in determination and prediction of spondylolisthesis progression, and grading scales which take these variables into account

ought to be developed in order to optimize future treatment.¹

Another useful grading scale was proposed by Wiltse et al and functions by separating the different etiologies of spondylolisthesis into five distinct categories.^{30,31} Type I of the Wiltse system corresponds to dysplastic spondylolisthesis resulting from congenital dysplasia that causes anterior and superior rounding of the S1 vertebrae, which allows the L5 vertebrae to slip anteriorly.³¹ Type II correlates with isthmic spondylolisthesis and is further divided into types IIA and IIB. Type IIA is the result of a stress fractures of the pars interarticularis and causes anterior slipping of the vertebrae. Type IIB is the result of repeated fractures and healing resulting in lengthening of the pars interarticularis. Both subtypes result in anterior slippage of the vertebrae. Type III correlates with degenerative spondylolisthesis and is most commonly due to arthritis, which leads to weakening of the ligamentum flavum which then allows anterior slipping of the vertebrae.^{31,32} Type IV correlates with traumatic spondylolisthesis caused by high energy trauma. Type V correlates with pathologic spondylolisthesis and can be caused by various pathologies such as osteoporosis, lytic neoplasms of the bone, and osteopetrosis. Type VI is iatrogenic in origin and is usually caused by spinal surgery such as laminectomy.³¹ The categorization proposed by Wiltse et al is helpful in many scenarios, it does not describe the severity of each subtype of spondylolisthesis, and also does not allow for monitoring for progression of disease.

CLINICAL FEATURES

A vast majority of patients with spondylolisthesis are asymptomatic.³³ Symptoms typically derive from either mechanical etiology or spinal stenosis, and patients frequently complain of intermittent neurogenic claudication; a consequence of spinal stenosis which presents with low back pain with radiation to the proximal bilateral lower extremities, with associated paresthesia and weakness while ambulating or standing.^{25,28} Isthmic spondylolisthesis patients most commonly experience symptoms including hamstring tightness and lower back or buttock pain that is worse with spinal extension.^{23,29} This radiculopathy is due to compression of the nerve roots in the area of the anterior slippage of the vertebral body.³¹ Similarly, clinical features of degenerative spondylolisthesis predominantly include lower back pain, radiculopathy, or neurogenic claudication.²³ This pain often worsens with activity and/or spinal extension, but the pain may be relieved by movements that cause spinal flexion such as sitting or leaning forward.^{25,27,34,35} Progressively worsening spondylolisthesis may present with new or augmented neurogenic symptoms, such as radicular pain, bowel and bladder dysfunction, and even cauda equina syndrome. Patients may also report a preceding traumatic event prior to onset of symptoms; however, many cases are correlated with insidious onset. Nighttime pain may also occur and is usually concerning for malignancy.²⁶

DIAGNOSTICS

Although spondylolisthesis is most often asymptomatic, a detailed history taking and a thorough musculoskeletal and neurologic physical exam are helpful in accurately diagnosing spondylolisthesis.^{26,29} Isthmic spondylolisthesis often presents with a palpable step-off which may be felt at the level below the affected segment, while degenerative spondylolisthesis presents with a step-off occurring at the level above the affect spinal cord segment.²³ Patients may also present with varying degrees of lumbar lordosis, with stooped posture, spinal muscle atrophy, tight hamstrings, and hip flexion contraction.^{28,29} Children with advanced spondylolisthesis may present with shortened stride length with excessive hip and knee flexion, and thus work up within the pediatric population should include extensive gait analysis.^{26,29} Additionally, children with isthmic spondylolisthesis with associated scoliosis may present with a positive stork test, which is a one-legged hyperextension maneuver and indicates impaired mobility of the sacroiliac joint.^{24,36}

When working up patients with clinical suspicion for spondylolisthesis, useful imaging includes supine oblique views of the lumbosacral spine as well as standing posteroanterior and lateral x-rays of the thoracolumbar spine.^{25,26,37} These views allow for optimal evaluation of the affected level of spondylolisthesis by judging the degree of anterior vertebral slippage.²⁶ When possible, supine radiographs should be avoided, as they potentially allow for the pathologic vertebra to temporarily reduce into an anatomically correct position.²⁵

When there is a high clinical suspicion of spondylolisthesis in spite of normal imaging results, single-photon emission CT of the lumbosacral spine is useful for further workup.^{26,38-40} Additionally, MRI is often used in patients who present with neurologic deficits, although MRI has been shown to possess a low positive predictive value and is therefore not preferable as a primary diagnostic tool.^{26,41} Thin-section CT with reverse gantry angle may also be useful in determining the degree of spondylolisthesis.^{26,42} Preoperative two-dimensional and three-dimensional CT reconstruction can be used in severe cases to further define the anatomy of the region of interest.²⁶

TREATMENT OPTIONS

CONSERVATIVE MANAGEMENT

Although there have been no prospective randomized clinical trials which outline the optimal conservative management algorithm, conservative modalities are widely considered the first line treatment for most cases of low-grade spondylolisthesis.²⁸ In fact, between 70-90% of athletes with spondylolisthesis can expect to return to athletic activities within 3-6 months with only conservative management.³⁷ The mainstay for conservative treatment is activity restriction, bracing, physical therapy, and pain control. Pain control can be achieved with either NSAIDs, narcotics, or muscle relaxants.^{29,31} If a patient elects to undergo conservative management, they are closely followed with full

physical exams and repeat imaging to monitor treatment efficacy.²⁹ Vibert et al. has stated that most physicians initially start with a 1- to 2- day trial of rest followed by a short course of anti-inflammatory medication. If the patient's symptoms have not resolved within two weeks, physical therapy is an appropriate next step in management. The benefits of activities such as cycling, swimming, and elliptical machines have been well documented to avoid further vertebral injury and are considered superior to other forms of high impact aerobic exercises such as running.^{27,43} Additionally, Kalichman and Hunter have referenced numerous other studies that have examined the efficacy of various conservative treatment modalities such as physiotherapy, bracing, flexion/extension strengthening exercises, and stabilization exercises.²⁷ If the patient fails to see improvement in symptoms after completing a 4-6 week course of physical therapy or other treatment modalities, it is often appropriate to consider more aggressive treatment options such as epidural steroid injections or selective nerve blocks.^{27,29,43} If the patient continues to fail conservative therapies and more invasive procedures such as epidural corticosteroid injections, further surgical management may be indicated.³⁴

SURGICAL MANAGEMENT

Although spondylolisthesis management has generally trended toward more conservative options in effort to minimize risk and maximize outcomes, surgical treatment should be considered in patients with persisting and debilitating symptoms with inadequate response to conservative management.⁴⁴⁻⁴⁶ Historically, degenerative spondylolisthesis was treated aggressively with focus on neural decompression, reduction, fixation, and fusion. Treatment has evolved throughout the years with emergence and re-emergence of techniques arriving in conjunction with the development of new technologies. Initially, isolated neural decompression was a popular procedure but resulted in increased likelihood of slippage progression in younger patients with dynamic instability due to lack of fusion.^{47,48} Posterior fusion using a posterior lumbar interbody fusion (PLIF) was described in the early-20th century, but was discouraged at the time due to high risk of complications and procedural difficulty. It was not until the advent of transpedicular screwing and the development of spinal instrumentation that led to breakthrough of transforaminal lumbar interbody fusion (TLIF) and other interbody fusion techniques. More recent advances including minimally invasive surgery (MIS) and stereotactic spinal guidance. MIS procedures has been shown to decrease muscular injury and perioperative pain, leading to faster recovery and improved quality of life. Similarly, stereotactic spinal guidance provides invaluable guidance of intraoperative anatomical landmarks and have been correlated with decreased likelihood of complications related to screw misplacement.⁴⁸

Surgical treatment of spondylolisthesis usually involves a combination of decompression, stabilization, and fusion. Although decompression is discouraged in patients with dynamic instability, it remains a viable option in the elderly and patients without dynamic instability due to lower asso-

ciated morbidity and mortality.⁴⁴ Stabilization with spinal instrumentation is often utilized to correct deformity and prevent deformity progression.⁴⁹ There currently remains a lack of consensus on the decision to reduce slippage versus in-situ fusion during surgical management. Those in favor of reduction prior to arthrodesis argue that while patients report improvement following in-situ fusion, there is a greater risk of decompensation and pseudoarthrosis due to uncorrected positive sagittal balance, especially in high grade slips. One study investigating this found that pseudoarthrosis was more frequent in the fusion in-situ group versus the reduction group (17.8% vs 5.5%).⁵⁰ Conversely, those in favor of in-situ fusion argue that patients demonstrate compensation for uncorrected positive sagittal balance through reduced thoracic kyphosis and pelvic retroversion. They also cite literature emphasizing a greater likelihood of neurological impairment with reduction, though there is also evidence denying any additional risk. Despite ongoing debate, treatment has begun focused on correcting segmental lordosis and global sagittal balance. It is proposed that reduction with anterior and posterior fixation results in improved outcomes and allows for optimal correction of deformity, indirect neuroforaminal decompression, greater surface area for arthrodesis, and increased biomechanical stability.⁵¹⁻⁵⁵

With recent recognition of the importance of slip angle and spinopelvic alignment to global sagittal alignment, more evidence suggests that at least partial reduction of slip angle should be considered in the setting of a high-grade slip. Interbody fusion is also favored in these cases to provide greater stability and increase fusion rates.⁵⁴⁻⁵⁶ There is a lack of randomized controlled trials confirming or negating the generally accepted techniques of reduction and anterior column support for treatment of high-grade spondylolisthesis, but smaller studies are frequently performed.⁵⁷ Nonetheless, the benefits of surgery are typically significant for patients with regard to health-related quality of life, especially in patients who can tolerate the procedures.⁵⁸

Newer techniques for surgical intervention and evaluation continue to arise for patients with high-grade slips. One example of innovative surgical techniques includes the extreme lateral interbody fusion, which has shown promising improvement in clinical outcomes with isthmic spondylolisthesis patients at each postoperative evaluation (1, 3, and 12 months), along with no signs of hardware loosening or failure.⁵⁹ Another novel technique to evaluate post-surgical outcomes includes a 3D finite element model (FEM) used to analyze the biomechanics of the spine after spinal fusion for spondylolisthesis at L5-S1. This model was described by Wang et al with an objective to determine the advantages of reduction versus no reduction in patients with "unbalanced" and "balanced" spines, which are defined by measurement of spinal parameters such as sacral slope and pelvic tilt. The "unbalanced" spine was correlated with high pelvic tilt and low sacral slope and showed significant improvements in pelvic alignment post-reduction, likely due to inherent inability to compensate through spinal extension. However, FEM showed a significantly increased inci-

dence of lumbosacral deformation and adjacent disc stress in “unbalanced” spines following reduction. Similarly, although the “balanced” spine (correlated with low pelvic tilt and high sacral slope) also exhibited improvements in spinal alignment post-reduction, there was no increase in incidence of lumbosacral deformation or adjacent disc stress. Further research is necessary to determine if the efficacy of reduction in treatment of spondylolisthesis in patients with “unbalanced” spinal alignment.⁶⁰

Care must also be taken to factor other spinal pathologies into the surgical treatment of spondylolisthesis. The current literature has not fully investigated the combination of spondylolisthesis and spinal tumors. In patients with concomitant tumors and spondylolisthesis, the location of one relative to the other is important in guiding treatment. Oncological treatment takes priority, however if that treatment involves spinal fixation, an adjacent spondylolisthesis can be included in the fusion construct and potentially reduced depending on symptomology and instability.⁶¹ Furthermore, congenital deformities of the spine, traumatic spondylolisthesis, and osteoporosis can pose unique challenges to surgical management of spondylolisthesis due to the complex presentations, peri-operative planning, and recovery.^{62,63}

There remains a significant degree of variability between providers regarding appropriate surgical recommendations. A survey of 445 U.S. spine surgeons sought to determine patterns in the treatment of spondylolisthesis and posed clinical/radiographic case scenarios on patients with spondylolisthesis, neurogenic claudication with and without mechanical back pain. Results showed that 64% and 71% of surgeons disagreed with regards to proper treatment of spondylolisthesis with and without mechanical back pain, respectively. Many factors influence operative decision making for a given condition, but awareness of this variability can guide research to develop better practice guidelines.⁶⁴ Data analysis from surgical registries may also prove invaluable in guiding future studies and improving outcomes of spondylolisthesis treatment. Examination of present management and outcomes can lead future studies in the right direction. There are several surgical options for treatment of spondylolisthesis which branch into a multitude of specific approaches and techniques. There is a need for a comprehensive surgical classification and treatment algorithm that would lead to a unified standard of care for patients with spondylolisthesis.^{65,66} Current management appears to exhibit positive outcomes and subjective improvements in most surgical patients, regardless of the specific procedure. However, many of the studies lack the power to provide strong evidence as a foundation for universal recommendation guidelines. Thus, further randomized trials and large-scale registry analysis will guide future research to demonstrate optimal surgical treatments and improve outcomes for all patients with spondylolisthesis.^{58,67}

Finally, although surgical management has been shown to be efficacious in treatment of spondylolisthesis, an often-overlooked aspect of surgery is cost effectiveness with respect to the patient. Although research is scarce in this area, operative treatment has been shown to be significantly more expensive than non-operative management due to fusion, instrumentation, and labor adding to the cost. Patients who receive surgical interventions do report improvement in quality of life, although more data needs to be gathered and analyzed to determine the appropriate cost/benefit between various surgical treatment options in patients with limited finances.⁶⁸

CONCLUSION

Spondylolisthesis refers to the anterior, lateral, or posterior slippage of a superior vertebral disc over the adjacent inferior disc, and is often separated into categories based on the causative etiology. Isthmic spondylolisthesis occurs due to damage to the pars interarticularis, resulting in instability and slippage between the lamina, pedicle, facet joints, and transverse process. Incidence of isthmic spondylolisthesis plateaus after age 18 and occurs most commonly at the L5-S1 joint. In contrast, degenerative spondylolisthesis occurs due to chronic degenerative processes such as arthritis and is observed in adults, with incidence directly correlated with age. Spondylolisthesis is most commonly described with the Meyerding classification system, with each grade corresponding to a given degree of disc slippage. Other classification scales have been proposed, such as one by Wiltse et al which categorizes spondylolisthesis based on the causative etiology. Spondylolisthesis is often asymptomatic but may present with low back pain and neurogenic claudication which is worsened with spinal extension and activity. A detailed history and physical exam is imperative in diagnosing spondylolisthesis, and evidence of disc slippage may be found on spinal xrays, single-photon emission CT, and MRI. Conservative therapy is first line and includes symptomatic management such as NSAIDs, narcotics, and muscle relaxants, as well as physical therapy, low impact exercises, and steroid injections. If a patient fails conservative therapy, surgical interventions such as decompression, stabilization, and fusion may be considered at that time.

FUNDING & CONFLICT OF INTEREST

The authors did not receive any funding or financial support or potential sources of conflict of interest.

The study has been performed in accordance with the ethical standards in the 1964 Declaration of Helsinki.

Submitted: December 09, 2021 EDT, Accepted: January 11, 2022 EDT

REFERENCES

1. Koslosky E, Gendelberg D. Classification in Brief: The Meyerding Classification System of Spondylolisthesis. *Clin Orthop Relat Res*. 2020;478(5):1125. doi:10.1097/CORR.0000000000001153
2. Ganju A. Isthmic spondylolisthesis. *Neurosurg Focus*. 2002;13(1):1-6. doi:10.3171/foc.2002.13.1.2
3. Beck AW, Simpson AK. High-Grade Lumbar Spondylolisthesis. *Neurosurg Clin N Am*. 2019;30(3):291-298. doi:10.1016/j.nec.2019.02.002
4. Tsirikos AI, Garrido EG. Spondylolysis and spondylolisthesis in children and adolescents. *J Bone Jt Surg - Ser B*. 2010;92(6):751-759. doi:10.1302/0301-620X.92B6.23014
5. Koreckij TD, Fischgrund JS. Degenerative Spondylolisthesis. *J Spinal Disord Tech*. 2015;28(7). doi:10.1097/BSD.0000000000000298
6. Hammerberg KW. New concepts on the pathogenesis and classification of spondylolisthesis. *Spine*. 2005;30(6 SPEC. ISS.):4-11. doi:10.1097/01.br.s.0000155576.62159.1c
7. Kreiner DS, Baisden J, Mazanec DJ, et al. Guideline summary review: an evidence-based clinical guideline for the diagnosis and treatment of adult isthmic spondylolisthesis. *Spine J*. 2016;16(12). doi:10.1016/j.spinee.2016.08.034
8. Logroscino G, Mazza O, Aulisa AG, Pitta L, Pola E, Aulisa L. Spondylolysis and spondylolisthesis in the pediatric and adolescent population. *Child's Nerv Syst*. 2001;17(11):644-655. doi:10.1007/s003810100495
9. Dunn B. Lumbar spondylolysis and spondylolisthesis. *J Am Acad Physician Assist*. 2019;32(12):50-51. doi:10.1097/01.JAA.0000604892.88852.c6
10. Kalichman L, Kim DH, Li L, Guermazi A, Berkin V, Hunter DJ. Spondylolysis and spondylolisthesis: Prevalence and association with low back pain in the adult community-based population. *Spine*. 2009;34(2):199-205. doi:10.1097/BRS.0b013e31818edcfd
11. Foreman P, Griessenauer CJ, Watanabe K, et al. L5 spondylolysis/spondylolisthesis: A comprehensive review with an anatomic focus. *Child's Nerv Syst*. 2013;29(2):209-216. doi:10.1007/s00381-012-1942-2
12. Belfi LM, Ortiz AO, Katz DS. Computed tomography evaluation of spondylolysis and spondylolisthesis in asymptomatic patients. *Spine*. 2006;31(24):907-910. doi:10.1097/01.brs.0000245947.31473.0a
13. Randall RM, Silverstein M, Goodwin R. Review of Pediatric Spondylolysis and Spondylolisthesis. *Sports Medicine and Arthroscopy Review*. 2016;24(4):184-187. doi:10.1097/ISA.0000000000000127
14. Wimberly RL, Laueran WC. Spondylolisthesis in the athlete. *Clinics in Sports Medicine*. 2002;21(1):133-145. doi:10.1016/S0278-5919(03)00062-0
15. Toueg C william, Mac-thiong J marc, Grimard G. Orientation in Young Gymnasts. 2015;28(6).
16. Hession PR, Butt WP. Imaging of spondylolysis and spondylolisthesis. In: *European Radiology*. Vol 6. ; 1996:284-290. doi:10.1007/BF00180595
17. Crostelli M, Mazza O. AIS and spondylolisthesis. *Eur Spine J*. 2013;22(SUPPL.2):172-184. doi:10.1007/s00586-012-2326-8
18. Hanley EN. Instructional Course Lectures. *J Bone Jt Surg*. 2004;86(11):2587-2588. doi:10.2106/00004623-200411000-00057
19. Metz LN, Deviren V. Low-Grade Spondylolisthesis. *Neurosurg Clin N Am*. 2007;18(2):237-248. doi:10.1016/j.nec.2007.02.010
20. Aono K, Kobayashi T, Jimbo S, Atsuta Y, Matsuno T. Radiographic analysis of newly developed degenerative spondylolisthesis in a mean twelve-year prospective study. *Spine*. 2010;35(8):887-891. doi:10.1097/BRS.0b013e3181cdd1aa
21. WILTSE LL. Spondylolisthesis in children. *Clin Orthop*. 1961;21(24):156-163. doi:10.1097/00007632-199912150-00011
22. Kreiner DS, Baisden J, Mazanec DJ, et al. Guideline summary review: an evidence-based clinical guideline for the diagnosis and treatment of adult isthmic spondylolisthesis. *Spine J*. 2016;16(12):1478-1485. doi:10.1016/j.spinee.2016.08.034

23. Koslosky E, Gendelberg D. Classification in Brief: The Meyerding Classification System of Spondylolisthesis. *Clinical Orthopaedics and Related Research*. 2020;478(5):1125-1130. doi:10.1097/CORR.0000000000001153
24. Marawar VS. The radiographic parameters for the prediction of spondylolysis and spondylolisthesis. *Seminars in Spine Surgery*. 2014;26(4):219-224. doi:10.1053/J.SEMSS.2014.09.003
25. Koreckij TD, Fischgrund JS. Degenerative spondylolisthesis. *J Spinal Disord Tech*. 2015;28(7):236-241. doi:10.1097/BSD.0000000000000298
26. R C, MJ H, EV C, PD P. Spondylolysis and spondylolisthesis in children and adolescents: I. Diagnosis, natural history, and nonsurgical management. *J Am Acad Orthop Surg*. 2006;14(7):417-424. doi:10.5435/00124635-200607000-00004
27. Kalichman L, Hunter DJ. Diagnosis and conservative management of degenerative lumbar spondylolisthesis. *Eur Spine J*. 2008;17(3). doi:10.1007/s00586-007-0543-3
28. Degenerative Lumbar Spondylolisthesis: Trends in Management : JAAOS - Journal of the American Academy of Orthopaedic Surgeons. Accessed August 1, 2021. https://journals.lww.com/jaaos/Fulltext/2008/04000/Degenerative_Lumbar_Spondylolisthesis_Trends_in.4.aspx
29. Attiah MA, Macyszyn L, Cahill PJ. Management of spondylolysis and spondylolisthesis in the pediatric population: A review. *Semin Spine Surg*. 2014;26(4):230-237. doi:10.1053/J.SEMSS.2014.09.005
30. Classification of Spondyloysis and Spondylolisthesis : Clinical Orthopaedics and Related Research®. Accessed August 1, 2021. https://journal.s.lww.com/clinorthop/citation/1976/06000/classification_of_spondyloysis_and.3.aspx
31. Gagnet P, Kern K, Andrews K, Elgafy H, Ebraheim N. Spondylolysis and spondylolisthesis: A review of the literature. *J Orthop*. 2018;15(2):404. doi:10.1016/J.JOR.2018.03.008
32. Benoist M. Natural history of the aging spine. *Eur Spine J*. 2003;12(Suppl 2):S86. doi:10.1007/S00586-003-0593-0
33. Tebet MA. Current concepts on the sagittal balance and classification of spondylolysis and spondylolisthesis. *Rev Bras Ortop*. 2014;49(1). doi:10.1016/j.rboe.2014.02.003
34. Matz PG, Meagher RJ, Lamer T, et al. Guideline summary review: an evidence-based clinical guideline for the diagnosis and treatment of degenerative lumbar spondylolisthesis. *Spine J*. 2016;16(3). doi:10.1016/j.spinee.2015.11.055
35. KUNZE KN, LILLY DT, KHAN JM, et al. High-Grade Spondylolisthesis in Adults: Current Concepts in Evaluation and Management. *Int J Spine Surg*. 2020;14(3). doi:10.14444/7044
36. Wiltse L. Spondylolisthesis : classification, diagnosis and natural history. *Semin Spine Surg*. 1989;1:78-94. Accessed August 7, 2021. <https://ci.nii.ac.jp/naid/10016136253>
37. Bouras T, Korovessis P. Management of spondylolysis and low-grade spondylolisthesis in fine athletes. A comprehensive review. *Eur J Orthop Surg Traumatol*. 2015;25:167-175. doi:10.1007/S00590-014-1560-7
38. JO L, JJ E, AD C, SJ G. SPECT evaluation of lumbar spondylolysis and spondylolisthesis. *Spine*. 1994;19(5):608-612. doi:10.1097/00007632-199403000-00018
39. RJ B, S H, DS D, JR G. The use of single photon emission computed tomography (SPECT) in the diagnosis of low-back pain in young patients. *Spine*. 1988;13(10):1155-1160. doi:10.1097/00007632-198810000-00018
40. RD B, DA S, ST T, LJ M. Low-back pain in adolescent athletes: detection of stress injury to the pars interarticularis with SPECT. *Radiology*. 1991;180(2):509-512. doi:10.1148/RADIOLOGY.180.2.1829845
41. A S, SJ B. The value of lumbar spine MRI in the assessment of the pars interarticularis. *Clin Radiol*. 1997;52(9):666-671. doi:10.1016/S0009-9260(97)80029-3
42. CJ H, JL R, A S, RL W. The radiological investigation of lumbar spondylolysis. *Clin Radiol*. 1998;53(10):723-728. doi:10.1016/S0009-9260(98)80313-9
43. BT V, CD S, HN H. Treatment of instability and spondylolisthesis: surgical versus nonsurgical treatment. *Clin Orthop Relat Res*. 2006;443(443):222-227. doi:10.1097/01.BLO.0000200233.99436.EA
44. Eismont FJ, Norton RP, Hirsch BP. Surgical management of lumbar degenerative spondylolisthesis. *J Am Acad Orthop Surg*. 2014;22(4):203-213. doi:10.5435/JAAOS-22-04-203

45. Wood KB, Fritzell P, Dettori JR, Hashimoto R, Lund T, Shaffrey C. Effectiveness of spinal fusion versus structured rehabilitation in chronic low back pain patients with and without isthmic spondylolisthesis: A systematic review. *Spine*. 2011;36(21 SUPPL.). doi:10.1097/BRS.0b013e31822ef8c5
46. Fedorchuk C, Lightstone DF, McRae C, Kaczor D. Correction of grade 2 spondylolisthesis following a non-surgical structural spinal rehabilitation protocol using lumbar traction: A case study and selective review of literature. *J Radiol Case Rep*. 2017;11(5):13-26. doi:10.3941/jrcr.v11i5.2924
47. Sasai K, Umeda M, Maruyama T, Wakabayashi E, Iida H. Microsurgical bilateral decompression via a unilateral approach for lumbar spinal canal stenosis including degenerative spondylolisthesis: Clinical article. *J Neurosurg Spine*. 2008;9(6):554-559. doi:10.3171/SPL.2008.8.08122
48. Bernard F, Mazerand E, Gallet C, Troude L, Fuentes S. History of degenerative spondylolisthesis: From anatomical description to surgical management. *Neurochirurgie*. 2019;65(2-3):75-82. doi:10.1016/j.neuchi.2019.03.006
49. Brown MD, Lockwood JM. Degenerative spondylolisthesis - PubMed. Instructional Course Lectures. Published 1983. Accessed June 28, 2021. <https://pubmed.ncbi.nlm.nih.gov/6546064/>
50. Longo UG, Loppini M, Romeo G, Maffulli N, Denaro V. Evidence-based surgical management of spondylolisthesis: Reduction or arthrodesis in situ. *J Bone Jt Surg - Ser A*. 2014;96(1):53-58. doi:10.2106/JBJS.L.01012
51. Beck AW, Simpson AK. High-Grade Lumbar Spondylolisthesis. *Neurosurg Clin N Am*. 2019;30(3):291-298. doi:10.1016/j.nec.2019.02.002
52. Oda I, Abumi K, Yu BS, Sudo H, Minami A. Types of Spinal Instability That Require Interbody Support in Posterior Lumbar Reconstruction. *Spine*. 2003;28(14):1573-1580. doi:10.1097/01.brs.0000076916.90238.37
53. He R, Tang GL, Chen K, Luo ZL, Shang X. Fusion in situ versus reduction for spondylolisthesis treatment: grading the evidence through a meta-analysis. *Bioscience Reports*. 2020;40(6). doi:10.1042/BSR20192888
54. Rengachary SS, Balabhadra R. Reduction of spondylolisthesis. *Neurosurg Focus*. 2002;13(1). doi:10.3171/foc.2002.13.1.3
55. Bridwell KH. Surgical Treatment of High-Grade Spondylolisthesis. *Neurosurg Clin N Am*. 2006;17(3):331-338. doi:10.1016/j.nec.2006.04.011
56. Randall RM, Silverstein M, Goodwin R. Review of Pediatric Spondylolysis and Spondylolisthesis. *Sports Med Arthrosc*. 2016;24(4):184-187. doi:10.1097/JSA.000000000000127
57. Kasliwal MK, Smith JS, Kanter A, et al. Management of High-Grade Spondylolisthesis. *Neurosurg Clin N Am*. 2013;24(2):275-291. doi:10.1016/j.nec.2012.12.002
58. Bourassa-Moreau É, Labelle H, Parent S, et al. Expectations for Postoperative Improvement in Health-Related Quality of Life in Young Patients with Lumbosacral Spondylolisthesis: A Prospective Cohort Study. *Spine*. 2019;44(3):E181-E186. doi:10.1097/BR.S.0000000000002788
59. Tamburrelli FC, Meluzio MC, Burrofato A, Perna A, Proietti L. Minimally invasive surgery procedure in isthmic spondylolisthesis. *Eur Spine J*. 2018;27(S2):237-243. doi:10.1007/s00586-018-5627-8
60. Wang W, Aubin CE, Cahill P, et al. Biomechanics of high-grade spondylolisthesis with and without reduction. *Med Biol Eng Comput*. 2016;54(4):619-628. doi:10.1007/s11517-015-1353-0
61. Cecchinato R, Boriani S. Spondylolisthesis and tumors: a treatment algorithm. *Eur Spine J*. 2018;27(Suppl 2):206-212. doi:10.1007/s00586-018-5589-x
62. Cheng C, Wang K, Zhang C, Wu H, Jian F zeng. Spondylolisthesis with Uncommon Congenital Deformity of L4-L5 Vertebral Fusion Treated by Oblique Lumbar Interbody Fusion. *World Neurosurg*. 2019;127:222-226. doi:10.1016/j.wneu.2019.04.021
63. Barsa P, Buchvald P, Suchomel P, Lukas R. [Traumatic spondylolisthesis of L5-S1] - PubMed. *Acta Chir Orthop Traumatol Cech*. Published 2003. Accessed June 28, 2021. <https://pubmed.ncbi.nlm.nih.gov/12807047/>
64. Lubelski D, Alentado VJ, Williams SK, et al. Variability in Surgical Treatment of Spondylolisthesis Among Spine Surgeons. *World Neurosurg*. 2018;111:e564-e572. doi:10.1016/j.wneu.2017.12.108
65. Mac-Thiong JM, Labelle H. A proposal for a surgical classification of pediatric lumbosacral spondylolisthesis based on current literature. *Eur Spine J*. 2006;15(10):1425-1435. doi:10.1007/s00586-006-0101-4

66. Steiger F, Becker HJ, Standaert CJ, et al. Surgery in lumbar degenerative spondylolisthesis: Indications, outcomes and complications. A systematic review. *Eur Spine J*. 2014;23(5):945-973. doi:[10.1007/s00586-013-3144-3](https://doi.org/10.1007/s00586-013-3144-3)

68. Harrop JS, Hilibrand A, Mihalovich KE, Dettori JR, Chapman J. Cost-effectiveness of surgical treatment for degenerative spondylolisthesis and spinal stenosis. *Spine*. 2014;39(22):S75-S85. doi:[10.1097/BRS.0000000000000545](https://doi.org/10.1097/BRS.0000000000000545)

67. Tumialán LM. Future Studies and Directions for the Optimization of Outcomes for Lumbar Spondylolisthesis. *Neurosurg Clin N Am*. 2019;30(3):373-381. doi:[10.1016/j.nec.2019.02.011](https://doi.org/10.1016/j.nec.2019.02.011)