Management of High-Grade Spondylolisthesis

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KEYWORDS

• Adolescents • Adult spondylolisthesis • Classification • High-grade spondylolisthesis • Management • Surgery • Complications

KEY POINTS

- Management of high-grade spondylolisthesis (HGS) remains challenging and is associated with significant controversies.
- Symptomatic patients presenting with intractable pain, neurologic deficits, or global deformity are often considered candidates for surgery.
- The best surgical procedure still remains debatable, considering the absence of high-quality studies in the literature demonstrating superiority of one approach over another.
- Recognition of the importance of overall spinopelvic alignment and global deformity has provided strong rationale for at least partial slip reduction.
- Complications associated with operative management of HGS still remains the key factor dictating the selection of surgical approach.

INTRODUCTION

The term spondylolisthesis is derived from the Greek words, *spondylos*, meaning "vertebrae" and *olisthesis*, meaning "to slip." High-grade spondylolisthesis (HGS) is defined as greater than 50% slippage of a spinal vertebral body relative to an adjacent vertebral body as per Meyerding classification, and most often affects the alignment of the L5 and S1 vertebral bodies (**Fig. 1**).[1] Although more than 50% of linear translation in the sagittal plane is used to define HGS, it is the associated rotational component that often plays a greater role in prognosis and overall management.[2,3] The treatment of high-grade lumbosacral spondylolisthesis differs from that of low-grade slips, and operative management remains challenging and is associated with significant controversies in terms of the optimal surgical technique.[4–7] This review highlights the pathophysiology, classification, clinical presentation, and management controversies of HGS in light of recent advances in our understanding of the importance of sagittal spinopelvic alignment and technologic advancements.

PATHOPHYSIOLOGY OF DEVELOPMENT OF HIGH-GRADE SPONDYLOLISTHESIS

The clinical syndrome of spondylolisthesis was first described in 1782 by the Belgian obstetrician Herbiniaux, long before an understanding of its pathophysiology, when he reported a bony

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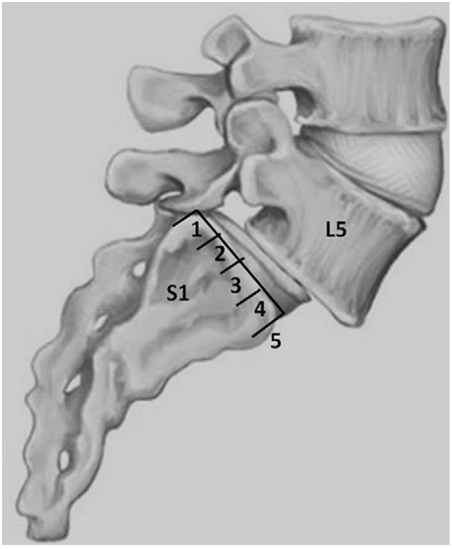

Fig. 1. Measurement of the transitional component of spondylolisthesis per Meyerding grade.

prominence anterior to the sacrum that created an impediment to vaginal delivery in a cohort of his patients. Spondylolisthesis shows a strong familial association, with an incidence in first-degree or second-degree relatives of approximately 25% to 30%.[8] A radiographic study by Wynne-Davies and Scott[9] showed that dysplastic spondylolisthesis has a familial incidence of 33%, whereas the isthmic variant has a familial incidence of 15%, with a multifactorial autosomal dominant pattern of inheritance with incomplete penetrance. Although the etiology of the condition is not completely understood, the evidence available thus far suggests that factors beyond developmental susceptibilities may play a significant role in the development of HGS. Activities that involve hyperextension and persistent lordosis such as gymnastics, weightlifting, diving, football, and volleyball increase shear stresses at the neural arch and have been implicated as causative factors in the development of spondylolysis, with subsequent development of spondylolisthesis in a subset of patients.[10] The majority of HGS cases are of the isthmic or dysplastic variety.[11] The presence of a congenitally dysplastic lumbosacral segment with incompetent posterior elements cannot withstand typical forces associated with maintenance of an upright posture; this often leads to development of a slip, which over time can result in an HGS.

Variations in the cross-sectional anatomy of the pars at each level in the lumbar spine likely contribute to the increased incidence of isthmic spondylolisthesis in more caudal segments, especially at the L5/S1 level. The pars is fairly large in diameter in the upper lumbar vertebra and relatively thin at the L5 level.[12] Fredrickson and colleagues[13] prospectively followed 500 elementary students and found a 4.4% incidence of spondylolysis at the age of 6 years, which increased to 6% in adulthood. Of note, the same investigators also evaluated 500 newborns and found no evidence of spondylolysis/spondylolisthesis, suggesting that development of a pars defect with subsequent development of spondylolisthesis is an acquired phenomenon.

Sagittal sacropelvic morphology and orientation modulate the geometry of the lumbar spine and, consequently, the mechanical stresses at the lumbosacral junction. There have been recent attempts to quantify the relation between the lumbosacral spine and the pelvis by means of various geometric parameters in an effort to better understand the development of spondylolisthesis.[3,14–16] These parameters include sacral slope (SS), pelvic tilt (PT), and pelvic incidence (PI). Multiple studies have demonstrated the importance of harmonious alignment among pelvic and spinal parameters with regard to standardized measures of health-related quality of life (HRQOL).[17–19] Various sagittal lumbosacral spine and spinopelvic parameters are illustrated in **Fig. 2** and are further described in **Table 1**.

Labelle and colleagues[20] found that PI, SS, PT, and LL (lumbar lordosis) measurements were significantly higher in subjects with spondylolisthesis than in controls. These investigators further demonstrated that the values increased with the severity of the spondylolisthesis, leading them to conclude that PI (and thus pelvic anatomy) influences the development of spondylolisthesis, and that an increased PI may be a risk factor for the development and progression of developmental spondylolisthesis.[20] Other reports have contributed increasing evidence that in high-grade L5-S1 spondylolisthesis, the sacropelvic morphology is abnormal and that, combined with the presence of a local lumbosacral deformity and dysplasia, it can result in an abnormal sacropelvic orientation and disturbed global sagittal alignment of the spine.[3,15,16,21,22] These findings have important implications for the evaluation and treatment of patients with HGS and have been the basis of recent spondylolisthesis classifications.[23–25] These data also provide a compelling rationale to reduce and realign the deformity in order to restore global spinopelvic alignment and improve the biomechanical environment for fusion.[26]

CLASSIFICATION OF HIGH-GRADE SPONDYLOLISTHESIS

The classification systems described by Wiltse and by Marchetti and Bartolozzi have remained the most

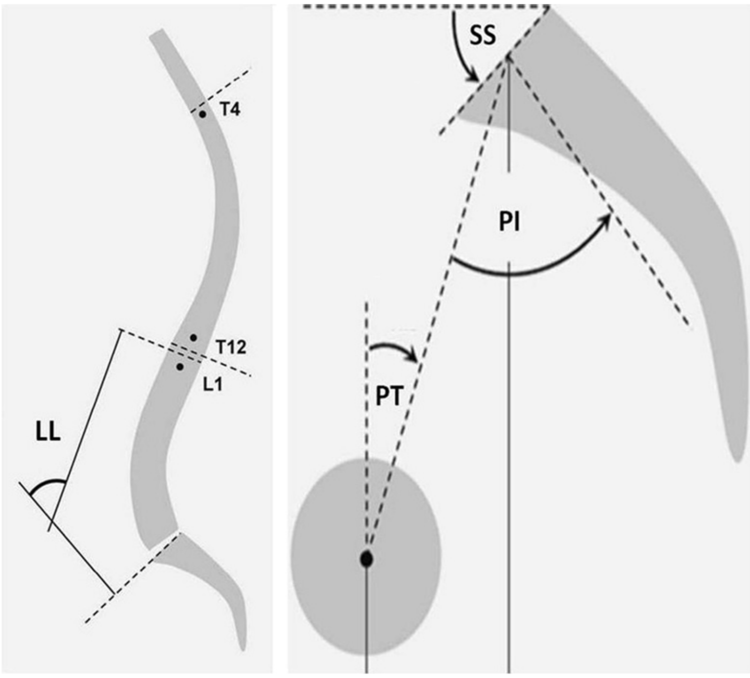

Fig. 2. Sagittal pelvic parameters assessed from the standing lateral radiograph. The pelvic incidence (PI) is always equal to the sum of the sacral slope (SS) and the pelvic tilt (PT). LL, lumbar lordosis.

Table 1
Description of various radiographic parameters used to define spondylolisthesis and sagittal spinopelvic alignment

Boxall slip angle (BSA)	The angle subtended by the inferior endplate of L5 with a line perpendicular to the posterior aspect of S1
Dubousset lumbosacral angle (Dub-LSA)	The angle subtended by the superior endplate of L5 with the posterior aspect of S1
Sacral slope (SS)	The angle between the horizontal line and the cranial sacral endplate tangent
Pelvic tilt (PT)	The angle between the vertical line and the line joining the middle of the sacral plate to the center of the bicoxofemoral axis
Pelvic incidence (PI)	The angle between the line perpendicular to the middle of the cranial sacral endplate and the line joining the middle of the cranial sacral endplate to the center of the bicoxofemoral axis
Sagittal vertical axis (SVA)	The horizontal offset between the C7 plumb line and the posterior superior aspect of the S1 vertebral body. Positive and negative values of SVA reflect cases in which the C7 plumb line falls anterior or posterior, respectively, to the posterosuperior corner of the S1 vertebral body
Lumbar lordosis (LL)	Cobb Angle measured from the superior endplate of L1 to the superior endplate of S1
C7 Plumb line	Vertical line drawn from the center of C7 vertebrae on a radiograph. Often used as a reference line for measuring sagittal balance. The distal reference point for this parameter is the posterosuperior corner of the sacrum

commonly used classifications for spondylolisthesis over the last few decades (**Figs. 3** and **4**).[27] Wiltse provided a classification based on etiology. By contrast, the classification system described by Marchetti and Bartolozzi divides spondylolisthesis into two types, developmental and acquired, with the distinction between them being the presence of either a high or low amount of bony dysplasia with developmental spondylolisthesis and lack of such dysplasia with the acquired type.[27] The vast majority of HGS seen in either pediatric or adult patients occurs in patients with developmental spondylolisthesis, particularly with a high amount of dysplasia. In general, progression of an acquired spondylolisthesis to high-grade slip is thought to be relatively uncommon.[22] The greater the degree of dysplasia present in a developmental spondylolisthesis, the greater the amount of secondary bony changes and slippage that occur, which include a rounding off of the sacrum, angulation of the inferior endplate of L5 (trapezoid L5), increased slip angle, and verticalization of the sacrum.

Although Marchetti and Bartolozzi were the first to introduce the concept of low-dysplastic and high-dysplastic developmental spondylolisthesis, they did not include strict criteria to differentiate these two subtypes. Another limitation of their classification system is a lack of consideration of spinopelvic alignment, which recently has been shown to differ significantly between high-grade and low-grade HGS, and even within HGS between the high-dysplastic and low-dysplastic cases.[22] Although rare, acquired spondylolisthesis may progress to high grades of slippage. Most are iatrogenic following a destabilizing surgical procedure of the underlying soft tissue including the disc, facet capsules, musculature, and ligaments. This type of HGS is more similar to posttraumatic kyphosis than to the dysplastic developmental types of spondylolisthesis, and reduction of an iatrogenic postsurgical acquired spondylolisthesis seems to have a lower risk of neurologic injury than developmental types of slippage.[28]

Although these classification systems have been popular for several years, there are substantial limitations; perhaps most notably they do not provide useful information on clinical management.[27] Furthermore, these classifications do not take sagittal sacropelvic alignment into account, which has been found to be very important in several recent studies for the evaluation and treatment of spondylolisthesis.[3,15,20,22,29] Mac-Thiong and colleagues[25] recently proposed a new classification of lumbosacral spondylolisthesis that is specifically intended to guide its evaluation and treatment. This system incorporates sagittal sacropelvic alignment and morphology, and defines 8 types based on the slip grade (low-grade vs high-grade), degree of dysplasia (low-dysplastic vs high-dysplastic), and sagittal sacropelvic alignment (**Table 2**). The Spine Deformity Study Group (SDSG) confirmed the validity of this classification and provided modifications, further dividing lumbosacral spondylolisthesis into 6 types based on 3 important characteristics that can be easily assessed from preoperative imaging studies. The SDSG-modified version of the classification has been reported to have significantly less interobserver and intraobserver variability in assessment of the grade of slip, the sacropelvic balance, and the global spinopelvic balance (**Table 3**).[24]

For the SDSG classification system modified from that of Mac-Thiong, first the degree of slip is quantified from the lateral radiograph, to determine if it is low grade (grades 0, 1, and 2, or <50% slip) or high-grade (grades 3, 4, and spondyloptosis, or ≥50% slip). Next, the sagittal alignment is measured by determining sacropelvic and global spinopelvic alignment, using measurements of PI, SS, PT, and the C7 plumb line. In HGS, sacropelvic alignment is assessed based on the SS and PT.[26,30] Each subject is classified as high SS/low PT (balanced sacropelvis) or low SS/high PT (unbalanced sacropelvis) (**Fig. 5**). Patients with low-grade spondylolisthesis can be subdivided into 3 types based on their sacropelvic balance : type 1, the nutcracker type, a subgroup with low PI <45°; type 2, a subgroup with normal PI (between 45°, and 60°); and type 3, the shear type, a subgroup with high PI (≥60°) (see **Table 3**). Patients with

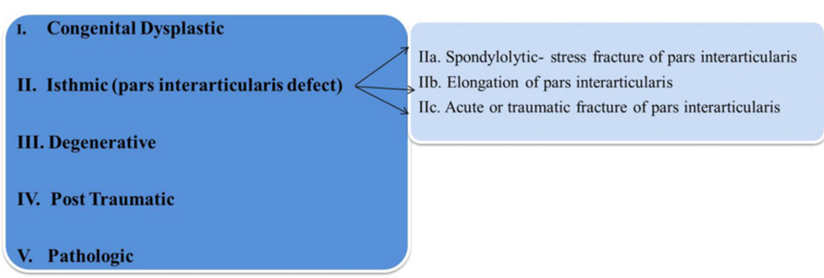

Fig. 3. Wiltse's classification of spondylolisthesis.

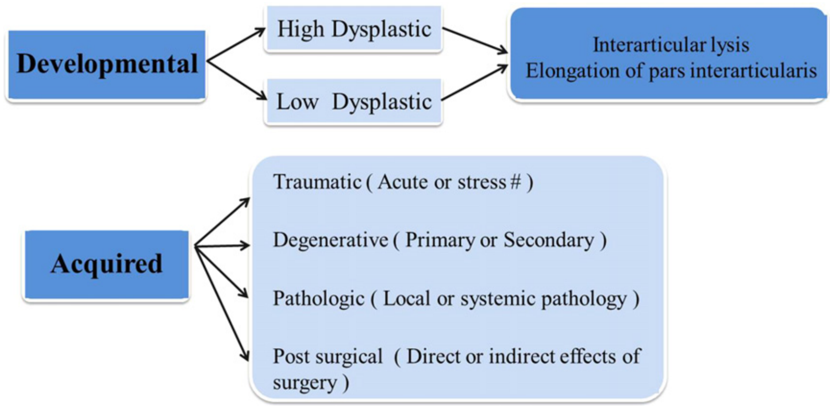

Fig. 4. Spondylolisthesis classification by Marchetti and Bartolozzi.

Table 2
Original classification system of lumbosacral spondylolisthesis as proposed by Mac-Thiong and Labelle

Grade	Dysplasia	Sacropelvic Balance	Example
Low grade (<50% slip)	Low-Dysplastic Minimal lumbosacral kyphosis Almost rectangular L5 Minimal sacral doming Relatively normal sacrum Minimal posterior elements dysplasia (eg, spina bifida occulta) Relatively normal transverse processes	Low PI/Low SS Sacral slope <40°	 Type 1
		High PI/High SS Sacral slope >40°	 Type 2
	High-Dysplastic Lumbosacral kyphosis Trapezoidal L5 Sacral doming Sacral dysplasia and kyphosis Posterior elements dysplasia Small transverse processes	Low PI/Low SS Sacral slope $\leq$40°	 Type 3
		High PI/High SS Sacral slope >40°	 Type 4

(*continued on next page*)

Table 2
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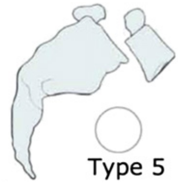
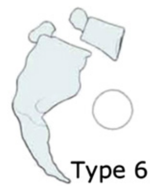
Grade	Dysplasia	Sacropelvic Balance	Example
High grade (≥50% slip)	Low-Dysplastic Minimal lumbosacral kyphosis Almost rectangular L5 Minimal sacral doming Relatively normal sacrum Minimal posterior elements dysplasia (eg, spina bifida occulta) Relatively normal transverse processes	High SS/Low PT (balanced pelvis) Balanced sacrum Sacral slope ≥50° Pelvic tilt ≤35°	
		Low SS/High PT (unbalanced pelvis) Vertical sacrum Sacral slope <50° Pelvic tilt ≥25°	
	High-Dysplastic Lumbosacral kyphosis Trapezoidal L5 Sacral doming Sacral dysplasia and kyphosis Posterior elements dysplasia Small transverse processes	High SS/Low PT (balanced pelvis) Balanced sacrum Sacral slope ≥50° Pelvic tilt ≤35°	
		Low SS/High PT (unbalanced pelvis) Vertical sacrum Sacral slope <50° Pelvic tilt ≥25°	

Abbreviations: PI, pelvic incidence; PT, pelvic tilt; SS, sacral slope.
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a high PI have a high shear stress across the lumbosacral junction and a higher likelihood of their spondylolisthesis progressing to a high grade. Patients with a low PI, on the other hand, have low shear stress across the lumbosacral junction and less chance of progression of their spondylolisthesis to a high grade.[20] Finally, global spinopelvic alignment is determined using the C7 plumb line. If this line falls over or behind the femoral heads the spine is aligned, whereas if it lies in front of both femoral heads the spine is malaligned.

CLINICAL PRESENTATION

Although HGS can often be asymptomatic, those who do become symptomatic usually present with back pain, leg pain, or a combination of these.[2,13,14,31–33] Complaints of back pain with activity that are relieved with recumbency are often described. The leg pain, which may also include numbness or paresthesias, described by symptomatic patients is predominately dermatomal in distribution, and often related to the nerve(s) being compressed in the lateral recess at the level of the pars defect. The leg symptoms are described as sclerodermal if they are referred into the broad region of the buttock or posterior thigh, which usually occurs as a result of the disc degeneration that often accompanies the pars defect. In addition, the postural changes associated with HGS in adults can lead to low back pain, tight hamstrings, and postural deformity.[34]

Table 3
SDSG classification of lumbosacral spondylolisthesis

Slip Grade	Sacropelvic Balance	Spinopelvic Balance	Spondylolisthesis Type
Low grade	Nutcracker (PI < 45°)		Type 1
	Normal pelvic incidence (60° > PI ≥ 45°)	—	Type 2
	High pelvic incidence PI ≥ 60°	—	Type 3
High grade	Balanced	—	Type 4
	Unbalanced	Balanced	Type 5
		Unbalanced	Type 6

On clinical examination, palpation of the spine may elicit midline tenderness, and a step-off of the spinous processes may be felt above the level of the slip. There will often be limited flexion of the lumbar spine caused by paraspinal spasm as those muscles attempt to prevent shear forces across the affected segment. There can be presence of trunk foreshortening, and hamstring tightness may be noted, with compensatory hyperlordosis above the slip and a waddling gait. Patients may have a classically described Phalen-Dickson sign (ie, a knee-flexed, hip-flexed gait). Neurologically, deficits may include motor weakness and/or sensory deficits depending on the degree of nerve compression in the lateral recess, which typically occurs as a result of the fibrocartilaginous mass or Gill lesion. Cauda equina syndrome is rare because of a relative enlargement of the canal that occurs as the cephalad vertebra slips anterior to the caudal vertebra, leaving the separated posterior elements of the cephalad vertebra in a posterior position. Unlike low-grade slips, whose manifestations are typically limited to painful segmental instability or neural compromise at the affected level, high-grade slips invariably provoke secondary changes in the regional pelvic anatomy, and thus contribute to global sagittal deformity.[15,20] Historically the cosmetic deformity of HGS has been underappreciated or considered to be of secondary importance to symptoms of pain. The local deformity of the high-grade slip invariably induces compensatory changes in the regional pelvic anatomy, forcing the patient into positive sagittal malalignment.[33] The body's attempts to restore alignment via tonic activation of the paraspinous (eg, erector spinae) muscles, and progressive retroversion of the pelvis (increased PT) is typically accompanied by clinical sequelae of low back pain (presumably caused by chronic paraspinous muscle activation and/or segmental instability), tight hamstrings, and postural deformity.[22,24–26,35] The presence of this global deformity contributes to the complexity of surgical management of HGS.

RADIOLOGY OF HIGH-GRADE SPONDYLOLISTHESIS

Radiographic evaluation should consist of anteroposterior and lateral flexion-extension radiographs. This combination allows the determination of translational instability. However, radiologic evaluation of HGS is no longer limited to assessment of the degree of translational slip alone. Long cassette scoliosis radiographs should also be evaluated to assess for overall sagittal alignment. Computed

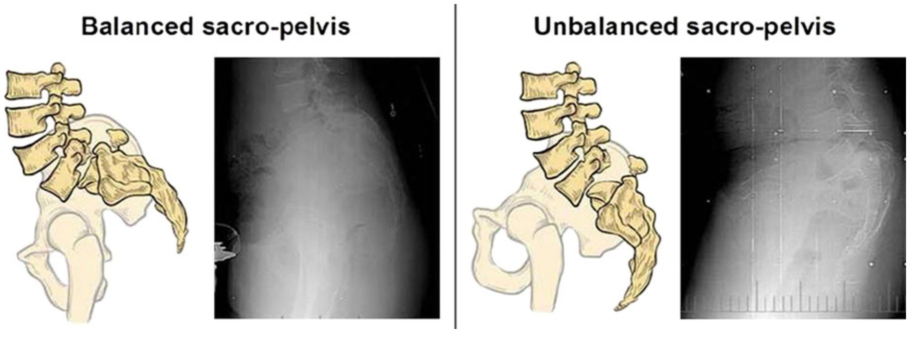

Fig. 5. Schematic figure demonstrating balanced versus unbalanced spinopelvis. (*Reprinted from* Mac-Thiong JM, Labelle H, Parent S, et al. Reliability and development of a new classification of lumbosacral spondylolisthesis. Scoliosis 2008;3:19; with permission from SpringerOpen.)

tomography scans provide excellent bony details of the pathologic status, and magnetic resonance imaging can give much better delineation of the soft-tissue abnormalities. **Table 1** summarizes key radiographic parameters used to characterize HGS. In spondylolisthesis, there are 2 primary components involved in the underlying deformity: translational and angular.[1,36,37] The diagnosis of HGS is overt even on plain radiographs, obviating any need of oblique radiographs to demonstrate the pars defect seen in spondylosis. Measurement of slip grade as per Meyerding classification clearly confirms the diagnosis of high-grade spondylolisthesis by grading the translational component of the deformity (see **Fig. 1**). By contrast, there are multiple techniques to measure angular deformity.[37] Normally the junction between the fifth lumbar and the first sacral vertebrae is lordotic. However, as the degree of slip progresses to higher grades, this relationship tends to become kyphotic in nature. Studies have suggested a role of lumbosacral kyphosis (LSK) in determining the risk of slip progression,[2,33,37,38] and have also suggested the importance of correcting LSK because this helps to restore global spinal alignment, enhances the biomechanics of fusion, and can protect against stretch of the L5 nerve root. The Boxall slip angle and lumbosacral angle (LSA) provide assessment of the angular component of deformity associated with HGS (**Fig. 6**).[39,40] With progression of slippage, the inferior endplate of L5 tends to become dysplastic and the L5 vertebral body may adopt a trapezoidal shape.[41–43] Moreover, remodeling of the S1 endplate can occur, referred to as sacral

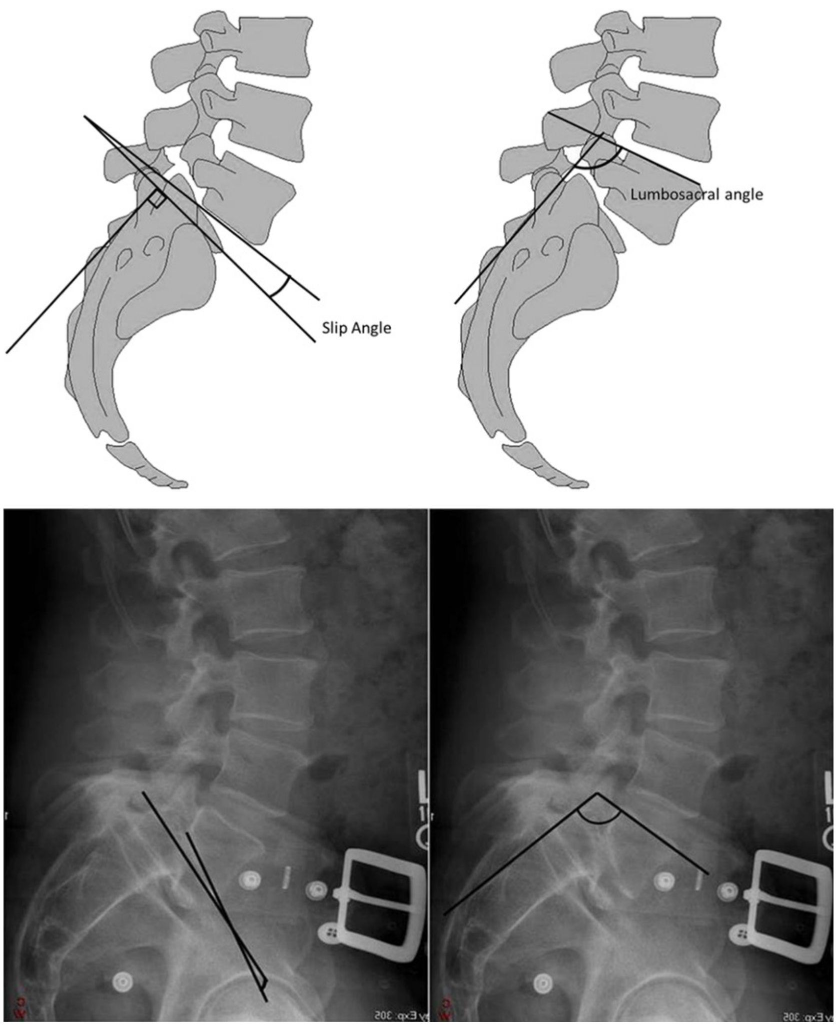

Fig. 6. Schematic diagram and lateral radiograph demonstrating measurement of Dubousset lumbosacral angle (*upper and lower right*) and Boxall slip angle (*upper and lower left*).

doming or rounding.[44] These changes can make the identification of the inferior endplate of L5 and superior endplate of S1 difficult, as can be observed in the radiograph shown in **Fig. 6**, favoring evaluation of the LSK based on the LSA rather than the slip angle. Positive and negative values of the sagittal vertical axis reflect cases whereby the C7 plumb line falls anterior or posterior, respectively, to the posterosuperior corner of the S1 vertebral body (**Fig. 7**).

NATURAL HISTORY: TO OPERATE OR NOT TO OPERATE?

Symptomatic high-grade isthmic spondylolisthesis in children and adolescents has an unfavorable natural history, with a high risk of progression and low likelihood of symptomatic relief. Conservative treatment is generally not recommended in symptomatic patients, who constitute the majority of patients with high-grade slips in this age group.[45,46] Pizzutillo and colleagues[47] found that only 1 of 11 symptomatic patients treated conservatively had significant pain relief at long-term follow-up. Asymptomatic patients can be treated with observation, and if symptoms do develop surgery is generally recommended. Some investigators have recommended surgical treatment for these patients regardless of symptoms, because of the high risk of progression.[46] However, Harris and Weinstein[5] reported that 10 of 11 patients with high-grade slips who were treated nonoperatively remained active and required only minor modifications in activity.

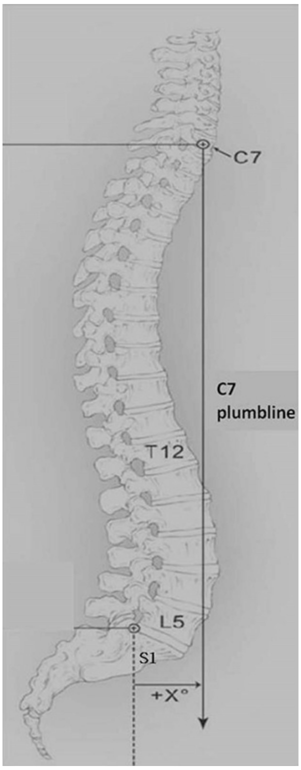

Fig. 7. Measurement of spinal vertical axis. The sagittal vertical axis is measured as the distance from the posterior superior corner of the sacrum to a vertical plumb line dropped from the C7 centroid (C7 plumb line).

In contrast to children or adolescents, adults with high-grade slips have often reached a stable position and typically do not experience progression, making slip progression less of a concern. Autofusion or ankylosis of the slipped level can occur. Some of these patients are asymptomatic or minimally symptomatic, and can be successfully treated with physical therapy and selective nerve-root injections if radicular symptoms are present. If conservative treatment fails, surgery is recommended in adult patients who have high-grade slips with back pain and/or radicular symptoms. Unlike low-grade slips, whose manifestations are typically limited to painful segmental instability or neural compromise at the affected level, high-grade slips invariably provoke secondary changes in the regional pelvic anatomy and can thus produce global sagittal deformity with clinical manifestations of intractable back pain or deformity, which might be another indication for surgery.[33]

INDICATIONS FOR SURGERY: WHEN TO OPERATE?

1. *Slip progression*. Progression is more common in skeletally immature patients who have not reached the adolescent growth spurt. The higher the grade of slip, the more likely it is to progress. Slip progression rarely occurs in adults. Although asymptomatic progression alone may be considered an indication for surgery, patients with progressive slips frequently have significant pain that does not respond to conservative treatment.
2. *Sagittal alignment*. High-grade slip with significant lumbosacral kyphotic deformity causing sagittal spinopelvic malalignment.
3. *Neurologic deficit*. In most cases of neurologic deficit, the L5 nerve root is involved. Objective weakness is not common in this condition, but if present, surgery should be strongly considered to relieve nerve-root compression.
4. *Back pain*. Low back pain unresponsive to a prolonged course of conservative treatment.
5. *Leg symptoms*. Radicular pain with associated nerve-root compression on imaging studies that is not responsive to conservative treatment.

PEDIATRIC VERSUS ADULT HGS: ARE THEY THE SAME?

There are several important differences between the pediatric and adult population regarding the overall approach to the management of HGS.

1. With degenerative changes contributing to nerve-root compression, adults are more likely to require direct neural decompression. Even in the presence of radicular symptoms, pediatric and adolescent patients often experience symptom relief with fusion alone when a hypermobile segment is stabilized.
2. Considering the higher risk of pseudarthrosis in adults secondary to smoking, poor general health, and secondary comorbidities, instances whereby a posterior-only approach may be suitable for adolescents may not be appropriate in the adult, in whom a circumferential fusion may be advisable to increase the likelihood of fusion success.
3. Reduction of high-grade slips is generally more difficult in adults because of the increased rigidity of the deformity and stiffness across the lumbosacral junction. Because of the presence of secondary degenerative changes in adults, the deformity tends to be less mobile.
4. Risk of progression is higher in children and adolescents than in adults. The younger the patient is at the time of diagnosis, the greater the risk of progression, because the deformity is likely to progress during periods of active spinal growth. For this reason, slip progression is a more common indication for surgery in children and adolescents with high-grade slips. Progression is uncommon in adults, and surgery is rarely indicated for this reason in the adult patient. Most adults with high-grade slips who need surgery have pain or radicular symptoms that have not responded to conservative treatment or are secondary to the chronic deformity attributable to HGS.

TO REDUCE OR NOT TO REDUCE: WHAT IS THE PROBLEM WITH REDUCTION?

Although slip reduction was contemplated as early as 1921, associated unacceptably high rates of neurologic injury made many experts believe that in situ fusion was safer and produced acceptable results. As recently as 1976, Nachemson and Wiltse[48] stated without equivocation that in situ fusion worked so well that reduction was rarely warranted, citing an increased risk of neurologic complications, longer operative time, and greater blood loss with reduction. Nevertheless, some surgeons continued to pursue reduction, believing that correction of the underlying deformity was supported by sound mechanical principles and, in the right hands, could be safely accomplished. Over the last quarter-century, tremendous advances have been made in surgical techniques, particularly in the realm of spinal instrumentation, with the result that reduction can now be accomplished more safely and effectively than ever before. Along with the importance of restoring the sagittal alignment, this has once again rekindled the discussions between proponents of reduction and advocates of in situ fusion. Unfortunately, no randomized controlled trials exist to definitively answer the question of whether one of these approaches is superior, and most of the available evidence in favor of reduction or use of anterior column support has been from retrospective studies and case series.[4,14,31,35,39,49–66]

The primary rationale behind a reduction maneuver in severe slips is to correct the lumbosacral kyphotic deformity to improve the sagittal malalignment and the patient's ability to stand upright, with a secondary advantage of a reduction procedure being an improvement in fusion rate.[3,15,16,22,26,67,68] From a biomechanical standpoint, an in situ fusion performed in the setting of severe lumbosacral kyphosis is subjected to significant shear forces.[68] Reducing the lumbosacral kyphosis should improve the biomechanical environment for a fusion by converting the shear forces to compressive forces and reducing the risk of further progression of deformity. In contemporary surgical practice, the understanding of complex deformity often associated with HGS and its secondary effects on pelvic version and global sagittal alignment have reignited enthusiasm in reconsidering the role of reduction.[14,15,20,24,25,39,41,57,68] First, high-grade slips almost invariably have a dysplastic component,[29] with implications for the feasibility of fixation and posterolateral fusion; and the slip angle becomes a greater source of deformity than the degree of forward translation.[2,3,20,39] Second, the local deformity of the high-grade slip invariably induces compensatory changes in the regional pelvic anatomy—changes that are propagated up the spinal column, ultimately producing a global postural deformity.[33] As L5 slips anteriorly and then inferiorly on the sacrum, the mass gravity line (and with it the trunk and head) is drawn forward, forcing the patient into positive sagittal malalignment. The postural changes (tonic activation of the paraspinous muscles, retroversion of the pelvis, external rotation of hip, knee flexion) secondary to this represent the end stage of severe lumbosacral spondylolisthesis and are typically accompanied by clinical sequelae of low back pain, tight hamstrings, postural deformity, and in some cases radiculopathy or even cauda equina syndrome. Although proponents of in situ fusion have argued that good results are predictably obtained simply through the elimination of abnormal segmental motion, reduction offers several benefits over in situ fusion. First, in situ fusion has been consistently associated with higher rates of nonunion, up to 44% in some series, presumably attributable to the continued presence of powerful shear forces acting at the lumbosacral junction and to a decrease in available surface area for fusion, specifically as a result of significant dysplastic changes associated with HGS.[29,45,55] The troublesome phenomenon of slip progression despite solid fusion, which has been reported after in situ fusion in up to 26% of cases, is further testament to the perils of leaving the kyphotic deformity of severe lumbosacral spondylolisthesis uncorrected.[45,55] Labelle and colleagues[16] have shown that whereas sacropelvic shape (PI), which is an anatomic parameter, is unaffected by attempts at surgical reduction, proper repositioning of L5 over S1 through partial or complete reduction significantly improves sacropelvic alignment and the orientation of the lumbar spine in developmental spondylolisthesis. Their results also emphasize the importance of subdividing subjects with HGS into types 4, 5, and 6, and further support the contention that reduction techniques might preferably be considered for SDSG types 5 and 6, as has been suggested in other studies also.[25,26] Finally, although some patients may not express dissatisfaction with their appearance, there are many patients for whom cosmetic concerns remain paramount. For this subset of patients, surgery that does not incorporate some element of reduction will inevitably produce an inferior result.

Historically the principal argument against reduction has been focused on the associated unacceptably high rate of neurologic deficit. It must be emphasized, however, that iatrogenic neurologic deficit is not a constant finding after reduction, and that when neurologic deficits do occur they are typically transient, with rates of permanent neurologic deficit after reduction averaging 5% and rarely exceeding 10%.[69] Moreover, in situ fusion is not completely innocuous, and deficits have also been reported after in situ fusion.[63] In 1988, the Scoliosis Research Society (SRS) morbidity and mortality report indicated no difference in the rates of neurologic deficit after reduction and in situ fusion in this patient population. This finding was subsequently echoed in another report by Kasliwal and colleagues[69] from the most recent SRS database on complication rates following surgery specifically for HGS. This report again demonstrated no difference in rates of neurologic deficits in patients with or without reduction of HGS. The existence of several series in which patients underwent reduction without neurologic complication is testament to the fact that, through adherence to the principles of wide decompression and judicious correction, reduction of high-grade lumbosacral spondylolisthesis can be achieved safely.[6,39,50,59] Moreover, partial reduction of the deformity, which also leads to correction of slip angle, may be adequate as opposed to full reduction, because slip angle has been correlated better than the degree of slip in predicting the risk of progression of spondylolisthesis.[39] Moreover, as studies have shown that most of the total L5 nerve strain occurs during the second half of reduction, attempting a partial reduction may be safer than total reduction, with the benefit of increasing the fusion rate and correcting overall deformity.[70]

Despite the facts that reduction offers overwhelming biomechanical advantages and that procedures not incorporating some degree of correction are at risk of providing an inferior result because of persistent physical deformity or construct failure, due in large part to the rarity of high-grade lumbosacral spondylolisthesis, no prospective studies exist comparing reduction with fusion in situ. A formal review of the literature by Transfeldt and Mehbod[7] found no randomized controlled trials or comparative prospective studies comparing fusion in situ versus reduction and fusion for HGS. In their analysis they found 5 comparative retrospective studies, none of which showed any benefit to reduction.[49,52,60,61,71] Of interest, Poussa and colleagues[49] found that in patients with HGS, the in situ fusion group performed better than the reduction group. However, there is ample evidence in the literature, mostly from retrospective studies and case series, reporting the safety of reduction procedures in HGS.[22,39,50,52,60,64,68,72–74]

In summary, at least partial reduction of the lumbosacral deformity should be considered in cases of HGS. Reducing the percentage of translation of L5 on S1 is of secondary importance because it is the lumbosacral kyphosis that is primarily responsible for the sagittal malalignment. Therefore, improvement of the slip angle should be the primary goal of any reduction attempt, and it has been recognized that partial reduction of the slip angle is the key to restoring sagittal alignment.[39] In situ fusion may be an option and may be preferred in the instance when the patient: (1) presents with back pain in the absence of radicular complaints, neurologic deficit, or cosmetic deformity; (2) has adequate neural foraminal space; and (3) has acceptable global sagittal spinopelvic alignment and good sagittal alignment of the proximal instrumented vertebra.

ANTERIOR COLUMN SUPPORT

Regardless of patient age, HGS creates increased shear stress at the lumbosacral junction. Various studies have reported high rates of pseudarthrosis and progression of the postoperative slip after posterior in situ fusion.[71,75] The addition of anterior column structural support not only provides greater stability at the lumbosacral junction but also, more importantly, leads to higher fusion rates because of the greater surface area available with an interbody fusion. Presence of significant dysplasia often associated with HGS leads to a reduction in the posterior surface area available for fusion, and hence lowers fusion rates in comparison with patients treated for low-grade slips.[29] If reduction is performed for HGS, circumferential fusion and stable fixation with iliac screws should be considered to prevent slip progression and pseudarthrosis. This aspect may be particularly relevant in patients with a high PI who have additional shear forces at the lumbosacral junction. If the severity of the slip precludes interbody fusion, a transsacral approach as described by Bohlman and Cook[76] can be used to provide anterior fixation, or the use of transvertebral fibular dowel and/or screws might be an option, as discussed next.[6,54,73]

SURGICAL OPTIONS

Basic Surgical Principles and Pearls

Irrespective of the surgical technique used, there are inherent principles that should be adhered to in order to maximize the chances of a successful outcome following the surgical treatment of HGS.

- The role of instrumentation is less controversial with high-grade slips. Instrumentation is recommended in patients who undergo in situ posterolateral fusion from L4 to S1.
- Partial reduction (particularly of slip angle) offers significant biomechanical advantages, whereas complete (anatomic) reduction though desirable is rarely necessary (**Fig. 8**).
- Wide decompression of the neural elements with particular attention to compressive dysmorphic elements (eg, fibrocartilaginous pars, sacral dome), in addition to judicious distractive reduction under direct visualization of the neural elements, is essential to avoid iatrogenic neural injury.
- Interbody fusion, whether performed from an anterior or posterior approach, may substantially improve the long-term success of the final construct.
- Consideration should be given to incorporating supplemental fixation such as iliac screws, S2 pedicle screws, and/or L4 pedicle screws to protect the construct from the powerful shear forces acting at the lumbosacral junction, especially if anatomic reduction is not performed. Extending the fusion proximally to L4 should be considered in HGS, especially if instability

Fig. 8. Lateral parasagittal T1-weighted magnetic resonance image (*left*) and lateral standing radiograph (*middle*) of a 21-year-old male patient with intractable back pain and high-grade spondylolisthesis (grade IV). (*Right*) Postoperative radiograph demonstrating L4-S1 posterior segmental instrumentation and partial reduction of HGS to grade I with correction of the slip angle.

is present at the L4-L5 segment, if the L5 transverse processes are very small with minimal area for a fusion mass, or in the presence of degenerative changes/stenosis at the L4-L5 level that may be contributing to the patient's symptoms. In a high-grade slip, fusion from L5 to sacrum creates a horizontally oriented fusion, which is under high shear stress and prone to failure. Inclusion of L4 improves the mechanical advantage by creating a more vertical fusion. Another difficulty with fusion of L5 to sacrum in a high-grade slip is the anterior position of the L5 transverse processes in relation to the sacral ala, which makes fusion technically challenging.

- Consider transsacral, transvertebral fibular dowel and/or screws when anatomic reduction is not performed.[6,7,54,66,73,76]
- Consider using the Gaines method when reduction of spondyloptosis is deemed necessary.[77]

SURGICAL TECHNIQUES

The various surgical techniques for the management of HGS can be summarized as follows.

1. Posterolateral instrumented in situ fusion (with or without decompression)
2. Posterior reduction of spondylolisthesis, decompression, and instrumented posterolateral fusion
3. Posterior reduction of spondylolisthesis, decompression, and circumferential fusion
4. Transsacral fibular dowel graft supplemented with posterolateral instrumented fusion (no reduction attempt)
5. Spondylectomy for spondyloptosis

Posterior In Situ Fusion

Historically, the mainstay for HGS surgery in both adolescents and adults has been posterior in situ arthrodesis, and this approach has been recommended by many investigators. In light of the limitations associated with noninstrumented posterolateral fusions, most proponents of in situ arthrodesis now recommend the addition of instrumentation to the posterior in situ arthrodesis for adolescents and adults. Although the pendulum for management of HGS seems to be shifting more toward some attempt at reduction, in situ fusion with instrumentation may still be preferred in patients with grade 3 or 4 lumbosacral spondylolisthesis who (1) present with back pain in the absence of radicular complaints, neurologic deficit, or cosmetic deformity; (2) have adequate neural foraminal space; and (3) have acceptable overall sagittal alignment and good sagittal alignment of the proximal instrumented vertebra.

Posterior Reduction of Spondylolisthesis, Decompression, and Instrumented Posterolateral Fusion

To avoid the neurologic risks associated with reduction procedures and the high pseudarthrosis rates seen with posterior in situ arthrodesis without instrumentation, it has been generally accepted that posterior spinal fusion with instrumentation has become the standard for patients with higher-grade spondylolisthesis. However, there has been mounting evidence recently in favor of the safety and efficacy of posterior reduction of spondylolisthesis, decompression, and instrumented posterolateral fusion. Hu[67] attempted to use autogenous iliac or fibular struts to provide anterior column support in HGS following partial reduction. However, often the severity of high-grade slips can make an anterior interbody approach extremely challenging. In the modern era, pedicle screw-rod fixation remains the most common instrumentation; however, considering the challenges associated with transpedicular screws into the listhesed L5 pedicles associated with HGS, transvertebral screws, in which transsacral S1 pedicle screws are extended across the sacral promontory into the slipped L5 vertebral body, may be successfully used in these cases, and not only provide support for the L5 body anterior to the sacrum but achieve tricortical bony purchase through the sacrum and L5 body. Fibular dowels and various cage implants have also been inserted through the sacrum into the L5 body through a posterior approach with good results, providing another option in patients who are difficult to reduce (see **Fig. 1**). As the L5 vertebral body slips anterior to the sacrum, a fibular strut can be inserted through the sacrum into the body of L5 through a reamed canal. Despite the perceived difficulty in this procedure, there is a general lack of reports of neurologic injury associated with this technique.

Posterior Reduction of Spondylolisthesis, Decompression, and Circumferential Fusion

In general, the use of interbody support is recommended for HGS to aid in deformity correction, provide greater stability at the lumbosacral junction, and facilitate higher fusion rates. Regardless of patient age, HGS creates increased shear stress at the lumbosacral junction, with multiple studies reporting high rates of pseudarthrosis and progression of the postoperative slip after posterior in situ fusion.[38,45,55,76,78] This situation arises because a posterior fusion mass in HGS is exposed to high tensile forces. Anterior interbody arthrodesis can be performed through separate anterior and posterior approaches or through a posterior approach alone (PLIF or TLIF). Molinari and colleagues[51] reported higher fusion rates following anterior support and arthrodesis when compared with posterior lateral fusion alone. Although there is absence of high-quality evidence to enable definitive recommendations, if reduction is performed, circumferential fusion should be strongly considered to improve the overall biomechanics for fusion and greater stability. This procedure may be particularly relevant in patients with a high PI who have additional shear forces at the lumbosacral junction. Also, the presence of significant dysplasia often associated with HGS leads to a reduction in the surface area available for fusion, and hence lowers fusion rates in comparison with patients with low-grade slips in the absence of anterior column support.[29]

Transsacral Fibular Dowel Graft Supplemented with Posterolateral Instrumented Fusion (No Reduction Attempt)

Methods that can be used to obtain a circumferential fusion include staged anterior and posterior approaches, a posterior (or transforaminal) lumbar interbody approach, and the transsacral approach. If the severity of the slip precludes interbody fusion, a transsacral approach as described by Bohlman and Cook[76] can be used to provide anterior fixation.[76] The angle of the lumbosacral disc space in HGS can make discectomy and arthrodesis difficult, requiring osteotomizing the anterior inferior corner of L5 to allow exposure of the L5-S1 disc space during an anterior approach. With severe slips an interbody fusion may not be possible, owing to minimal bony contact between the L5 and S1 vertebral bodies. Therefore, other methods of anterior column fusion can be pursued, which may involve either a transsacral approach using a fibular dowel or using transvertebral screws as described earlier.[6,73,76] Although reduction is not necessary with this technique, some investigators have performed a partial reduction followed by transsacral fusion with resection of the dome of the sacrum if additional lumbosacral kyphosis correction was desired.[54,66] Performance of sacral dome osteotomy, however, can be associated with an increased risk of neurologic deficit and should be kept in mind.[69]

Spondylectomy for Spondyloptosis

The Gaines vertebral resection remains an option for grade 5 spondylolistheses or spondyloptosis.[72,77] In these higher-grade and optosis deformities, the L5 vertebra is not in bony contact with the superior endplate of the sacrum, making the surgical approach challenging. The L5 vertebral body can be resected through an anterior retroperitoneal spinal approach and the vertebral body of L4, then placed directly superior to the S1 body and secured with pedicle screw-rod instrumentation.

COMPLICATIONS

The main complications associated with the surgical management of adult HGS include neurologic deficits (permanent or temporary), pseudarthrosis, instrumentation failure, accelerated adjacent segment degeneration, durotomy, malposition/failure, and deep wound infection.[69,79] Apart from the experience of the treating surgeon and clinical presentation, the potential for complications often significantly affects the choice of approach for the management of HGS, especially considering that there is currently no definitive literature proving the superiority of one approach over another.[7] Occurrence of new neurologic deficits remains the most common and among the most concerning complications with surgery for HGS, and the overall incidence has been reported to be approximately 10%.[69] Although performance of a reduction maneuver has been traditionally thought of as increasing the chances of neurologic deficit, there are no high-quality data supporting this presumption, and various studies have documented the rates of neurologic deficit being the same irrespective of whether a reduction maneuver is performed.[50,69,74] Anecdotal experience from some surgeons have suggested a role of keeping the patients in bed with knees and hips flexed immediately in the postoperative period following HGS reduction, to decrease stretch on L5 nerves and thus lower the incidence of foot drop. Fortunately many of the postoperative neurologic deficits resolve over time, with reports suggesting that only about 10% (1% overall) may be permanent.[14,41,60,64,69] The use of neuromonitoring during surgery for HGS may reduce the incidence of postoperative neurologic deficits, and its use has become more prevalent, especially when reduction maneuvers are planned. Nevertheless, there is a lack of published high-quality data demonstrating the benefit of neuromonitoring in reducing the incidence of postoperative neurologic deficits. Performance of a sacral dome osteotomy has been shown to be associated with a significantly higher incidence of new neurologic deficits, and caution should be exercised when performing this procedure. Although the addition of instrumentation and anterior interbody structural grafts has improved fusion rates, adjacent segment degeneration has been reported to occur in as many as 35% of cases and may require extension of instrumentation, often including iliac fixation.[80] Although the incidences are generally low, apart from surgical and neurologic complications these patients are prone to develop other complications such as peripheral nerve palsy associated with positioning, respiratory complications including pulmonary embolism, epidural hematoma, deep venous thrombosis, and postoperative visual acuity deficit.[69,79]

SUMMARY

Management of high-grade lumbosacral spondylolisthesis is complex and is associated with significant controversies. Although there is general consensus on the need for surgical treatment of symptomatic patients presenting with severe pain, neurologic deficits, or progressive deformity once symptomatic or progressive, the optimal surgical approach and techniques remain controversial. Recent advances in spinal instrumentation, improved understanding of the pelvic anatomy and its role in determining sagittal spinopelvic alignment, and its influence on the development of HGS have had a significant impact on surgical management of HGS. Although not proven in randomized studies, posterior instrumented fixation and fusion with attempted partial deformity reduction and interbody structural support have been gaining widespread acceptance, and have been shown to provide satisfactory rates of fusion and a good clinical outcome. Regardless of the choice of surgical technique, significant complications can be associated with the surgical treatment of HGS and may dictate the type of surgical approach chosen.

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