European Spine Journal (2019) 28:2060–2069
https://doi.org/10.1007/s00586-019-05954-x

ORIGINAL ARTICLE

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Criteria for surgical reduction in high-grade lumbosacral spondylolisthesis based on quality of life measures

Jean-Marc Mac-Thiong[1,2,3] · M. Timothy Hresko[4] · Abdulmajeed Alzakri[1,2,3,5] · Stefan Parent[1,2,3] · Dan J. Sucato[6] · Lawrence G. Lenke[7] · Michelle Marks[8] · Hubert Labelle[1,2]

Received: 17 July 2018 / Revised: 1 March 2019 / Accepted: 14 March 2019 / Published online: 26 March 2019

Abstract

Purpose Although surgical reduction in high-grade lumbosacral spondylolisthesis is often performed in young patients, criteria for defining adequate reduction leading to optimal outcomes have yet to be defined. The purpose of this study is to determine if surgical reduction in pelvic balance, slip grade, lumbosacral angle and L5 incidence are associated with quality of life after surgery, based on specific criteria proposed previously in the literature.

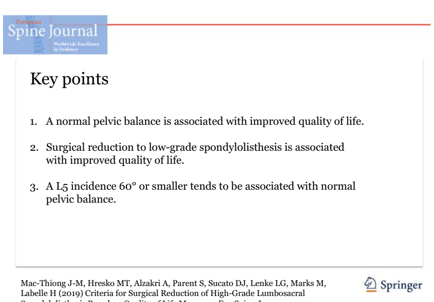
Methods A prospective cohort of 61 patients (14.4 ± 2.7 years) with high-grade lumbosacral spondylolisthesis was followed for a minimum of 2 years after surgery. SRS-22 scores, slip grade, lumbosacral angle, pelvic balance and L5 incidence were assessed before surgery and at the latest follow-up. Multivariable regression analyses were performed using postoperative SRS domain and total scores as the dependent variables. Independent variables consisted of the preoperative SRS scores, and specific criteria of pelvic balance, slip grade, lumbosacral angle and L5 incidence. The influence of slip grade, lumbosacral angle and L5 incidence on pelvic balance was also assessed.

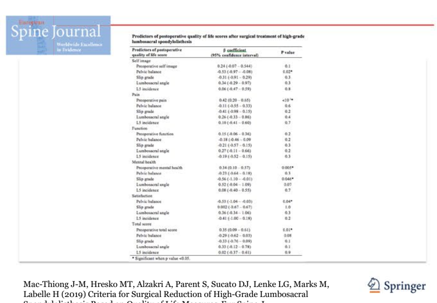
Results Obtaining a balanced pelvis postoperatively was mainly predictive of improved satisfaction with surgery and self-image and also tended to be associated with higher scores for other domains. Improved mental health was associated with reduction to a low-grade slip. Reduction in lumbosacral angle was not predictive of quality of life. Postoperative pelvic balance was mainly associated with preoperative pelvic balance, but there was a tendency for achieving normal pelvic balance when the postoperative L5 incidence was 60° or smaller.

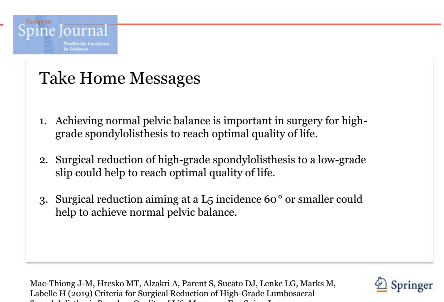
Conclusions When performing surgery in young patients with high-grade lumbosacral spondylolisthesis, achieving normal pelvic balance is the key because it is associated with improved quality of life. Reduction to a low-grade slip is predictive of improved mental health, but reduction in lumbosacral angle is not associated with postoperative quality of life. There was a tendency for obtaining normal postoperative balance in patients with postoperative L5 incidence 60° or smaller.

Graphical abstract

These slides can be retrieved under Electronic Supplementary Material.







Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-019-05954-x) contains supplementary material, which is available to authorized users.

Extended author information available on the last page of the article

Keywords Quality of life · Sagittal balance · Spinal deformity · Spine · Spondylolisthesis · Surgery

Introduction

Surgical treatment is often indicated in young patients with high-grade spondylolisthesis. However, the optimal surgical strategy to use in these patients remains unclear. In particular, surgical reduction is often performed but remains controversial due to the potential increased risk of complications [1] and limited evidence supporting its efficacy [2]. Surgical reduction in high-grade lumbosacral spondylolisthesis implies repositioning of L5 on top of sacrum/pelvis and is most commonly measured from the change in vertebral slippage (translational reduction) or in lumbosacral angle (angular reduction). However, the criteria used to define if reduction was achieved remain elusive, considering that reduction maneuvers can vary from postural reduction (positioning of patient on the operating table) with minimal change in the relative position of L5 and S1 to complex procedures done to fully reposition L5 on top of S1. This lack of consensus for defining reduction and the absence of multivariable analyses accounting for the wide variability in reduction maneuvers therefore limit the conclusions that can be drawn from previous studies on the effectiveness of reduction in high-grade spondylolisthesis.

The current best available evidence suggests that surgical reduction in high-grade spondylolisthesis in young patients can lower the rate of pseudarthrosis [2]. It is believed that correcting the local kyphotic deformity and reducing vertebral slippage will improve the overall spine biomechanics and alignment, leading to better outcomes [3, 4]. An anatomical study [5] suggested that partial translational reduction in a high-grade slip should be performed to minimize the risk of stretch injury to L5 nerve roots. Similarly, angular reduction with restoration of lordosis between L5 and S1 seems beneficial for reducing the risk of L5 nerve root injury. Accordingly, most studies recommend partial reduction when performing surgery for high-grade spondylolisthesis, with particular emphasis on angular reduction [6–12]. Labelle et al. [13] recommend that surgical reduction consists of translational reduction to a low-grade slip and angular reduction when lumbosacral angle is less than 80°. However, they did not provide data supporting the role of these specific criteria in reaching optimal outcomes.

Previous studies [14–16] suggested that reduction could improve pelvic balance and lumbar shape, especially in patients with an unbalanced pelvis (high pelvic tilt and low sacral slope). Achieving normal pelvic balance has been proposed as a major goal in successful surgical reduction in high-grade spondylolisthesis [14–16]. Furthermore, Labelle et al. [15] observed that postoperatively the lumbosacral angle was improved and the L5 incidence was decreased in patients with a postoperative balanced pelvis. More recently, Sebaaly et al. [17] suggested that a L5 incidence less than 61° is a good predictor of adequate pelvic balance in high-grade spondylolisthesis, but they did not evaluate patients undergoing surgical reduction in the spondylolisthesis.

Up to now, it is still difficult for surgeons to plan reduction in high-grade spondylolisthesis since there are no evidence-based criteria defining the extent of reduction required to achieve optimal outcomes. Previous studies on surgical reduction in high-grade spondylolisthesis have also failed to account simultaneously for all aspects of reduction (translational, angular and pelvic) that can potentially be modified by surgical maneuvers. In addition, the impact of surgical reduction on quality of life (QOL) remains largely unknown.

Therefore, the primary objective of the current study is to determine if surgical reduction in pelvic balance, slip grade, lumbosacral angle and L5 incidence are associated with postoperative QOL. Accordingly, we hypothesize that better postoperative QOL is associated with reaching these endpoints after surgery: a balanced pelvis, a low-grade slip, a lumbosacral angle $\geq 80°$ and a L5 incidence $\leq 60°$. These criteria have been proposed previously in the literature as potential criteria for adequate surgical reduction in high-grade lumbosacral spondylolisthesis. The secondary objective consists of determining if postoperative pelvic balance is associated with postoperative slip grade, lumbosacral angle and L5 incidence.

Materials and methods

This prospective observational study includes 61 patients enrolled prospectively at four institutions between April 1, 2002, and December 31, 2009. The inclusion criteria for the current study are the following: (1) diagnosis of developmental high-grade lumbosacral spondylolisthesis with pars interarticularis lysis or elongation as described by Marchetti and Bartolozzi [18], (2) surgical treatment of spondylolisthesis between ages 8 and 21 years, (3) availability of baseline preoperative radiographic and QOL data and (4) minimum follow-up of 2 years after surgery with available radiographic and QOL data. The exclusion criteria were the following: (1) previous spine or lower limb surgery, (2) associated syndrome or connective tissue disorder, (3) inability to see both femoral heads on full spine radiographs, and (4) failure to comply with follow-up requirements. The study has been approved by the institutional review board from each institution.

The decision to proceed with reduction and the surgical methods were determined by each surgeon. A total of 15 surgeons performed the cases throughout the length of the study: 14 surgeons performed 5 cases or less and 1 surgeon performed more than 5 cases. Indirect decompression (no formal laminectomy) and posterior L5 laminectomy (Gill procedure) was performed in 4 and 57 patients, respectively. Pedicle screw instrumentation was used in 60 patients, while 1 patient underwent posterior uninstrumented L4–S1 in situ fusion. Of the 60 patients undergoing instrumented fusion, L4 to S1, L5 to S1, L4 to the ilium and L5 to the ilium were instrumented in 21, 28, 11 and 1 patients, respectively. L5–S1 interbody fusion was performed using PLIF/TLIF, L5–S1 transfixation from S1 pedicle screws or a combination of L5–S1 transfixating cage and L5–S1 transfixation from S1 pedicle screws in 36, 7 and 3 patients, respectively. Neuromonitoring was used in 53 patients, including 3 patients monitored using a combination of somatosensory evoked potentials (SSEP), motor evoked potentials (MEP) and electromyography (EMG), 7 patients with SSEP and MEP, 12 patients with SSEP and EMG, 3 patients with MEP and EMG, 23 patients with SSEP only, 1 patient with MEP only and 1 patient with EMG only.

Patients were aged 14.4 ± 2.7 years. There were 43 girls and 18 boys. Ethnicity was Asian for 2 patients, African-American for 2 patients, Hispanic for 2 patients and Caucasian for 56 patients. A total of 59% of patients had an associated scoliosis, and none of these patients required long fusion for their scoliosis during the follow-up, and the index surgery was performed solely to treat the spondylolisthesis in these patients.

All patients had full spine postero-anterior and lateral standing radiographs showing the pelvis and both femoral heads, taken preoperatively and at 2-year postoperative follow-up. All parameters were measured by a single observer using a dedicated computer software. The translational deformity was measured from the percentage of slip using the technique described by Bourassa-Moreau et al. [19] (Fig. 1). A high-grade slip refers to a slip percentage ≥ 50%, while a low-grade slip refers to a slip percentage < 50%. Angular deformity was assessed using the lumbosacral angle following the technique described in Fig. 2. Pelvic balance (balanced vs. unbalanced) was determined from the technique described by Hresko et al. [14]. A first step consists of measuring pelvic tilt and sacral slope from the standing radiograph. Then, pelvic balance is determined using the scatter plot provided by Hresko et al. [14], in which the individual pelvic tilt and sacral slope values are reported with respect to a bisecting line that allows differentiating between a balanced pelvic and an unbalanced pelvic. A balanced pelvis refers to a relatively low pelvic tilt and high sacral slope, while an unbalanced pelvis refers to a relatively high pelvic tilt and low sacral slope, in the presence of a more vertical sacrum. L5 incidence was measured using the technique originally described by Roussouly et al. [20] to assess pelvic balance, consisting of the angle between a line joining the center of the upper endplate of L5 to the hip axis (midpoint of the line joining the center of the femoral heads) and a line perpendicular to the upper endplate of L5. Adequate reliability for measuring these parameters have already been described in previous publications for different spinal pathologies [21–32] and also after instrumentation of the spine [31] (Fig. 3).

QOL was assessed from the SRS-22 questionnaire, which is the only QOL assessment tool that has been validated for young patients with spondylolisthesis [36]. Function, pain, self-image and mental health domain scores, as well as the total score were calculated at baseline preoperatively, and postoperatively after a minimum 2 years follow-up. Satisfaction with management was also calculated from the SRS-22 questionnaire at the latest follow-up.

Statistical analyses were done using IBM SPSS Statistics version 24 software, and a level of significance of 0.05 was used. In addition to descriptive statistics, comparisons between preoperative and postoperative variables were carried out using paired Student t tests for continuous variables and Fisher's exact tests for binary variables (proportions). Multivariable regression analyses were performed using general linear models with postoperative SRS-22 total and

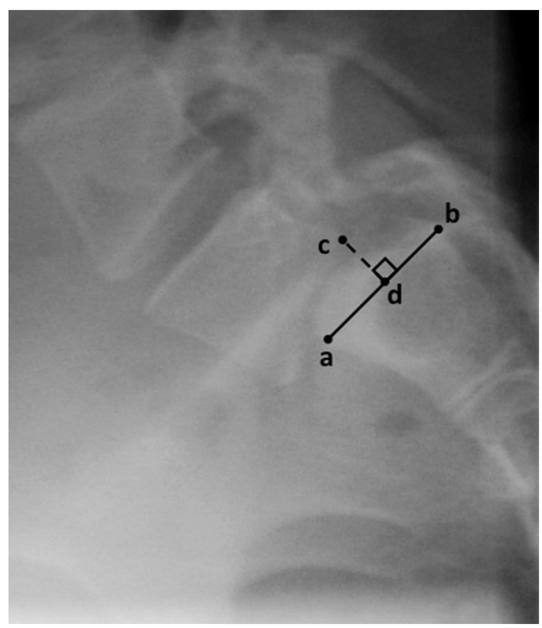


Fig. 1 Spondylolisthesis measurement technique. The sacral endplate is defined by lines a–b. The posterior–inferior corner of the L5 vertebral body (point c) is projected onto the sacral endplate (point d) using a line (lines c–d) perpendicular to the sacral endplate. The percentage of slip is calculated by dividing the distance of slip (distances b–d) by the length of the sacral endplate (distances a–b) and multiplying by 100

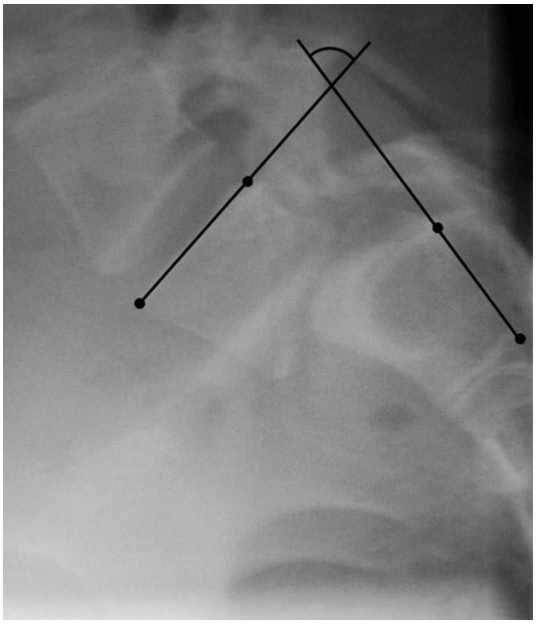


Fig. 2 Measurement of lumbosacral angle using the posterior border of the S1 vertebral body and the superior endplate of L5

individual domain scores as dependent variables. For each dependent variable (postoperative SRS score), the preoperative SRS score was entered in the model as an independent variable, except for satisfaction. The main independent variables consisted of four binary variables measured postoperatively: 1) pelvic balance (balanced vs. unbalanced pelvis), 2) slip grade (low-grade vs. high-grade), 3) lumbosacral angle (< 80° vs. ≥ 80°), and 4) L5 incidence (≤ 60° vs. > 60°). These four parameters were selected because they have been proposed previously [13–17] as potential guidelines when planning surgical reduction in spondylolisthesis. Results from the general linear models are expressed in terms of beta (β) coefficients with 95% confidence interval and corresponding p value.

Secondarily, a multivariable logistic regression analysis was performed to determine the association between a binary dependent variable (postoperative pelvic balance: balanced vs. unbalanced pelvis) and the following independent variables assessed postoperatively: 1) slip grade (low-grade vs. high-grade), 2) lumbosacral angle (< 80° vs. ≥ 80°), and 3) L5 incidence (≤ 60° vs. > 60°). Preoperative pelvic balance was also included in the analysis as an independent variable.

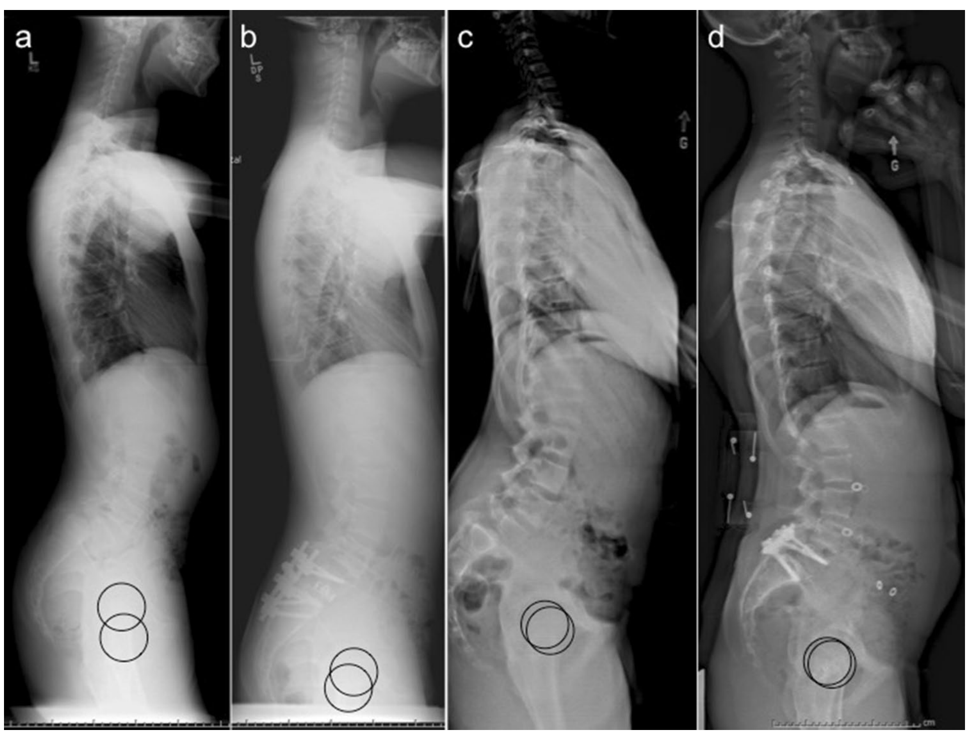


Fig. 3 Case illustration of a patient (**a**, **b**) with a 93% slip, 75° lumbosacral angle, 26° pelvic tilt, 50° sacral slope and 73° L5 incidence preoperatively (**a**) that was reduced to 8% slip, 86° lumbosacral angle, 40° pelvic tilt, 35° sacral slope and 49° L5 incidence postoperatively (**b**). The pelvis was balanced preoperatively and unbalanced postoperatively. His quality of life was deteriorated postoperatively for all domain scores and for the total score, while the satisfaction score was rated as 1/5. Another patient (**c**, **d**) had a 57% slip, 84° lumbosacral angle, 35° pelvic tilt, 45° sacral slope and 61° L5 incidence preoperatively (**c**) that was reduced to 9% slip, 87° lumbosacral angle, 20° pelvic tilt, 58° sacral slope and 56° L5 incidence postoperatively (**d**). The pelvis was unbalanced preoperatively and became balanced postoperatively. His quality of life was improved postoperatively for all domain scores and for the total score, while the satisfaction score was rated as 5/5

Results from the logistic regression model are expressed in terms of odds ratio with 95% confidence interval and corresponding p value.

Results

Pelvic balance, slip percentage, lumbosacral angle and L5 incidence were all significantly different between preoperative and postoperative assessments (Table 1). Overall, 33 (54.1%) and 36 (59.0%) patients had a balanced pelvis pre- and postoperatively, respectively. Of the 33 patients with a balanced pelvis preoperatively, 25 (75.8%) remained balanced while only 8 (24.2%) became unbalanced postoperatively. Of the 28 patients with an unbalanced pelvis preoperatively, a balanced pelvis was restored in only 11 (39.1%) patients, while 17 (60.1%) remained unbalanced postoperatively.

Although mean pelvic tilt and sacral slope varied by less than 2° due to surgery, the changes were highly significant. Postoperatively, mean slip percentage, lumbosacral angle and L5 incidence were significantly decreased, with 80.3% patients having a low-grade slip, 77.0% a lumbosacral angle ≥ 80° and 54.1% a L5 incidence ≤ 60°. QOL also significantly improved after surgery, as shown in Table 2. Pain, self-image, function, mental health and total score improved in 83.6%, 88.5%, 83.6%, 68.9% and 90.2% of patients, respectively.

Table 3 presents the results of the multivariable regression analyses related to QOL scores. Higher postoperative self-image score was mainly associated with a postoperative balanced pelvis ($p = 0.02$). Postoperative pain score was related to preoperative pain score ($p < 10^{-3}$), but not with postoperative pelvic balance, slip grade, lumbosacral angle nor L5 incidence. Function was not associated with any included dependent variables. Higher mental health score was associated with higher preoperative mental health score ($p = 0.005$) as well as having a postoperative low-grade slip ($p = 0.046$). Improved satisfaction from surgery was associated with having a postoperative balanced pelvis ($p = 0.04$). Postoperative total score was mainly associated with the preoperative total score ($p = 0.01$). There was also a tendency for obtaining a higher postoperative total score in the presence of a postoperative balanced pelvis, although statistical significance was not reached ($p = 0.08$).

Table 4 shows the results from the multivariable logistic regression model of postoperative pelvic balance. Postoperatively, the pelvis was more likely to be balanced when patients had a balanced pelvis preoperatively ($p = 0.02$). There was a tendency for obtaining a postoperative balanced pelvis in the presence of a postoperative L5 incidence ≤ 60°, but this finding did not reach statistical significance ($p = 0.09$).

Table 1 Preoperative and postoperative radiographic characteristics ($n = 61$)

Variable	Preoperative	Postoperative	p value
Continuous			
Pelvic tilt (°)	32.0 ± 11.6	30.4 ± 10.1	$< 10^{-10}$*
Sacral slope (°)	50.2 ± 10.7	51.8 ± 9.6	$< 10^{-7}$*
Slip percentage (%)	72.9 ± 17.9	31.0 ± 23.7	0.003*
Lumbosacral angle (°)	72.9 ± 19.6	89.8 ± 16.0	$< 10^{-12}$*
L5 incidence (°)	68.6 ± 21.0	57.6 ± 19.0	$< 10^{-12}$*
Binary			
Pelvic balance			
Balanced (n)	33	36	0.005*
Unbalanced (n)	28	25	
Slip grade			
Low-grade (n)	0	49	–
High-grade (n)	61	12	
Lumbosacral angle			
< 80° (n)	41	14	0.002*
≥ 80° (n)	20	47	
L5 incidence			
≤ 60° (n)	21	33	$< 10^{-5}$*
> 60° (n)	40	28	

*Significant when p value < 0.05

Table 2 Preoperative and postoperative scores of quality of life ($n = 61$)

Quality of life score	Preoperative	Postoperative	p value
Self-image	3.3 ± 0.7	4.2 ± 0.8	$< 10^{-12}$*
Pain	3.0 ± 0.9	4.0 ± 0.8	$< 10^{-9}$*
Function	3.5 ± 0.6	4.3 ± 0.5	$< 10^{-12}$*
Mental health	3.7 ± 0.8	4.2 ± 0.8	$< 10^{-5}$*
Satisfaction	–	4.5 ± 0.9	–
Total	3.4 ± 0.6	4.2 ± 0.6	$< 10^{-13}$*

*Significant when p value < 0.05

There were 3 patients with a dural tear that was primarily repaired during surgery. Another patient had persisting drainage from the wound raising a suspicion for a cerebrospinal fluid leak. This patient underwent reoperation 3 weeks after the index surgery and a dural tear was successfully repaired with no residual leak.

Postoperatively, 3 patients had transient unilateral L5 radiculopathy (1 motor/sensory, 1 sensory, 1 motor) and one patient had transient bilateral L5 sensory radiculopathy that were resolved at the 2-year follow-up. One patient had L5 motor radiculopathy, and another had S1 motor radiculopathy remaining 2 years after surgery. One patient had transient left meralgia paresthetica.

Table 3 Predictors of postoperative quality of life scores after surgical treatment of high-grade lumbosacral spondylolisthesis ($n = 61$)

Predictors of postoperative quality of life score	β coefficient (95% CI)	p value
Self-image		
Preoperative self-image	0.24 (−0.07 to 0.544)	0.1
Pelvic balance	−0.53 (−0.97 to −0.08)	0.02*
Slip grade	−0.31 (−0.91 to 0.29)	0.3
Lumbosacral angle	0.34 (−0.29 to 0.97)	0.3
L5 incidence	0.06 (−0.47 to 0.59)	0.8
Pain		
Preoperative pain	0.42 (0.20 to 0.65)	$< 10^{-3}$*
Pelvic balance	−0.11 (−0.55 to 0.33)	0.6
Slip grade	−0.41 (−0.98 to 0.15)	0.2
Lumbosacral angle	0.26 (−0.33 to 0.86)	0.4
L5 incidence	0.10 (−0.41 to 0.60)	0.7
Function		
Preoperative function	0.15 (−0.06 to 0.36)	0.2
Pelvic balance	−0.18 (−0.46 to 0.09	0.2
Slip grade	−0.21 (−0.57 to 0.15)	0.3
Lumbosacral angle	0.27 (−0.11 to 0.66)	0.2
L5 incidence	−0.19 (−0.52 to 0.15)	0.3
Mental health		
Preoperative mental health	0.34 (0.10 to 0.57)	0.005*
Pelvic balance	−0.23 (−0.64 to 0.18)	0.3
Slip grade	−0.56 (−1.10 to −0.01)	0.046*
Lumbosacral angle	0.52 (−0.04 to 1.09)	0.07
L5 incidence	0.08 (−0.40 to 0.55)	0.7
Satisfaction		
Pelvic balance	−0.53 (−1.04 to −0.03)	0.04*
Slip grade	0.002 (−0.67 to 0.67)	1.0
Lumbosacral angle	0.36 (−0.34 to 1.06)	0.3
L5 incidence	−0.41 (−1.00 to 0.18)	0.2
Total score		
Preoperative total score	0.35 (0.09 to 0.61)	0.01*
Pelvic balance	−0.29 (−0.62 to 0.03)	0.08
Slip grade	−0.33 (−0.76 to 0.09)	0.1
Lumbosacral angle	0.33 (−0.12 to 0.78)	0.1
L5 incidence	0.02 (−0.37 to 0.41)	0.9

*Significant when p value < 0.05

One patient presented low back pain and dysesthesia 9 months after L5–S1 pedicle screw instrumentation and TLIF. Supra-adjacent junctional spondylolisthesis was observed, and it was decided to undergo proximal extension to L4 using pedicle screws and TLIF, after which the symptoms resolved.

One patient was diagnosed with proximal deep vein thrombosis 9 days after L5–S1 transfixation from S1 pedicle screws. It was later found that the patient had a heterozygous factor V leiden. Although not in contact with the left common iliac vein, the left screw was revised 12 days after the index surgery—following placement of an inferior vena cava filter —in order to ensure that it did not extend beyond the anterior vertebral body wall of L5.

Table 4 Predictors of postoperative pelvic balance after surgical treatment of high-grade lumbosacral spondylolisthesis ($n = 61$)

Predictors of postoperative pelvic balance	Odds ratio (95% CI)	p value
Preoperative pelvic balance	4.3 (1.2–15.6)	0.02*
Slip grade	2.3 (0.4–13.6)	0.4
Lumbosacral angle	1.3 (0.2–7.8)	0.7
L5 incidence	3.5 (0.8–15.2)	0.09

*Significant when p value < 0.05

Another patient underwent complete implant removal 17 months after posterior in situ L4–S1 fusion with pedicle screws placed bilaterally at L4 and S1. Implant removal was performed because it was presumed that prominence of the implants was causing local back pain. Her pain resumed after implant removal.

Discussion

Despite some evidence supporting the relevance of surgical reduction in high-grade spondylolisthesis in young patients [2, 3], criteria defining adequate reduction leading to optimal outcomes have yet to be defined. Therefore, this study specifically investigated four parameters that have been proposed previously [13–17] to guide surgical reduction in spondylolisthesis, but have never been validated in a large prospective study design involving multivariable regression analyses. One of the major strengths of our study design is the use of an objective method to quantify reduction in terms of pelvic balance, slip percentage, lumbosacral angle and L5 incidence. Our objective method for quantifying reduction was preferred over a subjective determination by the surgeon since the definition and requirements for reduction vary widely between surgeons.

In addition, our cohort has been recruited in four different institutions and includes patients who underwent various types of procedures involving different magnitudes of reduction in terms of pelvic balance, slip percentage, lumbosacral angle and L5 incidence. The use of a validated QOL questionnaire and consideration of the preoperative QOL scores in our analyses also represent major assets for this study. Accordingly, the multivariable regression analyses have confirmed the significant influence of preoperative QOL scores on postoperative scores (Table 3).

While previous authors [14–16] have raised the importance of assessing pelvic balance in the surgical treatment of high-grade spondylolisthesis, our study provides evidence that pelvic balance is indeed an important predictor of QOL. Achieving a balanced pelvis postoperatively was associated with improved self-image and satisfaction. Although not reaching statistical significance, all other aspects of QOL were in line with these findings, as pain, mental health, function and total score also tended to increase postoperatively when achieving normal pelvic balance. Since an unbalanced pelvis—as described by Hresko et al. [14]—involves a relatively high pelvic tilt and low sacral slope, it is typically associated with the characteristic deformity observed in high-grade spondylolisthesis consisting in a retroverted pelvis with heart-shaped buttocks. Our findings therefore suggest that residual retroversion of the pelvis is particularly detrimental to self-image after surgery, and that self-image is an important aspect determining satisfaction after surgery.

It is surprising that the mean changes in mean pelvic tilt and sacral slope due to surgery were small (less than 2°, Table 1) although 80.3% of patients reached a low-grade slip postoperatively. In the study of Labelle et al. [15], the mean changes in pelvic tilt (4°) and sacral slope (3°) were also small even if 62 of their 73 patients underwent formal "surgical attempt at reduction." Similarly, Hresko et al. [16] observed small changes of 3° and 7°, respectively, in mean pelvic tilt and sacral slope, although partial reduction was performed in all 26 patients. These relatively small changes are explained by the fact that pelvic tilt and sacral slope do not always improve with surgery. Indeed, pelvic tilt and sacral slope can deteriorate (increase in pelvic tilt and associated decrease in sacral slope) or fail to improve in some patients after surgery, as reflected by the presence of 25 patients (40.9%) with an unbalanced pelvis postoperatively (Table 1). These findings highlight the unpredictable/unknown capacity of current surgical techniques to achieve normal pelvic balance, in addition to the need to further investigate predictors of postoperative pelvic balance as it was done in the current study.

Although the results highlight the benefits of achieving normal pelvic balance after surgical reduction, it was not possible to clearly determine from the logistic regression analysis the role of reducing the slip grade, lumbosacral angle and L5 incidence in obtaining normal pelvic balance postoperatively. Only preoperative pelvic balance was associated with postoperative balance, but there was a tendency for postoperative L5 incidence ≤ 60° to be associated with a higher likelihood of achieving a balanced pelvis. Based on these results, we performed post hoc logistic regression analyses (not shown) after subdividing the cohort according to the preoperative pelvic balance. Postoperative slip grade, lumbosacral angle and L5 incidence were not associated with postoperative pelvic balance in patients with a preoperative unbalanced pelvis ($n = 28$). However, a postoperative L5 incidence ≤ 60° was more likely to be associated with a balanced postoperative pelvis in patients who had a balanced pelvis preoperatively (95% confidence interval for odds ratio = 0.01–0.78; $p = 0.03$). These findings first suggest that restoring normal pelvic balance in patients with an unbalanced pelvis preoperatively is difficult with current reduction techniques, and that future studies should assess the effectiveness of proposed reduction techniques in this subgroup of patients. Secondly, it seems beneficial to aim for a L5 incidence ≤ 60° in patients with normal preoperative pelvic balance, in order to increase the likelihood of maintaining a balanced pelvis postoperatively. Postoperative L5 incidence was surprisingly not related with postoperative QOL scores in the multivariable linear regression analyses (Table 3), although L5 incidence is associated with pelvic balance in a subset of patients and pelvic balance is a consistent predictor of QOL. This finding reinforces that the relationship between postoperative L5 incidence and pelvic balance remains limited, and that future studies should further determine the interactions between L5 incidence and pelvic balance, as well as the subgroups of patients for which measuring L5 incidence would be clinically relevant.

Reduction to a low-grade slip grade was only predictive of improved postoperative mental health, although there were tendencies for improved self-image, decreased pain, improved function and increased total score postoperatively with reduction to a low-grade slip. These concordant results add to the available evidence supporting the benefits of reducing the slip grade on the outcome of patients surgically treated for high-grade spondylolisthesis [2, 3]. Although postoperative mental health is mainly predicted by preoperative mental health, the predictive value of slip grade reflects its predominant impact in the management of spondylolisthesis and though process of patients undergoing surgery. It is reasonable to believe that the mental health of patients with high-grade spondylolisthesis is significantly influenced by the slip grade, since it represents the main aspect that physicians refer to when discussing with patients about the pathology, the prognosis, the indication for surgery and the surgical procedure.

Contrary to the common belief that reduction in lumbosacral angle should be emphasized in the surgical treatment of high-grade spondylolisthesis [6–12], lumbosacral angle was not a significant predictor of QOL or pelvic balance in the current study. Moreover, post hoc analyses (not shown) using different threshold values of lumbosacral angle for defining reduction or stratifying patients did not result in any significant association with QOL scores. Although reaching a lumbosacral ≥ 80° was not associated with improved postoperative QOL, it does not mean that reduction in lumbosacral is not beneficial for high-grade spondylolisthesis. For example, reducing lumbosacral angle can potentially reduce the risk of L5 nerve root injury [5] and improve the biomechanical environment for successful fusion by decreasing the tension on the fusion mass [3].

While reduction can potentially decrease the risk of L5 nerve root injury [5], it has been reported that 5% of patients undergoing surgical treatment of pediatric spondylolisthesis sustain neurological complications [1]. Accordingly, the authors believe that the use of neuromonitoring can help to minimize the risk of permanent L5 nerve root, as suggested in previous reports [33–35]. However, further study is still required to determine the optimal modalities (SSEP, MEP and/or EMG) that should be used to decrease the number of permanent nerve root injuries.

Limitations

The main limitation relates to the relatively small cohort included in this study, although it is the largest in the literature involving young patients with high-grade spondylolisthesis and available pre- and postoperative QOL measures. Our study highlights the difficulty to prospectively recruit young patients with high-grade spondylolisthesis due to the small number of patients presenting with this pathology. It is believed that considerable efforts through a large multicenter study group should be invested to allow prospective recruitment of a large cohort of patients. However, this study represents a major contribution to the knowledge of high-grade spondylolisthesis despite the relatively small cohort, since we were able to identify the most important aspects of surgical reduction as related to QOL outcomes.

Another limitation relates to our failure to analyze the data according to a minimum clinical important difference (MCID) in QOL scores. Although the SRS outcome questionnaire has been used and validated in young patients with spondylolisthesis [36, 37], there is no MCID proposed in the literature for this specific population. Because the concept of MCID is disease specific, it was thus not possible to use MCID values developed for other populations in the current study.

As already mentioned earlier, the authors recognize that QOL is only one aspect of the outcome that needs to be optimized after surgery for high-grade spondylolisthesis. The risks of further progression of the spondylolisthesis and developing neurological deficit are often the primary indication for surgery. Therefore, definite conclusions on the need and extent of surgical reduction should also be based on factors other than QOL, such as achieving successful fusion and minimizing complications. Evaluating other outcomes such as gait pattern and mobility could also help to the better assess the relevance of spondylolisthesis reduction. In addition, future studies with follow-up longer than 2 years would also be interesting to understand the long-term implication of surgery on QOL.

There was no uniform protocol for surgical reduction used in this study. Although the variability in the reduction techniques could be perceived as a limitation, we believe that including various procedures for reduction and fusion was well adapted to our study design intended to assess independently different parameters involved during reduction. For example, if a single reduction technique had been used, it would have been difficult to obtain different magnitudes of reduction in terms of pelvic balance, slip percentage, lumbosacral angle and L5 incidence and to fully study the influence of reduction on QOL. This is also why our cohort includes patients who did not undergo reduction. However, future studies should also assess the performance of the different available techniques for achieving reduction and improve QOL.

Although the current study specifically evaluated the association between QOL and four specific criteria related to the extent of reduction, the authors acknowledge that other factors that those included in our analyses can potentially impact QOL, such as the indication for surgery/reduction, the patient's symptoms and psychological condition, radiological features, the type of surgical procedure that was performed, complications, surgeon's experience and volume. For example, the authors believe that particular attention should be given to the influence of lower extremities alignment on the outcome of surgical reduction, as previous studies have found an association between proximal femoral angle and QOL in subjects with high-grade spondylolisthesis [38], and better improvement in QOL with surgical reduction in patients with abnormal proximal femoral angle preoperatively [39]. Future studies are still needed to determine the best predictors of improved QOL in spondylolisthesis surgery.

Conclusions

This study specifically investigated if surgical reduction in pelvic balance, slip grade, lumbosacral angle and L5 incidence are associated with postoperative QOL in high-grade spondylolisthesis. Achieving normal pelvic balance was the most important and consistent predictor of increased QOL. Reduction to a low-grade slip was predictive of improved mental health, but reduction in lumbosacral angle was not associated with postoperative quality of life. There was a tendency for obtaining normal postoperative balance in patients with a postoperative L5 incidence ≤ 60°. Future studies should attempt to identify reduction techniques that can reliably restore or maintain pelvic balance after surgery.

Funding This research was funded by a Standard Investigator Research Grant from the Scoliosis Research Society.

Compliance with ethical standards

Conflict of interest J-M Mac-Thiong, H Labelle and S Parent are a co-founders, board members and shareholders of Spinologics Inc. J-M Mac-Thiong receives research support from Medtronic and Depuy-Synthes. S Parent receives research support from DePuy-Synthes. LG Lenke receives royalties from Medtronic and Quality Medical Publishing, is a consultant for Medtronic, and receives research support from EOS Imaging. DJ Sucato is a consultant from Globus.

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Affiliations

Jean-Marc Mac-Thiong[1,2,3] · M. Timothy Hresko[4] · Abdulmajeed Alzakri[1,2,3,5] · Stefan Parent[1,2,3] · Dan J. Sucato[6] · Lawrence G. Lenke[7] · Michelle Marks[8] · Hubert Labelle[1,2]

✉ Jean-Marc Mac-Thiong
macthiong@gmail.com

[1] University of Montreal, Montreal, Canada

[2] Division of Orthopedic Surgery, CHU Sainte-Justine, 3175 Côte-Sainte-Catherine, Montreal, QC H3T 1C5, Canada

[3] Hôpital du Sacré-Coeur, Montreal, Canada

[4] Boston Children's Hospital, Boston, MA, USA

[5] King Saud University, Riyadh, Saudi Arabia

[6] Texas Scottish Rite Hospital, Dallas, TX, USA

[7] The Spine Hospital New York-Presbyterian, New York, NY, USA

[8] Setting Straight Scoliosis Foundation, San Diego, CA, USA