North American Spine Society Journal (NASSJ) 19 (2024) 100516

Contents lists available at ScienceDirect

North American Spine Society Journal (NASSJ)

journal homepage: www.elsevier.com/locate/xnsj

Lumbar pedicle subtraction osteotomy: techniques and outcomes

Anouar Bourghli, MD[a], Louis Boissiere, MD[b], Ibrahim Obeid, MD[b,*]

[a] Spine surgery department, King Faisal Specialist Hospital and Research Center, Riyadh, Saudi Arabia
[b] Spine surgery department, Clinique du Dos, Elsan Jean Villar Private hospital, Bordeaux, France

ARTICLE INFO

Keywords:
Lumbar spine
Pedicle subtraction osteotomy
Adult spinal deformity
Sagittal malalignment
Coronal malalignment
Domino connector

ABSTRACT

Pedicle subtraction osteotomy has been thoroughly described and studied over the past 2 decades, being applied mainly in the lumbar spine, followed by the thoracic spine. Our better understanding of alignment biomechanics, and the progressive refinements of the surgical technique over time made it a very efficient procedure for the management of fixed sagittal malalignment. However, a long learning curve is mandatory to mitigate the associated risks particularly neurological deficits and achieve satisfactory clinical and radiological outcomes with an acceptable rate of complications.

Introduction

Inside the spine deformity surgeons' community, when one mention "spinal osteotomy" they usually mean a 3-column osteotomy and more specifically a pedicle subtraction osteotomy (PSO), rather than a vertebral column resection (VCR) which is usually termed as "spinal resection". In fact, when Thomasen first described the PSO in 1985 for the management of sagittal malalignment in Ankylosing Spondylitis (AS) patients [1], he called it "vertebral osteotomy", but after the technique started to spread amongst spinal deformity surgeons other synonymous names came out such as "Closing Wedge Posterior Osteotomy", "Transpedicular Vertebral Osteotomy", "Pedicle Subtraction Osteotomy", or simply "Spinal Osteotomy".

Indications of lumbar osteotomies

The general indication for a lumbar PSO is usually sagittal malalignment with loss of lumbar lordosis mainly in the distal arc with a stiff spine showing no mobility on dynamic flexion and extension views, or when obvious fusion is seen on preoperative x-ray or CT scan. The ideal indication being ankylosing spondylitis patients as it was described in the original Thomasen paper [1]. Because the spine is completely fused, the only way to correct the sagittal malalignment is by mobilizing all 3 columns through a pedicle subtraction osteotomy (Fig. 1). However, since the advent of efficient medical treatments [2], surgical indication for the correction of sagittal deformities in AS became rare and replaced mainly by degenerative lumbar kyphosis, postoperative flatback deformity and post-traumatic kyphotic deformity.

As a general rule, if the discs at the lower lumbar levels are mobile, good posterior release consisting of posterior column osteotomies (PCOs) with discectomies and cages insertion (transforaminal or posterolateral technique) should be enough to restore lumbar lordosis spread on multiple levels as this was shown in previous studies [3,4]. In addition, various papers demonstrated the advantages of anterior column realignment (ACR) where a combined posterior and anterior approach could obviate the need for a PSO and achieve similar results, the objective of the complementary anterior approach is to take the highest advantage of the flexible discs by performing complete removal and inserting high lordotic or expandable cages [5–9]. It was shown, for instance, that the lateral minimal invasive lumbar interbody fusion (MI-LIF) technique combined with ACR has the ability to correct SVA by 3.1 cm and lumbar lordosis by 12° at each treated level [6].

In order to facilitate communication regarding surgical planning, clinical research, or medicofinancial coding, a comprehensive anatomical realignment classification of ACR/osteotomy has been proposed [10], it proved to be reliable and consistent and it provided surgeons with a reference to achieve desired lordosis with varying degrees of anterior column release and spinal osteotomies. This emphasizes the fact that when lumbar flexibility is present, spinal osteotomy would be in theory prohibited as less aggressive technique could be applied achieving the same outcomes. This is why not all revision cases would require a PSO in case of sagittal malalignment when the discs still have some degrees of mobility anteriorly (as seen on MRI and CT). For instance, if a case has been fused in a flat back position with posterior or posterolateral fusion as demonstrated on X-rays and CT scan, a wide posterior release of the posterior scar and the fusion mass at the discs level would

FDA device/drug status: Not applicable.
Author disclosures: ***AB***: Nothing to disclose. ***LB***: Nothing to disclose. ***IO***: Nothing to disclose.

* Corresponding author. Spine surgery department, Clinique du Dos, Elsan Jean Villar Private hospital, Bordeaux, France.
E-mail address: Ibrahim.obeid@gmail.com (I. Obeid).

https://doi.org/10.1016/j.xnsj.2024.100516
Received 3 June 2024; Received in revised form 30 June 2024; Accepted 2 July 2024
Available online 6 July 2024

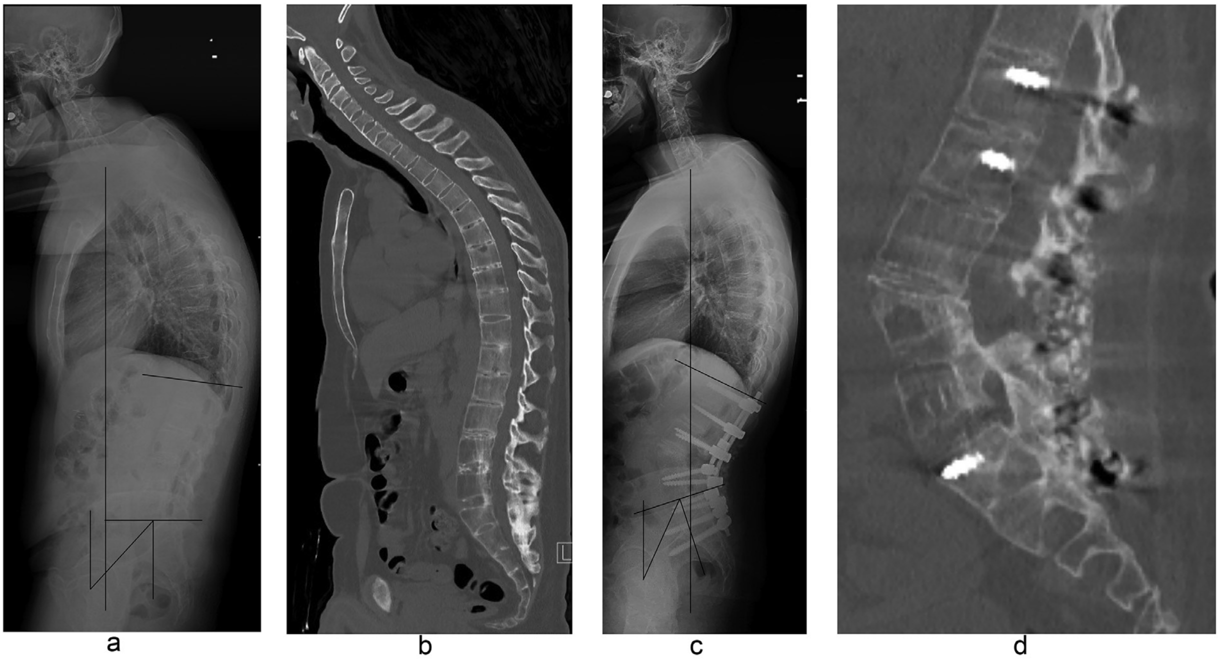

Fig. 1. Thirty y old patient with ankylosing spondylitis. Preoperative full spine lateral X-ray showing the forward imbalance with patient's gaze looking down (A), PI=43°, PT=44°, SVA=6 cm, Lumbar Lordosis (LL)=−4° CT scan demonstrating complete rigid spine (B). Postoperative X-ray after L4 PSO showing improvement of lumbar lordosis, global alignment and restoration of horizontal gaze (C), PI=44°, PT=25°, SVA=0 cm, LL=−42° Postoperative CT scan confirming satisfactory L4 PSO and posterior fusion.

enable significant increase of the lumbar lordosis without the need of a PSO. This would obviously depend on the patient's pelvic incidence and required amount of lordosis for the sagittal correction.

With regard to the amount of correction, it depends mostly on the pelvic incidence of the patient in order to give them a lumbar lordosis that would fit the requirements of their pelvic anatomy, however taking into account the ageing process is important as it was described by Sebaaly [11]; the authors showed that the different types of lordosis according to Roussouly show a progressive physiological decrease with age which may increase the PI-LL (Pelvic Incidence – Lumbar Lordosis) mismatch [12] therefore overcorrection should be avoided in older patients as it would increase the rate of mechanical complications such as proximal junctional kyphosis. The achieved correction depends on the initial lordosis of the patient as well. In fact, the lower is the initial angle of lordosis, the more will be the total amount of correction needed. This can be clearly seen in patients with initial lumbar kyphosis. For example, if the initial lumbar area presents a kyphosis of 15°, achieving a final lordosis angle of 35° to 40° (which can usually be achieved through a PSO or multiple PCOs or both) would mean that the total amount of correction needed is in fact 50° to 55° (Fig. 2).

A systematic review suggested potential benefits of patient-specific rods (PSRs) in achieving optimal spinopelvic parameters in adult spinal deformity (ASD) surgery [13], however the authors stated that the conclusions regarding the superiority of PSRs over traditional rods should be judiciously drawn given the absence of robust randomized controlled trials.

Target vertebras

Before being applied to all spinal regions, the initial PSO technique was reported only for the lumbar spine and even specifically for L2 [1] which was probably related to the fact that the population was ankylosing spondylitis patients with a flat lumbar spine and also the original Smith-Petersen osteotomy used to be applied at either L1L2 or L2L3 [14]. However, Van Royen [15] demonstrated in 1994 that applying the PSO at L4 would give a larger amount of correction as it is applied more distally when compared to L2. Despite the above-mentioned paper and the improvement in understanding the sagittal alignment principles after the publication of the Roussouly classification [16] and its many subsequent papers [17–19], many surgeons continued to apply the lumbar PSO at higher levels such as L1,L2 or L3 [20–22].

The degenerative loss of lumbar lordosis commonly occurs in the distal lumbar region and two thirds of the lumbar lordosis are located between L4 and S1 [18], therefore it seems more logical to target the distal lumbar area when correcting sagittal malalignment by performing the PSO at the level of L4 or L5. Various papers actually showed that applying the PSO at the distal L4 and L5 levels could lead to higher correction angles and also a decrease in mechanical complications especially the proximal junctional kyphosis [23,24]. By concentrating the lordosis in the lower lumbar arc, such PSOs would lead to a more harmonious lumbar spine that would respect the different types of the Roussouly classification where the apex and the distribution of the lower and upper arc of lordosis are different.

It should be noted that performing a lumbar PSO at L5 would not mean that the apex of lordosis would become at the level of L5. A patient type 4 of Roussouly, for example, whom the pelvic incidence is high requiring in theory an important lumbar lordosis with its the apex around the level of L3 would benefit more from a PSO at L5 than a PSO at L3. This is because the PSO at L5 would in fact give a higher amount of correction (given its distal location) and truly concentrate such correction between L4 and S1, but keeping the apex of lordosis around the L3 level by proper bending of the rods and spontaneous correction of pelvic retroversion (decrease of pelvic tilt) after surgery (Fig. 3).

A previous study [23] evaluating the radiological and clinical outcomes of L5 PSO for fixed sagittal and coronal malalignment, showed an average improvement obtained at L4S1 of 34.2° and demonstrated the effectiveness of such technique in restoring the lower lumbar lordosis. In addition, no proximal junctional kyphosis (PJK) occurred in any of the 10 patients of the described series during the whole follow-up with a minimum of 2 years. One additional interest of L5 PSO is the possibility of achieving a short construct with proximal screws at L3 according to the patient's pathology and sagittal profile which would leave

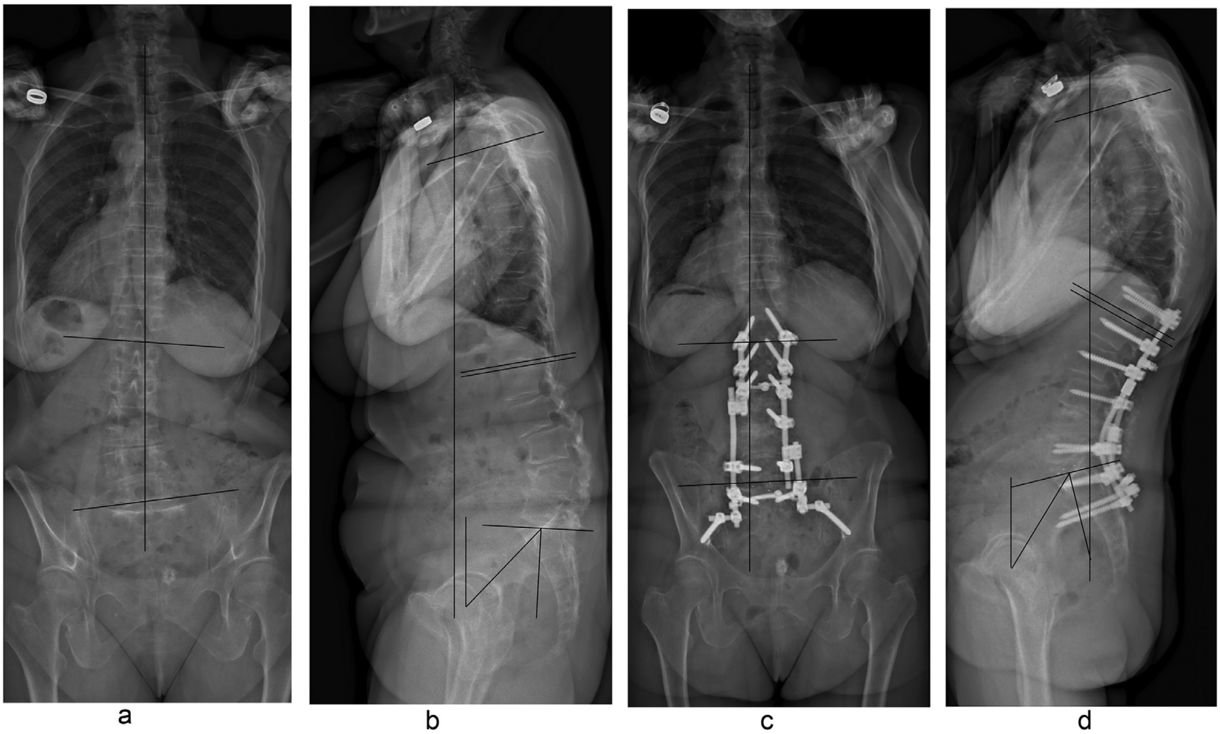

Fig. 2. Sixty-five y old patient with degenerative lumbar kyphosis. Preoperative full spine anteroposterior and lateral X-ray showing a lumbar kyphosis with compensatory distal thoracic lordosis and pelvic retroversion (A and B), C7-CSVL=0.2 cm, coronal Cobb=11°, PI=43°, PT=46°, SVA=7 cm, LL=+13°, thoracic kyphosis (TK)=7° Postoperative full spine anteroposterior and lateral X-ray after L4 modified PSO including the disc above and demonstrating restoration of lumbar lordosis, thoracic kyphosis and pelvic tilt (c and d), C7-CSVL=1.2 cm, coronal Cobb=0°, PI=43°, PT=31°, SVA=0 cm,LL=−42° (55° of total improvement), TK=45°

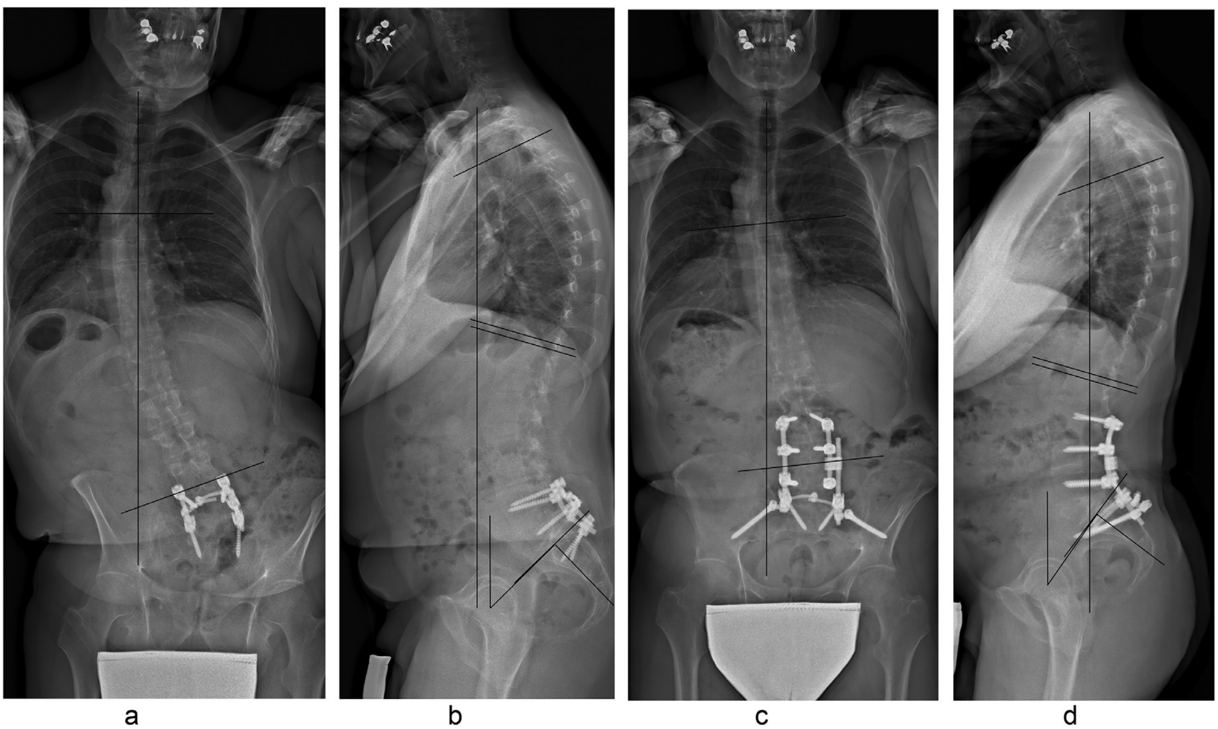

Fig. 3. Fifty-five y old patient with postoperative flatback. Preoperative full spine anteroposterior and lateral X-ray showing sagittal and coronal malalignment in a Roussouly type 4 patient (high pelvic incidence), and the apex of lumbar lordosis is at the level L1L2 (A and B), C7-CSVL=8 cm, coronal Cobb=20°, PI=88°, PT=46°, SVA=9 cm, LL=−60°, TK=41° Postoperative full spine anteroposterior and lateral X-ray after L5 PSO demonstrating improvement of lumbar lordosis with its apex at the L3L4 disc level, C7-CSVL=5 cm, coronal Cobb=1°, PI=86°, PT=32°, SVA=2 cm, LL=−70°, TK=38° It should be noted that the domino is placed at the opposite side of coronal imbalance in order to achieve simultaneous correction of both planes.

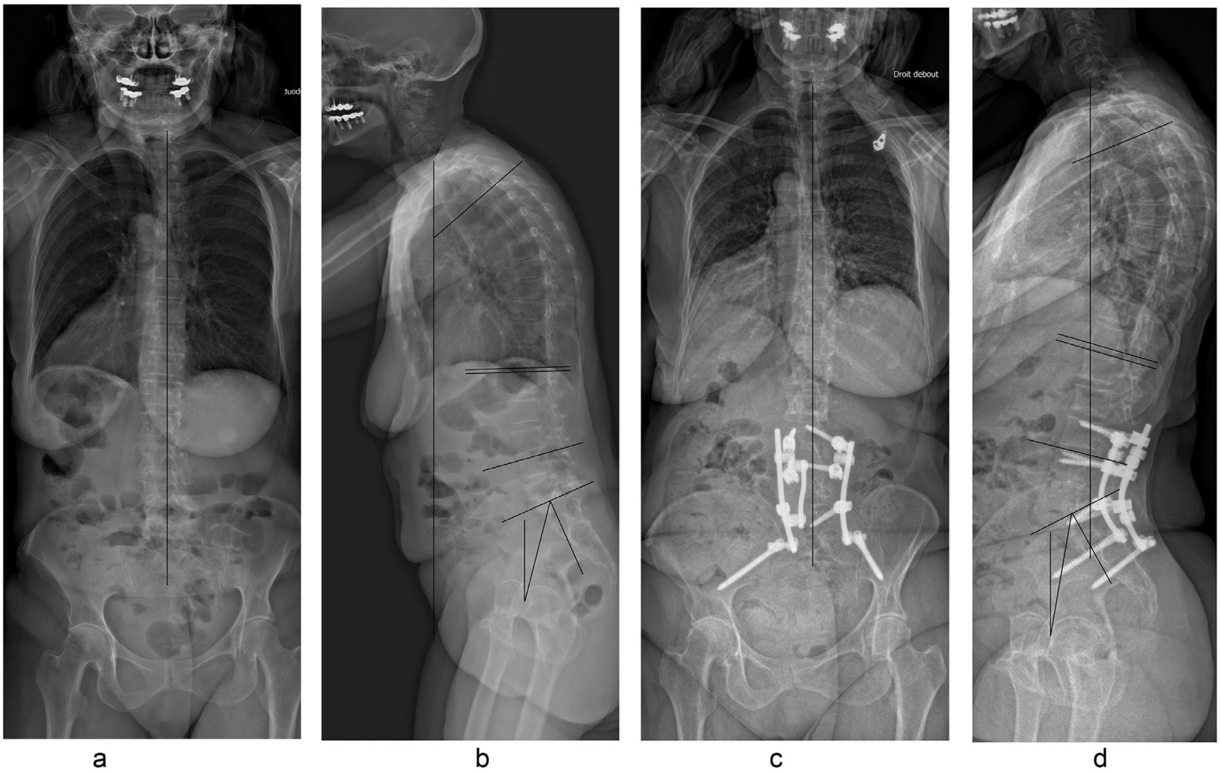

Fig. 4. Fifty y old patient with severe degenerative lumbar disease and flat back. Preoperative full spine anteroposterior and lateral X-ray showing mainly a lack of lordosis between L4 and S1 with compensatory long thoracolumbar lordosis (A and B), C7-CSVL=0 cm, PI=40°, PT=15°, SVA >10 cm, LL=−21°, L4S1=−7°, TK=38° Postoperative full spine anteroposterior and lateral X-ray after L5 PSO demonstrating significant improvement of the distal lumbar lordosis with a short L3 to iliac construct and multiple rods (C and D), C7-CSVL=0 cm, PI=38°, PT=10°, SVA=0 cm, LL=−42°, L4S1=−40°, TK=37°

the mobility of the proximal lumbar spine (Fig. 4). Lastly, L5 PSO is indicated in stiff convex coronal malalignment for the correction of the lumbosacral fractional curve (type 2A2 of the Obeid-Coronal Malalignment classification) and lumbosacral congenital anomalies with oblique take-off (type 2B of the same classification) [25].

Technical details

The classical PSO, initially reported by Thomasen [1], has been widely described and applied in the lumbar, thoracic and cervical areas. This corresponds to the grade 3 of the classification described by Schwab [26] (Fig. 5). The classification added the grade 4 which corresponds to a classical PSO that would include the disc above increasing the amount of correction and improving the fusion by achieving a bone on bone contact. In fact, many refinements of the classical PSO came progressively over the decades according to the needs of the spinal surgeons according to the amount of correction needed, shape of the vertebras, types of diseases and areas where to be applied.

The classification described by Bourghli summarized the majority of those refinements [27] (Fig. 6) and demonstrated their technical details and applications where a pedicle could be partially resected corresponding to a partial PSO, or the osteotomy anterior cuts could be shifted posteriorly toward the middle of the vertebral body in the anterior-posterior plane leading to closure of the middle column and opening of the anterior column corresponding to a closing opening osteotomy. This subclassification of PSOs represents a catalogue of the available spinal osteotomies, between a posterior column osteotomy and a vertebral column resection, that would help surgeons in their decision to tailor the type of osteotomy according to the encountered spinal condition.

Another technical detail regarding the PSO is the use of a cage inside the PSO site. Classically, the created wedge is closed as much as possible to achieve a bone on bone contact at the osteotomy site and cages may be inserted above and below the osteotomy level to avoid having a floating vertebra between flexible discs which would increase the nonunion rate. When the proximal disc is removed along with the bony wedge (Schwab grade 4), the gap becomes bigger and more difficult to close completely, and in such case a cage filled with autograft can be positioned anteriorly which helps in bridging the eventual gap increasing the chances of bone fusion. It also improves the lordosis correction by properly hinging the osteotomy on the anterior column, the cage serving as an anterior support and fulcrum, avoiding vertical collapse between the PSO site and the proximal vertebra and marked shortening of the spinal column [28].

Over time, our technique evolved toward generally resecting the proximal disc and inserting a cage in its anterior third to decrease the risk of shortening as previously mentioned, and maximize the correction around the newly created pivot. Through the posterior compression, a very firm contact is achieved between the cage and the bone above (lower endplate of the proximal vertebra) and the bone below (cancellous bone of the osteotomized vertebra) (Fig. 7). This technique of inserting a cage may also be combined to one of the PSO modifications such as the partial pedicle subtraction osteotomy (type 4A in the classification described by Bourghli [27]) where the pedicle is partially removed keeping its inferior cortex and lower part of the posterior arch which would protect the foramen below and increase the posterolateral fusion rate; adding the cage anteriorly would improve the correction and anterior fusion.

Dealing with distal lumbar PSO would require strong fixation points below the osteotomy and it has been widely demonstrated that stopping at S1 only may lead to nonunion or distal mechanical complications [29,30]. This is why going down to the pelvis with long anchors has been advocated [31,32].

Classical iliac screw fixation consisting of screw placement into the iliac wing from the posterior superior iliac spine (PSIS) has demon-

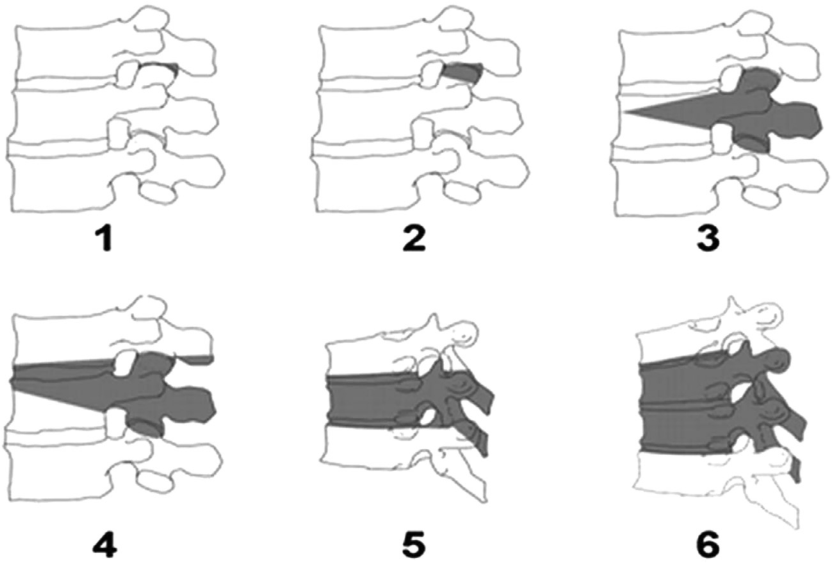

Fig. 5. Summary of the different degrees of the Schwab's osteotomy classification. Grade 3 corresponds to a classical PSO. Grade 4 corresponds to a PSO with resection of the proximal disc (modified or extended PSO).

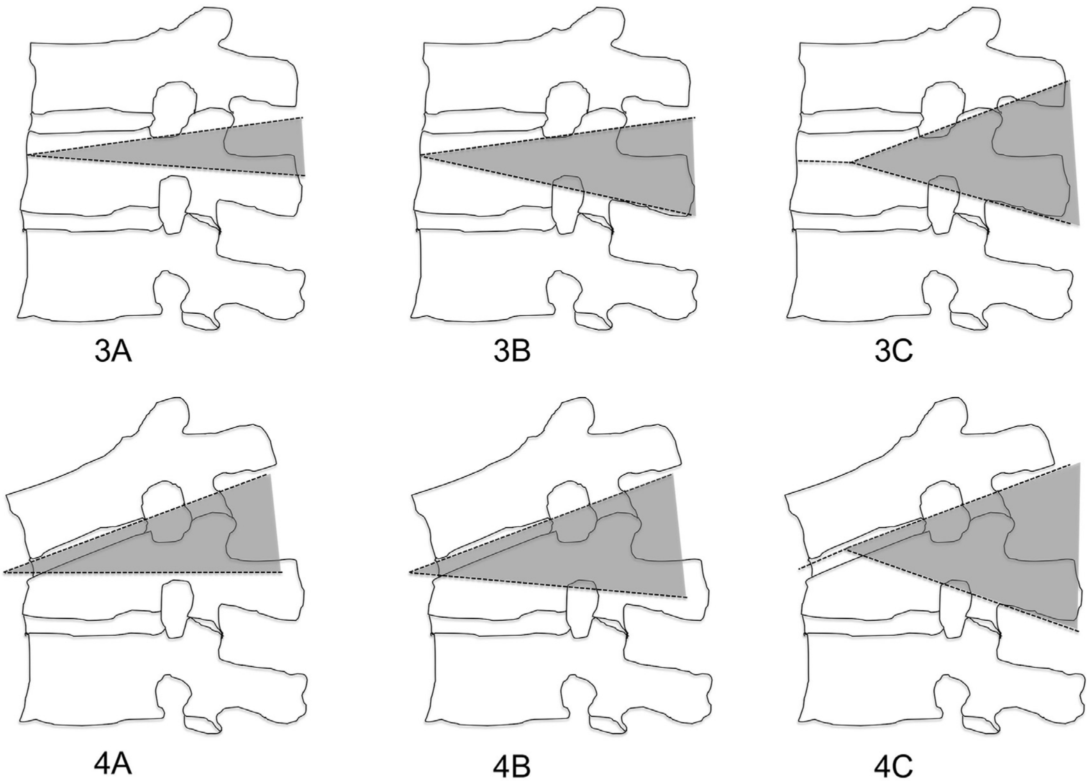

Fig. 6. Summary of the PSO classification as described by Bourghli. 3(A) is a partial pedicle subtraction osteotomy. 3(B) is a classical pedicle subtraction osteotomy. 3(C) is a closing-opening wedge osteotomy. 4(A) is a modified partial pedicle subtraction osteotomy. 4(B) is a modified or extended pedicle subtraction osteotomy. 4(C) is a modified closing-opening wedge osteotomy.

strated to be a very effective technique of sacropelvic fixation for over 2 decades, being applied in deformity, high grade spondylolisthesis and lumbopelvic reconstruction after sacral tumors resection [33]. Several disadvantages have been described such as implant prominence over the PSIS, wide muscle dissection laterally to expose the iliac wings and the need of a transverse connector for the implant to be in line with S1 pedicle screw. However, in practice when properly managed those disadvantages did not lead to high rate of complications or prevent successful outcome. Muscle dissection in terms of bleeding and postoperative pain is not higher in patients with classical iliac screws because they are usually part of major surgeries such as deformities that could require osteotomies and those parameters (bleeding and pain) are already high. Prominent iliac screws can be dealt with by removing the PSIS medial cortex and cancellous bone at the entry point which enables burying of the screw head below the level of the outer cortex eliminating the prominence issue. The use of a connec-

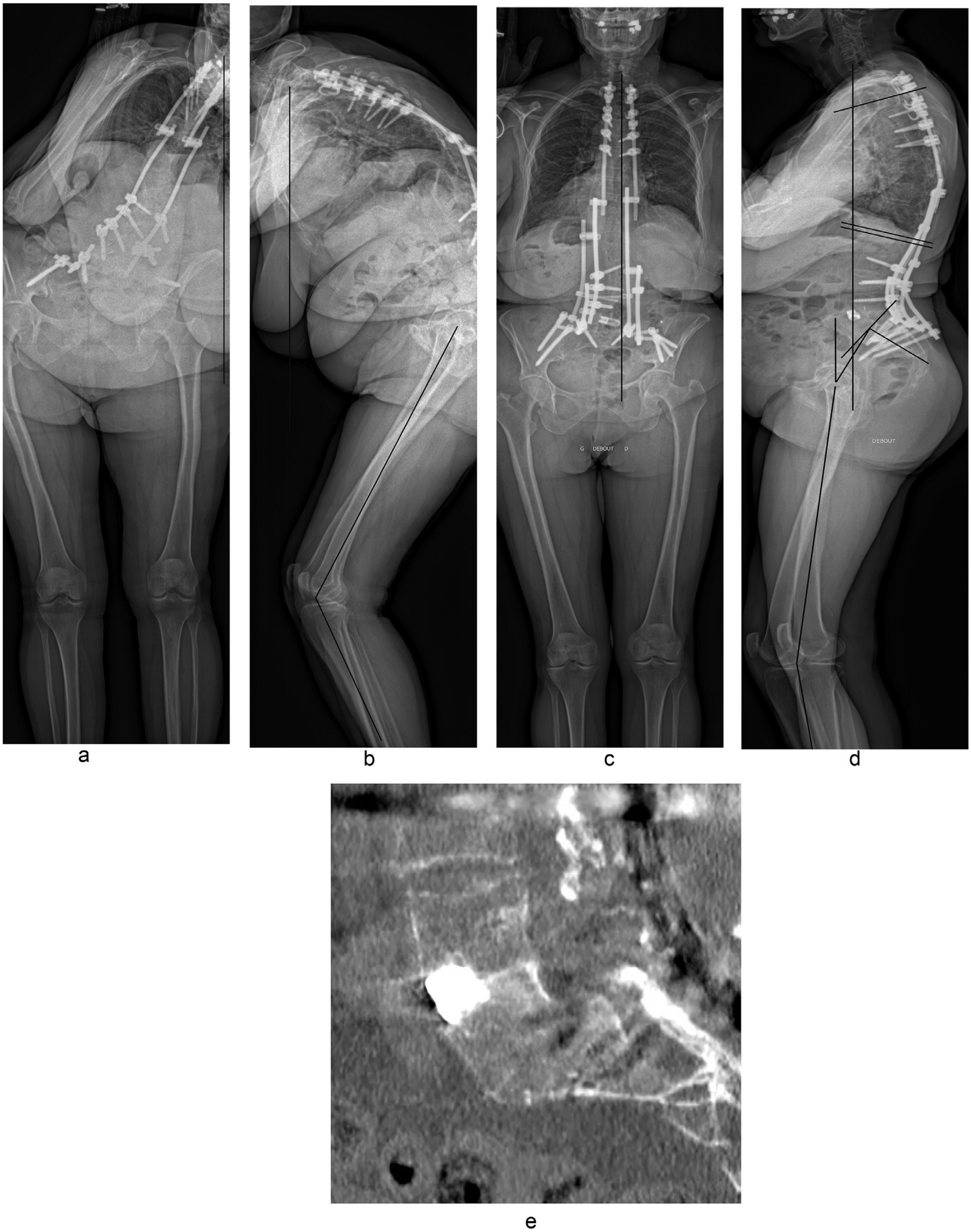

Fig. 7. Sixty seven y old patient with multiple previous surgeries. Preoperative full spine anteroposterior and lateral X-ray showing severe sagittal and coronal malalignment to the extent that the patient could not fit completely inside the EOS cabin's field, which illustrates the limits of the imaging system in such cases (A and B) with difficulties to measure pelvic parameters and LL, C7-CSVL>10 cm, SVA>10 cm, knee flexion=49° Postoperative full spine anteroposterior and lateral X-ray after L5 PSO demonstrating significant improvement of the patient's global alignment including knee flexion compensatory mechanism, a cage was inserted anteriorly inside the L5 osteotomy site (C and D), C7-CSVL=2 cm, PI=80°, PT=29°, SVA=4 cm, LL=−70°, TK=36°, knee flexion=13° Postoperative CT scan at 2 years illustrating clear fusion posterior to the cage with bony contact between L4 and L5 (E).

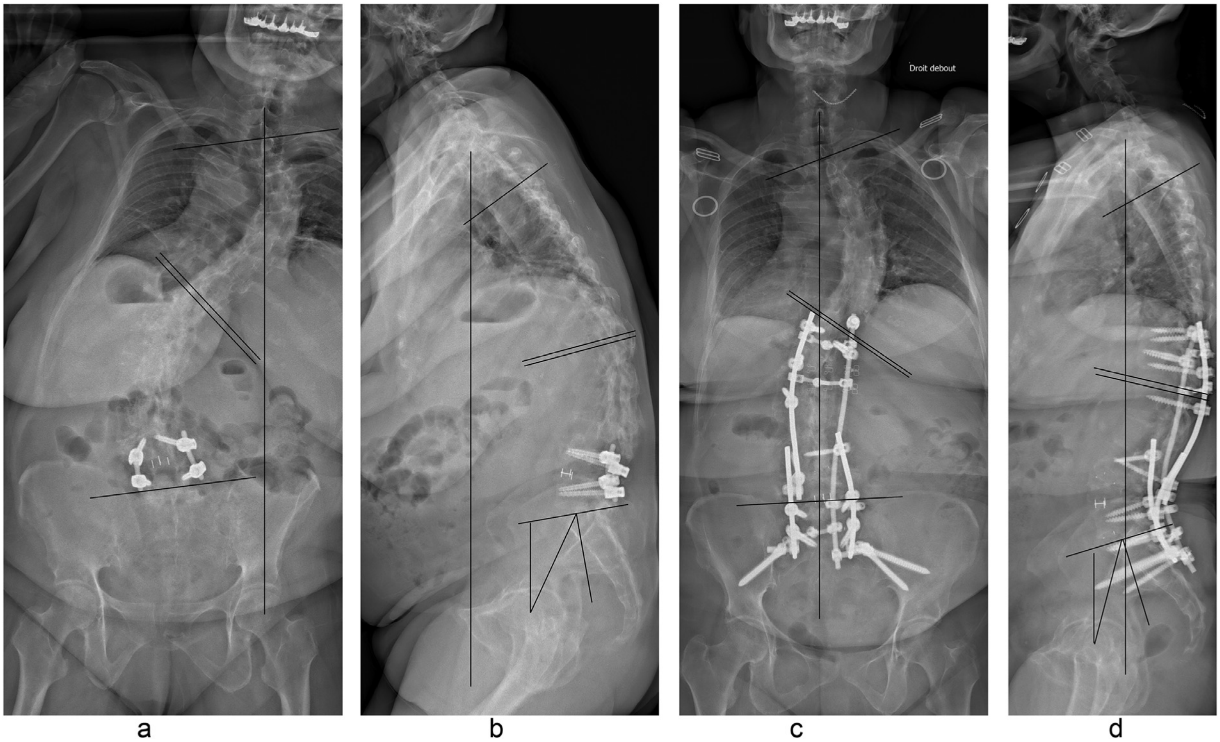

Fig. 8. Fifty-two y old patient with previous L4L5 fusion. Preoperative full spine anteroposterior and lateral X-ray showing thoracolumbar kyphosis leading to sagittal malalignment associated to coronal malalignment (a and b), C7-CSVL>10 cm, lumbar coronal Cobb=55°, thoracic coronal cobb=53°, PI=34°, PT=27°, SVA>10 cm, LL=+5°, TK=21° Postoperative full spine anteroposterior and lateral X-ray after L4 PSO demonstrating significant improvement of the patient's alignment in both planes, multiple iliac screws and rods were used for stronger construct (C and D), C7-CSVL=0.5 cm, lumbar coronal Cobb=38°, thoracic coronal Cobb=54°, PI=34°, PT=15°, SVA=1.5 cm, LL=−30°, TK=39°.

tor did not lead, in our practice, to technical difficulties or mechanical complications, in fact they remained little and the connector itself rarely broke postoperatively as a result of the remaining sacroiliac (SI) joint motion, the iliac screw itself more frequently broke, but similarly to other types of screws such as the S2 alar iliac (S2AI) screw.

S2AI screw has been widely popularized in the past decade, and proposed as an alternative to classical iliac screw [34], as being inserted through S2 makes it in line with the S1 pedicle screw obviating the need of a connector and requiring less dissection. However, the S2AI screw cannot be easily inserted with the free hand technique and usually requires fluoroscopic guidance. This is due to the fact that the screw goes through the SI joint, thus passing from the sacral ala (bony area) to the SI joint (no bone) reaching the ilium (bony area), therefore the feeling during the free hand technique becomes less reliable requiring X-ray. In contrast, the classical iliac screw can be easily inserted with the free hand technique and in practice fluoroscopic guidance has never been required. For all the previously mentioned reasons, many surgeons continued to use the classical iliac screw and did not shift to the S2AI screw (Fig. 2,3,4,7 and 8). Dual or multiple iliac screws could even be applied [35] especially in patients with multiple previous surgeries requiring distal PSO at L5 (Fig. 7) or L4 (Fig. 8).

It should be noted that the anatomical iliac screw has been also described [36]; it is a classical iliac screw where the entry point is located directly in the ilium, along the medial border of the PSIS, at the junction between the inner table of the ilium and the sacrum. It has been demonstrated to be a low profile pelvic fixation, remaining in line with S1 pedicle anchors, with low prominence and adapting better to the morphological features of the pelvis of each individual when compared to S2AI [37].

When performing a lumbar PSO, the construct may be short spanning only the lumbosacral area (Fig. 3 and 4), but it may also be long reaching the lower thoracic (thoracolumbar junction), the middle thoracic or the high thoracic region. Therefore, and depending on the sagittal and coronal alignment of the patient, some principles should be applied for the selection of the level of the upper instrumented vertebra in order to avoid junctional complications such as proximal junctional kyphosis. If the main pathology concerns the lumbar spine and the thoracolumbar area is non kyphotic, upper instrumented vertebra should be at the thoracolumbar junction (Fig. 2). In case of an associated thoracolumbar kyphosis, the thoracolumbar junction should be bypassed and the proximal instrumented level should be at the lower or middle thoracic spine (Fig. 8). If the thoracic spine presents a global kyphosis, upper instrumented vertebra should be at the upper thoracic spine (Fig. 7). In addition, care should be taken to avoid flattening of the thoracic spine in case of more proximal instrumentation by concentration the reduction at the concerned lumbar area and by respecting the normal sagittal thoracic rod contouring that would adapt to the patient's pelvic incidence. This would allow a smooth rod landing in the thoracic spine and decrease the risk of PJK.

Several techniques have been described in the literature for the closure of the PSO site including external maneuvers such as progressive bending of the operating room table [38] and internal maneuvers by application of forces through the pedicle screws and rods [39,40]. However, those techniques may show some limitations in case of osteoporosis or important required correction. The use of a side-to-side domino connector as a correction tool for PSO site closure has been previously described [41] and it was shown that such technique is safe, powerful and efficient for osteotomy site closure. In fact, by distributing the correctional forces across multiple screws, it increases the power of simultaneous compression at the osteotomy site together with the adjacent levels (Fig. 9). It improved lumbar lordosis correction angle when compared to other techniques not involving the domino with an acceptable rate of complications [41].

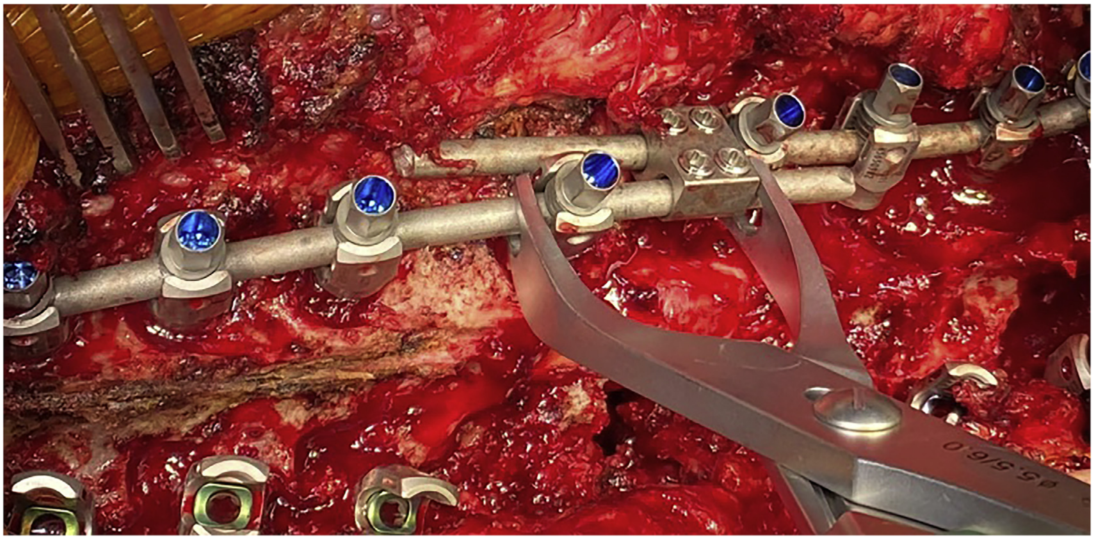

Fig. 9. Intraoperative picture showing compression on the domino for further closure of the osteotomy site.

As the domino-rods construct may be biomechanically weaker when compared to an intact rod, which would lead to a higher rate of mechanical complications, our practice shifted from using single rods (Fig. 2 and 3) to multiple rods alongside each domino (Fig. 4,7 and 8). In addition, in case of coronal malalignment associated to sagittal malalignment, greater bone resection at the convexity of the deformity is performed and the main domino for correction may be placed at the opposite side of coronal imbalance in order to achieve an asymmetrical closure of the PSO to correct simultaneously both planes (Fig. 3,7 and 8) [42].

Outcomes

A technically demanding technique such as PSO cannot be thoroughly described without mentioning intra and postoperative complications. Their incidence could reach up to 78% depending on the surgical series [43,44] and include either major complications such as neurological deficit, cardiopulmonary distress, deep wound infection, instrumentation failure or minor complications such as epidural haematoma, superficial infection, ileus and urinary tract infection. Neurological deficit remains a relatively common complication and the most serious one, with an incidence around 12%, however in the majority of cases deficits are not likely to be permanent with a prevalence of permanent deficits of 2.8% [45]. To lower such risk, central canal enlargement at the level of the PSO to avoid dural buckling is recommended with careful closure to prevent subluxation across the osteotomy. In addition, the role of neuromonitoring in detecting early neurological impairment and preventing postoperative deficit has been demonstrated [46].

In terms of correction, outcomes of lumbar PSO remain very satisfactory with an average of 30° of improvement of lumbar lordosis depending on the various studies [23,41]. The more distal the osteotomy, the higher the amount of correction, and the inclusion of the proximal disc may allow a greater focal angulation thus improving the final outcome [20].

Average revision rate after lumbar PSO for adult spinal deformities remains however relatively high around 25% and is mainly related to mechanical complications such as pseudarthrosis and proximal junctional kyphosis. Despite the use of interbody cages and multiple rods constructs [47], the rate of pseudarthrosis and rod fractures remains important as multiple factors may play a role in its occurrence such as PSO location, amount of angulation and correction, rod bending with mechanical stress, and sagittal alignment configuration. It was demonstrated, in a study comparing 2-rod and multiple-rod constructs after lumbar PSO, that the use of multiple rods did not show a better outcome in terms of incidence and types of mechanical complications however it improved functional outcome and coronal alignment [48]. Other studies showed that the use of multiple-rod construct could lead to a lower rate of rods fractures after lumbar PSO [49,50]. This shows that ultimately, there is no strong and definite evidence on such issue. Moreover, PJK remains an unsolved problem as in spite of the use of various soft-landing techniques proximally such as transverse hooks or sublaminar bands [51], the rate of proximal failure remains high. Pathophysiology for the occurrence of PJK remains incompletely understood with many factors being described as possible reasons including biological, mechanical or iatrogenic. Several studies emphasized the importance of sagittal alignment proper restoration as a protecting factor [52,53].

It has been previously demonstrated [54,55] that a long learning curve is the only warrant to decrease the rate of complications associated with the PSO technique. Decreasing the operative time and blood loss becomes increasingly complicated as it is proportional to doubling the number of cases [54], and surgeon years of experience is the most significant factor in mitigating neurological complications and improving quality measures [55].

Lumbar PSO generally leads to satisfactory clinical improvements as demonstrated by health-related quality of life scores. A meta-analysis including 8 studies with 431 PSO cases showed a statistically significant improvement of Oswestry Disability Index (ODI) score after PSO surgical correction, and the minimum clinically important difference (MCID) was achieved with both ODI and SRS scores [56]. In addition, patients who remain sagittally imbalanced have less improvement in HRQOL scores than those whose sagittal imbalance has been corrected [48,57,58]. However, it should be noted that the relatively high revision rate after PSO surgeries may lead to an increase of decisional regret following correctional surgery as demonstrated by Du et al. [59] where they showed that 3 column osteotomy was one of the risk factors for a patient to have a medium-high decisional regret in univariate analysis and in multivariate analysis only revision surgery was independently associated with increase in risk for medium-high decisional regret.

Conclusion

Lumbar pedicle subtraction osteotomy has been widely studied in the literature during the past 2 decades. Technical refinements and dedicated tools made it a very efficient procedure for the correction of rigid sagittal malalignment with satisfactory clinical and radiological outcomes, however associated risks and complications should not be overlooked and therefore a long learning curve is required.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Thomasen E. Vertebral osteotomy for correction of kyphosis in ankylosing spondylitis. Clin Orthop Relat Res 1985:142–52.

[2] Murphy SN, Nguyen BA, Singh R, et al. A brief human history of ankylosing spondylitis: a scoping review of pathogenesis, diagnosis, and treatment. Surg Neurol Int 2022;13:297. doi:10.25259/SNI_294_2022.

[3] Qandah NA, Klocke NF, Synkowski JJ, et al. Additional sagittal correction can be obtained when using an expandable titanium interbody device in lumbar Smith-Peterson osteotomies: a biomechanical study. Spine J 2015;15:506–13. doi:10.1016/j.spinee.2014.10.010.

[4] Mikula AL, Lakomkin N, Pennington Z, et al. Lumbar lordosis correction with transforaminal lumbar interbody fusion in adult spinal deformity patients with minimum 2-year follow-up. World Neurosurg 2022;167:e295–302. doi:10.1016/j.wneu.2022.08.003.

[5] Turner JD, Akbarnia BA, Eastlack RK, et al. Radiographic outcomes of anterior column realignment for adult sagittal plane deformity: a multicenter analysis. Eur Spine J 2015;24(3):427–32 Suppl. doi:10.1007/s00586-015-3842-0.

[6] Manwaring JC, Bach K, Ahmadian AA, Deukmedjian AR, Smith DA, Uribe JS. Management of sagittal balance in adult spinal deformity with minimally invasive anterolateral lumbar interbody fusion: a preliminary radiographic study. J Neurosurg Spine 2014;20:515–22. doi:10.3171/2014.2.SPINE1347.

[7] Saville PA, Kadam AB, Smith HE, Arlet V. Anterior hyperlordotic cages: early experience and radiographic results. J Neurosurg Spine 2016;25:713–19. doi:10.3171/2016.4.SPINE151206.

[8] Buric J, Conti R, Peressutti S. Lumbar lordosis correction with interbody hyperlordotic cages: initial experience, learning curve, technical aspects, and complication incidence. Int J Spine Surg 2018;12:185–9. doi:10.14444/5026.

[9] Wang MY. Improvement of sagittal balance and lumbar lordosis following less invasive adult spinal deformity surgery with expandable cages and percutaneous instrumentation. J Neurosurg Spine 2013;18:4–12. doi:10.3171/2012.9.SPINE111081.

[10] Uribe JS, Schwab F, Mundis GM, et al. The comprehensive anatomical spinal osteotomy and anterior column realignment classification. J Neurosurg Spine 2018;29:565–75. doi:10.3171/2018.4.SPINE171206.

[11] Sebaaly A, Grobost P, Mallam L, Roussouly P. Description of the sagittal alignment of the degenerative human spine. Eur Spine J 2018;27:489–96. doi:10.1007/s00586-017-5404-0.

[12] Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976) 2010;35:2224–31. doi:10.1097/BRS.0b013e3181ee6bd4.

[13] Picton B, Stone LE, Liang J, et al. Patient-specific rods in adult spinal deformity: a systematic review. Spine Deform 2024;12:577–85. doi:10.1007/s43390-023-00805-8.

[14] Smith-Petersen MN, Larson CB, Aufranc OE. Osteotomy of the spine for correction of flexion deformity in rheumatoid arthritis. Clin Orthop Relat Res 1969;66:6–9.

[15] van Royen BJ, Slot GH. Closing-wedge posterior osteotomy for ankylosing spondylitis. Partial corporectomy and transpedicular fixation in 22 cases. J Bone Joint Surg Br 1995;77:117–21.

[16] Roussouly P, Gollogly S, Berthonnaud E, Dimnet J. Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. Spine (Phila Pa 1976) 2005;30:346–53. doi:10.1097/01.brs.0000152379.54463.65.

[17] Roussouly P, Nnadi C. Sagittal plane deformity: an overview of interpretation and management. Eur Spine J 2010;19:1824–36. doi:10.1007/s00586-010-1476-9.

[18] Roussouly P, Pinheiro-Franco JL. Sagittal parameters of the spine: biomechanical approach. Eur Spine J 2011;20(5):578–85 Suppl. doi:10.1007/s00586-011-1924-1.

[19] Roussouly P, Pinheiro-Franco JL. Biomechanical analysis of the spino-pelvic organization and adaptation in pathology. Eur Spine J 2011;20(5):609–18 Suppl. doi:10.1007/s00586-011-1928-x.

[20] Buell TJ, Nguyen JH, Mazur MD, et al. Radiographic outcome and complications after single-level lumbar extended pedicle subtraction osteotomy for fixed sagittal malalignment: a retrospective analysis of 55 adult spinal deformity patients with a minimum 2-year follow-up. J Neurosurg Spine 2018;30:242–52. doi:10.3171/2018.7.SPINE171367.

[21] Eskilsson K, Sharma D, Johansson C, Hedlund R. Pedicle subtraction osteotomy: a comprehensive analysis in 104 patients. Does the cause of deformity influence the outcome? J Neurosurg Spine 2017;27:56–62. doi:10.3171/2016.12.SPINE16585.

[22] Tang ZL, Qian BP, Qiu Y, Liu ZJ, Zhao SZ, Huang JC. Does the level of pedicle subtraction osteotomy affect the surgical outcomes in ankylosing spondylitis-related thoracolumbar kyphosis with the same curve pattern? Global Spine J 2022;12:1392–9. doi:10.1177/2192568220980716.

[23] Alzakri A, Boissiere L, Cawley DT, et al. L5 pedicle subtraction osteotomy: indication, surgical technique and specificities. Eur Spine J 2018;27:644–51. doi:10.1007/s00586-017-5403-1.

[24] Bourghli A, Boissiere L, Chevillotte T, et al. Radiographic outcomes and complications after L4 or L5 pedicle subtraction osteotomy for fixed sagittal malalignment in 102 adult spinal deformity patients with a minimum 2-year follow-up. Eur Spine J 2022;31:104–11. doi:10.1007/s00586-021-07008-7.

[25] Obeid I, Berjano P, Lamartina C, Chopin D, Boissiere L, Bourghli A. Classification of coronal imbalance in adult scoliosis and spine deformity: a treatment-oriented guideline. Eur Spine J 2019;28:94–113. doi:10.1007/s00586-018-5826-3.

[26] Schwab F, Blondel B, Chay E, et al. The comprehensive anatomical spinal osteotomy classification. Neurosurgery 2014;74:112–20. doi:10.1227/NEU.0000000000000182o.

[27] Bourghli A, Boissiere L, Konbaz F, et al. On the pedicle subtraction osteotomy technique and its modifications during the past two decades: a complementary classification to the Schwab's spinal osteotomy classification. Spine Deform 2021;9:515–28. doi:10.1007/s43390-020-00247-6.

[28] Boachie-Adjei O, Ferguson JA, Pigeon RG, Peskin MR. Transpedicular lumbar wedge resection osteotomy for fixed sagittal imbalance: surgical technique and early results. Spine (Phila Pa 1976) 2006;31:485–92. doi:10.1097/01.brs.0000199893.71141.59.

[29] Edwards CC, Bridwell KH, Patel A, Rinella AS, Berra A, Lenke LG. Long adult deformity fusions to L5 and the sacrum. A matched cohort analysis. Spine (Phila Pa 1976) 2004;29:1996–2005. doi:10.1097/01.brs.0000138272.54896.33.

[30] Han B, Yin P, Hai Y, Cheng Y, Guan L, Liu Y. The comparison of spinopelvic parameters, complications, and clinical outcomes after spinal fusion to S1 with or without additional sacropelvic fixation for adult spinal deformity: a systematic review and meta-analysis. Spine (Phila Pa 1976) 2021;46:E945–53. doi:10.1097/BRS.0000000000004003.

[31] El Dafrawy MH, Raad M, Okafor L, Kebaish KM. Sacropelvic fixation: a comprehensive review. Spine Deform 2019;7:509–16. doi:10.1016/j.jspd.2018.11.009.

[32] Shin HK, Park JH, Jeon SR, et al. Sacropelvic Fixation for adult deformity surgery comparing iliac screw and sacral 2 alar-iliac screw fixation: systematic review and updated meta-analysis. Neurospine 2023;20:1469–76. doi:10.14245/ns.2346654.327.

[33] Harimaya K, Mishiro T, Lenke LG, Bridwell KH, Koester LA, Sides BA. Etiology and revision surgical strategies in failed lumbosacral fixation of adult spinal deformity constructs. Spine (Phila Pa 1976) 2011;36:1701–10. doi:10.1097/BRS.0b013e3182257eaf.

[34] O'Brien JR, Yu WD, Bhatnagar R, Sponseller P, Kebaish KM. An anatomic study of the S2 iliac technique for lumbopelvic screw placement. Spine (Phila Pa 1976) 2009;34:E439–42. doi:10.1097/BRS.0b013e3181a4e3e4.

[35] Bourghli A, Boissiere L, Obeid I. Dual iliac screws in spinopelvic fixation: a systematic review. Eur Spine J 2019;28:2053–9. doi:10.1007/s00586-019-06065-3.

[36] Harrop JS, Jeyamohan SB, Sharan A, Ratliff J, Vaccaro AR. Iliac bolt fixation: an anatomic approach. J Spinal Disord Tech 2009;22:541–4. doi:10.1097/BSD.0b013e31818da3e2.

[37] Galovich LA, Bordon JM, Blanco IC, et al. Anatomic trajectory for iliac screw placement adapts better to the morphological features of the pelvis of each individual than the S2 alar iliac screw: a radiological study. Acta Neurochir (Wien) 2023;165:2607–14. doi:10.1007/s00701-023-05692-6.

[38] Jones KE, Hunt MA, Martin CT, Polly DW. Controlled pedicle subtraction osteotomy site closure using flexible hinge-powered operating table. Oper Neurosurg (Hagerstown) 2019;17:E214–18. doi:10.1093/ons/opy397.

[39] Chiffolot X, Lemaire JP, Bogorin I, Steib JP. Pedicle closing-wedge osteotomy for the treatment of fixed sagittal imbalance. Rev Chir Orthop Reparatrice Appar Mot 2006;92:257–65. doi:10.1016/s0035-1040(06)75733-6.

[40] Gupta S, Gupta MC. The nuances of pedicle subtraction osteotomies. Neurosurg Clin N Am 2018;29:355–63. doi:10.1016/j.nec.2018.03.001.

[41] Bourghli A., Boissiere L., Cawley D., et al., European Spine Study G (2022) Domino connector is an efficient tool to improve lumbar lordosis correction angle after pedicle subtraction osteotomy for adult spinal deformity. Eur Spine J 31:2408–2414. 10.1007/s00586-022-07322-8

[42] Obeid I, Laouissat F, Vital JM. Asymmetric T5 pedicle subtraction osteotomy (PSO) for complex posttraumatic deformity. Eur Spine J 2013;22:2130–5. doi:10.1007/s00586-013-2942-y.

[43] Daubs MD, Brodke DS, Annis P, Lawrence BD. Perioperative complications of pedicle subtraction osteotomy. Global Spine J 2016;6:630–5. doi:10.1055/s-0035-1570088.

[44] Smith JS, Shaffrey CI, Klineberg E, et al. Complication rates associated with 3-column osteotomy in 82 adult spinal deformity patients: retrospective review of a prospectively collected multicenter consecutive series with 2-year follow-up. J Neurosurg Spine 2017;27:444–57. doi:10.3171/2016.10.SPINE16849.

[45] Buchowski JM, Bridwell KH, Lenke LG, et al. Neurologic complications of lumbar pedicle subtraction osteotomy: a 10-year assessment. Spine (Phila Pa 1976) 2007;32:2245–52. doi:10.1097/BRS.0b013e31814b2d52.

[46] Lau D, Dalle Ore CL, Reid P, et al. Utility of neuromonitoring during lumbar pedicle subtraction osteotomy for adult spinal deformity. J Neurosurg Spine 2019;31:397–407. doi:10.3171/2019.3.SPINE181409.

[47] Guevara-Villazon F, Boissiere L, Hayashi K, et al. Multiple-rod constructs in adult spinal deformity surgery for pelvic-fixated long instrumentations: an integral matched cohort analysis. Eur Spine J 2020;29:886–95. doi:10.1007/s00586-020-06311-z.

[48] Bourghli A, Boissiere L, Kieser D, et al. European spine study G (2021) multiple-rod constructs do not reduce pseudarthrosis and rod fracture after pedicle subtraction osteotomy for adult spinal deformity correction but improve quality of life. Neurospine 2021;2021(18):816–23. doi:10.14245/ns.2142596.298.

[49] Kankam SB, Zarei M, Moghadam N, et al. The advantages of 4-rod construct over the 2-rod techniques in adult spinal deformity patients who underwent pedicle subtraction osteotomy: a multicenter retrospective comparative study. World Neurosurg 2024;183:e530–9. doi:10.1016/j.wneu.2023.12.137.

[50] Lyu Q, Lau D, Haddad AF, Deviren V, Ames CP. Multiple-rod constructs and use of bone morphogenetic protein-2 in relation to lower rod fracture rates in 141 patients with adult spinal deformity who underwent lumbar pedicle subtraction osteotomy. J Neurosurg Spine 2022;36:235–45. doi:10.3171/2021.3.SPINE201968.

[51] Bourghli A, Boissiere L, Larrieu D, et al. Proximal junctional kyphosis after adult spinal deformity operated patients with long fusion to the pelvis. Does the type of proximal anchor matter? Eur Spine J 2024. doi:10.1007/s00586-024-08332-4.

[52] Zou L, Liu J, Lu H. Characteristics and risk factors for proximal junctional kyphosis in adult spinal deformity after correction surgery: a systematic review and meta-analysis. Neurosurg Rev 2019;42:671–82. doi:10.1007/s10143-018-1004-7.

[53] Lazaro B, Sardi JP, Smith JS, et al. Proximal junctional failure in primary thoracolumbar fusion/fixation to the sacrum/pelvis for adult symptomatic lumbar scoliosis: long-term follow-up of a prospective multicenter cohort of 160 patients. J Neurosurg Spine 2023;38:319–30. doi:10.3171/2022.9.SPINE22549.

[54] Bourghli A, Cawley D, Novoa F, et al. 102 lumbar pedicle subtraction osteotomies: one surgeon's learning curve. Eur Spine J 2018;27:652–60. doi:10.1007/s00586-018-5481-8.

[55] Lau D, Deviren V, Ames CP. The impact of surgeon experience on perioperative complications and operative measures following thoracolumbar 3-column osteotomy for adult spinal deformity: overcoming the learning curve. J Neurosurg Spine 2019;32:207–20. doi:10.3171/2019.7.SPINE19656.

[56] Tarawneh AM, Venkatesan M, Pasku D, Singh J, Quraishi NA. Impact of pedicle subtraction osteotomy on health-related quality of life (HRQOL) measures in patients undergoing surgery for adult spinal deformity: a systematic review and meta-analysis. Eur Spine J 2020;29:2953–9. doi:10.1007/s00586-020-06439-y.

[57] Funao H, Kebaish FN, Skolasky RL, Kebaish KM. Clinical results and functional outcomes after three-column osteotomy at L5 or the sacrum in adult spinal deformity. Eur Spine J 2020;29:821–30. doi:10.1007/s00586-019-06255-z.

[58] Kieser DC, Yuksel S, Boissiere L, European Spine Study G, et al. Impact of radiologic variables on item responses of ODI, SRS22 and SF-36. In adult spinal deformity patients: differential item functioning (DIF) analysis results from a multi-center database. Eur Spine J 2022;31:1166–73. doi:10.1007/s00586-021-07088-5.

[59] Du JY, Lovecchio FC, Kazarian G, et al. Decisional regret following corrective adult spinal deformity surgery: a single institution study of incidence and risk factors. Spine Deform 2024;12:775–83. doi:10.1007/s43390-023-00790-y.