Protection of L1 nerve roots in vertebral osteotomy for severe rigid thoracolumbar spine deformity

Hang Liao

Shenzhen University

Houguang Miao

Shenzhen University

Peng Xie

Shenzhen University

Yueyue Wang

Shenzhen University

Ningdao Li

Shenzhen University

Guizhou Zheng

Shenzhen University

Xuedong Li

Shenzhen University

Shixin Du (✉ DSX333126@126.com)

Shenzhen University

Research article

Keywords: Thoracolumbar deformity, Nerve roots injury, L1 nerve roots, Parallel endplate osteotomy

Posted Date: October 2nd, 2019

DOI: <https://doi.org/10.21203/rs.2.15567/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Background: This is a retrospective study of the use of parallel endplate osteotomy (PEO) for correction of severe rigid thoracolumbar spine deformity.

Methods : From July 2016 to June 2017, 10 patients with severe rigid thoracolumbar spine deformity underwent PEO on T12 or L1 vertebrae were studied.

Results : Following PEO performed at T12 or L1, the kyphosis and scoliosis correction rates reached averages of $77.4 \pm 8.5\%$ and $76.6 \pm 6.8\%$, intraoperative bleeding 1990 ± 1010 ml, operation time 7.12 ± 3.88 h. One year after surgery, the SF-36 scores of physical function, role-physical, bodily pain, general health, vitality, social function, role-emotional and mental health from 60 ± 30 , 47 ± 33 , 44 ± 30 , 32 ± 18 , 50 ± 30 , 46 ± 29 , 26 ± 40 and 52 ± 20 to 81 ± 16 , 69 ± 19 , 73 ± 11 , 66 ± 21 , 74 ± 16 , 74 ± 24 , 63 ± 37 and 76 ± 12 , respectively ($P < 0.01$). Three patients had symptoms of L1 nerve root injury, as reflected by knee extension and hip flexion of lower limb weakness and inner thigh numbness, which further confirmed by electromyography.

Conclusions : The parallel endplate osteotomy is simple, results in less bleeding, spinal cord and nerve root under direct vision and can effectively and safely correct severe rigid thoracolumbar spine deformity with better clinical results. However, it is important to identify, separate and protect L1 nerve roots during surgery in cases where patients have symptoms of back pain, muscle weakness and leg numbness on the convex side after surgery.

Key words: Thoracolumbar deformity, Nerve roots injury, L1 nerve roots, Parallel endplate osteotomy

Background

Severe rigid thoracolumbar spine deformity is a thoracolumbar spinal deformity with kyphosis or a scoliosis angle that remains over 80 degrees after bending or traction (flexibility $< 25\%$)^[1], and is comprised of a variety of spinal deformities, such as untreated adolescent idiopathic scoliosis into adulthood, spinal congenital malformations, spinal hemivertebra malformations, incomplete segmental malformations and deformity caused by ankylosing spondylitis^[2]. As the disease progresses, the above structure is ossified and the patient develops chest and back pain with stiffness. Patients with severe rigid thoracolumbar spinal deformity mostly have respiratory restriction, suffocating breathing and limited cardiac output^[3].

For severe rigid deformity, spinal osteotomy is recommended^[4]. Spinal osteotomy ideally should involve a single surgical approach to decompress the nerve, correct the deformity and stabilize the spine structure^[5]. Due to the pathological characteristics of spine deformity, osteotomy is extremely challenging for spine surgeons, and is accompanied by a high incidence of various complications, including neurological lesions, blood loss, infection, pseudarthrosis, fixation failure and loss of correction^[6]. Nerve root injury is a common disastrous problem in osteotomy^[7]. T12 or L1 are usually taken as the apical

vertebra for spinal osteotomy^[8]. Because canalis vertebralis at the T12 and L1 contains the spinal cord, nerve roots and medullary cone, spinal osteotomy at the T12 or L1 vertebra is more dangerous than at lower levels^[9]. As a result, T12 or L1 osteotomy is more likely to damage L1 nerve roots, especially in severely rotated vertebra on the convex side, where the L1 nerve roots could penetrate through the surface of vertebra, unlike T12 nerve roots, which causes symptoms such as back pain, muscle weakness and leg numbness, which will in turn influence daily activities^[10]. Therefore, it is necessary to reduce the risk of various complications, so as to effectively protect the L1 nerve roots.

Our research group used Mimics medical three-dimensional reconstruction software to reconstruct three-dimensional digital models of various vertebral bodies, and provide optimal osteotomy and fixed segments for the operation. We utilized parallel endplate osteotomy (PEO) to treat severe rigid thoracolumbar spinal deformity and got better clinical results. The PEO technique is preferable to one-stage osteotomy instead of traction before surgery. In particular, we pay special attention to identification, separation, reducing tension and protection of L1 nerve roots during surgery.

Methods

Patients

From July 2016 to June 2017, 10 patients with severe rigid thoracolumbar spine deformity, who underwent PEO at T12 or L1, were studied. Deformity necessarily was assessed both clinically and radiographically as part of the preoperative planning. Diagnosis of thoracolumbar spine deformity was made by human grid analysis, X-rays after bending or traction, three-dimensional CT and three-dimensional printing models. Patient complaints included: serious waist deformity, lower back pain and increased after activity, lower limb weakness and leg numbness. All patients underwent a one-stage osteotomy instead of preoperative traction.

Assessment of deformity

Using standard Cobb's method on standing lateral radiograph of the whole spine, the global thoracolumbar kyphosis or scoliosis was measured from the upper endplate of T1 to the lower endplate of L5. Severe rigid spinal deformity was defined as having curve angles more than 80°, with flexibility less than 25% by X-rays after bending or traction. Radiographic parameters were evaluated, and clinical records were reviewed. The osteotomy location was usually chosen as the vertebra that contributed most to the deformity, according to the apex of the deformity. Such a measurement not only represents the severity of the overall deformity, but also determines the amount of correction to be achieved by spinal osteotomy.

Operating procedure

The patient was placed prone over the table, which was in a flat position throughout the operation. A simple method to determine the location of the upper and lower end vertebrae was by mobile C-arm X-ray imaging before surgery. The vertebral column, from the upper to the lower end vertebrae, was prepared and draped. A straight vertical midline incision was made over the spinous processes and was extended to upper and lower end vertebrae. If the deformed vertebra had a rotation, the incision should be on the convex side, deviating approximately 1–2 cm from the centerline. The paraspinal muscles were dissected subperiosteally from the spinous processes and laminae, and then retracted laterally. After a careful dissection of the area around the facet joints, a large spinal retractor was applied. By spreading the spinal retractor and detachment of muscles around the facet joints, a wider exposure was obtained. The spinal retractor could reduce soft tissue damage and infection, and avoid long-term traction. An intraoperative radiograph with guide pins was obtained for accurate localization of the deformity and determination of the level and area for the osteotomy. Pedicle screws were then inserted into the segments from upper end vertebra to lower end vertebra using a free-hand technique at all levels planned prior to surgery. The osteotomy location was usually chosen as the vertebra that contributed most to the deformity, according to the apex of the deformity.

Usually the spine was stabilized with a short bent rod in situ adjacent to the resected area to avoid coronal and sagittal plane translation during the reduction maneuver. The first unilateral rod was temporarily fixed on the concavity side bend to maintain spinal stability after PEO. A complete laminectomy and facetectomy was performed to expose the spinal cord. Usually, the spinal cord was located in the concave curve side, sometimes slightly located in the convex curve side. If the spinal cord was located in the convex curve side, we needed to be more careful, because of neurological complications due to high tension of the spinal cord. In some cases the spinal cord was as tight as a cord with the diameter of only one-third of a normal spinal cord. Any slight maneuver would make the action potentials decline sharply by over 50%, or even disappear. Timely identification and prompt intervention must be performed, including enlarging the resected area to reduce the abrupt turning tendency of the spinal cord.

In our experience, we removed two levels nerve roots of the thoracolumbar spinal cord for the PEO operation, if necessary. These procedures allow circum spinal decompression of the spinal cord. One of the critical pitfalls in this step was the careless mistake of pulling out the preserved spinal nerve roots at the corresponding level. This was quite dangerous for the spinal cord, which is already compressed at the apex of the angular kyphotic deformity, because pulling out the nerve root increases the pressure of the spinal cord at the apex. When the initial PEO was carried out, we did not pay special attention to the L1 nerve roots. Due to the position variation, we made the careless mistake of regarded L1 as T12 nerve roots and damaged L1, which confirmed by the lower limb EMG after surgery. After that, we attempted to use a nerve stripper to separate and release the L1 nerve roots with the protection of somatosensory-evoked potential (SEP) and motor-evoked potential (MEP) monitoring, ultimately leaving the L1 nerve roots slack and floating in the gap.

The type of osteotomy performed was using the PEO technique in which the pedicle of vertebral arch, 2/3 posterior vertebral, bilateral wall of vertebral and back wall of vertebral ((5 mm to endplate)) were carefully removed using an osteotome, curette, rongeur and ultrasonic osteotome (Figure 1). The parallel endplate osteotomy area had two situations: a single vertebral osteotomy, if the angle of the curve was less than 90°, a multiple vertebral osteotomy, if the angle of the curve greater than 90°. If the spinal cord was compressed at the apex of the angular deformity, the lesion compressing the spinal cord was also drilled out using an L-shaped bone separator under direct vision from the lateral direction. A thin stripper was used to confirm whether the soft tissue, such as the posterior longitudinal ligament, attached to the dural sac was soft enough.

The osteotomy was performed carefully to avoid over-penetration of the anterior vertebral body cortex or anterior intervertebral disc, for the purpose of preventing injury to the major vessels in front of the vertebral body. Then we inserted another precontoured correction rod on the convex side to exchange the rods, 30 degrees per correction. It was important in this step to keep an adequate compression force on the concave rod while its adjunct screws on the cephalic side were slightly released until the concave rod and screws were tightened one by one. In situ rod bending on the concave side should never be performed because it is very dangerous procedure to the naked spinal cord, and applying too much torsion to the pedicle screws could easily cause screw loosening and rod bender stick out and injury the spinal cord. After repeated compression, shuttled segmental transient rod, at finally we placed the terminal fixation rods after the main correction was achieved. Then segmental derotation, compression, and distraction on the secondary curves were performed to achieve the final correction. During the entire correction procedure, the dural sac was closely observed to avoid migration in any direction, and tension of the spinal cord was assessed by observation and frequent palpation. Adequate and quick adjustments were needed to ensure that the spinal cord tension does not exceed the initial state under distraction, and to prevent excessive kinking of the dural sac after spinal shortening. Kawahara et al. confirmed that the spine shortened within one-third of the height of the vertebrae would not lead to a functional change of the spinal cord^[11]. During the osteotomy, we had a maximum spinal shortening of 5 centimeters, there were never monitoring warning by SEP and MEP. After completion of the resection and deformity correction, any residual gap could be filled with resected vertebral body bone chips. Finally, We checked the spinal cord is thoughtfully smooth. We gave the patients an autologous blood transfusion that was recycled, or allogeneic blood if the amount of bleeding was high.

Intraoperative monitoring technique and postoperative follow-up

We monitored the somatosensory-evoked potential (SEP) and motor-evoked potential (MEP) to effectively monitor spinal cord and nerve roots, under the supervision of an experienced neurophysiologic physician throughout the PEO procedure, and an additional wake-up test was performed after finishing the correction step at the end of the surgery to ensure the neurological status. Intraoperative and postoperative complications were recorded. For patients with L1 nerve roots injure, continuous

electromyography (EMG) monitoring is necessary. In an attempt to validate these patients' clinical outcome, 10 patients were also responded to the SF-36 quality of life questionnaire via telephone interview after a year of follow-up. Statistical analysis for the SF-36 scores was performed using STATA software.

Results

In total, 10 severe rigid thoracolumbar spine deformity patients received a PEO. The three-dimensional model provided accurate diagnostic and better surgical options. The kyphosis and scoliosis correction rates reached averages of $77.1 \pm 8.9\%$ and $76.9 \pm 7.1\%$, intraoperative bleeding 1990 ± 1010 ml and operation time 7.12 ± 3.88 h. Osteotomies were all performed at T12 or L1. Three patients had typical symptoms of L1 nerve root injury. Specifically, knee extension and hip flexion of lower limb exhibited weakness, and the inner thigh felt numb (Table 1). Table 2 shows the results for these patients' SF-36 scores according to preoperative and one-year postoperative. One year after surgery, the SF-36 scores of physical function, role-physical, bodily pain, general health, vitality, social function, role-emotional and mental health from 60 ± 30 , 47 ± 33 , 44 ± 30 , 32 ± 18 , 50 ± 30 , 46 ± 29 , 26 ± 40 and 52 ± 20 to 81 ± 16 , 69 ± 19 , 73 ± 11 , 66 ± 21 , 74 ± 16 , 74 ± 24 , 63 ± 37 and 76 ± 12 , RESPECTIVELY ($P < 0.01$). The quality of life has improved significantly in patients with PEO one year later.

However, although the clinical effect of the PEO technique was obvious, the complications were unavoidable. Three patients with L1 nerve roots injure occurred, with abnormal SEP and MEP waveforms during the operation and confirmed by the lower limb EMG after surgery. The symptoms of L1 nerve roots injure were significantly improved through therapy of mannitol, methylprednisolone and nutritional neurotherapy. And we could see that the L1 nerve roots function was obviously improved by the continuous monitoring of both lower limb EMG. Meanwhile, 1 case of hemopneumothorax, repair was effective without any leakage, and a closed thoracic drainage tube was placed post operation. One patient experienced paralytic ileus who have been healed after gastric decompression, promote intestinal motility and symptomatic medical treatment. Through one year follow-up of the patients, we did not find any other complications, such as dura laceration, superficial infection, nonunion/rod broken, distal screw loosening and adjacent segment kyphosis (Table 3).

Case 1

Female, 33y, housewife, with waist deformity for 18 years, increased over the last year. The spine deformity was serious. In the flexion test, the left side of the waist was raised 10 cm, muscle strength of both lower limbs was grade V grade, and the patient was feeling normal. The preoperative diagnosis was severe rigid thoracolumbar deformity, kyphosis Cobb 85° and scoliosis Cobb 67° was determined by X-rays after bending (Figure 2A). Osteotomy was performed at T11 and T12, and the upper and lower end vertebrae were T8 and L4 (Figure 2B). Due to position variation, we carelessly mistakenly identified L1 as the T12 nerve root, and damaged the L1 nerve root on the convex side of the side bend with abnormal

waveforms by SEP and MEP during the operation (Figure 2D). Despite postoperative kyphosis and scoliosis correction to Cobb 12° and 15° (Figure 2C), knee extension and hip flexion of left lower limb were weak grade II, and the inner thigh was feeling numb. We reconfirmed L1 nerve root damage by the lower limb EMG after surgery. After a period therapy of mannitol, methylprednisolone and nutritional neurotherapy, muscle strength of left lower limb had recovered to grade IV, and the symptom of numbness had been relieved before leaving the hospital. One year follow-up after surgery, the patient still had symptom of left lower limb weakness, which had an impact on daily life.

Case 2

Male, 21y, delivery man, with waist deformity for 10 years, increased over 4 year. In the flexion test, the left side of the waist was raised 8 cm, muscle strength of both lower limbs was grade V grade with no numbness. The preoperative diagnosis was severe rigid thoracolumbar deformity, kyphosis Cobb 90° and scoliosis Cobb 130° was determined by X-rays after bending (Figure 2A). Osteotomy was performed at T12 and L1, and the upper and lower end vertebrae were T5 and L5 (Figure 2B). Due to high tension, we carelessly mistakenly damaged the L1 nerve root on the convex side with abnormal waveforms by SEP and MEP during the operation (Figure 2D). Despite postoperative kyphosis and scoliosis correction to Cobb 25° and 40° (Figure 2C), knee extension and hip flexion of left lower limb were grade II, and the inner thigh was feeling numb. After surgery, the L1 nerve root damage was confirmed again by the EMG. After a period therapy, muscle strength of left lower limb had recovered to grade IV, and significant improvement in numbness before leaving the hospital. However, after one year of follow-up, the patient could not go up the stairs smoothly, which had an impact on his work.

Case 3

Male, 22y, had waist deformity for 8 years, increased over the two years. In the flexion test, the left side of the waist was raised 14 cm, muscle strength of both lower limbs was grade V, but feeling was normal, indicating the spine deformity was serious (Figure 3A). Preoperative diagnosis was severe rigid thoracolumbar kyphosis, with a kyphosis Cobb 102° and scoliosis Cobb 118°, as judged by X-rays after bending (Figure 3B, 3C and 3D). Osteotomy was performed at L1 and L2, and the upper and lower end vertebrae were T8 and S1. During the operation, we observed that the L1 nerve roots on the convex side of the scoliosis were pulling tension and easy damaged (Figure 3E). We tried to use nerve strippers to separate and protect the L1 nerve root while maintaining normal waveforms by SEP and MEP during the operation (Figure 3F). The L1 nerve roots were slack and floating in the gap (Figure 3E). The postoperative patient's kyphosis and scoliosis were corrected to Cobb 32° and 35°, respectively (Figure 3G). Postoperative, patient had no referable symptoms of nerve roots damage.

Discussion

Surgical intervention is the only effective method for the correction of severe rigid thoracolumbar spine deformity, and can restore the sagittal balance of the spine and the horizontal gaze, improve respiratory function, relieve pain and enhance quality of life. Current surgical methods include pedicular subtraction osteotomy (PSO) and vertebral column resection (VCR). The PSO is described as a vertebral wedge osteotomy for the correction of spine deformity. It has the advantage of obtaining a correction through three columns, from the posterior approach, without lengthening the anterior column, thereby maximizing the healing potential while avoiding stretching the major vessels and viscera anterior to the spine^[12]. However, its disadvantage is the large amount of blood loss and complications of rod breakage and pseudarthrosis^[13]. The VCR technique can achieve a 360° osteotomy of the entire spine and have better results^[14]. However, the operation is difficult because the spinal cord is at a high risk throughout the procedure, intraoperative blood loss is generally around 3000–5000 ml, and the operation time is average 9.3 h, thereby exposing the patient to serious complications of infection and nerve root injury^[15].

In addition, Valone et al. observed that lumbar nerve root weakness or injury can be variously attributed to operative manipulation or decompression and occurs in up to 30% of spinal deformity cases^[16]. Compressive injury may also occur during manipulation of the spinal column, especially after a 3-column osteotomy, whereby osseous or ligamentous structures come to rest on the nerve roots in proximity to the osteotomy^[17]. Over-pulling nerve roots often causes degeneration, leading to lower limb weakness and numbness. Moreover, nerve root tension often leads to position variation. As a result, the slim nerve root is often located, on the lateral side of the scoliosis vertebrae, where it is easily damaged. Sometimes L1 nerve roots are more likely to appear in the position of T12. In our experience, retention of the T12 nerve root is not required, due to its relatively low influence on lower limb function. However, we once carelessly mistook L1 to be the T12 nerve root and damaged it. After osteotomy, the L1 nerve roots are easily pinched in the osteotomy space. In general, for the T12 or L1 osteotomy, predicting and preventing L1 nerve root injury are paramount in improving postoperative health-related quality of life and function.

Therefore, we reconstruct a three-dimensional digital model of all vertebral bodies. Simulating the spinal cord change of severe rigid spinal deformity after osteotomy correction. It can provide more reasonable solutions for ideal correction degrees, thoracic reshaping, estimation of the spinal cord, post-somatic correction and nerve root safety. Severe rigid spinal deformity still follows the traditional method of preoperative traction. Traction as a form of spinal orthopedics has been widely used, plays an important auxiliary role in preoperative correction and second-stage osteotomy^[18]. While, traditional traction can cause additional pain to the patient and is more prone to serious complications, such as cranial nerve injury, cervical spondylosis, loose and infection^[19]. Our team used PEO technology for one-stage osteotomy, which don't need traction before surgery, dramatically reducing patient suffering, treatment costs and various complications.

With PEO using the anterior 1/3 of the vertebral body as a mechanical orthopedic hinge, the osteotomy is performed directly on the vertebral body (5 mm to endplate), which is simple and easy, bleeding is significantly reduced, avoids cumbersome operations and highly dangerous osteotomy. And this

osteotomy mark is easy to identify which have large operating space, especially suitable for pedicle deformity or agenesis. In some cases, the L1 nerve roots are pulled tight, causing position variation, and can adhere to surrounding tissues. L1 nerve root injury often causes lower limb weakness and numbness. As a result, we used a nerve stripper to separate, release and protect L1 nerve roots, while monitoring it by the SEP and MEP, in order to reduce the risk of nerve root damage. The osteotomy angle can reach 110°–140°, basically satisfying any angle requirements for correction of spinal deformity. The correction rate can reach 70%–86%, better than the traditional correction rate of 55%–60%^[20]. Since the PEO osteotomy does not require treatment of the vertebral blood vessels, there is less bleeding than VCR osteotomy. During the osteotomy, we had a maximum spinal shortening of 5 centimeters, but we did not worry about the excessive ruga of the dural sac. Because there were never monitoring warning by SEP and MEP. After osteotomy, the bone-bone fusion postoperative fusion rate is significantly improved with intervertebral bone graft. Short-term complications after surgery, such as L1 nerve roots injure, paralytic ileus and hemothorax were all improved or cured through treatment. One year follow-up after surgery, it is obvious from the SF-36 scores that all patients have got better clinical results and with no other complications. In addition, we are aware of the importance of protecting L1 nerve roots.

Conclusions

We utilization parallel endplate osteotomy (PEO) technological, performed directly on the vertebral body (5 mm to endplate), 1/3 of the vertebral body as a mechanical orthopedic hinge. And this osteotomy mark is easy to identify which have large operating space, especially suitable for pedicle deformity or agenesis, with the bone-bone fusion, which is simple, results in less bleeding, spinal cord and nerve root under direct vision and can effectively and safely correct severe rigid thoracolumbar spine deformity with better clinical results. Nerve roots injury is a commonly disastrous problem in osteotomy. As a result, due to the position variation, the T12 or L1 osteotomy is more likely to damage the L1 nerve roots which is not easy to identify, especially in the severely rotated vertebra on the convex side, usually approach through the surface of vertebra, unlike T12 nerve roots, which causes symptoms such as back pain, muscle weakness and leg numbness, which will in turn influence daily activities. Therefore, it is necessary to reduce the risk of various complications, so as to effectively protect L1 nerve roots, which has been demonstrated by a year of follow-up after surgery.

Abbreviations

Parallel endplate osteotomy (PEO), somatosensory-evoked potential (SEP), motor-evoked potential (MEP), electromyography (EMG), pedicular subtraction osteotomy (PSO) and vertebral column resection (VCR).

Declarations

Ethics approval and consent to participate

The study protocol has been approved by the Clinical Research Ethics Committee of the Shenzhen University on May 10th, 2016 and has been registered. All patients signed an informed consent form.

Consent to

publish

Consent was provided for images of the patients and techniques, clinical details and identifying information such as age, profession and gender to be included and published.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interests.

Funding

The study was supported by Science and Technology Research and Development Foundation of Shenzhen (JCYJ20160429172357751). SXD as the funder participated in drafting the manuscript, in designing the protocol and provides the original idea of the work.

Authors' contributions

HL and SXD participated in drafting the manuscript, in designing the protocol and provides the original idea of the work. HGM, participated in drafting the manuscript and in designing the protocol. PX and YYW participated in revising the manuscript critically and in designing statistical analysis. XDL and W participated in revising the manuscript critically with reference to the methods to evaluate variables. NDL and ZZZ, participated in revising the manuscript critically with reference to the treatment technics to be studied. All authors have read and approved the final manuscript and agreed to be accountable for all aspects of the work.

Acknowledgements

Not applicable.

Authors' Information

From the Department of Orthopedics, The 3rd Affiliated Hospital of Shenzhen University, Shenzhen, China.

*Address correspondence and reprint requests to Shixin Du, MD, PhD or Xuedong Li, MD, PhD, Department of Orthopedics, The 3rd Affiliated Hospital of Shenzhen University, Shenzhen 518000, PR China; Email: DSX333126@126.com or xdl622@sina.com

References

1. Hamzaoglu A, Alanay A, Ozturk C, Sarier M, Karadereler S, Ganiyusufoglu K (2011) Posterior vertebral column resection in severe spinal deformities: a total of 102 cases. *Spine* 36(5):E340–4.
2. Ji ML, Qian BP, Qiu Y, Wang B, Zhu ZZ, Yu Y (2013) Change of aortic length after closing-opening wedge osteotomy for patients with ankylosing spondylitis with thoracolumbar kyphosis: a computed tomographic study. *Spine* 38(22):1361–7.
3. Zeng Y, Chen Z, Qiang QI, Guo Z, Weishi LI, Sun C (2012) Clinical and radiographic evaluation of posterior surgical correction for the treatment of moderate to severe post-tuberculosis kyphosis in 36 cases with a minimum 2-year follow-up. *J Neurosurg Spine* 16(4):351–8.
4. Cahill PJ, Wang W, Asghar J, Booker R, Betz RR, Ramsey C (2012) The use of a transition rod may prevent proximal junctional kyphosis in the thoracic spine after scoliosis surgery: a finite element analysis. *Spine* 37(12):687–95.
5. Bridwell KH (2006) Decision making regarding Smith-Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. *Spine* 31(Suppl 1):171–8.
6. Zeng Y, Qu X, Chen Z, Yang X, Guo Z, Qi Q (2016) Posterior corrective surgery for moderate to severe focal kyphosis in the thoracolumbar spine: 57 cases with minimum 3 years follow-up. *Eur Spine J* 26:1–9.
7. Coe JD, Arlet V, Donaldson W, Berven S, Hanson DS, Mudiyaam R (2006) Complications in spinal fusion for adolescent idiopathic scoliosis in the new millennium. A report of the Scoliosis Research Society Morbidity and Mortality Committee. *Spine* 31(3):345–9.
8. Xu H, Zhang Y, Zhao Y, Zhang X, Xiao S, Wang Y (2015) Radiological and clinical outcomes comparison between single and two level pedicle subtraction osteotomies in correcting ankylosing spondylitis kyphosis. *Spine* 15(2):290–7.
9. Zheng GQ, Zhang YG, Wang Y, Huang P, Cui G (2014) Two-level spinal osteotomy for severe thoracolumbar kyphosis in ankylosing spondylitis. Experience with 48 patients. *Spine* 39(13):1055–8.
10. Wu W, Liang J, Ru N (2016) Microstructural changes in compressed nerve roots are consistent with clinical symptoms and symptom duration in patients with lumbar disc herniation. *Spine* 41(11):E661–6.

11. Kawahara N, Tomita K, Kobayashi T, Abdel-Wanis ME, Murakami H, Akamaru T (2005) Influence of acute shortening on the spinal cord: an experimental study. *Spine* 30(5): S91–2.
12. Park JH, Hyun SJ, Kim KJ, Jahng TA (2017) Comparative study between pedicle subtraction osteotomy (PSO) and closing-opening wedge osteotomy (fish-mouth PSO) for sagittal plane deformity correction. *Spine* 42:E899–905.
13. Hu X, Thapa AJ, Cai Z, Wang P, Shen H (2016) Comparison of smith-petersen osteotomy, pedicular subtraction osteotomy and poly-segmental wedge osteotomy in treating rigid thoracolumbar kyphotic deformity in ankylosing spondylitis a systematic review and meta-analysis. *BMC Surg* 16(1):1–10.
14. Kadoury S, Labelle H (2012) Classification of three-dimensional thoracic deformities in adolescent idiopathic scoliosis from a multivariate analysis. *Eur Spine J* 21(1):40–9.
15. Yang C, Zheng Z, Liu H, Jian W, Yong J, Kim C (2016) Posterior vertebral column resection in spinal deformity: a systematic review. *Eur Spine J* 25(8):2368–75.
16. Rd VF, Lyon R, Lieberman J, Burch, S (2014) Efficacy of transcranial motor evoked potentials, mechanically elicited electromyography and evoked electromyography to assess nerve root function during sustained compression in a porcine model. *Spine* 39(17):989–93.
17. Wang MY, Berven SH (2007) Lumbar pedicle subtraction osteotomy. *Neurosurgery* 60(2):171–6.
18. Sink EL, Karol LA, Sanders J, Birch JG, Johnston CE, Herring JA (2001) Efficacy of perioperative halo-gravity traction in the treatment of severe scoliosis in children. *J Pediatr Orthop* 21(4):519–24.
19. Rinella A, Lenke L, Whitaker C, Kim Y, Park SS, Peelle, M (2005) Perioperative halo-gravity traction in the treatment of severe scoliosis and kyphosis. *Spine* 30(4):475–82.
20. Cui G, Wang Y, Kao TH, Zhang Y, Liu Z, Liu B (2012) Application of intraoperative computed tomography with or without navigation system in surgical correction of spinal deformity: a preliminary result of 59 consecutive human cases. *Spine* 37(10):891–900.

Figures

Figure 1

(A, B, C, D, E and F) The three-dimensional demonstration of PEO operation. (G) Osteotomy range includes pedicle of vertebral arch, 2/3 posterior vertebral, bilateral wall of vertebral and back wall of vertebral.

Figure 2

Case 1, female, 33y, severe rigid thoracolumbar deformity. (A) Preoperative diagnosis was kyphosis cobb 85° and scoliosis cobb 67° by X-rays after bending and three-dimensional CT imaging. (B) Intraoperative osteotomy, pedicle screws fixed and correction, yellow arrow represents the injury L1 nerve root on the convex side of the scoliosis. (C) Postoperative kyphosis and scoliosis cobb was corrected to 12° and 15°.

which show in X-rays and three-dimensional CT Imaging. (D) Abnormal waveforms occurred in SEP and MEP of left lower limb during surgery, red arrow represents abnormal signal.

Figure 3

Case 2, male, 21y, severe rigid thoracolumbar deformity. (A) Preoperative diagnosis was kyphosis cobb 90° and scoliosis cobb 130° by X-rays after bending and three-dimensional CT imaging. (B) Intraoperative osteotomy, pedicle screws fixed and correction, yellow arrow represents the injury L1 nerve root on the

convex side. (C) Postoperative kyphosis and scoliosis cobb was corrected to 25° and 40°, which show in X-rays Imaging. (D) Abnormal waveforms occurred in SEP and MEP of left lower limb during surgery, red arrow represents abnormal signal.

Figure 4

Case 3, male, 22y, severe rigid thoracolumbar deformity. (A, B, C and D) Preoperative diagnosis was kyphosis cobb 102° and scoliosis cobb 118° by profile, X-rays after bending, three-dimensional CT and printing model imaging. (E) Intraoperative osteotomy, pedicle screws fixed and correction, yellow arrow represents the intact and slack L1 nerve root. (F) Normal waveforms occurred in SEP and MEP during surgery. (G) Postoperative kyphosis and scoliosis cobb was corrected to 32° and 35°, which show in X-rays and three-dimensional CT Imaging.