

Original Article

Evaluation of the influence of pedicle-lengthening osteotomy on lumbar stability

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Abstract: Pedicle-lengthening osteotomy (PLO) is a minimally invasive and effective surgical procedure for lumbar spinal stenosis syndrome. Compared with traditional surgery, PLO can effectively enlarge the spinal canal while minimizing the disruption of posterior anatomical structures of the lumbar vertebra, leading to reduced postoperative perineural scarring adhesion and good clinical outcomes using minimally invasive procedures. However, PLO is still in its early stages, and only a few relevant experimental and clinical studies have been reported. The present study was performed to investigate the influence of PLO on the stability of lumbar vertebrae. The results indicated that PLO can effectively enlarge the spinal canal, and no lumbar spondylolisthesis or other complications occurred in this study. Moreover, this procedure does not significantly affect the stability of the lumbar spine, suggesting a possible clinical application.

Keywords: Pedicle-lengthening osteotomy, lumbar vertebra, lumbar spinal stenosis

Introduction

Lumbar spinal stenosis syndrome (LSS) is the primary or secondary cause of structural abnormalities of the spinal cord, including narrowing of the intervertebral discs. Patients usually present with lower back or leg pain, with intermittent claudication manifesting as a primary clinical feature. LSS seriously affects patients' quality of life, not only causing patients to suffer from disease and affecting their ability to work but also increasing the economic burden on society [1].

Surgery is an effective treatment for LSS, as it can improve lower extremity pain, intermittent claudication, cauda equina syndrome, and patients' quality of life [1, 2]. Currently, distinct from classical surgical treatments, pedicle-lengthening osteotomy (PLO) provides a novel surgical strategy for LSS. Compared with traditional surgery, PLO can effectively enlarge the spinal canal while minimizing the disruption of posterior anatomical structures of the lumbar vertebra, leading to reduced postoperative perineural scarring adhesion and good clinical outcomes using minimally invasive procedures

[3, 4]. Our research team conducted an anatomic study for this surgical approach and found that a 2-mm or greater lengthening of the pedicle can enlarge the spinal canal area and increase the anteroposterior diameter of the neural foramina, with statistically significant results [3]. We also applied anatomic and imaging analyses to determine the correct pedicle osteotomy site [4]. Kiapour [5] et al. conducted relevant biomechanical experiments for the PLO procedure and concluded that applying single or bilateral PLO to lumbar segments can enlarge the spinal canal area and neural foramina, with no significant effect on motion in any direction. Mlyavykh [6] et al. first applied this surgical approach in clinical practice. They analyzed the 12-month follow-up results for 19 patients who received the PLO procedure and found that this surgery is safe and effective and has satisfactory clinical efficacy. Furthermore, bone fusion at the osteotomy site occurred in all patients by 6 months postoperatively, and the average increase in the spinal canal area was 115% of the preoperative size.

Studies have shown that PLO is a minimally invasive and effective surgical procedure for

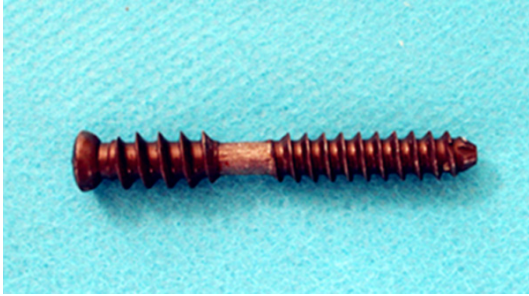


Figure 1. The extensible pedicle screw consists of a threaded screw body with a proximal thread, a smooth section, and a distal thread. The pitch of the proximal end of the thread is larger than that of the distal end, resulting in distraction when it is screwed into the pedicle.

LSS. However, PLO is still in its early stages, and only a few relevant experimental and clinical studies have been reported. When the upper and lower facet joints are in the occluding position, the upper facet joint in particular can prevent the vertebral arch from moving backward. Therefore, in the pedicle-lengthening process, when the posterior structure of the lumbar vertebrae is shifted backward, there must be a force that moves the vertebral body forward. The question is whether such a force would lead to spondylolisthesis (i.e., a slipping forward of the vertebra) and, moreover, whether this force could affect the stability of the lumbar spine. No relevant studies have been performed thus far; however, these issues are important and need to be answered in PLO evaluations.

Materials and methods

General information

The experiment was performed on 10 formalin-fixed adult cadaveric lumbar vertebral specimens including T11 to S2 segments. Of the specimens, 6 were male and 4 were female, with an average age of 56 years and an average weight of 61 kg. X-ray examination was used to exclude bone fractures, tuberculosis, cancer, and abnormalities. Psoas muscle, erector spinae muscle, and other adhesive tissue were excluded; the spine ligament, interspinous ligament, anterior ligament, intervertebral disc tissue, and other ligaments were reserved; and the facet-joint capsules were carefully protected. Specimens were frozen and prepared for experimentation.

The surgical instruments included a pedicle cutter, extensible pedicle screws, matching needles, and a screwdriver. Extensible pedicle screws consist of a threaded screw body with a proximal thread, a smooth section, and a distal thread. The pitch of the proximal end of the thread is larger than that of the distal end, resulting in distraction when it is screwed into the pedicle. The extensible pedicle screw is shown in **Figure 1**.

Methods

The vertebral specimens were thawed for 24 hours, as described by Zhang [4] et al.; a bilateral pedicle transection was performed on the L3, L4, and L5 vertebrae, as shown in **Figure 2**. Extensive pedicle screws were screwed. Then, the pedicle screws were completely screwed into the pedicle passage, leading to maximal expansion of the gap at the osteotomy site and an increase in the area of the spinal canal, as shown in **Figure 3**. The distance lengthened by the pedicle screw was 3 mm, as shown in **Figure 4**. The reconstructed computed tomography (CT) image is displayed in **Figure 5**.

Thin-section CT scanning was performed on vertebral specimens preoperatively and postoperatively. The midline of the L3 vertebrae was considered a reference plane for sagittal reconstruction. Picture Archiving and Communications System (PACS) tools were used for actual measurements. At the pedicle transverse position, the upper, middle, and lower edges of the spinal canal area of L3, L4, and L5 were measured, and the average value was recorded as the cross-sectional area of the canal (CSAC) of each segment. The segmental angle (SA) of each vertebra was measured and recorded as L2/3, L3/4, L4/L5, and L5/S1. We used two methods to measure lumbar lordosis (LL): the lumbar Cobb angle (LCA), which was the angle formed between the upper edge of the L1 vertebrae and the upper edge of the S1 vertebrae, and Harrison's posterior tangent angle (HA), which was the angle formed between the tangent lines at the posterior margins of the L1 and L5 vertebrae. These angles are illustrated in **Figure 6**.

We used the following methods to record the anterior or posterior displacement of the vertebrae. A connection line was drawn between the lower posterior edge of the T12 vertebra and

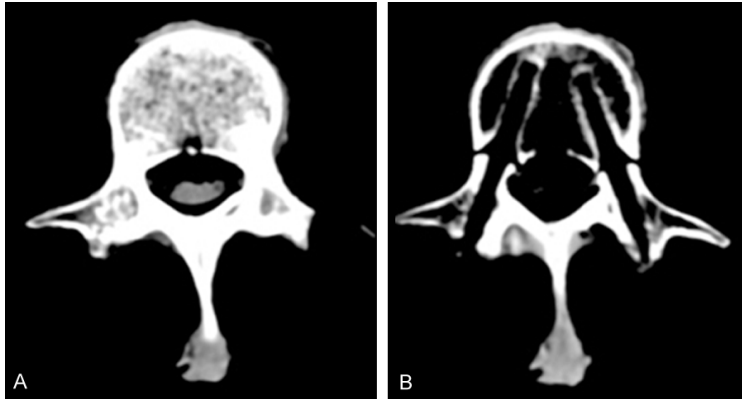


Figure 2. The CT scan shows that a bilateral pedicle transection was performed on the vertebrae.

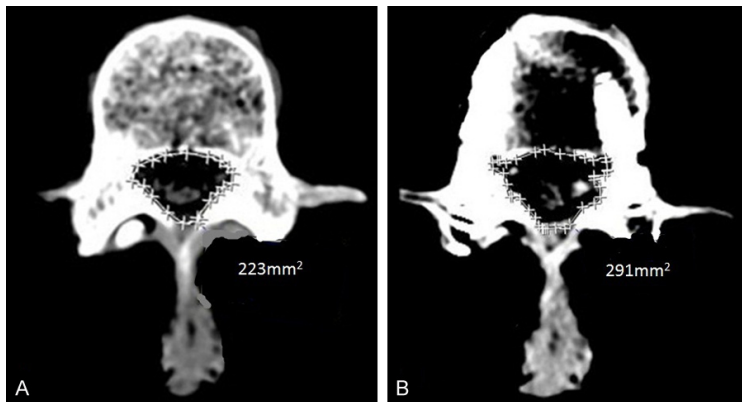


Figure 3. Pedicle-lengthening implants were screwed into the pedicle passages, leading to expansion of the gap at the osteotomy site and an increase in the area of the spinal canal.

the upper posterior edge of the S1 vertebra, and the vertical distances between the upper posterior edges of the L3, L4, and L5 vertebrae and this line (distance to the lumbar curvature line-DLCL) were measured. A change in distance is considered to be caused by the relative displacement of vertebrae, as shown in **Figure 7**. The connection line between the middle of the L3 vertebral body and the spinous process from a reconstructed plane from the sagittal image reconstruction of preoperative and postoperative thin-section CT scans was considered and was used to ensure measurement at the same reference position. Two researchers took every measurement three separate times, and the results were taken from the average value.

Statistical analysis

IBM SPSS 19.0 software was used to perform statistical analyses. A paired t-test was used to

compare preoperative and postoperative data within the same group of specimens. All data are presented as $\bar{x} \pm s$. $P < 0.05$ is considered statistically significant.

Results

The pedicle of each lumbar vertebra lengthened a total of 3 mm. The spinal canal cross-sectional area increases were 16.1% at the L3 segment, 15.9% at the L4 segment, and 13.1% at the L5 segment. The preoperative and postoperative segmental angle values of each vertebra did not differ significantly ($P > 0.05$) (**Table 1**). The postoperative lumbar Cobb angle and Harrison's angle did not differ significantly from the preoperative values ($P > 0.05$) (**Tables 2 and 3**). Compared with the preoperative values, the relative displacements of the L3, L4, and L5 vertebrae after surgery were not statistically different ($P > 0.05$) (**Table 4**).

Discussion

LSS refers to a narrowing of the spinal canal, nerve root canal, and neural foramina. This definition was first proposed by Verbiest et al. in 1949. After being developed over 60 years, the concept is now comprehensively understood.

Surgical strategies for LSS, such as posterior lumbar interbody fusion (PLIF) and other surgical procedures, have gained tremendous popularity. Laminectomy with exposure of the posterior spinal anatomic structures for treating pathogenesis inside the spinal canal is one of the classical methods for creating a surgical passage in the surgical treatment of LSS. However, with increased follow-up periods, the long-term outcomes are unsatisfactory in certain cases. Moreover, considering that surgical procedures can disrupt posterior anatomic structures, vertebral interbody fusion and pedicle screw fixation might affect the normal biomechanical stability of the lumbar vertebrae,

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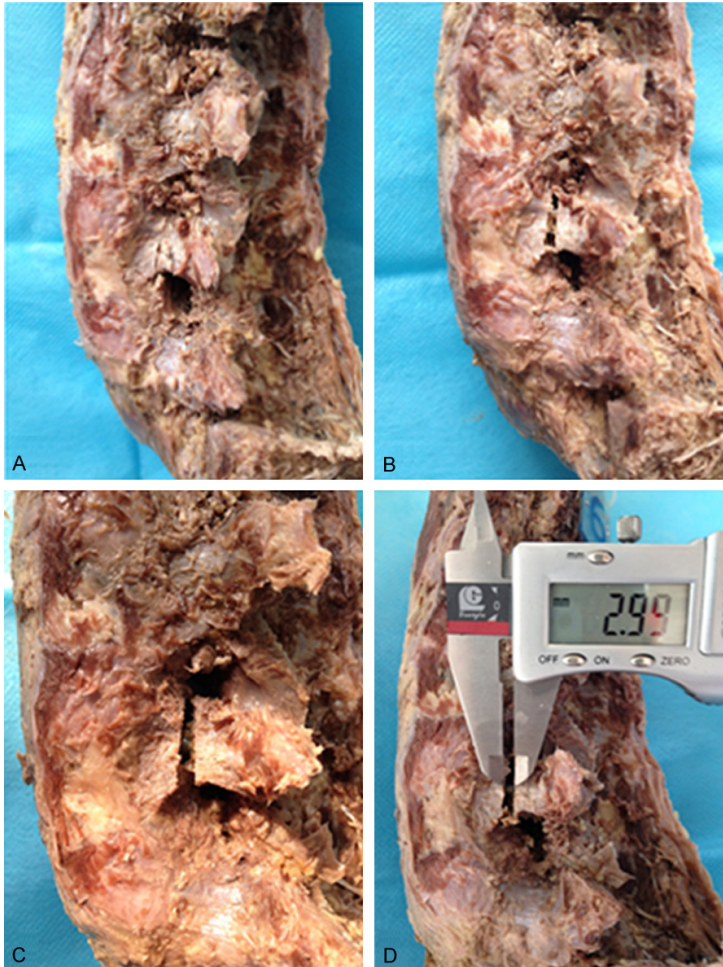


Figure 4. A. After the L4 pedicle was transected, the fiber structure could be observed at the osteotomy site. B. After the screw was implanted in the pedicle passage, the gap at the osteotomy site was expanded, suggesting that a small amount of soft tissue remained connected. C. The pedicle lengthening screw was visible within the gap at the osteotomy site after clearing the soft tissues. D. When the screw was completely inserted into the pedicle passage, the pedicle lengthening reached its maximum, which was measured as 3 mm.

which is an important factor leading to degeneration in adjacent segments and disease recurrence [7, 8]. Therefore, developing a less-invasive surgical approach for LSS treatment has been a critical issue for both basic research and clinical practice.

There are many existing minimally invasive surgical approaches for treating LSS with minimal effects on lumbar stability, such as applying an interspinous distraction system to perform non-fusion fixation. Static devices include X-Stop, Exten Sure, and Wallis, among others. Coflex and DIAM are considered representatives of dynamic devices. Biomechanical stud-

ies have found that non-fusion fixation can reduce the stress on the surgical segment, which is beneficial for reducing degeneration in adjacent segments [9-11]. In addition, decompression laminectomy using a minimally invasive endoscopic procedure has received increasing attention [13].

Mlyavykh [6] et al. first applied PLO in clinical practice. Compared with traditional surgical approaches, PLO can effectively enlarge the spinal canal while minimizing the disruption of posterior anatomical structures of the lumbar vertebra, leading to reduced postoperative perineural scarring adhesions and better clinical outcomes using a minimally invasive approach [6]. Kiapour [5] et al. conducted a relevant biomechanical experiment and 3D finite element analysis for the PLO surgical procedure and found that applying single or bilateral PLO to the lumbar segment could enlarge the spinal canal area and neural foramina with no significant effects on overall or segmental kinematics. Mlyavykh [6] et al. analyzed the 12-month follow-up results for 19 patients who received PLO treatment and found that the spinal canal area was significantly increased after pedicle-lengthening screw fixation at L4 or L5. These results

included reduced nerve compression and a relatively good therapeutic effect. Furthermore, bone fusion of the osteotomy site had occurred in all patients by 6 months postoperatively, indicating permanent enlargement of the spinal canal. This research is relatively encouraging. The practical significance of the PLO surgical approach has been verified by this study.

A pedicle is a bridge connecting a vertebral body and a vertebral arch. Each pedicle passage is surrounded by a hard bony wall, and this anatomic feature is the premise for establishing the surgical passage of the pedicle. By creating this pedicle passage, a pedicle screw can

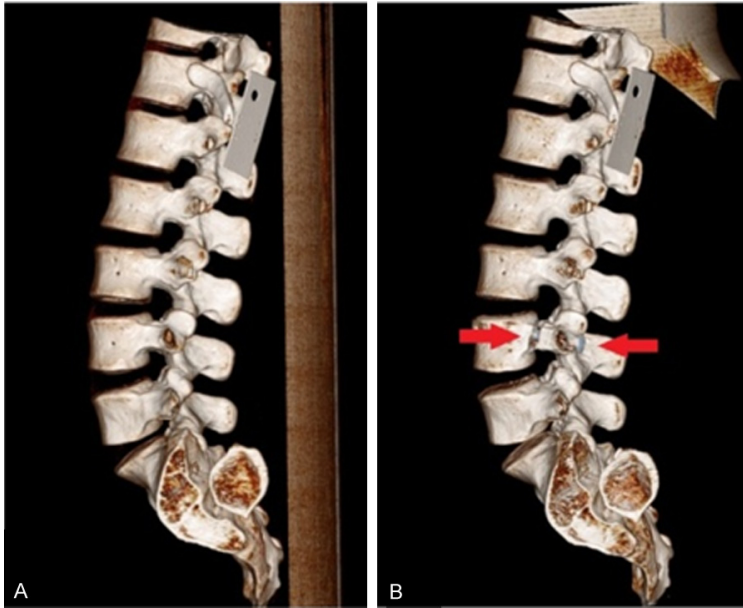


Figure 5. A. Three-dimensional CT reconstruction before the procedure. B. Three-dimensional CT reconstruction after L4 pedicle transection and screw implantation. The front arrow indicates the gap at the osteotomy site. The screw is visible within the pedicle passage. The back arrow indicates the distal end of the screw.



Figure 6. a. Segmental angle (SA): the angle between the inferior and superior endplates of the adjacent segment. b. Lumbar lordosis (LL): the upper edge of the L1 vertebra and the upper edge of the S1 vertebra. c. Harrison's posterior tangent angle (HA): the angle formed by the tangent lines at the posterior margins of the L1 and L5 vertebrae.

be inserted into the passage; a working cannula can also be deployed in the passage for various procedures [4]. Because of the wide application of kyphoplasty surgery, tremendous experience has been accumulated concerning the method of how to accurately place working sleeves via a percutaneous pathway and intraoperative fluoroscopy [12]. This procedure also provides a clinical basis for percutaneous pedicle osteotomy laminoplasty, screw implantations, and other procedures.

However, because a pedicle is only the bony structure of a bridge between the anterior and posterior structures of the vertebral body, the PLO procedure also faces a critical issue: when the posterior structure of the lumbar vertebrae shifts backward, how much forward force can it generate on a vertebral body? Would such a force lead to spondylolisthesis? Could the force affect the stability of the lumbar spine? No relevant study has been reported thus far.

Lumbar instability is a major cause of chronic low back pain, sciatica, and failed back surgery syndrome (FBSS) [13]. Lumbar instability is defined by the American Academy of Orthopedic Surgeons (AAOS) as when, under a normal physiological load, the lumbar vertebrae cannot maintain a normal congruent alignment, which presents as back pain, nerve dysfunction, and a series of clinical symptoms [14]. Lumbar instability is one of the primary causes of FBSS, not only causing clinical symptoms but also leading to the degeneration of intervertebral discs and adjacent segments, low fusion of



Figure 7. The distance to the lumbar curvature line (DLCL): the vertical distance between the upper posterior edge of the L3, L4, and L5 vertebrae and the line drawn between the lower posterior edge of T12 and the upper posterior edge of S1.

Table 1. Preoperative and postoperative segmental angle values of the L2/3, L3/L4, L4/L5, and L5/S1 vertebrae

		Preoperative value (degree)	Postoperative value (degree)	t	P
L3	L2/3	7.1±2.1	6.8±1.8	0.2	0.42
	L3/4	5.7±1.9	5.7±1.6	0.04	0.49
	L4/5	7.9±2.1	7.9±2.2	0.03	0.49
	L5/S1	10.5±2.3	10.6±2.1	0.07	0.47
L4	L2/3	7.1±2.0	6.3±1.6	0.68	0.26
	L3/4	5.7±1.9	5.6±1.6	0.15	0.44
	L4/5	7.9±2.1	7.5±1.8	0.34	0.37
	L5/S1	10.5±2.3	10.1±2.8	0.3	0.39
L5	L2/3	7.1±2.0	6.4±1.5	0.6	0.28
	L3/4	5.7±1.9	5.5±1.6	0.18	0.43
	L4/5	7.9±2.1	8.3±2.2	0.25	0.41
	L5/S1	10.5±2.3	10.7±2.2	0.11	0.46

intervertebral bodies, and loss and/or breakage of implanted fixations. Therefore, whether lumbar instability is caused is a critical factor affecting the success of lumbar surgery. For

lumbar spinal fusion surgery, e.g., a PLIF procedure, if spondylodesis is successfully performed, it can stabilize the anterior column of the vertebrae, reducing the risk of postoperative intervertebral instability and implantation failure. However, the possibility of anterior column instability is significantly increased in non-fusion surgery. After conducting animal studies, Raynor [15] et al. suggested that in a single motion segment of the spine, greater than 50% of bilateral facetectomies would lead to instability. Thus, they considered that decompression laminectomy with a greater than 50% facetectomy of small facet joints would cause iatrogenic instability. Therefore, it is even more critical to evaluate the postoperative lumbar vertebral stability for non-fusion surgery.

Lumbar instability can be divided into clinical and radiographic instability. Because the clinical

manifestations of lumbar instability include a lack of specificity, it is essential to radiographically diagnose lumbar instability. Frymoyer [16] et al. performed a lateral X-ray on patients with lumbar extreme flexion and hyperextension with the diagnostic criterion of an adjacent intervertebral angle of over 15° or more than 3 mm of displacement. If necessary, pressurized supine position with lateral flexion radiographs were taken to observe whether intervertebral joints were loose and to measure the degree of looseness. These standards can be used as diagnostic criteria and as one of the markers of therapeutic effect. Iguchi [13] et al. measured the angle and displacement in the anterior-posterior axis between intervertebral L4/5 using X-rays of anterior flexion and posterior extension positions in 1090 patients with low back/leg pain. They found that the Japanese Orthopedic Association (JOA) scores were significantly lower in patients with more than 3 mm of displacement than in those with less than 3 mm of displacement. There were no significant differences in the scores between patients with vertebral angles ≥10° and <10°.

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Table 2. Cobb angles before and after surgery

	Preoperative value (degree)	Postoperative value (degree)	t	P
L3	43.8±6.4	44.5±5.8	2.31	0.08
L4		44.3±7.2	0.98	0.38
L5		43.4±6.9	1.55	0.19

Table 3. Harrison's posterior tangent angles before and after surgery

	Preoperative value (degree)	Postoperative value (degree)	t	P
L3	31.4±5.1	30.8±4.4	1.19	0.17
L4		31.3±6.1	2.04	0.09
L5		31.0±5.8	2.63	0.27

Table 4. Relative displacement of each vertebra before and after surgery

	Preoperative value (mm)	Postoperative value (mm)	t	P
L3	14.10±4.87	14.46±4.83	0.12	0.45
L4	12.00±2.35	12.56±2.39	0.37	0.36
L5	4.98±1.92	5.06±1.26	0.08	0.47

The patients with displacements ≥ 3 mm and angles $\geq 10^\circ$ had the lowest scores, with significantly higher incidence rates of low back/leg pain and higher numbers of clinic visits than the other groups.

Our measurements showed that after L3, L4, and L5 pedicle-lengthening laminoplasty, no statistically significant changes were observed in the angle between each vertebral body after surgery. Additionally, no statistically significant changes were observed in the Cobb and Harrison angles after surgery. When the vertebral displacements were compared before and after surgery, the difference was not statistically significant. Why did the pedicle-lengthening laminoplasty not cause the vertebrae to slip forward? We believe that the lumbar ligaments and muscle tissue play important roles. Furthermore, the role of the ligament tissue in maintaining the stability of the lumbar spine is even more important because the lumbar spine has a complicated ligament organization. The upper and lower facet joints are in an occlusal state. During the implementation of the pedicle-lengthening laminoplasty, the resistance from the anterior and posterior ligaments and

the resistance from the adjacent thick vertebrae facet joint capsule must be overcome to appropriately extend the ligaments and to lightly move the facet joints, ultimately achieving the goal of pedicle lengthening. In this process, the ligament tissue in front of the pedicle breaking space, i.e., the lumbar longitudinal ligament, posterior longitudinal ligament, and fiber intervertebral disc, become stronger, resulting in a smaller range of lengthening and deformation, which plays an important stabilizing role in the vertebral body. In comparison, although the posterior ligamentous complex (PLC), including the supraspinous ligament, the interspinous ligament, the ligamentum flavum, and the capsules of the facet joint, are all important structures for maintaining the stability of the lumbar spine, they have greater extensibility and greater ranges of lengthening [17]. Similarly, in a cadaveric study of lumbar spines, the forward displacement instability of the sagittal plane can only occur when the posterior longitudinal ligament is completely torn from the fiber disk attached to the posterior edge of the intervertebral disk and spinal nucleus [18]. In addition, during the process of bone screw placement, the force of the anterior-to-posterior expansion cannot be greater than the force of bone screw insertion into the bone tissue. Otherwise, the screws will become loose in the bone channel, and the goal of lengthening cannot be achieved. In this study, we found that when the tail section of the bone screw was inserted into the bone tissue, the lengthening effect began to occur. After the screw implant was completely inserted, the lengthening distance was 3 mm, indicating that the screw threads in the pedicle channel did not become loose. In summary, we believe that pedicle-lengthening laminoplasty can prevent vertebrae from slipping forward and can also reduce the possibility of lumbar spine instability to a minimum in the short term.

Conclusion

This study performed measurements on reconstructed sagittal CT images. The results showed no significant changes in the segmental angle and lumbar lordosis after the PLO procedure and no significant changes in relative segmental displacement, suggesting that pedicle-lengthening laminoplasty has relatively few effects on lumbar stability. This minimally invasive surgical approach has certain prospective

clinical applications for the treatment of LSS. However, the current investigation also presented several limitations. First, because formalin-fixed human cadaveric vertebral specimens were selected for use in this study, the tissue toughness was different from that of fresh or living specimens. Second, the specimen number in this study was small. When a screw was implanted into each segment, the other two segments were fixed with screws, aiming to most closely simulate a state in which the pedicle had not been transected. Third, because the lumbar vertebrae can present different mechanical distributions under different postures, flexion, extension, rotation, and other complicated motions would be accompanied by complicated biomechanical changes. Therefore, further experimental studies are still necessary to solve certain problems, such as biomechanical measurements under pressure loading in different directions and the fixation strength of screws after repeated motion.

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Disclosure of conflict of interest

None.

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