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EXPERIMENTAL SUBSTANTIATION OF TECHNICAL VARIANTS OF PEDICLE-LENGTHENING OSTEOTOMY FOR DECOMPRESSION OF THE DURAL SAC AND NERVE ROOTS IN THE LUMBAR SPINE

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Objective. To determine experimentally the mechanical conditions required for decompression of the dural sac and spinal nerve roots during pedicle-lengthening osteotomy (PLO) with elongation of pedicles at the lumbar level.
Material and Methods. The experiments were conducted on three cadaver specimens of L1–L5 vertebral motor segments obtained at the forensic section from individuals aged 45–60 within two days after death in compliance with the standards for preparing human tissue for biomechanical studies. The contents of the vertebral and root canals were removed from the specimens of the lumbar spine, leaving all elements of the osteoligamentary support complex intact. Three experiments were conducted on each specimen. In the first experiment, bilateral pedicle lengthening osteotomy imitating PLO was performed on the L4 vertebra of the anatomical specimen. In the second experiment, osteotomies of the inferior articular processes of L3 at the level of their base were performed on the same specimen in order to mobilize the posterior support complex. In the third experiment, bilateral pedicle osteotomy was additionally performed on the L3 vertebra. The described experiments were repeated three times on three anatomical specimens. The obtained data were recorded in protocols, and then statistical processing was performed using descriptive statistics methods. The sets of study results measured on a quantitative scale for normality were checked using the Kolmogorov–Smirnov Z-criterion. To prove the statistical significance (or lack thereof) of the values of the compared parameters, the Mann–Whitney U-test was used. Results were considered significant if the level of statistical significance p was less than or equal to 0.05.
Results. The increase in the sagittal spinal canal size after PLO due to the elongation of the L4 pedicles by 4 mm is achieved with a traction force of 97 N, by 5 mm – with 162 N, by 6 mm – with 240 N, and by 7 mm – with 306 N. Mobilizing osteotomy of the inferior articular processes of the L3 reduces the traction forces necessary for decompression to 30 N, 73 N, 125.5 N, and 182 N, respectively, which is 1.7–3.2 times less than the PLO values without mobilization. Additional bilateral pedicle osteotomy on the overlying L3 vertebra does not provide further decrease in the traction forces necessary to increase the sagittal size of the spinal canal.
Conclusion. The technique of decompression of the dural sac and nerve roots in the lumbar spine by means of pedicle-lengthening osteotomy with elongation of pedicles is a promising option for surgical treatment of lumbar spinal stenosis. The data obtained in this study may be of interest, especially with the possible development of another technical solution and instrumentation for implementing PLO.
Key Words: lumbar stenosis; decompression; pedicle lengthening osteotomy; experiment; cadaver specimen.
Please cite this paper as: *Afaunov AA, Basankin IV, Bagaudinov AB, Mlyavykh SG, Gulzatyan AA, Bogdanov SB. Experimental substantiation of technical variants of pedicle-lengthening osteotomy for decompression of the dural sac and nerve roots in the lumbar spine. Russian Journal of Spine Surgery (Khirurgiya Pozvonochnika). 2025;22(2):45–54. In Russian. DOI: http://dx.doi.org/10.14531/ss2025.2.45-54*

Lumbar spinal stenosis (LSS) is a common spinal disorder, including in the elderly; it is usually characterized by anatomical reduction in the spinal canal volume or in the size of intervertebral foramen [1]. No rigorous epidemiological studies have been conducted in regard to the LSS prevalence; however, according to Ravindra et al. [2], approximately 103 million individuals worldwide are annually diagnosed with LSS, with the highest incidence in Europe (2.2%) and the lowest in Africa (0.94%).

Degenerative LSS may involve the central canal, lateral recess, intervertebral foramina, or may be combined, i.e. of complex origin. Central stenosis may develop as a result of a decrease in the anteroposterior, transverse, or combined diameters of the spinal canal because of intervertebral disc protrusion and/or hypertrophy of the facet joints and the ligamentum flavum. Criteria for central stenosis include a decrease in the sagittal size of the spinal canal of less than 12 mm (relative stenosis) and less than 10 mm (absolute stenosis) according to MRI, SCT, or SCT myelography results [3].

There are different surgical approaches aimed at eliminating degenerative spinal stenosis; the technique selection is still debatable [4]. Surgical decompression of the dural sac with spinal fusion of compromised spinal motion segments (SMS) provides good clinical results, however, has the following shortcomings: large blood loss, wound infection, iatrogenic instability, development of cicatrical adhesions, long recovery, and long learning curve [5, 6].

Closed pedicle-lengthening osteotomy (PLO) with pedicle elongation is a relatively new treatment option for LSS [7]. Compared with conventional surgery, PLO can effectively widen the spinal canal and intervertebral foramina, with minimal damage to the posterior lumbar anatomical structures, what results in good clinical outcomes. However, the PLO technique is currently at its early stage of development, with only several published experimental and clinical trials on its effectiveness [8]. Moreover, it is questionable what force should be applied to the posterior osteoligamentous column elements after pedicle-lengthening osteotomy to achieve clinically significant diastasis in the area of the dissected pedicles, as well as whether the mechanical load on metal implants can be reduced when performing dural sac and root decompression using pedicle elongation.

The objective is to determine experimentally the mechanical conditions required for decompression of the dural sac and spinal nerve roots during pedicle-lengthening osteotomy with elongation of pedicles at the lumbar level.

Material and Methods

The experiments were conducted in the Laboratory of Physical and Mathematical Methods for Material Measurements, Kuban State Technological University, using three anatomical specimens of L1–L5 SMS obtained in the Forensic Section, Department of Forensic Medicine, Kuban State Medical University, from individuals aged 45–60 years within two days after death, in compliance with the standards for preparing human tissue for biomechanical studies [9]. The causes of death did not affect the SMS structure. The specimens were subjected to morphometric measurements and radiological examination in two planes. The specimens prepared for the experiments conformed to the anatomical norm in shape and size. No visual or radiological abnormalities were detected, and the bone structure demonstrated no signs of osteoporosis. These control measures are considered sufficient when conducting biomechanical experiments with sectional anatomical specimens [10, 11].

The contents of the spinal and radicular canals were removed from the lumbar spine specimens leaving all elements of the osteoligamentary complex intact. Bilateral pedicle-lengthening osteotomy (PLO) was performed on the L4 vertebra using a Gigli saw (Fig. 1).

Then, two flexible cables, 2.5 mm in diameter, were passed through the radicular canals at the L3–L4 and L4–L5 levels. One cable is wrapped around the L4 body, and the second cable is wrapped around the L4 arch with the corresponding anatomical elements of the posterior osteoligamentous column at this level (Fig. 2).

The anatomical specimen was fixed in a laboratory mechanical testing bench, so that the cable gripping the L4 body was attached to the fixed beam of the bench, and the second cable gripping the L4 arch with the elements of the posterior support complex was attached to the movable beam of the bench. An electronic traction force meter with 0.01 N measurement accuracy was placed between the movable beam of the bench and the anatomical specimen tested (Fig. 3).

After, a graduated increasing distraction force was applied between the beams of the bench that was transmitted through the cables to the L4 vertebra as a distraction in sagittal direction between the vertebral body and its posterior osteoligamentous column, as shown in Fig. 4.

As the sagittal distraction load increased, diastasis appeared and increased in the area of the performed pedicle-lengthening osteotomies (PLO) indicating growth in the sagittal size of the spinal canal at the L4 level, as well as of the radicular canals at the L3–L4 and L4–L5 levels. The increasing diastasis was measured until it reached 7 mm; then the load testing was stopped.

We considered the 7 mm diastasis achieved in the experiment to be acceptable in regard to exclude destructive force effects on the structures of the osteoligamentary complex of the analyzed spinal motion segments remaining within the limits of "plastic" deformations, therefore, it allowed to repeat the load testing several times using the same anatomical specimen; it was at the same time sufficient in the context of clinical practice to achieve decompression of the dural sac. The diastasis in the osteotomy of the pedicles was determined using a kit of probes 1, 2, 3, 4, 5, 6 and 7 mm thick to constantly measure its value during the experiment (Fig. 5).

The corresponding value of the distraction force was registered after each 1 mm of diastasis increase in the area of the pedicle-lengthening osteotomy. The data obtained were specified in the experimental protocol. After reaching a 7 mm diastasis, the distraction load was stopped. The bench was returned to its initial position. The experiment was repeated two more times using the same anatomical specimen; the non-destructive nature of the mechanical effects on the analyzed specimen reduced the effect of possible measurement errors on the mean values obtained. After repeating the experiment three times, the specimen was removed from the bench.

In order to release the posterior ligamentous complex, osteotomies of the L3 lower articular processes were performed at the level of their base. After dissection from the arch, the lower articular processes were not removed; they were left in their original position and contacted with the capsule of the intervertebral joints (Fig. 6).

The lumbar spine specimen was again attached between the beams of the bench, as in the previous experiment. Upon that, a gradually increasing distraction force was applied between the beams of the bench; it was transmitted through the cables to the L4 vertebra as distraction in sagittal direction between the vertebral body and its posterior osteoligamentary column. As the sagittal distraction load increased, the diastasis in the area of the performed L4 pedicle-lengthening osteotomies increased as well. As in the previous experiment, the increasing diastasis was measured up to a size of 7 mm. The data obtained were registered in the experimental protocol; then, the traction load was stopped. The bench was returned to its initial position. This experimental version was repeated two more times. After repeating the experiment three times, the specimen was removed from the bench.

To conduct the third experiment, a bilateral pedicle osteotomy was additionally performed on the L3 anatomical specimen using a Gigli saw. Thus, additional release of the posterior support complex at the L4 level included not only osteotomies of the L3 lower articular processes at the level of their base, but also the L3 bilateral pedicle osteotomy (Fig. 7).

The specimen was attached between the beams of the bench, as in the previous experiment. Likewise, distraction in sagittal direction was applied between the L4 body and its posterior osteoligamentous column. The increasing diastasis in the area of the pedicle-lengthening osteotomies was measured until it reached 7 mm. In this case, as in the previous experiments, the corresponding value of the distraction load was registered after each 1 mm of increase in diastasis in the pedicle osteotomy area. The data obtained were specified in the experimental protocol. The third version of the experiment, along with two previous ones, was repeated three times.

Thus, the lumbar SMS stiffness values after L4 bilateral pedicle-lengthening osteotomy (PLO) were experimentally analyzed in relation to non-destructive sagittal distraction load leading to widening of the spinal and radicular canals in the sagittal direction, as well as the reduction of the stiffness parameter due to releasing bilateral osteotomies of the lower articular processes and bilateral pedicle osteotomies of the superjacent vertebra.

Statistical processing and analysis of the results were carried out using descriptive statistics methods. The normality of the sets of results measured on an interval scale was checked using the Kolmogorov–Smirnov Z test. The Mann–Whitney non-parametric U test was used to prove the statistical significance (or the lack thereof) for the compared parameters. Results were considered significant if the statistical significance value p was $\leqslant$0.05. Statistical analysis of the data was performed using SPSS for statistical data processing for Windows, version 23.0.

Results

The experiments revealed that gradually increasing distraction load in sagittal direction between the L4 body and its posterior support complex, after bilateral pedicle-lengthening osteotomy, leads to the gradually increasing diastasis in the area of osteotomies of the right and left pedicles; it increased symmetrically on the right and left with an increase in distraction force. The values obtained in three experiments are provided in the Table.

Based on the results obtained, the plot was developed for correlation of the increase in diastasis in the area of the L4 pedicle-lengthening osteotomies and the distraction forces applied in sagittal direction between the L4 body and the elements of its posterior support complex (Fig. 8).

As is seen from the data obtained, the increase in diastasis in the area of pedicle-lengthening osteotomies up to 3 mm is not directly proportional to the increasing distraction force (Fig. 7). After reaching 3 mm, the further increase up to 7 mm is directly proportional, and this

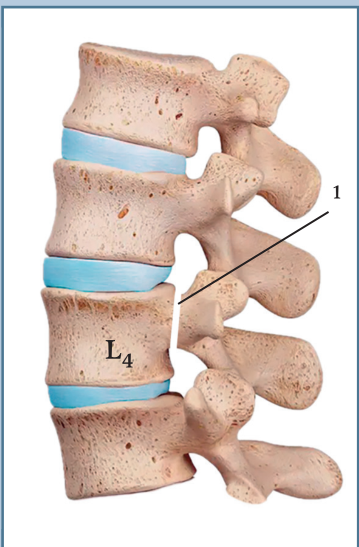

Fig. 1
Diagram of pedicle-lengthening osteotomy *(1)* on the L4 vertebra

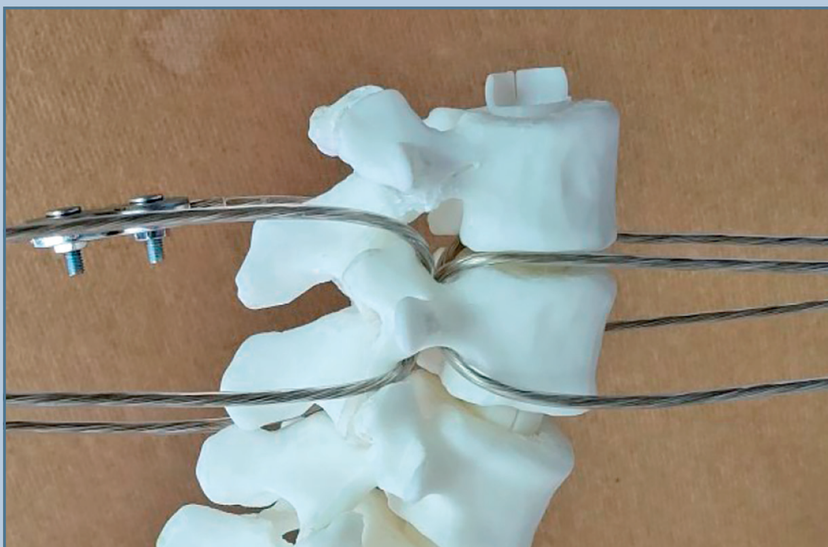

Fig. 2
Simulation of the arrangement of force elements (cables) on a model of the lumbar spine to implement a sagittally directed distraction force between the L4 vertebral body and the elements of the posterior osteoligamentary support complex

Fig. 3
Anatomical specimen of the lumbar spine after bilateral pedicle-lengthening osteotomy of the L4 is fixed between the beams of the mechanical testing bench

fact confirms the absence of irreversible structural damage in the anatomical specimens under the loads applied in our experiments.

Calculations for all achieved diastasis values in the PLO region demonstrated that the mobility of the L4 posterior osteoligamentary column following L4 PLO was statistically significantly different from its mobility after the L4 PLO with releasing facetectomy of the L3 inferior articular processes at 3–7 mm diastasis. The mobility of the L4 posterior osteoligamentary column after the L4 PLO is also statistically significantly different compared with the mobility after the L4 PLO with releasing facetectomy of the L3 inferior articular processes and the L3 pediculotomy.

Meanwhile, the results of statistical calculations demonstrated that the mobility of the L4 posterior osteoligamentary column after L4 PLO with releasing facetectomy of the L3 inferior articular processes has no statistically sig-

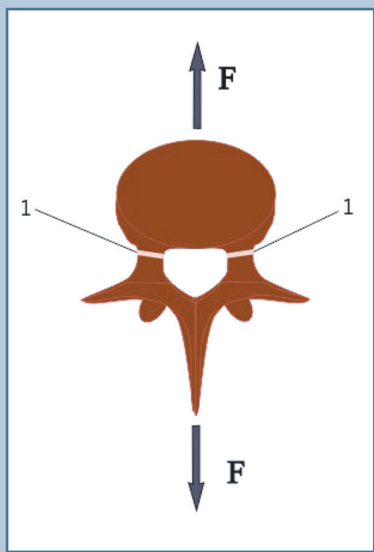

Fig. 4
Diagram of bilateral pedicle-lengthening osteotomy of a lumbar vertebra *(1)* and sagittally directed distraction force *(F)* between the vertebral body and elements of the posterior support complex

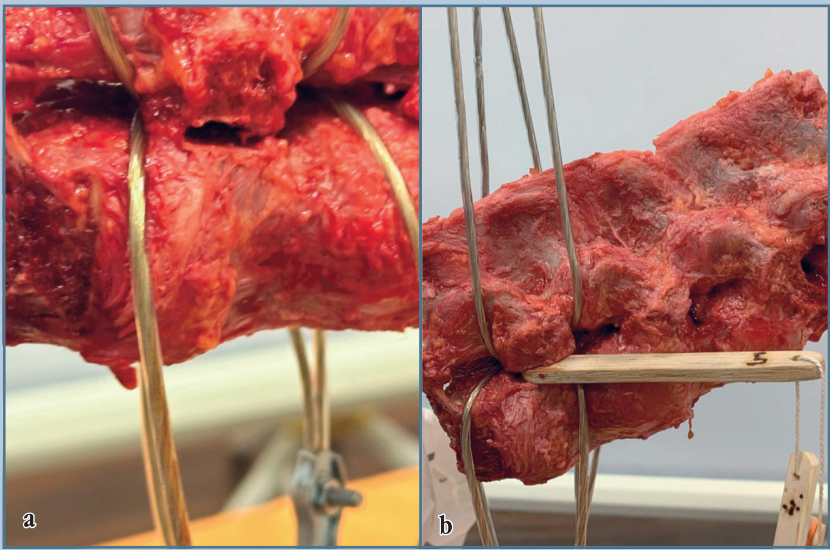

Fig. 5
Diastasis in the region of pedicle-lengthening osteotomy **(a)** and measurement of its size using a probe **(b)**

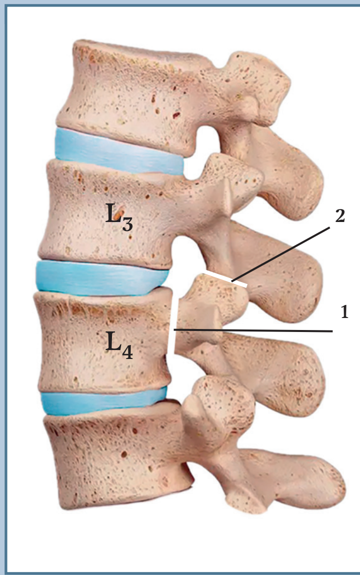

Fig. 6
Diagram of the L4 pedicle-lengthening osteotomy *(1)* and releasing osteotomy of the L3 inferior articular processes *(2)* in the lumbar spine

nificant differences compared with the mobility after the L4 PLO with releasing facetectomy of the L3 inferior articular processes of and the L3 pediculotomy.

A diastasis of at least 4 mm in the area of pedicle osteotomies can be considered clinically significant for achieving decompression of the dural sac and spinal nerve roots. As is seen from the obtained results, it is achieved at a force of 97 N applied in sagittal direction. A diastasis of 5 mm is achieved at 162 N, 6 mm at 240 N, and 7 mm at 306 N. Osteotomies of the L3 lower articular processes significantly released the L4 posterior support complex in regard to the possibility of its dorsal displacement in relation to the vertebral body. To achieve a 4 mm clinically significant diastasis in the area of pedicle osteotomies, a force of 30 N was required, 5 mm at a force of 73 N, 6 mm at 125 N, and 7 mm at 182 N. These values are 1.70–3.23 times lower than in the case without releasing osteotomies of the L3 lower articular processes (see Table, Fig. 8). The third experiment, with the releasing interventions including not only osteotomy of the L3 lower articular processes, but also bilateral pedicle osteotomy of the same vertebra, demonstrated that there is no further decrease in the sagittal distraction force to achieve clinically significant diastasis in the area of osteotomy of the L4 pedicles compared to the second experiment (see Table, Fig. 8; plots 2 and 3 are almost overlapping).

Discussion

The definition of *lumbar spinal stenosis* was first proposed in 1949 by Verbiest et al. Surgical techniques for the management of this abnormality have been developing for more than 70 years [8]. As surgical technologies developed and clinical retrospective data accumulated, certain surgical techniques became popular or were criticized.

Currently, dorsal root decompression in combination with transpedicular fixation and intercorporal spinal fusion performed using the posterior or posterolateral approach to the intervertebral discs is widely used. This type of surgery implements the neuro-orthopedic approach to the treatment of lumbar stenosis [12]. Along with proper decompression of neurovascular structures, transpedicular spinal systems allow eliminating segmental instability or spondylolisthesis and normalizing the anatomical relationships in the SMS and the sagittal balance of the spine. It should be mentioned that the results of treatment of patients with degenerative lumbar stenosis equally depend on the quality of the decompression performed, the accurate correction of anatomical relationships in the treated SMS, and the reliable stabilization allowing bone block formation [13].

Currently, various minimally invasive surgical approaches for LSS management with minimal impact on the SMS stability are also very popular, especially in elderly and senile patients. However, this approach makes difficult control over the appropriateness of the main stage of the intervention, and the risk of intraoperative complications and iatrogenic instability of the treated segments increases [14].

S.G. Mlyavykh et al. [15] were the first to use PLO in clinical practice proposing the Altum Pedicle Osteotomy System that includes instrumentation for

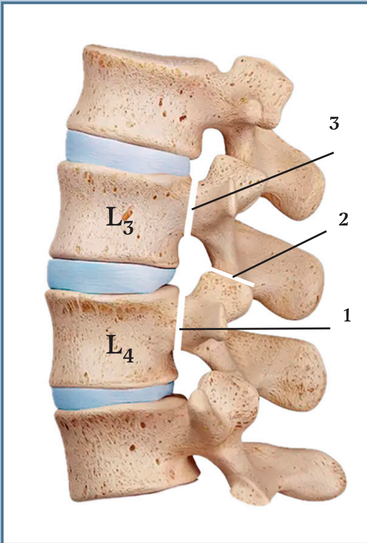

Fig. 7
Diagram of the L4 pedicle-lengthening osteotomy *(1)*, mobilizing osteotomies *(2)* of the L3 inferior articular process, and the L3 pedicle osteotomies *(3)* in the lumbar spine

its performing and pedicle screws of a special design. The screws enable distraction of the arch pedicles after osteotomy and, accordingly, increasing the sagittal size of the spinal and radicular canals at the SMS level where the osteotomy was performed. Compared to conventional surgeries, PLO widens the spinal canal with minimum damage to the dorsal anatomical structures of the lumbar spine. Kiapour et al. [16] conducted a biomechanical experiment and 3D analysis and found that the use of unilateral or bilateral PLO in the lumbar spine could increase the area of the spinal canal and intervertebral foramina without significantly affecting the global or segmental kinematics.

Gao et al. [8] conducted a research to study the effect of PLO on the SMS stability. The results demonstrated that PLO could effectively widen the spinal canal, with no spondylolisthesis or other complications observed. Moreover, this intervention produced no significant effect on lumbar stability supporting its potential clinical application. S.G. Mlyavikh et al. [17] analyzed the short- and long-term treatment results in patients who underwent PLO and found that the volume of the spinal canal significantly increased after surgical intervention, and patients experienced regression of neurological symptoms. Moreover, 6 months after surgery, fusion of pedicles in the area of elongation and the diastasis after PLO was registered in all patients.

It should be mentioned that the particular idea of PLO may have extensive application in the treatment of patients with lumbar stenosis. However, the Altum instrumentation for osteotomy presents significant technical complexity. Expandable pedicle screws for elongation of pedicles after the described PLO [8, 16] are characterized with a very complex design and a large diameter (up to 11 mm or more); this is potentially unfavorable considering the possible indications for revision surgery.

Because of the required import substitution of the applied instrumentation and implants, there is a relevant issue of developing alternative PLO technique and subsequent decompression of the dural sac and roots by elongation of pedicles using conventional 6–7 mm pedicle screws for the lumbar spine. In this respect, the possible significant reduction of the force required for decompression applied to the anatomical structures of the SMS treated will be of significant practical value.

Our experimental study is related to a clinically significant aspect of the PLO technique: analysis of the effect of various options for releasing the lumbar SMS before PLO on the conditions of subsequent correction of the sagittal size of the spinal canal. Successful releasing will obviously allow achieving the required elongation with less corrective measures. Consequently, instrumentation fixation structures will be subject to fewer loads after this releasing, which will reduce the possibility of destabilization and loss of the achieved correction.

Experimental trials of this type were conducted by other authors in order to determine the possibilities of correcting anatomically altered SMS in other clinical cases [10, 18]. This study demonstrates the possibility of a significant reduction in the corrective measures required for an effective increase in the sagittal size of the spinal and radicular canals at the level of surgical intervention, which may be of great practical importance in the further advancement of the dural sac decompression technique using PLO.

Conclusion

Gradual elongation of pedicles after pedicle osteotomy requires a significant sagittal traction force between the vertebral body and the anatomical elements of the posterior support complex. An increase in the sagittal size of the spinal canal due to elongation of pedicles after pedicle-lengthening osteotomy at the L4 level by 4 mm is achieved using a traction force of 97 N, by 5 mm – at 162 N, by 6 mm – at 240 N, and by 7 mm – at 306 N. Releasing osteotomy of the L3 lower articular processes reduces the traction force required for decompression to 30 N, 73 N, 125.5 N and 182 N, respectively, which is 1.7–3.2 times less than the PLO values without releasing measures. An additional bilateral pedicle osteotomy on the superjacent L3 vertebra does not provide a further decrease in the traction forces required to increase the sagittal size of the spinal canal.

Decompression technique for the dural sac and nerve roots of the lumbar spine using pedicle-lengthening osteotomy with elongation of pedicles may be a high-potential option for surgical treatment of LSS. The data obtained in this study may be of interest, especially with the possible development of another technical solution and instrumentation for implementing PLO.

The study had no sponsors. The authors declare that they have no conflict of interest.
The study was approved by the local ethics committees of the institutions.
All authors contributed significantly to the research and preparation of the article, read and approved the final version before publication.

Table

Mobility of the L4 posterior osteoligamentous column after the L4 PLO alone, the L4 PLO with releasing bilateral osteotomy of the L3 inferior articular processes and the L4 PLO with releasing bilateral osteotomy of the L3 inferior articular processes and the L3 bilateral pedicle osteotomy

Achieved diastasis in the area of the L4 bilateral pedicle-lengthening osteotomy	Distraction force to achieve diastasis (N)		
	L4 PLO	L4 PLO + facetectomy of L3 inferior facets	L4 PLO + facetectomy of L3 inferior facets + L3 pediculotomy
2 mm	10.0	3.0	2.8
3 mm	24.8	7.4	7.0
4 mm	97.0	30.0	28.0
5 mm	162.0	73.0	70.3
6 mm	240.0	125.5	120.0
7 mm	306.0	182.0	168.0

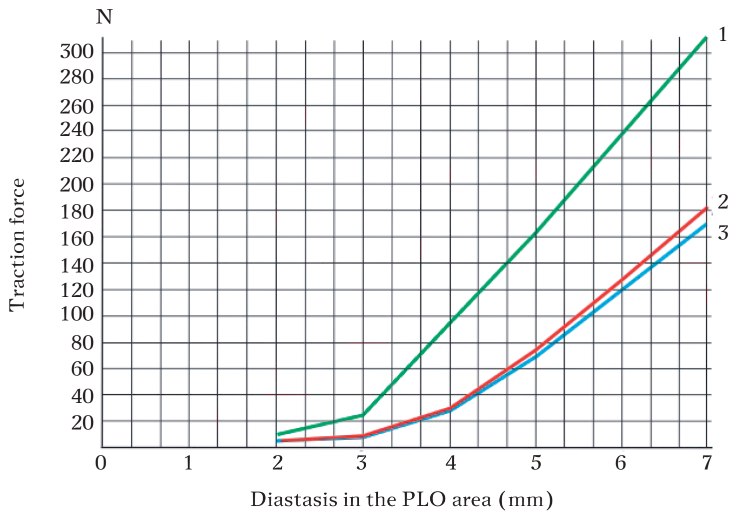

Fig. 8

Plots of the dependence of the diastasis magnitude in the area of the L4 pedicle-lengthening osteotomies (PLO) on the value of the sagittally directed distraction force between the L4 vertebral body and the elements of its posterior osteoligamentary support complex: *1* – the L4 pedicle-lengthening osteotomy; *2* – the L4 pedicle-lengthening osteotomy and releasing osteotomy of the L3 inferior articular processes; *3* – the L4 pedicle-lengthening osteotomy, releasing osteotomy of the L3 inferior articular processes and the L3 releasing pedicle osteotomy

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Received 21.02.2025
Review completed 09.04.2025
Passed for printing 20.04.2025

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