

ARTICLE



Effect of posterior decompression with and without fixation on a kyphotic cervical spine with ossification of the posterior longitudinal ligament

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STUDY DESIGN: Biomechanical study.

OBJECTIVE: Cervical ossification of the posterior longitudinal ligament (C-OPLL) causes myelopathy. Though posterior decompression for C-OPLL showed positive results, poor outcomes were seen in patients with a kyphotic alignment. Posterior decompression with fusion (PDF) tends to show better results compared to posterior decompression. The aim of this study is to evaluate the effects of the posterior procedures for C-OPLL.

SETTING: Yamaguchi University.

METHODS: Based on 3D finite element C2-C7 spine created from medical images and a spinal cord, the following compression models were created: the intact model, K-line 0 mm model, and K-line 2 mm model. These models were used to analyze the effects of posterior decompression with varied lengths of fixation. The stress of the spinal cord was calculated for intact, K-line 0 mm, and K-line 2 mm as preoperative models, and laminectomy (LN)-K-line 0 mm, PDF (C4-C5)-K-line 0 mm, PDF (C3-C6)-K-line 0 mm, LN-K-line 2 mm, PDF (C4-C5)-K-line 2 mm, and PDF (C3-C6)-K-line 2 mm model as operative models in a neutral, flexion, and extension.

RESULTS: As the compression increased, stress on the spinal cord increased compared to the intact model. In the neutral, posterior decompression decreased the stress of the spinal cord. However, in flexion and extension, the stress on the spinal cord for LN-K-line 0 or 2 mm, PDF (C4-C5)-K-line 0 or 2 mm, and PDF (C3-C6)-K-line 0 or 2 mm models decreased by more than 40%, 43%, and 70% respectively compared to the K-line 0 or 2 mm model.

CONCLUSIONS: In kyphotic C-OPLL, it is essential to control intervertebral mobility in the posterior approach.

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INTRODUCTION

Cervical ossification of the posterior longitudinal ligament (C-OPLL) causes spinal compression and myelopathy. In a survey of patients with C-OPLL, myelopathy was observed in 42.4% of patients, and the initial symptoms of cervical OPLL in descending order include paresthesia in the upper and lower limbs, nuchal pain, weakness, and gait disturbance [1]. There were several reports of the usefulness of the posterior approach for C-OPLL accompanied by myelopathy. Posterior decompression (laminectomy and laminoplasty) for C-OPLL has positive outcomes, although it is an indirect decompression. Despite this, there have been reports indicating that patients with a kyphotic cervical alignment endured post-operative complications such as instability and axial pain [2, 3]. Additionally, posterior decompression for C-OPLL had poor outcomes in patients with K-line (-) (a straight line that connects the midpoints of the spinal canal at C2 and C7 on the lateral cervical radiographs). C-OPLL did not exceed the K-line in the K-line (+) and did exceed it in the K-line (-), with a kyphotic alignment, and those with large, ossified lesions (canal occupying ratio 60%) [4, 5].

There are reports that suggest anterior decompression with fusion (ADF) can be effective even in cases with kyphotic cervical alignment or large ossified lesions [6–8]. However, ADF was associated with significant surgical invasion and higher incidences of surgical complications. In practice, surgeons often use the operative technique, especially for posterior decompression, that they are most familiar with. The most common surgical procedure for cervical OPLL is posterior decompression, though posterior decompression with instrumented fusion (PDF) has gained popularity following recent developments in spinal instrumentation [9]. Improvements for patients with a kyphotic cervical alignment tended to be better with PDF than with posterior decompression [1]. Comparing the posterior decompression and PDF limited to patients with K-line (-) and those with large ossified lesions for whom the therapeutic outcomes of the posterior decompression are poor, the recovery rate tended to be better for PDF than for the posterior decompression [1, 10]. Regarding the pre-to-postoperative change in the C2-C7 angle between the two procedures, lordosis was significantly preserved in PDF than in the

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posterior decompression though the incidence of postoperative upper limb paralysis was significantly higher in PDF [10]. There are many clinical reports for C-OPLL, however, no reports in the literature have examined the biomechanical changes of the spinal cord for patients with the kyphotic C-OPLL for different posterior decompression procedures. We hypothesize that the posterior surgical procedures may provide different stresses in the compressed spinal cord.

Based on a three-dimensional (3D) finite element (FE) C2-C7 spine created from medical images and spinal cord model, the following compression models were created: the intact model, K-line 0 mm model, and K-line 2 mm model. These models were used to analyze and compare the effects of posterior decompression with varied lengths of fixation.

MATERIAL AND METHODS

Model development

The FE model was created based on the computed tomography (CT) images of an OPLL and kyphotic cervical alignment adult subject, the ethics committee approved using these images at the Center for Clinical Research at the corresponding author's facility. CT images (slice thickness of 0.6 mm) of the spine were obtained using the Brilliance 64 CT scanner (Philips Healthcare, Amsterdam, Netherlands). The model construction was performed with finite element analysis software (simpleware ScanIP, version M-2017.06; Synopsis Inc., Mountain View, CA, USA). After the spine was extracted, vertebral bodies were mapped as cancellous and cortical bones, and interbody discs were also mapped. The cortical and cancellous bones were then separated. The computer was unable to separate the facet joints due to their small size automatically. Therefore, manual distinctions were performed while examining CT scans. A 3D spine model was constructed by mapping all vertebrae and intervertebral discs from C2-C7 regions. Facet joint spaces were created at all levels for each vertebra to move independently. The facet joints in the model were represented using surface-surface sliding contact. The posterior longitudinal ligament (PLL), and ligamentum flavum (LF) were added to the model (Fig. 1A). Cervical spine alignment parameters reported in the literature were used to develop a kyphotic model [11]. The following parameters were measured in the C2-C7 model: cervical sagittal vertical axis (cSVA): the distance from a vertical plumb line dropped from the center of the C2 vertebral body to the posterior superior corner C7 vertebra [12]. The cervical spine sagittal parameters of a standing posture in an adult subject used in this study were as follows: C2-C7 kyphosis angle: 15°, cSVA: 20 mm (Fig. 1C, D). However, no validation was done for the intact model due to the lack of available in-vitro data for the kyphotic cervical spine. In this model, the total numbers of elements and nodes were 764,100 and 201,837. Spinal cord models were modeled using the mean transverse and anterior-posterior diameter at each spinal cord segment of the report of Kameyama et al [13] (Fig. 1B). The dura mater was contoured to fit within the spinal canal. The spinal cord and dura mater in the model were represented using surface-surface sliding contact.

In this analysis, the Young's modulus and Poisson's ratio for the various components of the spine was obtained from the literature [14–20] (Table 1).

OPLL model

The K-Line was used for the degree of compression [4]. A compression model equal to the K-line at the C4-C5 level (K-line 0) and a model 2 mm beyond K-line (K-line 2) was created (Fig. 2A).

Development of the posterior decompression: Laminectomy (LN) Model. To simulate laminectomy at a cervical spine level, part of the lamina was removed until the medial side of the facet joints. This method was used to create laminectomies at the C3-C6 levels (LN model) (Fig. 2A).

Development of the posterior decompression fixation (PDF) model. The instrumentation in the LN models comprised of a 3.5 mm diameter and a 16 mm length C4-C5 and C3-C6 lateral masses screws (LMS). Next, a 3.5 mm rod was connected to the head of the lateral mass screws. The lateral mass screws and rods were assigned titanium alloy (Ti-6Al-4V) material properties [19]. The interaction between the screw-bone and the screw head-rod was simulated via "TIE" constraint in software to simulate a rigid connection between these components (Fig. 2A).

Loads and boundary conditions

A pure moment of 1.5 Nm was applied to the C2 odontoid process, cervical spine, and dura matter to simulate flexion/extension. The inferior endplate of the C7 vertebra was fixed. The model was subjected to the compressive follower load of 100 N to represent the weight of the head/cranium and cervical muscle contractions [21]. Analyses were performed using Patran and MARC (MSC Software, Newport Beach, CA, USA).

Data analyses

The stress of the spinal cord was calculated for intact, K-line 0 mm, and K-line 2 mm as preoperative models, and LN-K-line 0 mm, PDF (C4-C5)-K-line 0 mm, PDF (C4-C6)-K-line 0 mm, LN-K-line 2 mm, PDF (C4-C5)-K-line 2 mm, and PDF (C3-C6)-K-line 2 mm model as operative models in a neutral posture, flexion, and extension. The maximum von Mises stress were noted for the spinal cord and intervertebral disc. The percentage change (%) was calculated using the following equation:

$$\text{Percentage change(\%)} = \frac{\text{Operation Model Data} - \text{Pre-operative Model Data}}{\text{Intact Model Data}} * 100$$

RESULTS

Comparison of intact, K-line 0 mm, and K-line 2 mm (Pre-operative model)

In the neutral posture, flexion, and extension, as the compression increased, stress on the spinal cord increased compared to intact model (Fig. 3).

K-line 0 mm model

In the neutral posture, the stress on spinal cord for LN-K-line 0 mm, PDF (C4-C5)-K-line 0 mm, and PDF (C4-C6)-K-line 0 mm models decreased by 82% respectively compared to the K-line 0 mm model. In flexion, the stress on the spinal cord for LN-K-line 0 mm, PDF (C4-C5)-K-line 0 mm, and PDF (C4-C6)-K-line 0 mm models decreased by 41%, 44%, and 77% respectively compared to the K-line 0 mm model. In extension, the stress on the spinal cord for LN-K-line 0 mm, PDF (C4-C5)-K-line 0 mm, and PDF (C4-C6)-K-line 0 mm models decreased by 74%, 74%, and 80% respectively compared to the K-line 0 mm model.

K-line 2 mm model

In the neutral posture, the stress on the spinal cord for LN-K-line 2 mm, PDF (C4-C5)-K-line 2 mm, and PDF (C4-C6)-K-line 2 mm models decreased by 52%, 52%, and 61% respectively compared to the K-line 2 mm model. In flexion, the stress on the spinal cord for LN-K-line 2 mm, PDF (C4-C5)-K-line 2 mm, and PDF (C4-C6)-K-line 2 mm models decreased by 49%, 49%, and 80% respectively compared to the K-line 2 mm model. In extension, the stress on the spinal cord for LN-K-line 2 mm, PDF (C4-C5)-K-line 2 mm, and PDF (C4-C6)-K-line 2 mm models decreased by 54%, 55%, and 82% respectively, compared to the K-line 2 mm model.

DISCUSSION

A 3D-FE kyphotic C-OPLL model was created from medical images, and a stress analysis of the spinal cord was performed with the decompression and fixation models.

Clinically, the posterior decompression for C-OPLL has been reported as a relatively easy surgical procedure and with positive results, although it is an indirect decompression technique [3]. However, in patients with kyphotic cervical spine alignment or high spinal canal occupancy of ossification, posterior shift (indirect decompression) of the spinal cord is insufficient, resulting in poor clinical outcomes [5, 22]. Although it is more invasive, the addition of posterior fixation has shown to have similar outcomes to an anterior decompression with fusion; though both procedures have shown to be better than the posterior decompression [1, 10, 23]. The posterior fixation prevents kyphosis deformity and provides stability to the cervical segment mobility. However, it is inconclusive whether a

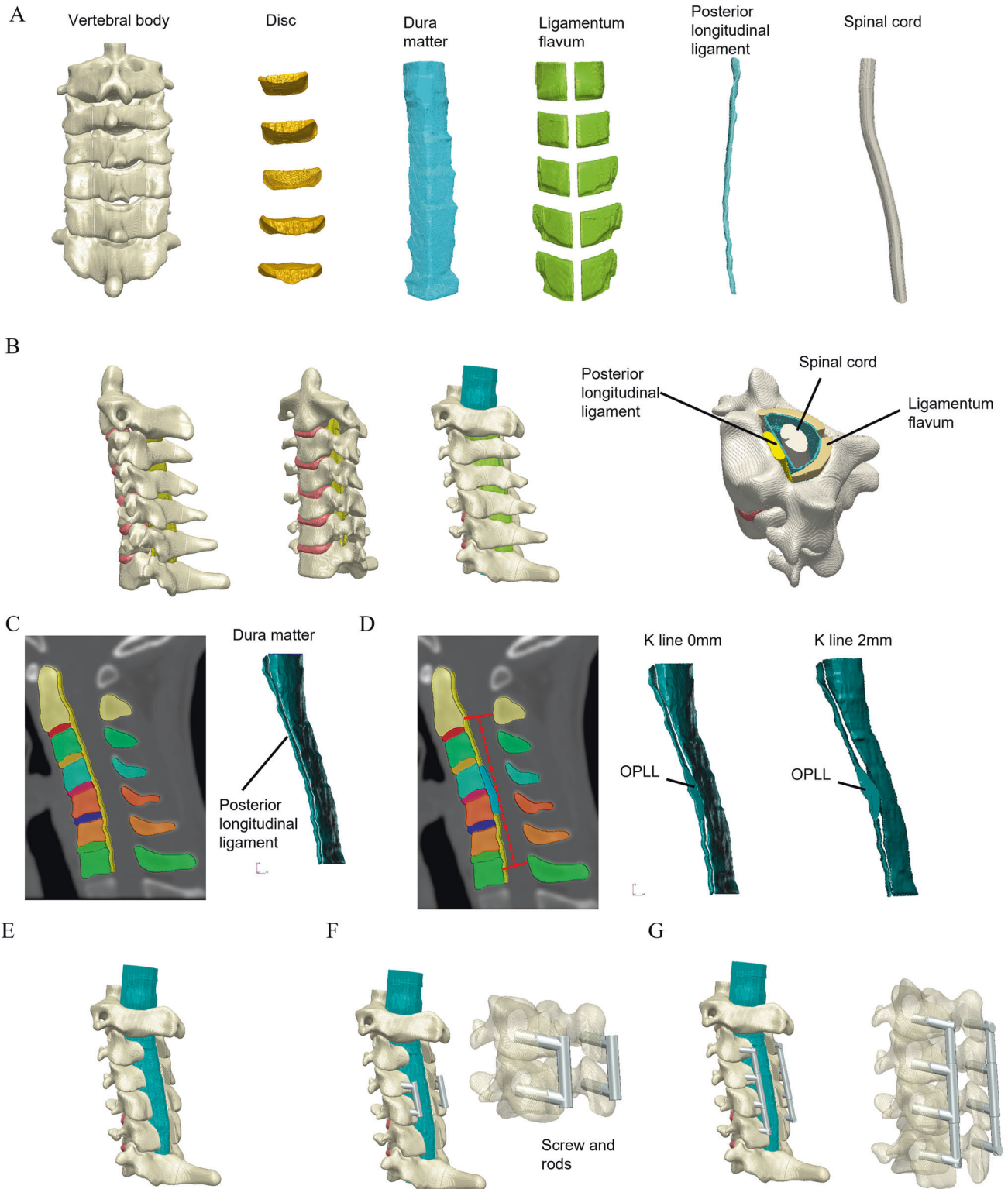


Fig. 1 The intact (C2-C7) FE model. **A, B** The vertebral body, disc, dura matter, ligamentum flavum (LF), posterior longitudinal ligament (PLL), and spinal cord were modeled. **C** Intact model. Dura matter and PLL. **D** Compression model. Dura matter and PLL of K-line 0 mm and K-line 2 mm model. **E** C3-C6 laminectomy model (LN), **(F)** C4-C5 posterior decompression fixation model (PDF (C4-C5)), **(G)** C3-C6 posterior decompression fixation model (PDF (C3-C6)).

short or long length of fixation should be performed. A K-line (-) indicates high ossified occupancy and kyphotic alignment. Our results indicated that the K-line 2 mm model had higher intraspinal stress. In addition, posterior decompression decreases the intraspinal

stress in the neutral posture, K-line 0 mm, and K-line 2 mm. However, in LN and PDF (C4-C5), intraspinal stress increased, especially in flexion and extension and was more pronounced with K-line 2 mm, which is consistent with previous reports [4, 5]. Long-length

fixation for C-OPLL can prevent an increase in the stress of the spinal cord.

In biomechanical studies, cadaver experiments have not reported spinal cord compression of OPLL but have reported intraspinal pressure of the kyphotic cervical spine. Chavanne et al directly measured the spinal cord intraparenchymal pressure (IMP) in human cadavers. They reported that IMP is significantly elevated in cervical kyphosis when it exceeds 20 degrees [24]. Winestone et al created a kyphotic cervical deformity and analyzed IMP in the spinal cord after posterior decompression. The intact model had 0 mmHg of intraspinal pressure at C4-C5 but was increased to 40 mmHg to create a cervical kyphotic deformity.

Table 1. Young's modulus, Poisson ratio, and mass density [14–20].

Part	Young's modulus E [MPa]	Poisson ratio
Cortical bone	12000	0.3
Cancellous bone	1500	0.3
Annulus fibrosus	25	0.3
Nucleus pulposus	1	0.45
Anterior longitudinal ligament	68	0.3
Posterior longitudinal ligament	96	0.3
Ligamentum flavum	28.6	0.3
Spinal cord	0.222	0.3
Dura matter	63	0.3
Ti-6Al-4 V: rod and screw	127000	0.33

Posterior decompression reduced the pressure by only 20%. They concluded that there was a relatively minor effect from posterior decompression on the stress of the spinal cord in cervical kyphotic deformities [25]. Some studies showed that increased kyphosis led to an increase in stresses on the spinal cord. In reviewing spinal cord forces/stresses, Harrison et al concluded that in kyphosis the forces can be broadly divided into longitudinal tensile forces and transverse loading forces [26]. In in vitro and in vivo studies of canine spinal cords, cord elongation of greater than 22% resulted in dramatic spinal cord interstitial pressure increases [27, 28]. Henderson reported that stretch injury of the spinal cord is caused when the cord is displaced in kyphosis and stretched out. At the cervicothoracic junction, where flexion is greatest, the spinal cord stretches 24% of its length. In the presence of pathological displacement, strain can exceed the material properties of the spinal cord and cause transient or permanent neurological injury [29]. These results may be why, clinically, decompression is less effective in a kyphotic cervical spine. In our study, both the preoperative and decompression models showed increased intraspinal stress in flexion. This was likely due to an increased kyphosis and tensile force of the spinal cord. It is also possible that the angle of kyphosis increased locally with C-OPLL.

In FE studies, though spinal cord compression analyses have been performed using OPLL, only the spinal cord was extracted and analyzed [30, 31]. Nishida et al reported that stresses of the spinal cord increased as the size of OPLL increased (10%, 20%, and 30%), with increased segmental motion (5°, 10°, and 15°) and that fixation reduces intervertebral mobility and prevents the increase of stress [32, 33]. However, in this analysis, the spinal cord was not linked with the motion of the vertebral body, the compression was expressed in terms of the anteroposterior diameter of the spinal cord, and alignment was not considered. Using the K-line in the

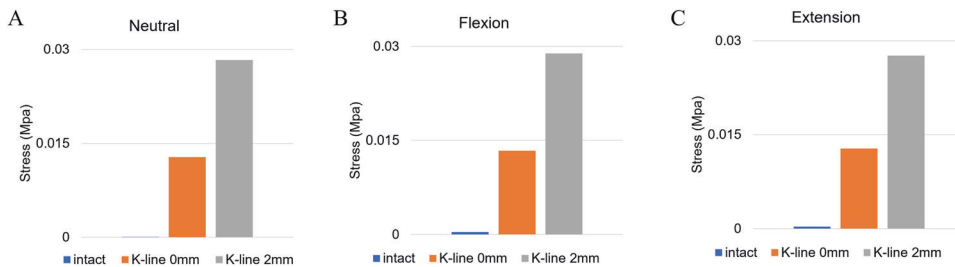


Fig. 2 The stress of spinal cord. **A** neutral, **B** flexion, **C** extension. The vertical axis is stress (Mega Pascal; MPa), the horizontal axis is intact, K-line 0 mm, and K-line 2 mm model.

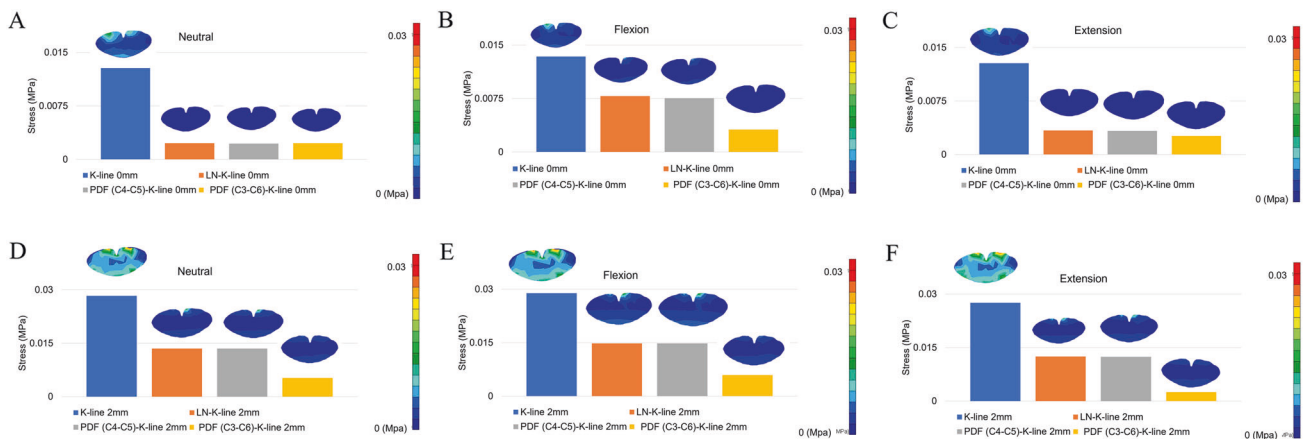


Fig. 3 The stress of the spinal cord for pre-operative and each surgical procedure. **A–C** The stress of spinal cord of K-line 0 mm model. **A** neutral, **B** flexion, **C** extension. The vertical axis is stress (MPa), the horizontal axis is intact, LN, PDF (C4-C5), and PDF (C3-C6). **D–F** The stress of spinal cord of K-line 2 mm model. **D** neutral, **E** flexion, **F** extension. The vertical axis is stress (MPa), the horizontal axis is intact, LN, PDF (C4-C5), and PDF (C3-C6). Right bar is the chart of stress (MPa).

present study, we found that the intraspinal stress increases with increasing compression. In addition, LN and short PDF did not decrease spinal stress due to residual dynamic factors in the spinal cord. To the authors' knowledge, the current report is the first to analyze the kyphotic cervical spinal cord, decompression, and length of fixation. We expect that it will apply to various studies in the future.

Some limitations need to be addressed. Cervical OPLL can be used to classify ossified lesions into four types: continuous type, segmental type, mixed type, and localized type [34]. In this analysis, we conducted an analysis on the continuous type of OPLL, only. Intervertebral local motion has been reported as a cause of poor results in posterior decompression [35], though only increased kyphosis of the whole cervical spine has been considered in this study. Multiple types of ossification should be considered in the future. In addition, the effect of the age-related degeneration was not considered in the FE analysis. Analysis errors were reduced by not including the denticulate ligament, cerebrospinal fluid, grey matter, and nerve roots. Additionally, this analysis was fixed in a kyphotic alignment, and kyphosis correction was not considered. However, considering a stress analysis of C-OPLL created from a medical image may be helpful for future research in this area. In posterior decompression of C-OPLL with kyphosis, it is difficult to determine whether a relatively long fixation (e.g., C2-Th1) should be used to prevent kyphotic deformity or whether a short fixation is sufficient in terms of invasiveness. Knowing how the spinal cord's stresses change using finite element analysis is essential.

CONCLUSIONS

This study investigated the biomechanical stresses of the spinal cord of C-OPLL and posterior decompression, and PDF using FE analysis. K-line (-) and cervical kyphotic alignment increases intraspinal stress, and posterior decompression and short fixation has a poor decompression effect. In kyphotic cervical OPLL, it is essential to control spine mobility in the posterior approach.

DATA AVAILABILITY

The data presented in this study are available.

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AUTHOR CONTRIBUTIONS

Conceptualization: N.N. Data curation and Formal analysis: T.A., R.T. and F.J. Funding acquisition: N.N. Methodology: N.N., Y.I., H.S. and M.F. Project administration: N.N. and C.X. Supervision: T.S. Validation: T.A., R.T. and N.N. Visualization: T.S. Writing—original draft: N.N. Writing—review & editing, Y.K., and J.O. All authors have read and agreed to the published version of the manuscript.

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COMPETING INTERESTS

The authors declare no competing interests.

ETHICS APPROVAL

The present study was approved by the Ethics Committee at the Center for Clinical Research, Yamaguchi University Hospital (Ube, Japan; approval no. H28-054). Written informed consent for this study and its publication was obtained from all subjects.

ADDITIONAL INFORMATION

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