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Changing rod stiffness to moderate stress of adjacent disc in oblique lumbar interbody fusion - a finite element analysis

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Abstract

Background OLIF (oblique lumbar interbody fusion) is a minimally invasive surgery to treat spinal instability. However, clinical studies indicated the early degeneration of adjacent segments after surgery. The rod stiffness of OLIF was associated with change at adjacent segments. Therefore, the study aimed to compare the biomechanical effects of OLIF with different rod material properties using the finite element (FE) method.

Methods A validated L1-L5 lumbar spine was conducted in the biomechanical analysis using FE software ANSYS. The FE model of OLIF with a rod was created. Current biocompatible materials for the rod of the OLIF model were changed, including titanium alloy (OLIF_Ti), nickel-titanium alloy (OLIF_NiTi), and polycarbonate urethane (OLIF_PCU) rod. Four FE models, consisting of the intact model (INT) and implant models, were created. Hybrid control loads, such as flexion, extension, rotation, and lateral bending, were subjected to four models on the L1 vertebral body. The bottom of the L5 vertebral body was fixed.

Results At the surgical level, while compared to the INT model, the OLIF_Ti and OLIF_NiTi model resulted in a ROM reduction of over 40% at least, but the OLIF_PCU changed about 10% in flexion and extension. At adjacent level L2-L3, the FE results indicated that the OLIF_Ti and OLIF_NiTi model increased more stress by about 12% at least than the INT model at the adjacent segment, but it demonstrated that the OLIF_PCU would not result in stress rise at the adjacent level L2-L3 in flexion and extension.

Conclusion The study concluded that rod stiffness was associated with change at the adjacent segments. The use of OLIF surgery with PCU rods can minimize the impact of the adjacent segment after lumbar fusion.

Keywords OLIF, Adjacent segment, Lumbar spine, Finite element analysis

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Introduction

Low back pain is one of the most critical problems in decreasing the quality of life as a result of lumbar disc degeneration [1]. Low back pain is thought to result from degenerative intervertebral disc and facet joints [2]. Disc degeneration may lead to segmental instability, associated lateral recess, and foraminal stenosis, significantly contributing to symptomatic mechanical back pain, sciatica (leg radiation pain from buttock to calf), and neurogenic claudication [3, 4]. Conservative treatment such as rehabilitation programs and medication of NSAID (non-steroid anti-inflammatory drug) are first recommended for these symptomatic patients with sciatica and neurogenic claudication. Surgical goals are aimed to restore spinal stability with pedicle screws fixation and fusion and neural foramens completely decompressed. A spinal interbody fusion cage is effective in achieving fusion and restoring the original height of the intervertebral disc. The oblique lumbar interbody fusion (OLIF) is the current trend in minimally invasive spine surgery among existing fusion procedures.

The OLIF can provide a larger support area to increase disc height and foraminal height to alleviate nerve compression pain. A review of the clinical literature [5–8] showed that the patient satisfaction rate for OLIF surgery ranged from 87.5 to 100%, indicating good satisfaction. However, a primary concern after posterior lumbar spine arthrodesis is the potential for adjacent segment degeneration (ASD) cephalad or caudad to the fusion segment due to stress concentration at the adjacent levels. Park et al. reported that the incidence of radiographic ASD ranges from 7.1 to 100% with retrolisthesis and disc height loss [9]. However, the incidence of symptomatic adjacent segment disease ranges from 5.2 to 18.5% [10]. The etiology is biomechanical alterations affecting the levels adjacent to a fused segment, as well as progressive spinal degeneration with age. The risk factors are instrumentation, fusion length, sagittal malalignment, facet injury, age, and degenerative changes.

In a meta-analysis and systemic review [9], the potential risk factors for ASD are posterior lumbar interbody fusion, injury to the facet joint of the adjacent segment fusion length, sagittal alignment, and degenerated disc at the adjacent level, lumbar stenosis, age, osteoporosis, female gender, and post-menopausal state. Using only radiographic criteria, the incidence of ASD was generally higher, with rates varying from 8 to 100%. In contrast, studies involving symptomatic ASD reported incidence ranging from 5.2 to 18.5%. Previous studies using the finite element (FE) method have also developed the lumbar spine with an OLIF model to analyze the stress at the adjacent disc, and the results have shown that OLIF surgery does cause an increase in disc stress at the adjacent level [11–15]. Zhang et al. reported that OLIF with bilateral pedicle screw fixation could obtain good spinal stability [12]. However, Du et al. addressed OLIF raised a risk of accelerating the degeneration of segments adjacent to the fusion site [14].

From the above studies, it can be confirmed that OLIF with metal pedicle screw and rod fixation caused an increase in ROM and disc stress at the adjacent segment. The main reason for this may be the rod's strength, as most of the current cage materials have been changed to PEEK, reducing its rigidity. The spinal fusion with a semi-rigid rod has been used in the clinic. Selim et al. [16] analyzed five studies (1 prospective and four retrospectives) that included 177 participants (156 received PEEK rods, and 21 received titanium rods). Meta-analysis of interbody fusion success rate in PEEK rod patients has shown satisfactory clinical outcomes (95%). In biomechanical study, Biswas et al. [17] tried to use lower stiffness rods, including UHMWPE and PEEK, to analyze biomechanical change. They reported that the PEEK rods might be considered for a better implant design to get better ROM. Liu et al. [18] addressed that the PEEK rod (ROM reduced by 57%) reserved more micromotion at a surgical level than the rigid titanium rod (ROM reduced by 91%) under a total of 74 patients follow-up from 2017 to 2019. It meant that a semi-rigid rod was a way to reduce adjacent disc stress.

The Dynesys with PCU rod was also successfully used in clinical treatment, especially in preserving adjacent motion segments. Therefore, adding semi-rigid PCU rods to OLIF surgery might be a consideration of clinical treatment. Regarding the stiffness of the PCU rod, Jacobs et al. [19] addressed that the axial stiffness (37 N/mm) and bending stiffness (2 N/mm) in the PCU rod were much lower than the axial stiffness (22768 N/mm) and bending stiffness (1076 N/mm) in the titanium rod. Their results indicated that lower rod stiffness generated lower intradiscal pressure during physiological load. If the PEEK rod was successfully used in spinal fusion, the PCU rod could apply to OLIF surgery. From those clinical and biomechanical literatures, this study aimed to implement the FE method to investigate the influence of lower stiffness rods in OLIF surgery on the lumbar spine, especially in adjacent discs.

Materiral & method

In this study, a validated three-dimensional FE lumbar spine model was conducted using ANSYS 2021(Swanson Analysis System Inc., Houston, TX, USA), included osseoligamentous L1–L5 vertebrae,

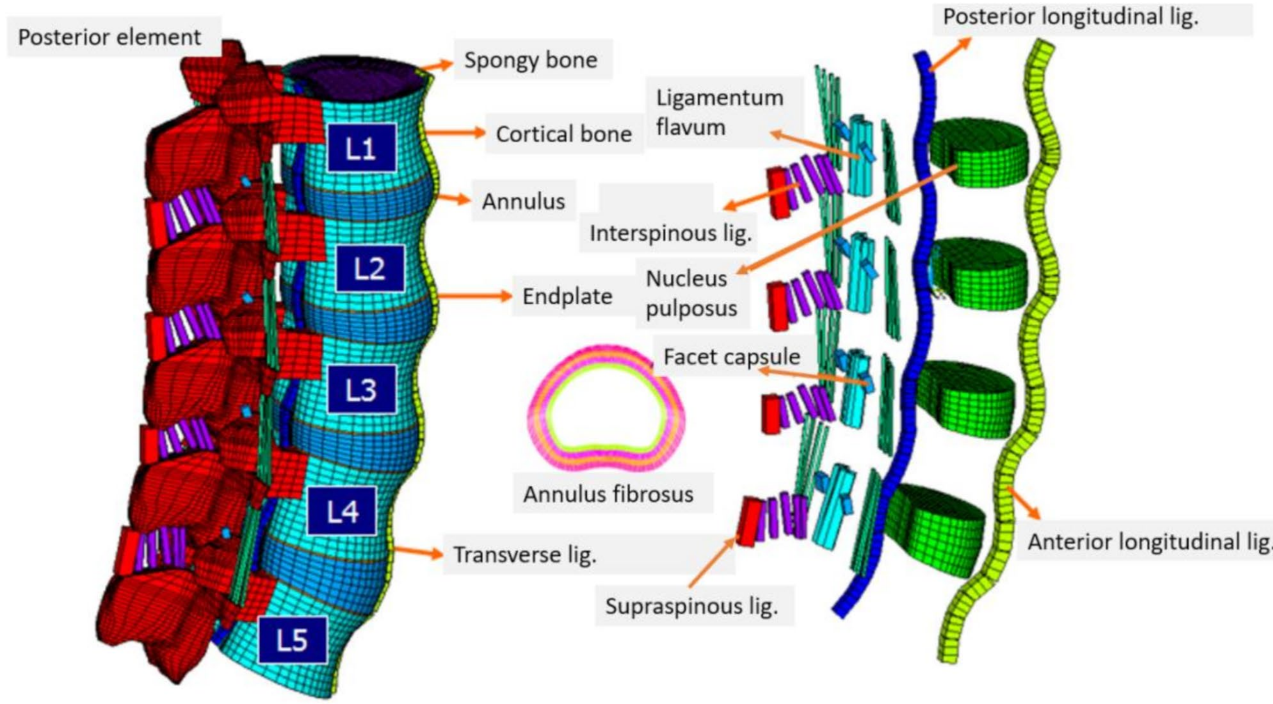

Fig. 1 FE model of the intact lumbar spine

intervertebral discs, endplates, posterior bony elements, and seven ligaments. The intervertebral disc comprised an annulus fibrosus and nucleus pulposus, with 12 double cross-linked fiber layers embedded in the ground substance. The annulus ground substance was modeled based on a Mooney-Rivlin formulation, while the nucleus pulposus was modeled as an incompressible fluid. A non-linear hyperelastic, two-parameter Mooney-Rivlin solid model simulated the elastic modulus of the ground substance in a spinal disc. This model employs the constants C10 and C01, used in FE analysis to describe hyperelastic deformation based on the material constants C1 and C2, as defined by the Mooney-Rivlin model [20–21]. A previous study conducted a convergence test with three different mesh densities: the finest model included 112,174 elements and 94,162 nodes; the standard model had 27,244 elements and 30,630 nodes; the coarse model comprised 4,750 elements and 4,960 nodes [21]. The study assessed the variability in range of motion (ROM) and ultimately opted for the finest mesh density. This choice was made because its variations compared to the standard model were minimal: within 1.03% for flexion ($<0.2°$), 4.39% for extension ($<0.5°$), 0.01% for torsion ($<0.2°$), and 0.001% for lateral bending ($<0.1°$) [22]. Consequently, this validated model was chosen as the FE model for the current study (Fig. 1).

The OLIF surgery models were simulated with pedicle screws and rod systems consisting of conical titanium alloy screws with different materials of the rod. Some current implant materials consisting of titanium alloy rods (Ti-alloy), nickel-titanium alloy rods (Ni-Ti alloy), and polycarbonate urethane (PCU) rods were added to the lumbar spine model, respectively [21]. These three materials were chosen because they are all implantable in the human body and are already in clinical spinal surgery. The interbody fusion device model with oblique cage, made from polyetheretherketone (PEEK), featured as CLYDESDALE Spinal System (Medtronic, Minneapolis, MN, USA) (Table 1; Fig. 2). The INT model consisted of 112,174 element and 94,162 nodes, and the OLIF model consisted of 294,619 elements and 126,021 nodes. In the OLIF model, the 6.4 mm diameter pedicle screws were implanted in L3 and L4, and the 5.5 mm diameter rod was used as the connection between the two pedicle screws, both of which were made of titanium alloy. The bonding setting using contact elements was used in the screw-bone and cage-bone interfaces to examine the biomechanical change of adjacent segments after the bony union.

Table 1 Material parameters of the rod

Material	Young's Modulus (MPa)	Poisson's Ratio
Ti-alloy	110,000	0.28
Ni-Ti alloy	47,000	0.3
PCU	68.4	0.4

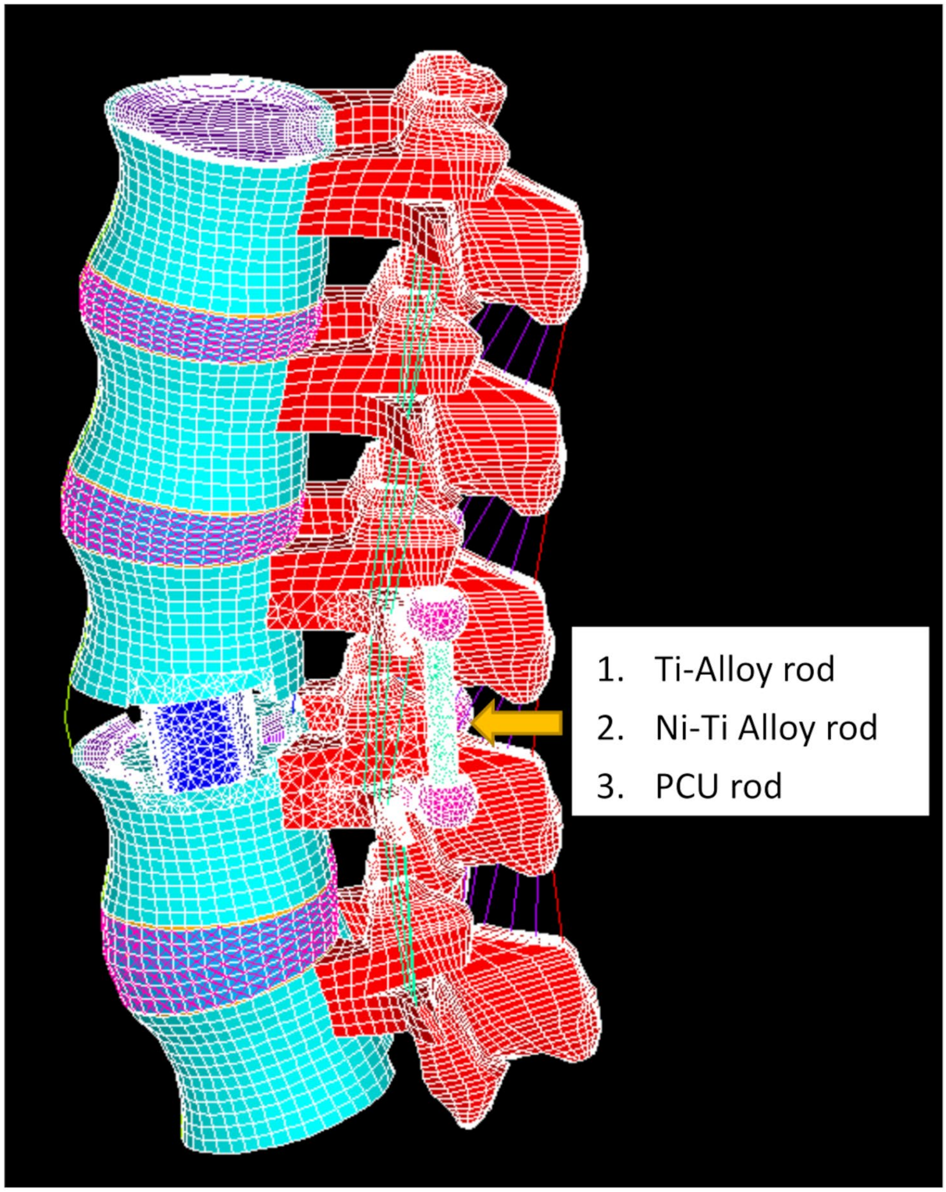

Fig. 2 FE model of the OLIF surgery with different materials of rods

Boundary and loading conditions

In this study, we fully constrained the inferior surfaces of the L5 vertebrae. The loading conditions were set as follows:

1. An axial load of 150 N was applied to the superior surface of the L1 vertebrae.
2. A bending moment was applied to the superior surface of the L1 vertebrae with these parameters: flexion at 21°, extension at 12°, lateral bending at 11°, and rotation at 15°. The ROM included the maximum ranges of all finite element models.

Biomechanical evaluation

Fusion surgeries can excessively restrict ROM. Thus, this study focused on analyzing the ROM at the affected segment. Lumbar fusion with OLIF might lead to the problem of ASD, so the FE study aimed to concentrate on intervertebral disc stress and the facet contact force (FCF) at the adjacent segment. The surgery levels L3-L4 and adjacent levels L2-L3 were investigated in terms of ROM, disc stress, and FCF.

Result

3 – 1 comparison of ROM

The implantation of titanium rods (OLIF_Ti and OLIF_NiTi) resulted in a remarkable reduction in

Table 2 ROM of the lumbar spine in different groups

Model		L1-L2	L2-L3	L3-L4	L4-L5	Total
Flexion	**INT**	4.86	5.15	5.17	6.66	21.8
	OLIF_Ti	5.71 (+18%)	6.03 (+17%)	3 (-42%)	6.94 (+4%)	21.7
	OLIF_NiTi	5.53 (+14%)	5.84 (+13%)	3.01 (-41%)	6.87 (+3%)	21.3
	OLIF_PCU	4.86 (0%)	5.12 (0%)	5.39 (+4%)	6.18 (-7%)	21.6
Extension	**INT**	3.38	3.23	2.9	3.27	12.8
	OLIF_Ti	3.9 (+15%)	3.72 (+15%)	1.39 (-52%)	3.67 (+12%)	12.7
	OLIF_NiTi	3.85 (+14%)	3.66 (+13%)	1.41 (-51%)	3.65 (+11%)	12.6
	OLIF_PCU	3.36 (-1%)	3.23 (0%)	2.64 (-9%)	3.23 (-1%)	12.5
Rotation	**INT**	3.19	3.39	3.88	5.3	15.8
	OLIF_Ti	3.89 (+22%)	3.92 (+16%)	1.62 (-58%)	6.37(+20%)	15.8
	OLIF_NiTi	3.83 (+20%)	3.88 (+15%)	1.74 (-55%)	6.37 (+20%)	15.8
	OLIF_PCU	3.48 (+9%)	3.64 (+7%)	2.68 (-31%)	5.97 (+13%)	15.8
Bending	**INT**	2.66	2.79	2.83	3.17	11.5
	OLIF_Ti	3.29 (+24%)	3.36 (+20%)	0.62 (-78%)	3.83 (+21%)	11.1
	OLIF_NiTi	3.09 (+16%)	3.19 (+14%)	0.63 (-78%)	3.67 (+16%)	10.6
	OLIF_PCU	3.08 (+16%)	3.2 (+15%)	1.37 (-52%)	3.66 (+16%)	11.3

Note: Percentage = ((OLIF groups-INT)/(INT))*100%

Unit: degree

Table 3 Adjacent disc stress in different groups

Model		L2-L3	L3-L4
Flexion	**INT**	791	723
	OLIF_Ti	964 (+22%)	-
	OLIF_NiTi	927 (+17%)	-
	OLIF_PCU	793 (0%)	-
Extension	**INT**	495	415
	OLIF_Ti	567 (+15%)	-
	OLIF_NiTi	559 (+13%)	-
	OLIF_PCU	498 (1%)	-
Rotation	**INT**	551	602
	OLIF_Ti	678 (+23%)	-
	OLIF_NiTi	666 (+21%)	-
	OLIF_PCU	600 (+9%)	-
Bending	**INT**	555	543
	OLIF_Ti	651 (+17%)	-
	OLIF_NiTi	619 (+12%)	-
	OLIF_PCU	621 (+12%)	-

Note: percentage = ((OLIF groups-INT)/(INT))*100%

Unit: KPa

ROM at the surgical levels as listed in Table 2. This also increased from 7 to 20% in ROM of adjacent level L2-L3 in the OLIF_Ti and OLIF_NiTi models. However, after implantation of the PCU rod, the increase in ROM at the adjacent level L2-L3 was less. Especially in flexion and extension, the OLIF_PCU model was comparable to the INT model at the L2-L3 level.

3 – 2 comparison of adjacent disc stress

The OLIF_PCU model is almost identical to the INT model in flexion and extension, as listed in Table 3. After implanting the titanium rod, the OLIF_Ti and OLIF_NiTi model increased stress by about 12%, at least than the INT model. It demonstrated that the OLIF_PCU would not result in stress raise at adjacent level L2-L3 in flexion and extension as shown in Figs. 3 and 4. Higher stress at adjacent disc L2-L3 was concentrated on posterolateral region in extension and anterior region in flexion. In torsion, the adjacent disc stress of the OLIF_PCU model was higher than that of the INT model but was much smaller than that of the OLIF_Ti and OLIF_NiTi models.

3–3 comparison of facet joint force in adjacent level L2-L3

In extension, the OLIF_PCU model almost had the same contact force as the INT model, while OLIF_Ti and OLIF_NiTi models were respectively increased by 25% and 22%, at least as listed in Table 4. However, in rotation, the OLIF_PCU model (+14%) was higher contact force than the INT model, but still lower than the OLIF_Ti (+37%) and OLIF_NiTi (+34%) model.

3–4 stress distribution of the entire implanted lumbar spine

In flexion and extension, after implantation of posterior rods with different materials in the lumbar spine, it could be seen that the Ti alloy model absorbed more stress, as shown in Fig. 5. However, after implantation of PCU rods, it can be seen that the stress distribution of the posterior bone elements decreased and was closer to the INT model.

Discussion

Among lumbar fusion surgeries, the OLIF approach can effectively stabilize the lumbar spine structure, shorten the operation time, reduce blood loss,

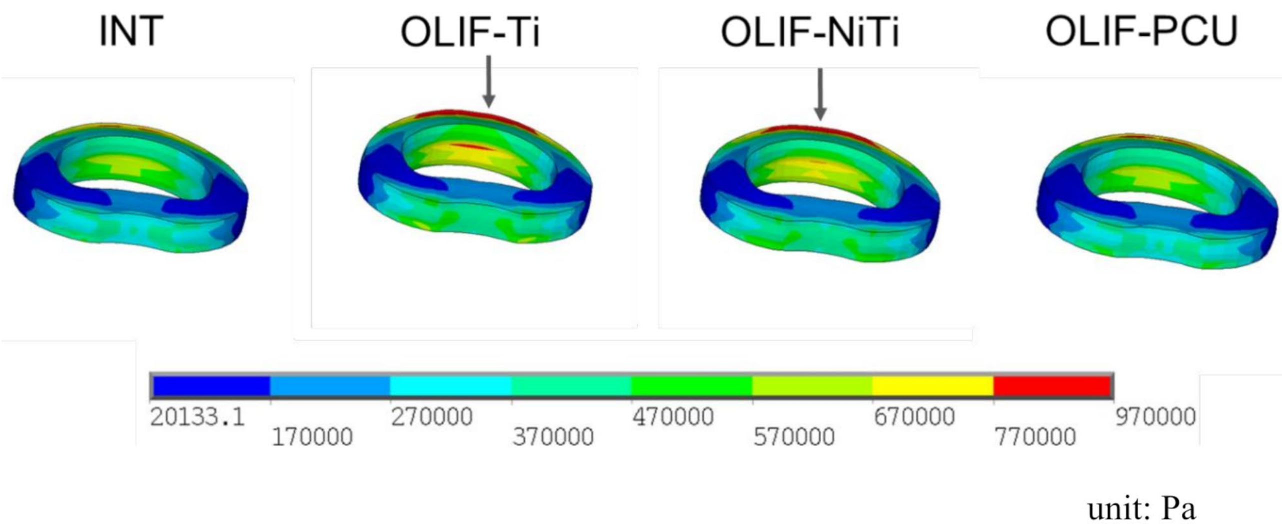

Fig. 3 Comparison of stress distribution at adjacent disc L2-L3 in flexion
Note: arrow indicates the region of higher stress

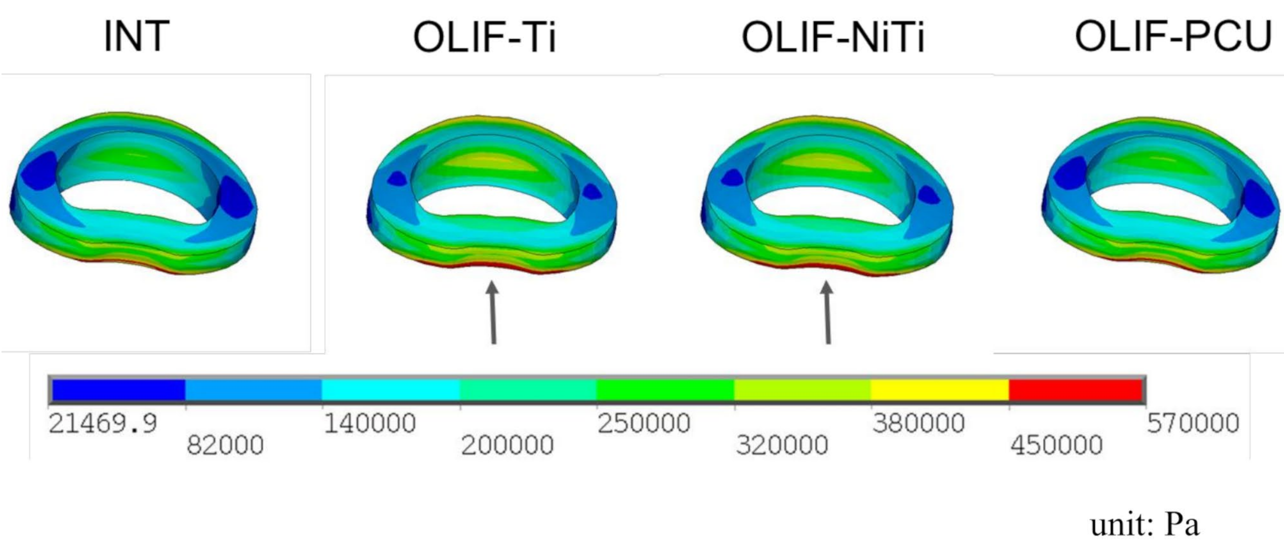

Fig. 4 Comparison of stress distribution at adjacent disc L2-L3 in extension
Note: arrow indicates the region of higher stress

Table 4 The contact force of adjacent facet joints in different models in extension and rotation

Model	Level	Extension		Rotation	
		Left	Right	Left	Right
INT	L2-L3	97	97	0	258
OLIF_Ti	L2-L3	121 (+25%)	121 (+25%)	0	354 (+37%)
OLIF_NiTi	L2-L3	118 (+22%)	118 (+22%)	0	346 (+34%)
OLIF_PCU	L2-L3	97 (+0%)	97 (+0%)	0	293 (+14%)

Note: percentage = ((OLIF groups-INT)/(INT))*100%

Unit: *N*

and improve postoperative recovery. Moreover, it causes less damage to the lumbar spine tissues during the operation, which makes it a mainstream minimally invasive lumbar spine surgery in recent years. However, from the clinical literature [23], there is still a problem of adjacent segment disease after OLIF surgery consisting of early adjacent disc degeneration and adjacent facet joint hypertrophy. Currently, the flexible rod such as Dynesys with PCU rod was successfully used in clinical treatment, especially in preserving adjacent motion segment. In 53 months of follow up, Wu et al. [24] addressed that the ROM of stabilized segments at the final follow-up decreased from 6.20° to 2.76° in Dynesys group and 6.56° to 0.00° in the posterior lumbar inter body fusion with rigid rod, respectively. Zhang et al. [25] investigated 56 patients consisted of Dynesys group with PCU rod and fusion group with rigid rod to find that Dynesys group

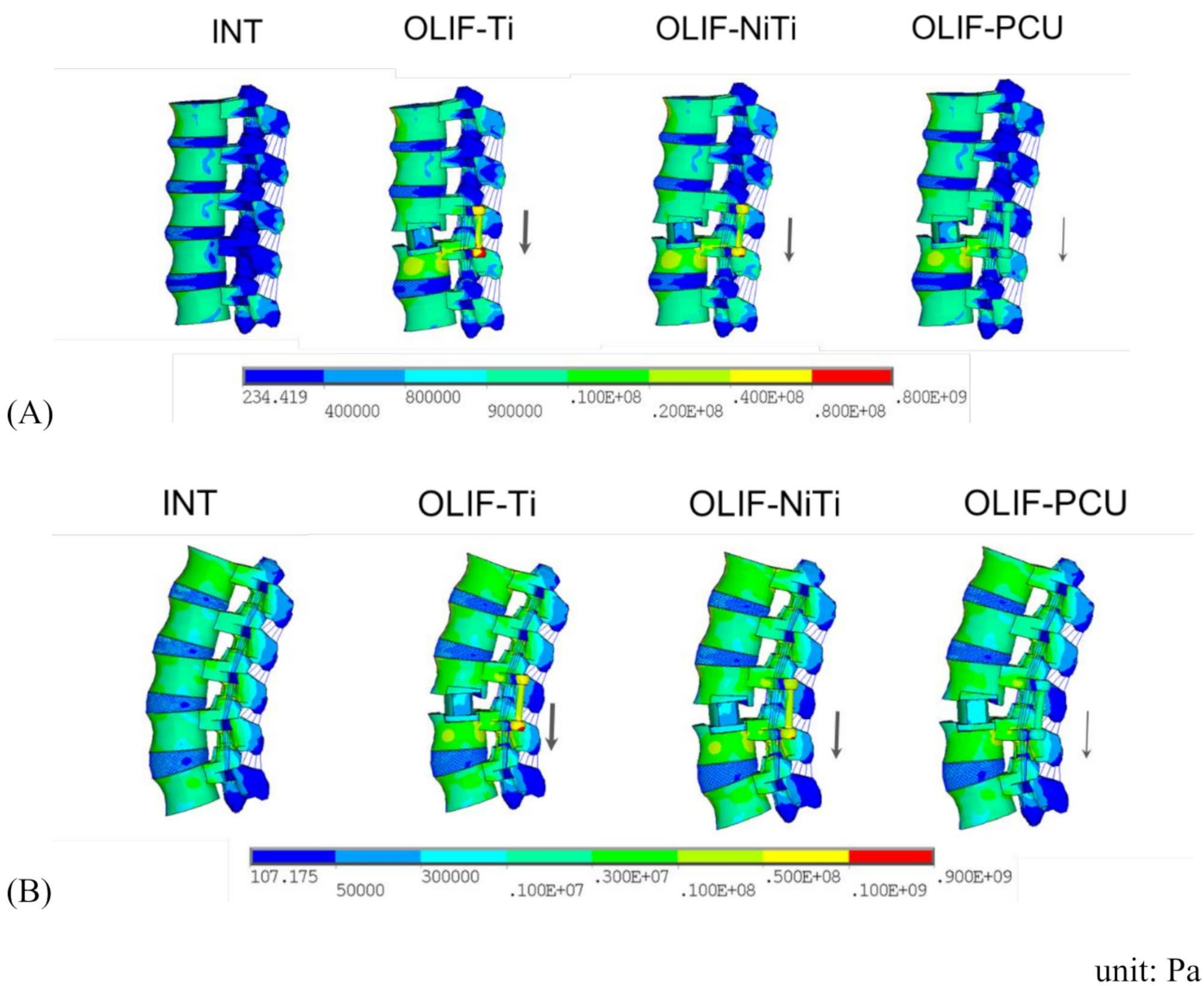

Fig. 5 Comparison of stress distribution in the lumbar spine with different materials of rods (**A**) flexion (**B**) extension
Note: The greater arrow indicates higher stress on the rod

partially maintained surgical level ROM and adjacent level ROM reserved more than that in the fusion group. In these literatures reviewed, the application of the PCU rod in either Dynesys or interbody fusion was thought to allow micromotion at surgical level. These were helpful to avoid generation of adjacent segment disease. Additionally, the PCU rod was soft and thus exhibited a good endurance in clinic application. Therefore, the study implemented the FE model to change different rod materials to realize whether it's possible to alleviate the change of adjacent segments after OLIF surgery with PCU rod.

Our FE results had a similar trend to a previous study in which OLIF with bilateral pedicle screw fixation could stabilize the lumbar spine [12]. Wang et al. [26] used the FE model to investigate the condition of the adjacent segments implanted in the OLIF fusion model. They reported that adjacent ROM of the OLIF with posterior fixation increased from 13 to 23% compared to the INT model. The adjacent segment mobility of Wang et al. did not differ significantly from that of this study in all four loading modes. The adjacent ROM increased from 15 to 20% in our FE analysis. Compared to past studies, the overall trend was consistent with an increase in adjacent segment mobility after implantation of the OLIF with posterior fixation.

Regarding comparing the adjacent facet joint contact forces between the Du et al. [14] OLIF fusion model, the present study showed a 53% torsion, and the facet joint contact forces were more significant than those in the present study. It is attributed to the reason for such differences is that the force of preload applied by Du et al. (500 N) was different from that of the present study (150 N), which resulted in greater force transfer to the facet joints in the Du et al. study. The 150 N axial load was adopted from a previous Yamamoto et al. study [27] in an entire lumbar spine without any muscle only supported a 150 N axial load. If the given load was more than 150 N, the lumbar spine could occur in buckling. However, Du et al. applied a follower load of 500 N to an L3-S1 lumbar spine, which was more physiological because it was directly added to the center of the vertebral body and not affected by buckling problems. However, the two studies found the same trend regarding the increase of adjacent facet joints. In a change of ROM at the surgical level, Yu et al. [28] tested a lumbar spine with OLIF and bilateral pedicle screw fixation on a preload of 500 N with 10 N-m moment, including flexion, extension, torsion, and lateral bending. Their ROM results at the surgical level were similar to ours, with a reduction of ROM of over 40% at the surgical level. The applied moment had more influence on the FE results of the lumbar spine than a preload because we gave similar applied moments.

Regarding the stress distribution, the adjacent disc's maximum stress occurred between bone and disc annulus in flexion and extension, as shown in Figs. 3 and 4. Early adjacent disc degeneration and osteophytes occurred around these locations. Higher stress would induce a disc annulus tear and the disc endplate's ossification. Due to these changes, endplate damage and ossification are significant contributors to disc degeneration because of the limited blood supply to the intervertebral disc, which is confined to the outer layer of the annulus. In extension, the higher stress occurred at the posterolateral side of the adjacent disc. It is possible to compromise the spinal cord. Such a biomechanical change for the adjacent disc after the OLIF surgery would induce adjacent segment disease.

As to the cage subsidence, this study collected the maximum von Mises strain of the vertebral bodies to represent cage subsidence. More strain value on the cage and vertebral body interface meant more cage subsidence. Our study found that the OLIF_PCU ($\varepsilon = 0.0604$) was higher than the OLIF_NiTi ($\varepsilon = 0.043$) and OLIF_Ti ($\varepsilon = 0.040$) group in terms of maximum von Mises strain in flexion. This indicated that using a soft PCU rod could allow micromotion but also result in more cage subsidence than using the traditional rigid rod. Fan et al. [29] also addressed a similar phenomenon, and they reported that compared with a conventional rigid rod, using a non-rigid polyetheretherketone (PEEK) following lumbar interbody fusion might increase the risks of cage subsidence.

The results indicated that the spinal stability is enough under the addition of a spinal cage with different rods as listed in Table 2. Our study proposed three materials for the rod to realize micromotion at the surgical level. This study found that the NiTi alloy rod had a biomechanical effect similar to that of the Ti alloy rod. This meant that a much lower-stiffness rod could be considered for clinical application. Considering that the existing material was compatible with the lumbar spine, the PCU rod was one good choice because it had lower stiffness and successful experience applying the Dyneys system. Moreover, the cage was instead of the spinal disc in the OLIF. According to material mechanics, cage stiffness was higher than intact spinal disc stiffness. Therefore, it is enough to offer sufficient spinal stability. However, to enhance spinal stability, a rigid rod and spinal cage were used in the treatment of spinal instability, thus resulting in early adjacent disc desecration. As a result, it is suggested that a semi-rigid rod be provided to allow micromotion at the surgical level. However, how to judge appropriate spinal instability to select either a rigid or semi-rigid device is an important issue.

Clinically, the decision to use a softer rod depends on the stability of the lumbar spine. If the patient has better lumbar spine stability after implantation of the fusion device, it is recommended that a less rigid rod be given. However, suppose the patient's lumbar spine stability is poorer. In that case, a rod with a higher rigidity is still needed to provide immediate better stability to assist with the bony fusion. This is to avoid the inability to complete the bony fusion before the adjacent segment problem has occurred. However, further research is needed to investigate how clinical lumbar stability should be determined.

The main assumptions and limitations of this study are as follows.

1. The model used in this study did not build up muscles and soft tissues, so the value of the model's loading was lower than the range of normal physiological movements in the human body.
2. Regarding the implant model, the pedicle screws in this study were not threaded, and the teeth of the fusion device were not considered. The study assumed complete fusion and, therefore, simulated the biomechanical effects of the implant in the postoperative period, and the results focused on the stiffness of the overall structure and the influence of the adjacent segment.

Conclusion

The rod material was associated with the change of adjacent segments in OLIF surgery. Adding Ti or NiTi alloy rods can result in a greater reduction of ROM at the surgical level, which causes an increase in disc stress and facet joint contact force at the adjacent segment. After replacing the PCU rod, the cephalic disc stress and facet joint contact force generated in flexion and extension were close to the intact spine. Therefore, compared to titanium alloy rods, the use of OLIF surgery with PCU rods can minimize the impact of the adjacent segment after lumbar fusion.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-025-08504-3.

Supplementary Material 1

Author contributions

CSC participated in the conception and design of the study, acquisition, analysis, and interpretation of the data, as well as the drafting and final preparation of the manuscript. PHC participated in the conception and design of the study, analysis, and interpretation of the data, as well as the drafting and final preparation of the manuscript. SLS and JJC participated in the study's design, acquisition, analysis, and final preparation of the manuscript. STW and CLL participated in the study's conception and design and the manuscript's final preparation. All authors have read and approved the final manuscript.

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Data availability

Data is provided within the manuscript or supplementary information files. Further detailed datasets are available from the author CSC on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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