RESEARCH ARTICLE

Biomechanical Evaluation of the Cross-link Usage and Position in the Single and Multiple Segment Posterior Lumbar Interbody Fusion

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Objective: Previous studies have neither explored the usage of cross-links nor investigated the optimal position of the cross-links in posterior lumbar interbody fusion (PLIF). This study evaluates biomechanical properties of cross-links in terms of different fixation segments and optimal position in single- and multi-segment posterior lumbar interbody fusion.

Methods: Two finite element (FE) models of instrumented lumbosacral spine with single-(L4/5) and multi-segment (L3-S1) PLIF surgery were simulated. On the basis of the two models, the benefits of the usage of cross-links were assessed and compared with the status of no application of cross-links. Moreover, the effects of position of cross-links on multi-segment PLIF surgery were studied in Upper, Middle, and Lower positions.

Results: No significant difference was found in the range of motion (ROM), intersegmental rotational angle (IRA) of adjacent segments, and intradiscal pressure (IDP) regardless of the usage of cross-links in the single-segment PLIF surgery, while the cross-link increased the maximum von Mises stress in the fixation (MSF) under the axial rotation (53.65 MPa *vs* 41.42 MPa). In the multi-segment PLIF surgery, the usage of cross-links showed anti-rotational advantages indicated by ROM (Without Cross-link 2.35°, Upper, 2.24°; Middle, 2.26°; Lower, 2.30°) and IRA (Without Cross-link 1.19°, Upper, 1.08°; Middle, 1.09°; Lower, 1.13°). The greatest values of MSF were found in without cross-link case under the flexion, lateral bending, and axial rotation (37.48, 62.61, and 86.73 MPa). The application of cross-links at the Middle and Lower positions had lower values of MSF (48.79 and 69.62 MPa) under the lateral bending and axial rotation, respectively.

Conclusion: The application of cross-links was not beneficial for the single-segment PLIF, while it was found highly advantageous for the multi-segment PLIF. Moreover, the usage of cross-links at the Middle or Lower positions resulted in a better biomechanical stability.

Key words: Biomechanics; Cross-link; Finite element analysis; Lumbar surgery; Spinal fusion

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Introduction

Spinal fusion surgery is widely used to achieve satisfactory spinal stabilization and alignment correction in the treatment of spinal disorders. Over the past decades, the total number of lumbar fusion surgeries has increased dramatically.[1] A cross-link, also known as a transverse connector, is designed to connect two rods of the posterior fixation instruments to enhance its stability in the spinal fusion surgery.

The usage of cross-links in posterior lumbar internal fixations remains controversial in previous biomechanical and clinical studies. For instance, on the one hand, several biomechanical studies reported that cross-links only enhanced the torsional stability of the instrumented human lumbar spine,[2,3] while a research revealed that cross-links were also able to improve the lateral bending stability of the instrumented calf lumbar spine.[4] On the other hand, cross-links were proved to increase the flexion, extension, and torsional stiffness of the instrumented porcine lumbar spine by fixing 3-, 4-, and 5-vertebral segments,[5] and in particular showed a tendency to improve the torsional stiffness of the instrumented calf lumbar spine,[6] however, they did not significantly improve the stiffness of the instrumented human lumbar spine.[7] In clinical studies, the application of cross-links was proved to be not necessary in thoracolumbar surgery,[8–10] and it might cause potential issues, such as prolonging operation time, increasing the risk of neurologic injury, a higher incidence of infection, irritation, pseudarthrosis, and extra costs for implantation.

To the best of our knowledge, previous studies have not explored the biomechanical effects of cross-links on different fixation segments of the whole lumbar spine. Moreover, enough attention has not been paid to optimize the position of cross-links in long-segment lumbar fixation surgery. Therefore, we developed finite element (FE) models of lumbosacral spines to simulate single and multiple segment posterior lumbar interbody fusion (PLIF) surgeries. The present study aimed to investigate the biomechanical performance of cross-links in two aspects: (i) the necessity of the application of cross-links in single and multiple segment PLIF surgery; (ii) the optimal position of cross-links in multi-segment PLIF surgery.

Materials and Methods

FE Model of Lumbosacral Spine

Computed tomography (CT) scan (Philips Brilliance iCT 256; Philips Healthcare, Amsterdam, the Netherlands) with slices of 1 mm thickness was performed for a normal adult without any lumbar disk disease in Shanghai Changzheng Hospital, China. A written informed consent form was signed by the participant prior to enrollment, and the study protocol was approved by the institutional ethics committee. FE model of lumbosacral spine (i.e., L1-S1 vertebrae, Fig. 1A) was reconstructed by Mimics 16.0 software (Materialise, Leuven, Belgium). In detail, each vertebra was separated into outer cortical bone with a thickness of 1mm and inner cancellous bone by 3-Matic 8.0 software (Materialise, Leuven, Belgium). Moreover, the endplates with a thickness of 0.5 mm and intervertebral discs were included. All the components of the lumbosacral spine

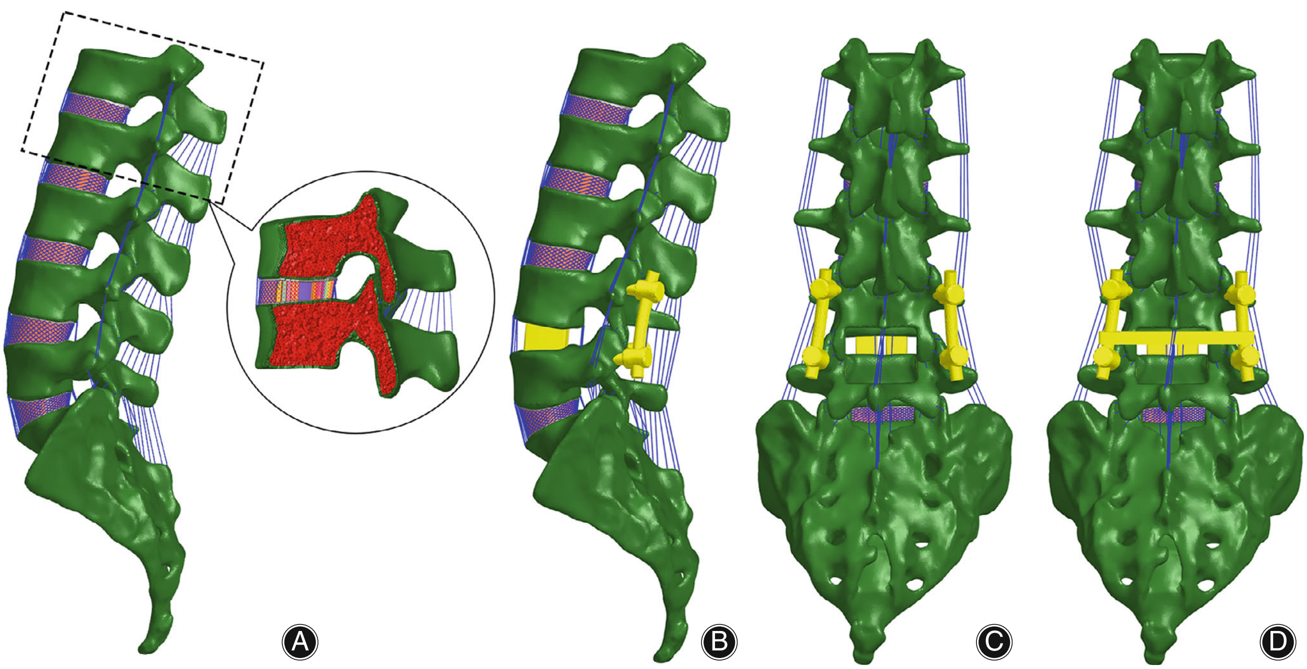

Fig. 1 (A) Lumbosacral spinal model with the posterior lumbar interbody fusion (PLIF) in Hypermesh. (B–D) Single-segment PLIF models without and with cross-links

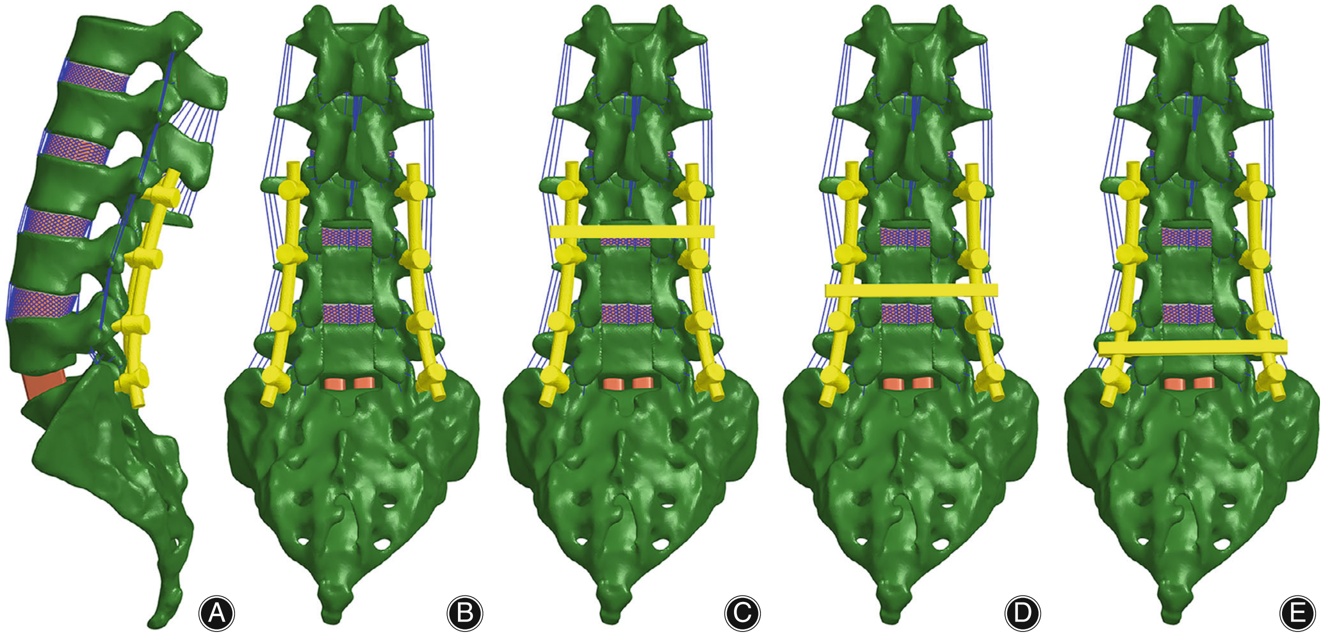

Fig. 2 (A) Lateral view of the lumbosacral spinal model with the multi-segment PLIF. (B–E) Multi-segment PLIF models: Without cross-link, at Upper, Middle, and Lower positions

were assembled and meshed by HyperWorks13.0 software (Altair Engineering, Inc., Executive Park, CA, USA). The mesh size of cortical and cancellous bone ranged from 1.0 to 1.5 mm. The element type of vertebrae was four-node tetrahedral element (C3D4), and the element type of intervertebral discs and endplates was eight-node hybrid hexahedral element (C3D8H). Specifically, the intervertebral disc was partitioned into innernucleus pulposus and outerannulus ground substance, and both assigned with isotropic, hyper-elastic Mooney-Rivlin material.[11,12] The annulus ground substance was reinforced by multi-orientational collagen fibers, which could be modeled *via* tension-only truss element (T3D2) in the pattern of six layers of concentric lamellae.[13] Frictionless surface-to-surface contact was set between the facet joints. Seven major ligaments (anterior longitudinal ligament [ALL], posterior longitudinal ligament [PLL], ligamentum flavum [LF], capsular ligament [CL], intertransverse ligament [ITL], interspinous ligament [ISL], and supraspinous ligament [SSL]) were modeled by tension-only SpringA element.[14] Mechanical properties of the above-mentioned materials are listed in Table 1.

FE Models of Surgical Strategy

To promote the application of cross-links in the clinical practice, single- and multi-segment PLIF surgeries were modeled at the L4-L5 and L3-S1 segments, respectively. The single-segment fixation was divided into two cases: with (W) and without (WO)cross-link (Figs 1B–D). The multi-segment fixation consisted of four cases: Without, Upper, Middle, and Lower cross-links (Figs 2B–E). According to the surgical techniques of PLIF, pedicle screws with a diameter of 6 mm were inserted along the central axis of pedicle and parallel to the corresponding superior endplates. Partial resections of the spinous processes, inferior laminae of the upper adjacent vertebra, and medial half of the facet joints were performed. The targeted disc and endplates were removed and replaced by two cube-shaped cages. The contact between vertebrae and screws, as well as upper and lower surfaces of vertebrae and cages, was set as tie constraints to limit their relative motions. The rods were simulated by fitting lines passing though centers of screw caps. Cross-links with the same cross-sectional area were designed to connect the bilateral rods. In cases with cross-links, cross-links and rods were set as a whole titanium component with no contact. Ti6Al4Vand PEEK were assigned to the materials of the posterior fixation system and cages, respectively, and their mechanical properties are also presented in Table 1.

Boundary and Loading Conditions

The finite element analysis (FEA) of the above-mentioned surgery was performed by Abaqus 6.14 software (Simulia Inc., Providence, RI, USA). Six degrees of freedom of all nodes of S1 vertebra were fixed. A follower load of 500N was applied to a centerline linking central points of all vertebral bodies to simulate upper body weight and muscle forces.[18] Meanwhile, a 7.5 N·m moment was applied to the centroid of the L1 vertebra body to enable the lumbar flexion, extension, lateral bending, and axial rotation.[19] Range of motion (ROM) of the instrumented lumbosacral spine, intersegmental rotational angle (IRA) of adjacent levels,

TABLE 1 Material properties of the FE model

Components	Element type	Young's Modulus (MPa)	Poisson's ratio	Density (g/cm^3)	Cross-section (mm^2)	Reference
Bones						
Cortical bone	C3D4	12 000	0.3	1.7e-6		Goel *et al*. 1994[15]
Cancellous bone	C3D4	100	0.2	1.1e-6		
Endplate	C3D8H	23.8	0.4	1.2e-6		Ueno *et al*. 1987[16]
Intervertebral Disc						
Annulus ground substance	C3D8H	$C_{10} = 0.18$, $C_{01} = 0.045$		1.05e-6		Schmidt *et al*. 2007[17]
Nucleus pulpous	C3D8H	$C_{10} = 0.12$, $C_{01} = 0.03$		1.02e-6		
Annulus fiber layers						Polikeit *et al*. 2003[13]
Outermost	T3D2	550	0.3	1.0e-6	0.70	
Second	T3D2	495	0.3	1.0e-6	0.63	
Third	T3D2	440	0.3	1.0e-6	0.55	
Fourth	T3D2	420	0.3	1.0e-6	0.49	
Fifth	T3D2	385	0.3	1.0e-6	0.41	
Innermost	T3D2	360	0.3	1.0e-6	0.30	
Fixation Devices						
Screw, Rod, Cross-link (Ti6Al4V)	C3D4	113 000	0.3			
Cage (PEEK)	C3D8H	3500	0.3			

Ligaments	Element type	Strain (%)	Stiffness (N/mm)	Strain (%)	Stiffness (N/mm)	Strain (%)	Stiffness (N/mm)	Strain (%)	Stiffness (N/mm)	Reference
Anterior longitudinal ligament	Spring A	ε < 0	0	0 < ε < 12.2	347	12.2 < ε < 20.3	787	20.3 < ε	1864	Rohlmann A *et al*.2006[14]
Posterior longitudinal ligament	Spring A			0 < ε < 11.1	29.5	11.1 < ε < 23	61.7	23 < ε	236	
Ligamentum flavum	Spring A			0 < ε < 5.9	7.7	5.9 < ε < 49	9.6	49 < ε	58.2	
Intertransverse ligament	Spring A			0 < ε < 18.2	0.3	18.2 < ε < 23.3	1.8	23.3 < ε	10.7	
Capsular ligament	Spring A			0 < ε < 25	36	25 < ε < 30	159	30 < ε	384	
Interspinous ligament	Spring A			0 < ε < 13.9	1.4	13.9 < ε < 20	1.5	20 < ε	14.7	
Supraspinous ligament	Spring A			0 < ε < 20	2.5	20 < ε < 25	5.3	25 < ε	34	

intradiscal pressure (IDP) of adjacent segmental discs, and maximum von Mises stress in fixation (MSF) were computed for statistical analysis.

Model Validation

To validate the proposed FE model, a normal lumbosacral model was also developed for model validation *vs* previous studies.[11,20,21] A follower load of 280 N combined with increasing moments from 0.0 to 7.5 N·m with interval 2.5 N·m were applied to the FE model in flexion, extension, lateral bending, and axial rotation tests. The ROM of the lumbosacral model and IDP in L4/5 segments were compared with these *in vitro* biomechanical experiments.

Results

Model Validation

The ROM-Moment curves in the model validation stage were consistent with an *in vitro* study conducted by Rohlmann *et al.* under flexion, extension, lateral bending, and axial rotation (Supplementary Materials S1).[20] The IDP in L4/5 segments showed a consistency in axial rotation,

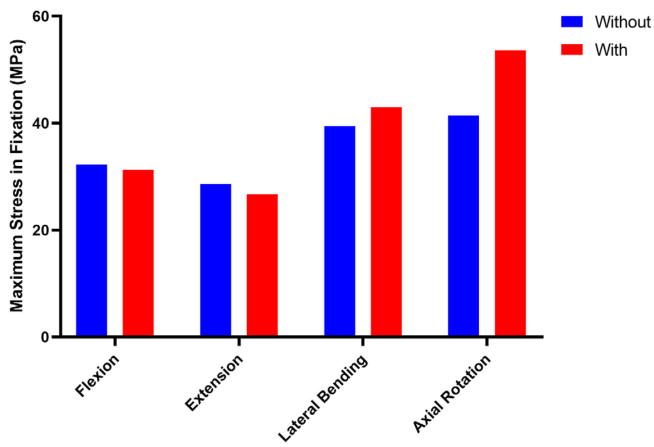

Fig. 3 Comparison of the maximum von Mises stress in fixation (MSF) for the single-segment PLIF without and with cross-link. After using the cross-link, MSF slightly reduced under the flexion and extension, whereas it increased under the lateral bending and axial rotation

while a discrepancy was found in flexion, extension, and lateral bending (Supplementary Materials S2). Except for the personalized spine, a plausible explanation was that muscles

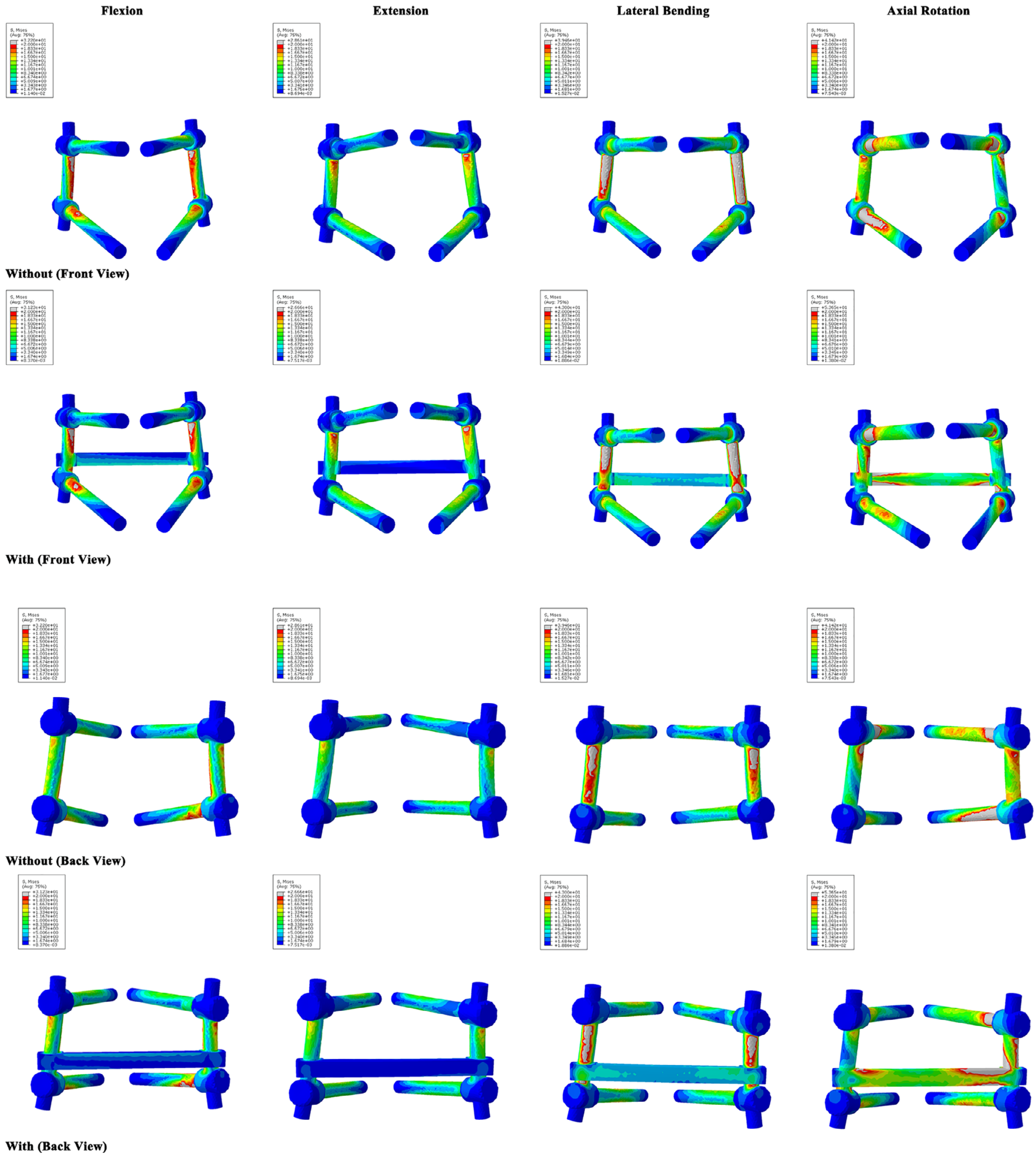

Fig. 4 Front/back views of stress distribution in the screw-rod system for the single-segment PLIF without and with cross-link under the flexion, extension, lateral bending, and axial rotation. A high stress area is mainly concentrated on bilateral rods in lateral bending and thread run-out under the axial rotation

or tendons connecting the spine in the *in vitro* experiments might reduce IDP[17]. It should be mentioned that IDP in the present study still fell in the ranges summarized by Naserkhaki *et al.* and Dreischarf *et al.*[11,21]

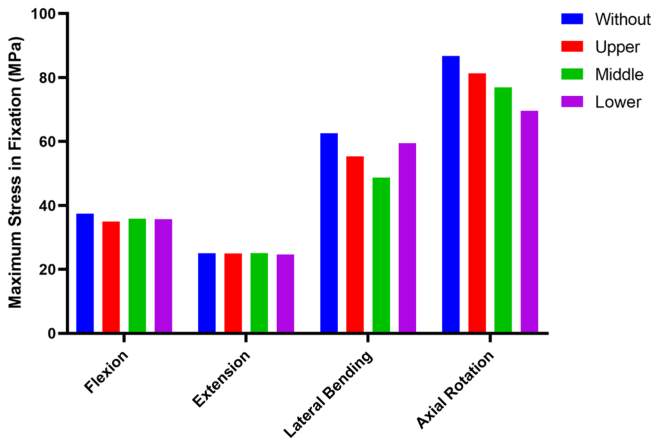

Fig. 5 Comparison of the maximum von Mises stress in fixation (MSF) for the multi-segment PLIF cases (Without cross-link, at Upper, Middle, and Lower positions).In all three cases using the cross-link, MSF significantly reduced under the flexion, lateral bending, and axial rotation. Specifically, the Middle case had the lowest value of MSF under the lateral bending, and the Lower case had the lowest value of MSF under axial rotation

Single-Segment PLIF Model

In the single-segment PLIF model, no significant difference was observed in ROM, IRA, and IDP in the adjacent L3/4 and L5/S1 discs under the four actions regardless of the usage of cross-links. The values of MSF for the two cases are illustrated in Fig. 3. Under the flexion and extension, the MSF in the W case was slightly lower than that in the WO case (i.e., 31.23 MPa *vs* 32.2 MPa and 26.66 MPa *vs* .28.61 MPa). However, under the lateral bending and axial rotation, a higher MSF was found in the W case compared with that in the WO case (i.e., 41.68 MPa *vs* 40.39 MPa and 53.65 MPa *vs* 41.42 MPa). In particular, the difference was more pronounced under the axial rotation. The stress distribution of the fixation is displayed in Fig. 4.

Multi-Segment PLIF Model

In multi-segment PLIF model, a slightly reduction of ROM was observed in the Upper, Middle, and Lower cases under the axial rotation compared with the case without cross-link. Moreover, the smallest ROM (2.24°) occurred in the Upper case, followed by Middle case (2.26°), Lowercase (2.30°), and the case without cross-link (2.35°). However, a very small difference in ROM was found under the flexion, extension or lateral bending. Similarly, IRA for the L2/3 segments was in ascending order as the Upper case (1.08°) < Middle case (1.09°) < Lowercase(1.13°) < the case without cross-link (1.19°) under the axial rotation, and IRA weakly differed under the flexion, extension or lateral bending. In addition, there was no significant difference in IDP among cases under all actions.

The values of MSF under the four actions subjected to a 7.5N·m moment are shown in Fig. 5. The greatest values of MSF were found in the case without cross-link under the flexion, lateral bending and axial rotation, and they were 37.48, 62.61, and 86.73 MPa, respectively. The minimum values of MSF were 34.96 MPa in the Upper case under the flexion, 48.79 MPa in the Middle case under the lateral bending, and 69.62 MPa in the Lowercase under the axial rotation. There was no significant difference in MSF among the four cases under the extension. The greater stress mainly concentrated on two pairs of top and bottom screws, and on the rods (Figs 6 and 7). Moreover, a wider dispersion of stress concentration appeared under the axial rotation. Meanwhile, the stress concentration on the rods slightly decreased with the usage of cross-links.

Comparison between Single- and Multi-Segment PLIF Models

Smaller ROMs, IRAs, and IDP for adjacent segments were found in the four multi-segment PLIF cases compared with the two single-segment PLIF cases under the four actions. Except for the increased MSF under extension, the reduced values of MSF were found in the multi-segment PLIF under flexion, lateral bending, and axial rotation. This indicated that the increased fusion levels sacrificed finite motion of the lumbar spine, whereas decreased the risk of adjacent segmental degeneration.

Discussion

The present study evaluated the application and position of cross-links by numerically simulating single- and multi-segment PLIF models in posterior lumbar surgery. The biomechanical results are instructive to regulate and optimize clinical application of cross-links.

Necessity of the Application of Cross-links on Single-Segment PLIF Surgery

In the single-segment PLIF model, the results revealed that there was no significant difference in ROM, IRA, and IDP regardless of the application of cross-links. The stress distribution under the fixation showed that a high stress area was mainly concentrated on bilateral rods in lateral bending and thread run-out under the axial rotation. The usage of connection also reduced stress concentration on two lower screws under the axial rotation. Importantly, MSF increased under the axial rotation after using a cross-link, and this indicated that the cross-link was not appropriate for the clinical practice in the single-segment PLIF model to achieve satisfactory spinal alignment restoration.

Necessity of the Application of Cross-links on Multi-Segment PLIF Surgery

In the multi-segment PLIF model, although there was no difference between four multi-segment PLIF surgery models under flexion, extension and lateral bending, the usage of cross-link in all three cases (Upper, Middle and Lower)

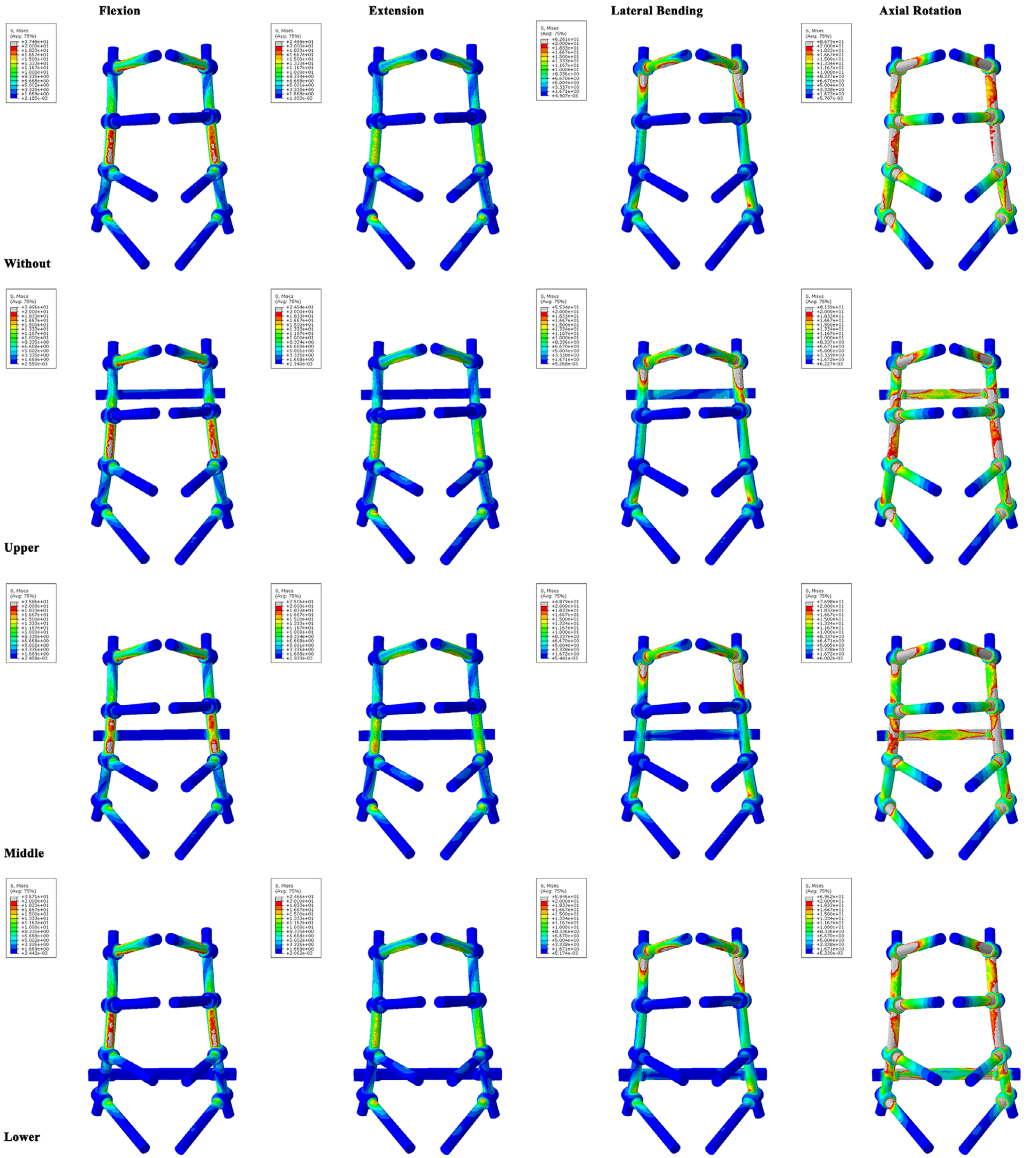

Fig. 6 Front view of stress distribution in the screw-rod system for the multi-segment PLIF cases (Without, Upper, Middle, and Lower) under the flexion, extension, lateral bending, and axial rotation. A high stress is mainly distributed in bilateral rods and thread run-out under the axial rotation. The application of a cross-link reduced stress concentration in bilateral rods under the axial rotation, and it is further pronounced in the Middle position

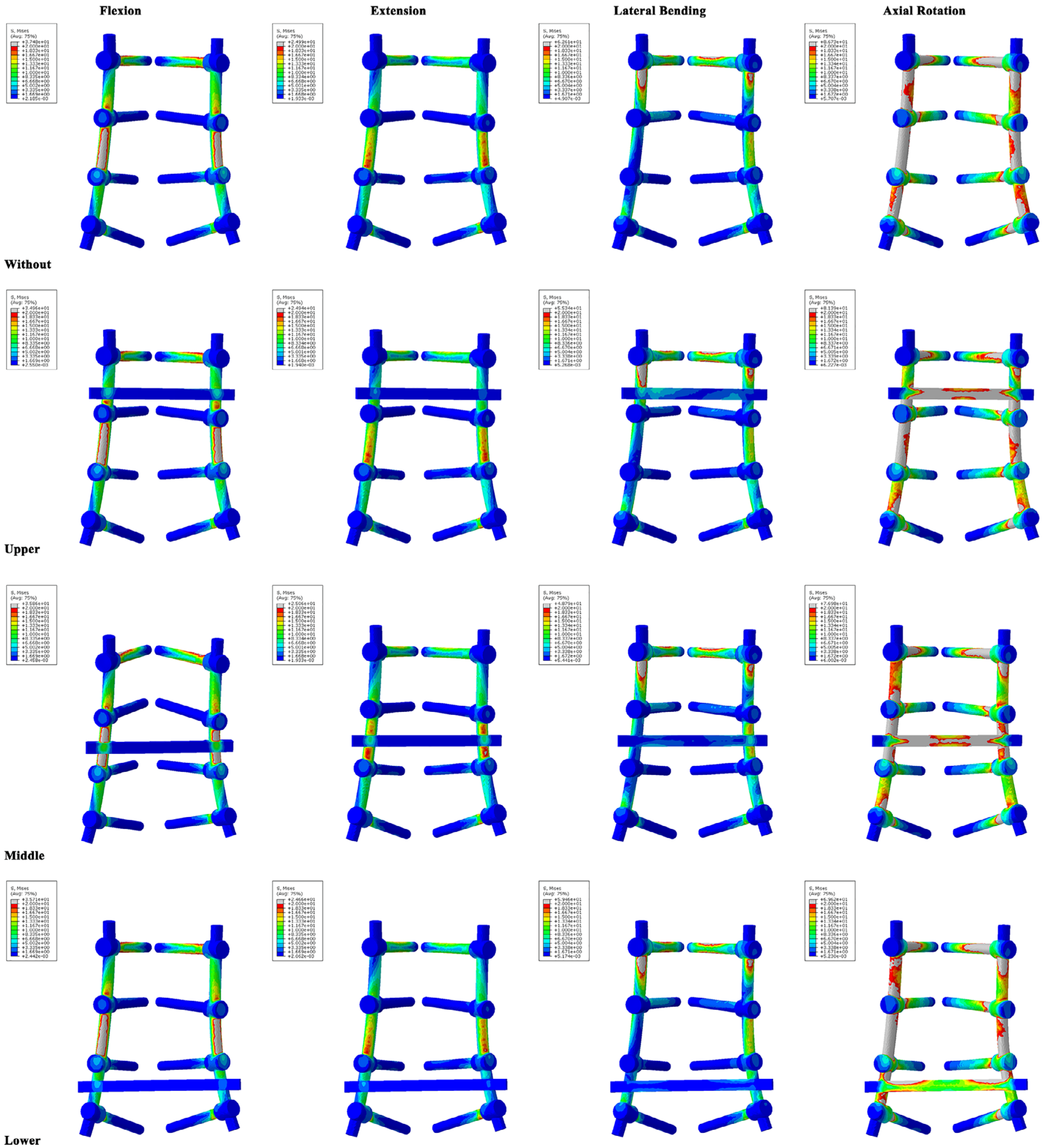

Fig. 7 Back view of stress distribution in the screw-rod system in the multi-segment PLIF cases (Without, Upper, Middle, and Lower) under the flexion, extension, lateral bending, and axial rotation. The description of stress distribution could be referred to Figure 6 legend

showed slender anti-rotational advantages compared with the status of no application of cross-links, which was reflected in the aspects of ROM and IRA. Moreover, a better performance was manifested in MSF on posterior screw-rod fixation system under the flexion, lateral bending, and axial rotation. Hence, a cross-link could be likely beneficial for biomechanical stability during multi-segment PLIF surgery in clinical practice.

Optimal Position of Cross-links in Multi-Segment PLIF Surgery

Regarding the optimal position of a cross-link, the Upper position was better than other positions in terms of ROM and IRA. A smaller rotational displacement indicated a higher fixation stability and a lower risk of stress concentration on the adjacent disc, even with long-term adjacent segment degeneration. From another perspective, the Middle and Lower positions had markedly lower values of MSF on the posterior fixation under the lateral bending and axial rotation, which represented a higher fixation reliability. Regarding the stress distribution of the fixation, it was indicated that a high stress was mainly distributed in bilateral rods and thread run-out under the axial rotation. The application of a cross-link reduced stress concentration in bilateral rods under the axial rotation, and it was further pronounced in the Middle position. On the whole, the results for multi-segment PLIF model revealed the necessity of the usage of a cross-link and its positioning at the Middle or Lower cases was associated with a better biomechanical stability.

Studies on Cross-Links

To date, the validity of cross-links has remained a debated issue in previous biomechanical studies. Doulgeris *et al.* used six cadaveric lumbar spines (L1-S1), in which posterior and middle column injuries were simulated at L3-L5, and found that a cross-link only reduced the ROM in the axial rotation.[2] FEA of L3-L5 model also indicated that the usage of a cross-link slightly decreased the axial rotational displacement and strain in posterior fixation.[3] *In vitro* animal research conducted by Lim *et al.* showed that a cross-link could significantly strengthen the lateral bending and axial rotation stability.[4] A recent systematical review reported that previous biomechanical experiments could reach a relatively consistent conclusion in anti-rotational performance, while inconsistencies were found under flexion, extension, and lateral bending.[22] The proposed FEA model of the multi-segment PLIF surgery also showed the lumbar rotational stability under the usage of a cross-link. In contrast, in specimens with L2-L4 dorsal instrumental fixation, it was revealed that the inclusion of cross-links could not significantly enhance the stiffness of fixation.[7] Moreover, Park *et al.* reported that the application of a cross-link significantly increased strain on the rod when placed at the L4 pedicle subtraction osteotomy site of an L1-S1 model.[23] However, the present model showed lower MSF in cases with the application of cross-links compared with the case without cross-link usage. The possible explanation is that pedicle subtraction osteotomy increases the shear force under the flexion and extension.

Various shapes of cross-links can be designed in clinical practice. From the perspective of surgeons, a well-designed cross-link can offer sufficient stability and rigidity, and leave sufficient space for bone grafting. It is also essential that the distance between rods should be flexibly adjusted, thereby facilitating the easy installation and uninstallation of cross-links. However, only few clinical studies appraised the usage of cross-links in the posterior spinal fixation. Dhawale *et al.* reported that the usage of a cross-link did not change the radiological correction, Scoliosis Research Society (SRS) score, and complications in adolescent idiopathic scoliosis (AIS) patients after a follow-up period of over two years.[10] A similar conclusion was obtained by a retrospective analysis of the usage of a cross-link in AIS patients undergoing pedicle screw fixation.[8] Kulkarni *et al.* reviewed 208 patients who underwent the posterior spinal fixation with fused segments ranging from 1 to 15 without the usage of cross-links.[9] They also found that the usage of cross-links is unnecessary in clinical practice. However, previous studies did not consider factors, such as etiology, involvement of vertebral levels, and the number of fused segments. Therefore, further clinical research with additional solid evidences are required to comprehensively assess the effects of cross-links on lumbar fusion with internal fixation.

Strengths and Limitations

It should be noted that some researches on cross-links have mainly concentrated on cervical, thoracic or thoracolumbarspine.[24–28] However, regional differences of spine, especially various regional curvatures and facet joint orientations, could result in distinctive biomechanical characteristics. Moreover, a rib cage in a thoracic spine restricts the motion of thoracic vertebrae and provides additional biomechanical stability. Thoracolumbar spine is a transitional area between the stiff and kyphotic thoracic spine and the mobile and lordotic lumbar spine. Hence, the above-mentioned differences in biomechanical properties indicated the necessity of an in-depth study with consideration of the lumbar region.

The strength of current study is that it fully investigated the biomechanical properties of different strategies of cross-link usage in lumbar spine. The optimization of cross-link usages provides promising and efficient guidance during PLIF surgery and the patients could also gain potential benefits, such as lower cost of surgery and better prognosis, from the research findings. This study also shows high reliability because it strongly controlled variables that are commonly involved in clinical researches, such as characteristics of patients and surgery.

There are some limitations in the present study. First, the FE model could not perfectly reflect the *in vivo* environment, while it has been greatly refined in the aspects of the microscopic structure of the intervertebral discs and addition of ligaments, which simulated the anatomical structure of the lumbar spine. Second, the shape or size of cross-links was not herein discussed.[28] Third, the patient-specific anatomic structures of lumbar spine might lead to different results. Fourth, the physiological state of lumbar spine in daily activities is more complex with respect to the present kinematic model. Although the present study provided some references for the application of cross-links in PLIF surgery, further research is necessary to determine the role of cross-links in clinical practice.

Conclusions

This study evaluated the usage and position of cross-links by modeling the single-and multi-segment PLIF surgeries from the perspective of biomechanics. The findings indicated that the usage of cross-links was not beneficial for the single-segment PLIF surgery, while the usage of cross-links in the multi-segment PLIF surgery possessed advantages. Moreover, cross-links positioned at the Middle or Lower cases had a better biomechanical stability.

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Supporting Information

Additional Supporting Information may be found in the online version of this article on the publisher's web-site:

Supplementary Materials S1 Range of motion (ROM)-moment curves for model validation. Dashed and solid lines represent Rohlmann *et al.*'s *in vitro* study and the current study.

Supplementary Materials S2 Comparison of intradiscal pressure (IDP) in L4/5 segments for model validation between Rohlmann *et al.*'s *in vitro* study and the current study.

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