Assessment of risk factors affecting mechanical stress on the adjacent segments after lumbar fusion

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Assessment of risk factors affecting mechanical stress on the adjacent segments after lumbar fusion

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ABSTRACT

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Introduction. The ablation of proximal posterior ligament complex (PLC) continuity and the presence of pedicle screws have been reported to affect the biomechanics at adjacent segments after lumbar fusion. However, there have been few studies regarding the quantitative assessment of their contribution to overstress at adjacent segments after lumbar fusion. Therefore, the purpose of this study is to investigate the changes in the disc stress and range of motion (ROM) at adjacent segments after lumbar fusion based on the presence of pedicle screws or the preservation of the proximal PLC.
Methods. In the validated intact lumbar finite element model including L2 through L5, four types of L3-4 fusion models were simulated. These models included the preservation of the PLC continuity with pedicle screws (Pp WiP), the preservation of PLC continuity without pedicle screws (Pp WoP), the sacrifice of PLC with pedicle screws (Sp WiP), and the sacrifice of PLC without pedicle screws (Sp WoP). In each scenario, the ROM and maximal von Mises stress of discs at adjacent segments were analyzed under 4 pure moments.
Results. Among the 4 models, the Sp WiP yielded the greatest increase in the ROM and the maximal von Mises stress of the disc at adjacent segments under four moments. Following the SP WiP, the order of increase of the ROM and the disc stress was Pp WiP, Sp WoP, and Pp WoP. Furthermore, the increase of ROM and disc stress at the proximal adjacent segment was more than at the distal adjacent segment under all

4 moments in each model.
Conclusions. The current study suggests that the preservation of the PLC continuity or the removal of pedicle screws after complete fusion could decrease the stress at adjacent segments, and their combination could act synergistically.

Key words : lumbar fusion, adjacent segment degeneration, pedicle screws, posterior ligament complex, finite element model

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I. INTRODUCTION

Adjacent segment degeneration (ASD) is one of the troublesome sequelae following spinal fusion surgery,[1-3] and has become more widespread with the increase of spinal fusions performed in recent years.[3] Even though there have been conflicting results,[4-6] many biomechanical studies have shown that the fusion process could impose significant amounts of disc stress and increased motion at the adjacent segment.[1,2,7,8]

The potential risk factors for ASD have been investigated and were found to include instrumentation, posterior lumbar interbody fusion, injury to the facet joint of the adjacent segment, fusion length, age, and sagittal alignment.[2,7,9] However, the actual significance of these risk factors still remains uncertain and controversial. These divergent views on the risk factors of ASD may be due to different patient populations and methodologies.[2] Even though fusion affects the motion and disc stress of the adjacent segment, there are significant questions that remain. To what extent does each risk factor impact ASD? Are there interactions among the risk factors on ASD?

In order to answer these questions, we investigated the stress and the range of motion (ROM) at adjacent segments after fusion, using a finite element (FE) model of the lumbar spine. Two important risk factors were chosen. They were the instrumentation (pedicle screws) and the ablation of proximal posterior ligament complex (PLC). Therefore, the purpose of this study was to investigate the changes of the disc stress and ROM at adjacent segments after lumbar fusion according to whether pedicle screws are removed or not, and whether the continuity of the proximal PLC is preserved or not.

II. MATERIALS AND METHODS

1. Finite element model

A 3-dimensional (3D) nonlinear FE model of the lumbar spine that consisted of four lumbar vertebrae, three intervertebral discs, and associated spinal ligaments was developed. Geometrical details of the human lumbar spine (L2-L5) were obtained from high-resolution CT images of a forty six-year-old male subject who had no spinal deformities. Digital CT data were imported to a software program (Mimics; Materialise Inc., Leuven, Belgium) that was used to generate the 3-dimensional geometrical surface of the lumbar spine. The exported IGES files from the Mimics software were input into Unigraphics NX 3.0 (Siemens PLM Software, Torrance, CA, USA) to form solid models for each vertebral segment. The solid model was then imported into Hypermesh 8.0 (Altair Engineering, Inc., Troy, MI, USA) to generate FE meshes. The FE method was analyzed with commercially available software (ABAQUS 6.6-1; Hibbitt, Karlsson and Sorenson, Inc., Providence, RI, USA).

Three-dimensional isotropic solid elements were used for modeling the cortical and cancellous cores, the posterior bony parts of the vertebrae. The anterior longitudinal ligament, posterior longitudinal ligament, intertransverse ligament, ligament flavum, capsular ligament, interspinous ligament, and supraspinous ligament were modeled using tension-only truss elements. Three-dimensional surface-to-surface contact was used to simulate the interaction between the articulating surfaces of facet joints. The cartilaginous layer between the facet surfaces was simulated by ABAQUS's "softened contact" parameter, which exponentially adjusted force transfer across the joint. The initial gap between articulating surfaces was based on CT images.

Based on this intact model, 4 scenarios of one segment lumbar fusion were simulated, which are the preservation of the continuity of PLC with pedicle screws (Pp WiP), the preservation of continuity of PLC without pedicle screws (Pp WoP), the sacrifice of PLC with pedicle screws (Sp WiP), and the sacrifice of PLC without pedicle screws (Sp WoP) (Figure 1).

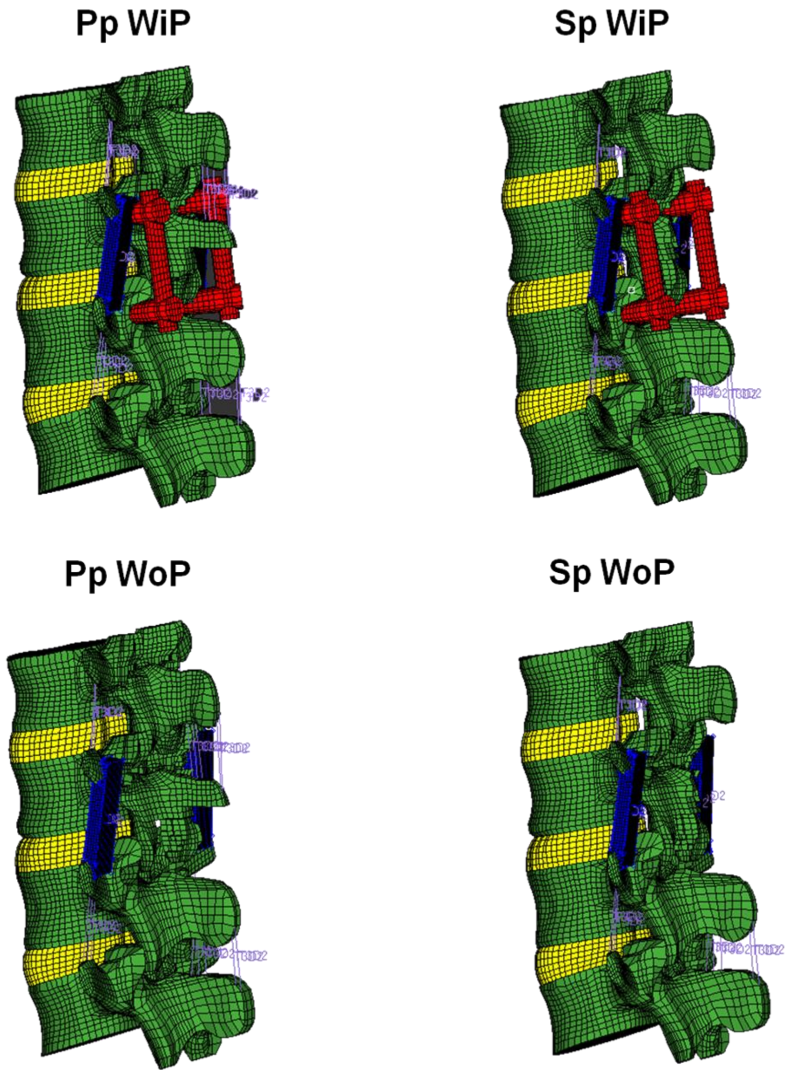

Figure 1. The four FE models in the current study

2. *Material properties*

Material properties were selected from various sources in the literature (Table 1).[8,10-13] The cortical and cancellous regions of the vertebrae were modeled independently. Differentiation between cortical and trabecular bone in the posterior region was difficult to delineate; therefore, the posterior elements were all assigned a single set of material properties.

Table 1. Material properties in the present FE models

Component	*Young's modulus (MPa)*	*Cross-section (mm2)*	**Poisson's ratio**	Reference
Cortical bone	12,000		0.3	8, 10, 11
Cancellous bone	100		0.2	8, 10, 11
Posterior elements	3,500		0.25	8, 10, 11
Nucleus pulposus	1.0		0.499	8, 12, 13
Annulus	Hypoelastic material			8, 12, 13
Ligaments				
Anterior longitudinal	7.8(<12%) 20(>12%)	63.7		12
Posterior longitudinal	10(<11%) 20(>11%)	20.0		12
Ligamentum flavum	15(<6.2%) 19.5(>6.2%)	40.0		12
Capsular	7.5(<25%) 32.9(>25%)	30.0		12
Interspinous	10(<14%) 11.6(>14%)	40.0		12
Supraspinous	8.0 (<20%) 15(>20%)	30.0		12
Intertransverse	10(<18%) 58.7(>18%)	1.8		12
Fusion mass	3,500		0.25	8
Pedicle screws, rod (Ti6Al4V)	110,000		0.3	17

The anulus fibrosis of the intervertebral disc was assumed to follow an isotropic hyperelastic law.[14] The polynomial form of strain energy potential was chosen from the ABAQUS material library. Experimental data from Wagner *et al* were used.[15] The nucleus pulposus was modeled as nearly incompressible. Spinal ligaments were represented by nonlinear material properties. Naturally changing ligament stiffness (initially low stiffness at low strains, followed by increasing stiffness at higher strains) was simulated through the “hypoelastic” material designation (Table 1). Three- dimensional truss elements were used to simulate ligaments, which were active only in tension.

3. Simulation of preservation of PLC (Pp) and Sacrifice of PLC (Sp)

In order to simulate the decompression state, a supraspinous ligament and interspinous ligament between L3 and L4 spinous processes were removed along with partial removal of L3 and L4 spinous processes. Furthermore, the inferior portion of L3 lamina, and ligamentum flavum of L3-4 were removed. The Pp model has the continuity of the proximal PLC between the L2 spinous process and the remained L3 spinous process, while the L3 spinous process and PLC between L2 and L3 were totally removed in the Sp model.

4. Simulation of instrumented posterolateral fusion (WiP) and posterolateral fusion state without instruments (WoP)

The WiP model simulated the scenario of the instrumented posterolateral fusion. First, posterolateral fusion was represented as bilateral rectangular columns of fusion mass between the posterior surfaces of the transverse processes of L3 and L4. The volume of each posterolateral fusion mass was 15 mm x 40 mm x 5 mm (3.0 cm^3) (Figure 1), and the material property of the fusion mass was identical to the posterior element of the vertebral body. This was consistent with the previous clinical measures by Ha et al.[16] No motion was permitted between the fusion mass and transverse processes at the fused sites. This would parallel the clinical situation in that there would be no interface motion with a solid fusion.

A posterior pedicle screw fixation was added to the L3-4 posterolateral fusion. All screws had a sharp thread to prevent relative motion at the bone-screw interface. Except for the screw tip, the remaining surface of the screw was fixed to the bone without allowing relative motion. A “tie” contact condition was used, which enabled the screw threads and vertebrae to be bonded together permanently by full constraint. The diameter of all pedicle screws was assumed to be 5.0 mm, the mean diameter of 6.5 mm outer diameter (including thread height) of real screws. The length of the screws was 40 mm in L3 and L4. The screws were inserted into the pedicles of L3 and L4. Insertion of the screws was in a horizontal direction with inward inclination of 10 degrees. The rods were 5.5 mm in diameter. All instruments were made of titanium alloy (Ti6Al4V).[17]

The simulation of the WoP model, which represented the clinical scenario of the posterolateral fusion state with removal of pedicle screws after fusion achievement, was made by removal of the pedicle screws and rods of the previous WiP model.

5. Boundary and loading conditions

This FE investigation included two types of loading conditions corresponding to loads used in the experimental part of the study[18] for model validation and model predictions for clinically relevant loading scenarios. Validation included loading the model with 10 Nm of moments. The nodes of the inferior surfaces of the inferior-most vertebral body were completely fixed in all directions. To validate the model, the same loading conditions used in the Yamamoto *et al*'s study were applied.[18] Nodes on top of the L2 vertebra were defined as the coupling nodes. A reference node was created and connected to all coupling nodes. A coupling element was, thus, created to distribute moments on the reference node. Therefore, 10 Nm flexion, 10 Nm extension, 10 Nm torsion, and 10 Nm lateral bending moment under the 150 N preload were imposed on the L2 vertebral body, respectively. To reach 10 Nm moments, the five load steps were applied to three models.

The second type of loading condition was a hybrid testing protocol, which was implemented during the flexibility testing of the FE models as described by Goel et al[19] for the study of adjacent level biomechanics (ROM and maximal Von mises stress of the disc). This protocol involved the applied pure moment for the intact and four fusion models until its L2–L5 rotation (displacement) equaled the intact load control case values.

III. RESULTS

1. Model validation

The following definition was used for validating the model responses, and the results were compared to those of a previous Yamamoto *et al*'s cadaver study.[18] Experimental cadaver study and the current simulated loading protocols were identical. The data of this study were within ± 1 standard deviation of the average of the Yamamoto *et al's in vitro* study (Figure 2).

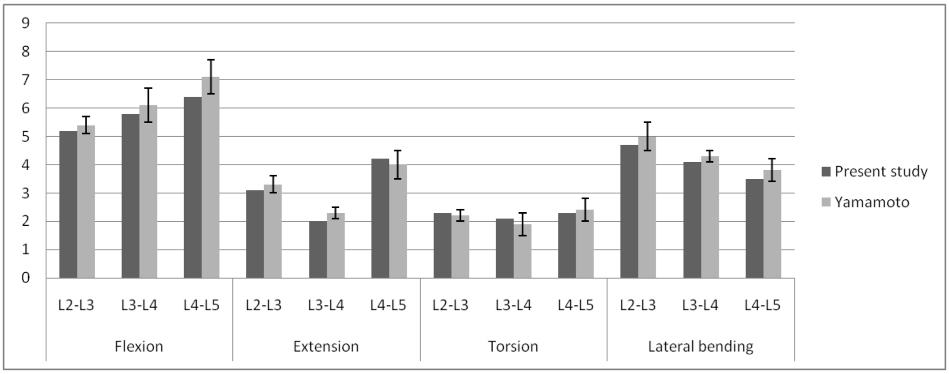

Figure 2. The comparison between the current intact model and a previous study

2. Comparison of ROM among models

The ROM at each corresponding level was compared among the 4 fusion models. The change of ROM was described as percent change from the intact model in each moment under a hybrid protocol (Figure 3).

Flexion moment

Under the flexion moment, a significant increase of ROM at both proximal and distal adjacent segments was observed in all 4 models, as compared with the values of an intact model. ROM changes at the proximal adjacent segment levels amounted to a 50% increase in the Sp WiP model, and to 37%, 31%, and 23% increases in the Pp WiP, Sp WoP, and Pp WoP models, respectively. The SP WiP led to the greatest increase of ROM at proximal/distal adjacent segments and other models had lower values of increase of ROM in the following order, Pp WiP, Sp WoP, and Pp Wop (Figure 3). In each fusion model, the increase of ROM at the proximal adjacent segment was more than that at the distal adjacent segment.

Relatively larger motion was noted at the fusion segment (L3-L4) in the Sp WoP and Pp WoP models, as compared to the corresponding WiP models. This larger motion at the fusion segment led to a smaller increase in ROM at the adjacent segments in the WoP models (Figure 3).

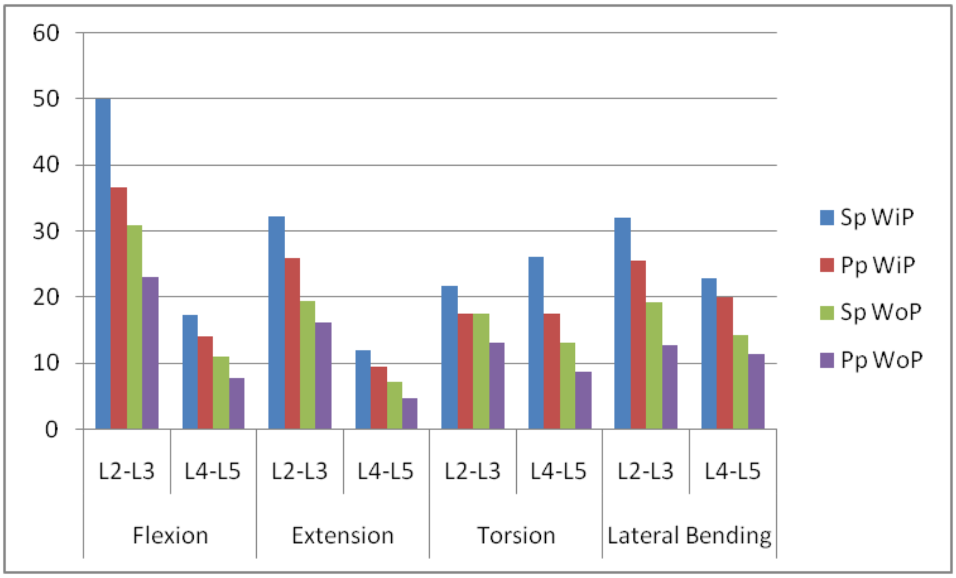

Figure 3. The percent change of the ROM at each corresponding segment among the four fusion models

Extension moment

L3-4 fusion also produced an increased ROM at both adjacent segments under the extension moment. The increased ROM (32%) was most pronounced at the proximal adjacent segment in the Sp WiP. The results of the Pp WiP, Sp WoP, and Pp Wop showed a similar trend to the flexion moment (Figure 3). In each fusion model, the increased ROM at the proximal adjacent segment was greater than at the distal adjacent segment.

Torsion (axial rotation) and lateral bending moment

Similar patterns of ROM changes at adjacent segments were also noted under torsion (axial rotation) and the lateral bending moment (Figure 3). The increased ROM at adjacent segments was most prominent in the Sp WiP model.

3. *Changes of disc stress in four fusion models*

The four fusion models showed increased maximal von Mises stress of the disc at adjacent segments under 4 moments similar to the ROM changes. The model that represents the scenario of the existence of pedicle screws and the ablation of proximal PLC in lumbar fusion (Sp WiP) led to the largest increase of maximal von Mises stress of the disc at adjacent segments under all 4 moments. Compared to the intact model, Sp WiP yielded an increase of disc stress of 83%, 16%, 36%, and 65% at the proximal adjacent segment under the moments of flexion, extension, torsion, and lateral bending, respectively (Figure 4). Following Sp WiP, the order of increase of disc stress at adjacent segments was Pp WiP, Sp WoP, and Pp WoP under all 4 moments. In each model, the increase of disc stress at proximal adjacent segment was always greater than at the distal adjacent segment under the same moment.

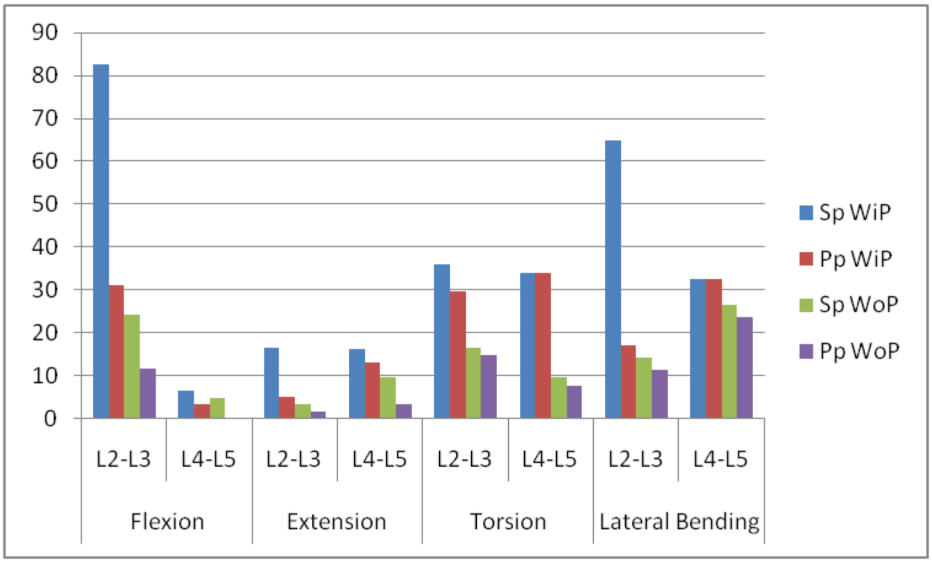

Figure 4. The comparison of the percent change of maximal von Mises stress of the intervertebral disc at each corresponding segment in the four models

IV. DISCUSSION

Many risk factors about ASD have been reported, including instrumentation, lumbar interbody fusion, injury to the facet joint of the adjacent segment, fusion length, age, sagittal alignment, and previous arthritic changes at the adjacent facet joint.[1-3,9,20] Authors chose to evaluate the presence of pedicle screw and the preservation of PLC, because their significance has not yet been fully determined. Four FE models were used in the present study. The Sp WiP model included both risk factors (the ablation of PLC and existence of pedicle screws), while the Sp WoP model and Pp WiP models included only one risk factor of the ablation of PLC and the presence of pedicle screws, respectively. The Pp WoP model represented the fusion model having neither of two risk factors.

As expected, the ablation of PLC with disruption of proximal segment continuity, simulated in Sp WiP and Sp WoP models, caused a greater ROM increase at adjacent segments, compared to the Pp WiP and Pp WoP models. These results are consistent with a previous clinical study, in which the group without PLC preservation showed adjacent instability in more cases than the control group with PLC preservation.[21] Moreover, Cardoso et al have reported that the complete laminectomy without PLC preservation significantly increased adjacent level flexion/extension ROM.[22] Even though the partial or total removal of the posterior element, including the lamina, facet joints, and PLC may be necessary for complete decompression procedures, preservation of the PLC continuity with proximal adjacent segment is paramount to prevent overstress at the proximal adjacent segment, especially in instrumented lumbar arthrodesis.

This study also demonstrated that the pedicle screw fixation created greater mechanical stress at adjacent segments even after fusion. Conversely, in the Pp WoP and Sp WoP models that simulated the scenario of pedicle screw removal, relatively more motion was allowed at the fusion segment (L3-4) under 4 moments. The simultaneously compensatory motion and disc stress were reduced at the adjacent segments, as compared to corresponding WiP models. This is explained by the decrease of stiffness of fusion segments resulting from the removal of pedicle screws. These findings are also in line with our previous *in vivo* study in which non-instrumented fusion had less ROM at adjacent segments on the dynamogram than instrumented fusion.[9] Moreover, the ROM at the fusion segment in the Sp WoP and Pp Wop models is consistent with the results of a previous study in which residual motion of the fusion segment was 2° to 3°.[23]

For the change of von Mises stress of the disc, a similar tendency was observed as with the change of ROM. However, the difference among four models was more pronounced. Under the flexion moment, which induced the largest difference of disc stress among the models, the change of von Mises stress at the proximal adjacent segment in the Sp WiP model amounted to an 83% increase, as compared to the intact model. There was only an 11% increase of von Mises stress at the proximal adjacent segment under the same moment in the Pp WoP model. Furthermore, the disc stress at the proximal adjacent segment was almost always more of an increase than at the distal adjacent segment. These findings suggest that the actual disc stress of the proximal adjacent segments seems to be significantly influenced in the lumbar fusion *in vivo* by the fusion method and decompression technique, such as removal of the pedicle screws and preservation of proximal PLC continuity. Among the four fusion models, Sp WiP showed the most increase of maximal von Mises disc stress at adjacent segments under 4 moments. Following Sp WiP, the order of increase of disc stress at adjacent segments was Pp WiP, Sp WoP, and Pp WoP under all 4 moments, similar to the change of ROM at adjacent segments. Considering the order of the increase of disc stress and ROM at adjacent segments, the removal of the pedicle screws would make a larger contribution to decrease of disc stress at adjacent segments than the PLC preservation.

Moreover, the combination of two risk factors, represented by the Sp WiP model, led to an 83% increase in disc stress at the proximal adjacent segment under the flexion moment, while the ablation of PLC (Sp WoP) and the presence of pedicle screws (Pp WiP), causes only a 24% and 31% increase in disc stress at the corresponding segment under the flexion moment, respectively. These findings mean that there could be synergistic interaction of these two risk factors in increasing the disc stress at adjacent segments following lumbar fusion. This phenomenon was also noted under other moments. In the extension moment, the Sp WiP model caused a 16% increase in disc stress at the proximal adjacent segment, while the Pp WiP and Sp WoP models produced a 5% and 3% increase in disc stress, respectively, at the corresponding segment. Furthermore, in the lateral bending moment, the Sp WiP model showed a 65% increase in disc stress at the proximal adjacent segment. The Pp WiP and Sp WoP models produced a 17% and 14% increase in disc stress, respectively, at the proximal adjacent segment. These results suggest that the overstress of adjacent segments can be reduced synergistically if these two risk factors would be simultaneously controlled in the lumbar fusion *in vivo*.

It is acknowledged that this study has certain limitations. First, the simulations were performed only under four moments. However, loading conditions are more complex in the lumbar spine *in vivo*. Second, we did not simulate lumbar spine muscles in the current FE model. In the *in vivo* state, back muscles might have significant influence on the biomechanical perspective. Third, in spine fusion *in vivo*, the stiffness and shape of the fusion mass is not constant. Even though we assumed the specific shape of the fusion mass and the material properties, the ROM at the fusion segment in the WoP models is similar to that of a previous *in vivo* study and an FE study.[9,23] Therefore, the results from the present FE models could demonstrate a trend similar to that of the clinical findings.

From many previous studies, the fusion itself seems to lead to increased stress at adjacent segments and be a main factor of ASD.[1,2] However, the current study suggests that fusion would not only be a cause of ASD, but the decompression procedure, that is the ablation of PLC, could also be a significant factor leading to increased stress at a proximal adjacent segment. Furthermore, the instrumentation also imposed an additional stress on adjacent segments due to increased stiffness. The combination of these two risk factors produced the synergistically adverse effect on the stress of adjacent discs.

V. CONCLUSION

This study demonstrates that the pedicle screws and the injury of continuity of proximal PLC could produce adverse effects on the disc stress of adjacent segments, and interact synergistically. However, future study is necessary to determine the clinical significance. Additionally other *in vivo* biomechanical studies should precede clinical application.

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ABSTRACT (In Korean)

요추 유합술 후 인접 분절의 생역학적 부하에 영향을 미치는 요인들에 대한 분석

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요추 유합술 후 생기는 인접분절 조기 퇴행성 변화의 위험인자들에 대해서는 그 동안 많은 연구가 있어 왔지만, 이러한 위험인자들의 임상적 중요성에 대한 정량적 분석이나 위험인자들의 상호작용에 대해서는 아직 연구가 부족하다. 본 연구의 목적은 요추 유합술 후 인접분절 조기 퇴행성 변화의 위험인자들 중에서 척추경 나사못의 유무와 후방 인대 연속성의 유무에 따른 인접 분절의 생역학적 변화에 대해 알아보고자 하였다. 46세 성인 남자의 CT image를 통하여 제 2-5 요추의 유한 요소 모델을 만든 후, 척추경 나사못을 이용한 제 3-4 요추 후외측 유합모델을 만들었다. 이 유합모델에서 척추경 나사못의 제거 유무와 제 2, 3 요추 사이의 극상 인대 (supraspinatus ligament), 극간 인대 (interspinous ligament)로 구성된 후방 인대 복합체 (posterior ligament complex, PLC)의 보존 유무에 따라서 4가지 시나리오를 만들었다. 즉, 후방 인대의 연속성을 보존하면서 척추경 나사못을 제거한 모델 (Pp WoP)과 제거하지 않은 모델 (Pp WiP), 후방 인대의 연속성을 제거한 상태에서 척추경 나사못을 제거한 모델 (Sp WoP)과 제거하지 않은 모델 (Sp WiP)을 가정하였다. 각 시나리오에 따른 인접분절의 운동각 변화와 추간판 압력 변화를 정상 요추와 비교하여 분석하였다.

운동각을 비교해 보았을 때 4가지 시나리오 중 Sp WiP 모델의 경우에서 유합에 따른 인접분절의 운동각의 증가가 가장 크게 나타났으며, Pp WoP 모델의 경우 운동각의 증가가 가장 작게 나타났다. 이러한 경향은 상위 인접 분절, 굴곡 모멘트에서 가장 크게 나타났다. 추간판의 스트레스 변화 역시 운동각의 변화와 유사한 양상으로 나타났으며, Sp WiP 모델에서 상위 인접분절의 추간판 스트레스가 가장 크게 증가 하였고, Pp WoP 모델에서 유합에 따른 인접분절의 영향이 가장 적었다. 이러한 현상은 운동각 변화와 마찬가지로 굴곡 모멘트에서 가장 크게 나타났다. 이와 같은 결과를 비추어 볼 때, 요추 유합술 시행 시, 인접 분절과 후방 인대 복합체의 연속성을 유지하면서 감압술을 진행하고, 유합 종괴가 완전히 형성된 이후에는 척추경 나사못을 제거하는 것이 생역학적으로 유합에 따른 인접 분절의 스트레스의 증가를 최소화 하는데 도움이 될 것으로 생각된다.

핵심되는 말 : 요추 유합술, 인접 분절 조기 퇴행성 변화, 척추경 나사못, 후방 인대 복합체, 유한 요소 분석

PUBLICATION LIST

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