Biomechanical effect of bone resorption of the spinous process after single-segment interspinous dynamic stabilization device implantation

A finite element analysis

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Abstract

This study aims to explore the influence of bone resorption of the spinous process after single-segment interspinous process device (IPD) implantation on the biomechanics of the lumbar spine.

The 3D finite element model of the lumbar spine (L3-L5) was modified, and 2 models that simulated the presence and absence of bone resorption of the spinous process were developed using an IPD (Wallis). Its biomechanical effects, such as change in range of motion (ROM) and intervertebral disc and facet stress, were introduced at operative (L4/5) and adjacent (L3/4) levels.

Compared with the INT model, the Wallis model and Wallis-BR model had similar ROMs in lateral flexion and rotation. However, the Wallis model had a lower L3–5 ROM in flexion (20.4% lower) and extension (26.4% lower), and L4–L5 ROM in flexion (74.1% lower) and extension (70.8% lower), while the overall ROM of the Wallis-BR model was greater than that of the Wallis model. The stress on the L3/4 intervertebral disc and facets was similar for all 3 models. Compared with the INT model and Wallis-BR model, the stress on the L4/5 intervertebral disc and facets under all movements significantly decreased in the Wallis model. The stress on the L5 process was greater than that on the L4 process in both the Wallis model and Wallis-BR model, and the load on the processes that underwent bone resorption was lower than that of the Wallis model.

The function of the IPD slowly decreased with the occurrence of bone resorption of the interspinous process. This bone remodeling may be associated with high stress after IPD implantation.

Abbreviations: ASD = adjacent segment degeneration or diseases, ASD= adjacent segment degeneration, CT = computed tomography, FE = finite element, FEA = finite element analysis, FEMs = finite element models, IPD = interspinous process devices, MRI = magnetic resonance imaging, PEEK = polyetheretherketone, PJK = proximal junctional kyphosis, ROM = range of motion.

Keywords: finite element, interspinous dynamic stabilization device, spinous process bone resorption, Wallis system

1. Introduction

Fusion of the lumbar spine, a conventional and effective surgical technique, has been widely applied to treat various degenerative lumbar diseases in recent years. However, certain well-known complications, such as adjacent segment degeneration (ASD), proximal junctional kyphosis (PJK), and lower back stiffness, can be caused by limited spinal flexibility and excessive pressure on the adjacent segments.[1-3] In order to reduce the incidence of ASD associated with rigid fusion of the lumbar spine, nonfusion, and dynamic flexible interspinous devices for the lumbar spine have been developed. The Wallis system, the second generation of interspinous process implants, either fixes the pathologic lumbar segments or maintains the range of motion (ROM) of symptomatic spinal levels. The rationale for using interspinous process devices (IPDs) is that the spacers reduce the motion of flexion and extension of the symptomatic segments and the pressure on discs and facets, further decreasing the incidence of ASD.[4,5]

The use of interspinous device technology remains under debate. Furthermore, several long-term follow-up studies have revealed numerous drawbacks and complications for the Wallis system. Moreover, several recent reports have shown a significantly higher reoperation rate with IPD use, when compared with traditional lumbar techniques.[6] A clinical study revealed that 13% of patients experienced recurrent lumbar disc herniation at the treated section after receiving Wallis implants at an average of 16 months of follow-up.[7] The Wallis system can reduce, but not eliminate, the ROM of the surgical segment, and can reduce the pressure on facets and discs during flexion and extension. However, during lateral bending, Wallis implants cannot effectively share the pressure on the lumbar intervertebral disc.[8] Short-term results have shown a phenomenon of bone...
resorption in the spinous process of the contact part of the prosthesis, which is characterized by a L5 spinous process bone resorption of approximately 22.93 ± 1.63%.[9] It remains unknown how this bone resorption process might change the stress on the lumbar spine, and whether it is related to complications, especially ASD.

The aim of the present study was to evaluate the biomechanical effects of bone resorption of the spinous process after the implantation of a dynamic IPD using finite element analysis (FEA).

2. Materials and methods
A total of 3 nonlinear finite element models (FEMs) of the L3-L5 lumbar spine were established in the present study. The FEM consisted of intervertebral discs, posterior elements, and vertebral bodies, which in turn consisted of the cortical bone, cancellous bone, and numerous ligaments. This was developed through the previously validated lumbar spine of the investigators (Fig. 1).[10] The present study was conducted with the approval of the Ethics Committee of our hospital.

3. FEM of the intact lumbar spine
In order to develop this model, serial thin-section computed tomography (CT) scans of the lumbar spine (from L3 to L5) of a 25-year-old healthy male volunteer were obtained. These images were analyzed, and the geometrical surface model of the vertebra was constructed using Mimics 15.0 software (Materialise Inc., Leuven, Belgium). The vertebral surface was smoothed using Geomagic Studio 12.0 software (Geomagic Inc., Research Triangle Park, NC). ANSYS Workbench 15.0 (ANSYS Inc., Canonsburg, PA) was applied to mesh the solid model of the vertebra. The average thicknesses used for the cortical bone were 1.0 mm.[11] The intervertebral discs, including the disc annulus, disc nucleus and endplates, were developed and situated between the vertebrae, according to anatomical data. The fiber content of the annulus fibrosis was located at a mean of 24° to 45° from the horizontal plane.[12] Five ligaments simulating the ligamentous structures of the lumbar spine were integrated into this model, including the anterior and posterior longitudinal ligaments, capsular ligaments, ligamentum flavum, and interspinous ligament. The various material properties of these different tissues were obtained from a literature[10] (Table 1). Tension-only spring elements with nonlinear material properties were used to model the ligaments and facet capsules. The material properties and element types used in the FEM of the lumbar spine were based on data obtained from previously references.

In the present study, the bond contact was used to stimulate the interaction of the vertebra and discs. The contact relationship between the articulating surfaces of the joints was set as surface-to-surface contact, and the friction coefficient was set at 0.1.[13]

4. FEM of the Wallis model and Wallis-BR model
The FEM of the intact lumbar spine was developed to stimulate the Wallis model and Wallis-BR model (Fig. 1). The L3-L5 model was

Figure 1. FE models of the lumbar spine (A and B: The L3-L5 INT model; C and D: Wallis model; E and F: Wallis-BA model).
Comparison of ROM between the INT model and previous experimental studies.

| Material properties | Young Modulus (MPa) | Cross-section, mm² | Poisson ratio |
|---------------------|--------------------|--------------------|--------------|
| Cortical bone       |                    |                    |              |
|                     | Ex = 11,300        | Vxy = 0.48         |              |
|                     | Ey = 11,300        | Vxz = 0.20         |              |
|                     | Ez = 22,000        | Vyz = 0.20         |              |
|                     | Gx = 3800          |                    |              |
|                     | Gy = 5400          |                    |              |
|                     | Gz = 5400          |                    |              |
| Cancellous bone     | Ex = 140           | Vxy = 0.45         |              |
|                     | Ey = 140           | Vxz = 0.32         |              |
|                     | Ez = 200           | Vyz = 0.32         |              |
|                     | Gx = 48.3          |                    |              |
|                     | Gy = 48.3          |                    |              |
|                     | Gz = 48.3          |                    |              |
| Posterior bone      | 3500               | 0.25               |              |
| Nucleus             | 1.0                | 0.50               |              |
| Annulus ground substance | 4.2             | 0.45               |              |
| Annulus fibers      | 400                | 0.30               |              |
| Endplate            | 24.0               | 0.40               |              |
| Ligament            |                    |                    |              |
| Anterior longitudinal | 20                | 63.7               |              |
| Posterior longitudinal | 20                | 20.0               |              |
| Ligamenta flavum    | 19.5               | 40.0               |              |
| Facet capsules      | 32.9               | 30.0               |              |
| Interspinous        | 11.6               | 40.0               |              |
| Supraspinous        | 15                 | 20.0               |              |
| Transverse          | 58.7               | 1.8                |              |
| PEEK cage (Wallis system) | 3500          | 0.40               |              |
| Nylon rope (Wallis system) | 2400         | 0.40               |              |

used to simulate the Wallis model and Wallis-BR model. In the L3-L5 FEM of the lumbar spine, the L4-L5 posterior segment of the superior segment of the spinous process, interspinous ligament, caudal part of the L4 spinous process, and lateral part of the L5 spinous process were resected. Then, the Wallis system was inserted to obtain the model. On the basis of the Wallis model, the Wallis-BR model was developed by resecting 16% of the L4 spinous process and 22% of the L5 spinous process at the point of contact between the Wallis system and interspinous process.[59] In the Wallis model and Wallis-BR model, the second-generation interspinous process implant (the Wallis system; 23 mm in height, 15 mm in thickness, and 12 mm in distraction height) was used.[100] The relationship between the Wallis system and contact surface of the upper and lower spinous processes was bonded.

5. Boundary and loading conditions

In the L3-L5 FEM, Wallis model and Wallis-BR model, the inferior surface of the L5 vertebral body was fixed. An axial load of 500N, which corresponds to the upper body weight of a healthy adult, was imposed on the L3 vertebral body in these models. Moreover, 10-Nm flexion, extension, rotation, and lateral bending movements were applied to the superior surface of the L3 vertebral body. The ROM of the lumbar spine, stress of the bilateral facet joint, intervertebral disc, and the L4-L5 spinous process were measured.

6. Statistical analysis

For convenience, the FE numerical value was derived for use in nonparametric tests. The collected data were analyzed using SPSS 20.0 software (SPSS, Inc, Chicago, IL). \( P < .05 \) was considered statistically significant.

7. Results

7.1. Validation results of the model

The FEM was validated by comparing the ROM of the whole lumbar spine with previously published studies. The predicted results of the L3-L5 FEM had a good agreement with previous experimental studies[14-17] (Table 2).

7.2. Stress on the facets

For all models, similar stress on the facets during all motions was observed at the L3-L4 level, and the difference was not statistically significant (Fig. 2A). However, statistically significant differences were observed for the stress on the facets (\( P < .05 \)) at the L4-L5 level of the Wallis model and Wallis-BR model in extension, lateral bending, and rotation, but not flexion (\( P = .61 \)). Compared with the facet stress in the Wallis model, the L4-L5 facet stress in the Wallis-BR model was similar in flexion, but with significantly increased extension, rotation, and lateral bending. In addition, the L4-L5 facet stress of the INT model was greater than that of the Wallis-BR model, and there was a significant difference in all motions, except in flexion (Fig. 2B).

7.3. Stress on the intervertebral discs

The 3 surgical simulations did not significantly differ in terms of the von Mises stresses on the annulus of the L3-L4 disc in all motions (Fig. 2C). The stresses on the L4-L5 disc were significantly reduced in the Wallis models (\( P < .05 \)). When combined with the Wallis-BR model, the L4-L5 disc stresses of the Wallis model significantly decreased in all motions. In extension, the stresses on the L4-L5 disc for the INT model were greater than those for the Wallis-BR model (Fig. 2D).

7.4. Range of motion (ROM)

In the present study, INT model data were used as baseline values for describing the ROM changes in these FEMs. For example, ROM change rate = \( \frac{ROM_{WALLIS} - ROM_{INT}}{ROM_{INT}} \times 100 \% \), where \( ROM_{WALLIS} \) and \( ROM_{INT} \) represent the

| Material properties | Young Modulus (MPa) | Cross-section, mm² | Poisson ratio |
|---------------------|--------------------|--------------------|--------------|
| Cortical bone       |                    |                    |              |
|                     | Ex = 11,300        | Vxy = 0.48         |              |
|                     | Ey = 11,300        | Vxz = 0.20         |              |
|                     | Ez = 22,000        | Vyz = 0.20         |              |
|                     | Gx = 3800          |                    |              |
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|                     | Ez = 200           | Vyz = 0.32         |              |
|                     | Gx = 48.3          |                    |              |
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| Posterior bone      | 3500               | 0.25               |              |
| Nucleus             | 1.0                | 0.50               |              |
| Annulus ground substance | 4.2             | 0.45               |              |
| Annulus fibers      | 400                | 0.30               |              |
| Endplate            | 24.0               | 0.40               |              |

3
ROM for each motion segment in the Wallis model and INT model, respectively.\(^{[18]}\)

Compared with the ROM of the INT model, the ROMs of the Wallis and Wallis-BR models at L3-L4, L4-L5, and L3-L5 were similar in lateral bending and rotation. The ROM was < 5%. The L3-5 ROM of the Wallis model was 20.4% lower in flexion and 26.4% lower in extension, while the L4-5 ROM was 74.1% lower in flexion and 70.8% lower in extension, when compared with the INT model. However, the L3-L4 ROM was 18.9% higher in flexion and 19.2% higher in extension. Between the Wallis and Wallis-BR models, the ROMs of L3-L4, L4-L5, and L3-L5 increased more than 20% in flexion and extension. Similar ROM (< 5%) change rates in extension were observed for the Wallis-BR and INT models. However, the ROM change of the Wallis-BR model was 6.69% higher in flexion (Fig. 3).

### 7.5. Stress on the spinous process

In the Wallis and Wallis-BR models, there was a significant difference in L4 and L5 spinous process stress with the flexion, extension, rotation, and lateral bending movements. Moreover, the stress on the spinous process in the Wallis model was greater than that in the Wallis-BR model, and the difference was statistically significant ($P < .001$, Fig. 4).
to 15% in patients who were implanted with an IPD, which was have reported that the incidence of radiographic ASD was 4.1% have an interspinous spacer.[5,6] Long-term results revealed that retaining segmental motion.[24]

preventing accelerated ASD due to the protective effects of the segments adjacent to the fusion mass have been considered to play a key role. Moreover, the hypothesis behind the use of the Wallis spacer is that increasing the distance of the intervertebral disc with the implantation of an IPD between spines can avoid lumbar fusion and distribute the axial stress of the lumbar intervertebral disc. However, in the present study, it was found that during the early period after the implantation of the Wallis system, the intervertebral disc pressure during various motion states significantly decreased. Furthermore, the intervertebral disc pressure in all types of motion states were significantly elevated in cases of bone resorption, reaching or even exceeding normal lumbar intervertebral disc stress levels. The exception was that these stress levels were lower than the normal lumbar intervertebral disc stress in the posterior extension state. This result could be correlated with the recurrence of lumbar disc herniation.

9. Stress on the intervertebral disc

Lumbar disc herniation recurrence, prosthesis loosening, and adjacent segment compression fractures are common postoperative complications of Wallis implants. The reported incidence of the postoperative recurrence of intervertebral disc herniation was 13% after Wallis implantation.[17] Normally, the lumbar intervertebral disc bears 80% of the axial stress of the lumbar spine. The etiology of lumbar degeneration remains unclear, but high pressure in the lumbar disc has been considered to play a key role. Moreover, the hypothesis behind the use of the Wallis spacer is that increasing the distance of the intervertebral disc with the implantation of an IPD between spines can avoid lumbar fusion and distribute the axial stress of the lumbar intervertebral disc. However, in the present study, it was found that during the early period after the implantation of the Wallis system, the intervertebral disc pressure during various motion states significantly decreased. Furthermore, the intervertebral disc pressure in all types of motion states were significantly elevated in cases of bone resorption, reaching or even exceeding normal lumbar intervertebral disc stress levels. The exception was that these stress levels were lower than the normal lumbar intervertebral disc stress in the posterior extension state. This result could be correlated with the recurrence of lumbar disc herniation.

10. Stress on the facet

Several recent studies have found that facet stress during posterior extension is significantly higher than during flexion.[27] In addition, facet stress alters as the body position is changed and reaches its maximum in the posterior extension position. A recent FE analysis study revealed that facet stress in adjacent segments after lumbar fusion increased by 80% to 90% and 20% to 90% in the posterior extension and rotation, respectively.[18] In the same way, another study has proven that the facet stress on the adjacent segment after lumbar fusion significantly increased in a biomechanical experiment in vitro.[28] Moreover, Wiseman et al revealed changes in facet stress after interspinous process implantation, suggesting that facet stress could slightly decrease along with the implantation of IPDs at the surgical segment with no obvious influence on the adjacent segment facet.[19] In the present study, the same stress changes were found. That is, in every motion state, except flexion, postoperative facet stress decreased, compared with preoperative facet stress. Furthermore, there was no significant difference in postoperative facet stress in
the flexion state. Moreover, after bone resorption occurred, facet stress was significantly greater than before bone resorption. The most significant stress change occurred in the posterior extension condition. To some extent, these findings explain the causes of the stress on the facets of the lumbar vertebra after IPD implantation.

11. Stress on the spinous process

The advantage of Wallis system implants is its ability to retain the flexion and posterior extension motions of the surgical segment, while increasing the stress on the surgical spinous process.\(^{[8,26]}\) The Wallis system absorbs some of the axial stresses of the spine. The stress load transmitted from the cranial to caudal segments of the spine is mainly concentrated on the spinous process of the surgical segments, and the caudal segment experiences the greatest stress. In addition, the bundling belt of the Wallis device is fixed on the spinous process, increasing the stress on the spinous process and prosthesis. In the present study, it was found that before the bone resorption of the spinous process, stress was greater in the L5 spinous process than in the L4 spinous process. Tanne et al.\(^{[31]}\) found in 1990 that traction and compression stress were associated with bone resorption. Their FE analysis revealed that increased local stress could correspondingly lead to bone resorption and bone remodeling. Furthermore, through FE studies and animal experiments, Takuma et al.\(^{[32]}\) proposed that these mechanical stress changes resulted in bone resorption and bone remodeling. According to the data obtained from the present experiment model, immediately after surgery, there was no obvious difference between the L4 and L5 spinous process under the upright condition. However, when the flexion and extension positions were compared, the stress on the surgical segment obviously increased, and the stress on the L5 spinous process was greater than the stress on the L4 spinous process. After bone resorption, stress at the L4 and L5 spinous process was significantly lower, compared with that before bone resorption, and there was no statistically significant difference between L4 and L5. As the Wallis nylon bind belt limits spine motion, stress on the L4 spinous process was greater than that on the L5 spinous process under flexion. In the extension state, stress on the spinous process was significantly greater than that in the flexion state.

In comparing the Wallis and Wallis-BR groups, it was found that spinal stress after bone resorption was significantly lower than that before bone resorption occurred. This finding illustrates that the extent of bone resorption might be associated with stress.

12. ROM of the lumbar spine

Second-generation interspinous process implants (the Wallis system) are made of polyetheretherketone (PEEK), and are developed to decrease the gap in the spinous processes, absorb part of the load of the corresponding segment’s intervertebral disc and facets, limit the extension of the segment, and restrict excessive flexion through the spine bundling belts.\(^{[33,34]}\) The Wallis device reduces the stress on the surgical segment’s intervertebral disc and facet, while retaining a certain ROM in the corresponding segment. When spinal bone resorption occurs, the spinous process cannot provide stable stress transmission, which causes biomechanical changes in the surgical segment and increases the stress on its intervertebral disc and facet, thereby changing the motion of the surgical segment. In the present study, compared with normal lumbar ROM, the motion of the spinal model with the Wallis implantation was reduced to more than 1° in the flexion and posterior extension states. In the short-term, Wallis implantation could limit the lumbar flexion and posterior extension motions to provide stability for the lumbar spine.

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**Figure 5.** (A) The magnetic resonance imaging (MRI) for the 54-year-old Chinese woman is shown. (B) The X-ray at postoperative 1 month is shown.
However, the ROM after bone resorption was greater than 1° in the flexion state. Compared with lumbar ROM during the early postoperative period, the motion of the lumbar spine with bone resorption obviously increased. This could indicate a decrease in the ability of the Wallis device to reduce the motion of the segment and decrease stress on the disc and facet.

13. Case presentation

A 54-year-old Chinese woman visited our hospital due to a 6-month history of low back pain and right-sided sciatica. The lumbar plain film revealed osteophyte formation without instability at the lateral dynamic X-ray. The magnetic resonance imaging (MRI) revealed that the bulging L4/L5 level right-sided lumbar intervertebral disc, the facets, and the yellow ligaments hypertrophy caused lumbar canal stenosis (Fig. 5A). The patient was diagnosed with sciatica induced by lumbar canal stenosis. The JOA score was 18 and the VAS score was 6. The patient was treated with a Wallis system implantation at the L4/L5 segment. The symptoms of lumbalgia and sciatica significantly improved after surgery. In addition, the JOA score was 25 and the VAS score was 1. The X-ray results at postoperative one month revealed the Wallis system was placed well. After 1 year, the patient sought for an evaluation at our Outpatient Department for the reoccurrence of right-sided sciatic pain. The lumbar plain film revealed a decrease in disc space height and the spinous process bone resorption at the L4-L5 level. The MRI revealed L4/L5 segment disc prolapse (Fig. 5B).

Bone resorption of the spinal process after the implantation of the Wallis device refers to a process of bone remodeling associated with stresses that may be related to postoperative intervertebral disc and facet degeneration, recurring lumbar disc herniation, and postoperative low back pain. After bone resorption, the function of the Wallis device may gradually decrease.

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References

[1] Lee J, Park YS. Proximal junctional kyphosis: diagnosis, pathogenesis, and treatment. Asian Spine J 2016;10:593–600.

[2] Wu H, Pang Q, Jiang G. Medium-term effects of Dynesys dynamic stabilization versus posterior lumbar interbody fusion for treatment of multisegmental lumbar degenerative disease. J Int Med Res 2017;45:1562–73.

[3] Wang H, Wang T, Wang Q, et al. Incidence and risk factors of persistent low back pain following posterior decompression and instrumented fusion for lumbar disk herniation. J Pain Res 2017;10:1019–25.

[4] Sénegas J, Vital JM, Pointillart V, et al. Long-term actuarial survivorship analysis of an interspinous stabilization system. Eur Spine J 2007;16:1279–87.

[5] Korovessis P, Repantis T, Zacharatos S, et al. Does Wallis implant reduce adjacent segment degeneration above lumbosacral instrumented fusion? Eur Spine J 2009;18:50–40.

[6] Stremeyer BH, Berg S, Gerdborn P, et al. X-stop versus decompressive surgery for lumbar neurogenic intermittent claudication: randomized controlled trial with 2-year follow-up. Spine (Phila Pa 1976) 2013;38:1436–42.

[7] Floman Y, Millgram MA, Smorgick Y, et al. Failure of the Wallis interspinous implant to lower the incidence of recurrent lumbar disc herniations in patients undergoing primary disc excision. J Spinal DiscTech 2007;20:337–41.

[8] Wilke HJ, Drumm J, Häusler K, et al. Biomechanical effect of different lumbar interspinous implants on flexibility and intradiscal pressure. Eur Spine J 2008;17:1049–56.

[9] Wang K, Zhu Z, Wang B, et al. Bone resorption during the first year after implantation of a single-segment dynamic interspinous stabilization device and its risk factors. BMC Musculoskelet Disord 2015;16:117.

[10] Zhu Z, Liu C, Wang K, et al. Topping-off technique prevents aggravation of degeneration of adjacent segment fusion revealed by retrospective and finite element biomechanical analysis. J Orthop Surg Res 2015;10.10.

[11] Panjabi MM, Chen NC, Shin EK, et al. The cortical shell architecture of human cervical vertebral bodies. Spine (Phila Pa 1976) 2001;26:2478–84.

[12] Lee SH, Im YJ, Kim KT, et al. Comparison of cervical spine biomechanics after fixed and mobile-core artificial disc replacement: a finite element analysis. Spine (Phila Pa 1976) 2011;36:700–8.

[13] Polkheit A, Ferguson SJ, Nolte LP, et al. Factors influencing stresses in the lumbar spine after the insertion of intervertebral cages: finite element analysis. Eur Spine J 2003;12:413–20.

[14] Yamamoto I, Panjabi MM, Grasso T, et al. Three-dimensional movements of the whole lumbar spine and lumbosacral joint. Spine (Phila Pa 1976) 1998;14:1256–60.

[15] Heth JA, Hitchon PW, Goel VK, et al. A biomechanical comparison between anterior and transverse interbody fusion cages. Spine (Phila Pa 1976) 2001;26:E261–7.

[16] Lu S, Wang Z, Ni X, et al. Establishment and biomechanical analysis of three-dimensional nonlinear finite element model of three-pieces segment arch. Hua Xi Kou Qiang Yi Xue Za Zhi 2013;31:74–9.

[17] Dong F. The contributions of facet joint to the stiffness of the lumbar spine. Zhonghua Wai Ke Za Zhi 1993;31:417–20.

[18] Chen SH, Lin SC, Tsai WC, et al. Biomechanical comparison of unilateral and bilateral pedicle screws fixation for transforaminal lumbar interbody fusion after decompressive surgery: a finite element analysis. BMC Musculoskeletal Disord 2012;13:72.

[19] Brox JJ, Sorensen R, Friis A, et al. Randomized clinical trial of lumbar instrumented fusion and cognitive intervention and exercises in patients with chronic low back pain and disc degeneration. Spine (Phila Pa 1976) 2003;28:1913–21.

[20] Burmeikiene S, Nelson EL, Mason A, et al. Complications in patients undergoing combined transforaminal lumbar interbody fusion and posterior instrumentation with deformity correction for degenerative scoliosis and spinal stenosis. Surg Neurol Int 2012;3:25.

[21] Cho KJ, Suk SI, Park SR, et al. Complications in posterior fusion and instrumentation for degenerative lumbar scoliosis. Spine (Phila Pa 1976) 2007;32:2232–7.

[22] Nakashima H, Kawakami N, Tsuji T, et al. Adjacent segment disease after posterior lumbar interbody fusion: based on cases with a minimum of 10 years of follow-up. Spine (Phila Pa 1976) 2015;40:E831–41.

[23] Schnake KJ, Scharen TN, Jeanneret B. Dynamic stabilization in addition to decompensation for lumbar spinal stenosis with degenerative spondylolisthesis. Spine (Phila Pa 1976) 2006;31:442–9.

[24] Yue ZJ, Liu YW, Lu Y, et al. Middle-period curative effect of posterior lumbar intervertebral fusion (PLIF) and interspinous dynamic fixation (Wallis) for treatment of L45 degenerative disease and its influence on adjacent segment degeneration. Eur Rev Med Pharmacol Sci 2015;19:4481–7.

[25] Sénegas J, Vital JM, Pointillart V, et al. Clinical evaluation of a lumbar interspinous dynamic stabilization device (the Wallis system) with a 13-year mean follow-up. Neurosurg Rev 2009;32:335–41. discussion 341–342.

[26] Lafage V, Gangnet N, Sénegas J, et al. New interspinous implant evaluation using an in vitro biomechanical study combined with a finite-element analysis. Spine (Phila Pa 1976) 2007;32:1706–13.
[27] Hedman TP, Fernie GR. Mechanical response of the lumbar spine to seated postural loads. Spine (Phila Pa 1976) 1997;22:734–43.

[28] Kim HJ, Kang KT, Son J, et al. The influence of facet joint orientation and tropism on the stress at the adjacent segment after lumbar fusion surgery: a biomechanical analysis. Spine J 2015;15:1841–7.

[29] Ma J, Jia H, Ma X, et al. Evaluation of the stress distribution change at the adjacent facet joints after lumbar fusion surgery: a biomechanical study. Proc Inst Mech Eng H 2014;228:665–73.

[30] Wiseman CM, Lindsey DP, Fredrick AD, et al. The effect of an interspinous process implant on facet loading during extension. Spine (Phila Pa 1976) 2005;30:903–7.

[31] Tanne K, Nagataki T, Matsubara S, et al. Association between mechanical stress and bone remodeling. J Osaka Univ Dent Sch 1990;30:64–71.

[32] Takuma M, Tsutsumi S, Tsukamoto H, et al. The influence of materials difference on stress distribution and bone remodeling around alumina and titanium dental implants. J Osaka Univ Dent Sch 1990;30:86–96.

[33] Kuslich SD, Danielson G, Dowdle JD, et al. Four-year follow-up results of lumbar spine arthrodesis using the Bagby and Kuslich lumbar fusion cage. Spine (Phila Pa 1976) 2000;25:2636–62.

[34] Rigby MC, Selmon GP, Foy MA, et al. Graf ligament stabilisation: mid-to long-term follow-up. Eur Spine J 2001;10:234–6.