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ORIGINAL ARTICLE

Biomechanical properties of novel transpedicular transdiscal screw fixation with interbody arthrodesis technique in lumbar spine: A finite element study

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Bilateral pedicle screw system;
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Abstract *Purpose:* The purpose of this study was to investigate finite element biomechanical properties of the novel transpedicular transdiscal (TPTD) screw fixation with interbody arthrodesis technique in lumbar spine.
Methods: An L4–L5 finite element model was established and validated. Then, two fixation models, TPTD screw system and bilateral pedicle screw system (BPSS), were established on the validated L4–L5 finite element model. The inferior surface of the L5 vertebra was set immobilised, and moment of 7.5 Nm was applied on the L4 vertebra to test the range of motion (ROM) and stress at flexion, extension, lateral bending and axial rotation.
Results: The intact model was validated for prediction accuracy by comparing two previously published studies. Both of TPTD and BPSS fixation models displayed decreased motion at L4–L5. The ROMs of six moments of flexion, extension, left lateral bending, right lateral bending, left axial rotation and right axial rotation in TPTD model were 1.92, 2.12, 1.10, 1.11, 0.90 and 0.87°, respectively; in BPSS model, they were 1.48, 0.42, 0.35, 0.38, 0.74

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and 0.75°, respectively. The screws' peak stress of above six moments in TPTD model was 182.58, 272.75, 133.01, 137.36, 155.48 and 150.50 MPa, respectively; and in BPSS model, it was 103.16, 129.74, 120.28, 134.62, 180.84 and 169.76 MPa, respectively.
Conclusion: Both BPSS and TPTD can provide stable biomechanical properties for lumbar spine. The decreased ROM of flexion, extension and lateral bending was slightly more in BPSS model than in TPTD model, but TPTD model had similar ROM of axial rotation with BPSS model. The screws' peak stress of TPTD screw focused on the L4—L5 intervertebral space region, and more caution should be put at this site for the fatigue breakage.
The translational potential of this article: Our finite element study provides the biomechanical properties of novel TPTD screw fixation, and promotes this novel transpedicular transdiscal screw fixation with interbody arthrodesis technique be used clinically.

Introduction

Lumbar interbody fusion is a widely used and efficient treatment for many lumbar degenerative conditions [1—4], such as lumbar spinal stenosis [5], spondylolisthesis [6], lumbar segmental instability [7], sciatica [8,9] and low back pain [10]. Posterior bilateral pedicle screw system (BPSS) with an interbody cage has been recognised as the "gold standard" technique. However, traditional open surgery often demands considerable trauma, prolonged operative time as well as an increased implant-related complication and surgical site infection [11,12]. Many minimally invasive spinal fixation techniques with comparable stability of BPSS were designed and developed in last decades.

It was pioneered by Grob et al [13] to use two screws for treating patients with spondylolisthesis with anterior slippage of at least 25% and disc height decreased at least 75% of the original height. Birkenmaier et al [14] combined this technique with robot-assisted navigation for advantages of minimal invasion. Aghayev et al [15] reported a novel designed transpedicular transdiscal (TPTD) screws combining with transforaminal lumbar body fusion technique for non-spondylolisthesis and found that transdiscal and pedicle screw system had comparable immediate stabilisation in an *in vitro* biomechanical model, but without data of transdiscal screws—cage model. Wu et al [16] also reported that TPTD screws could be used in nonspondylolisthesis patients percutaneously [17]. Therefore, TPTD screws have many potential clinical advantages, such as minimally invasive, less screw use, lower cost, shorter skin incision as well as quicker recovery.

However, there is still no finite element study working on TPTD screws combined with interbody cage. In this study, we investigated ROM, screw stress and vertebral stress of TPTD screw fixation with interbody fusion and compared its properties with intact lumbar spine and "gold standard" BPSS fixation with interbody fusion.

Table 1 Material properties used in the finite element analysis of lumbar spine.

Material properties	Young's modulus (MPa)	Poisson's ratio μ	Element type
Cancellous bone	100	0.2	Tetrahedral
Cortical bone	12,000	0.3	Shell
Endplate	1000	0.3	Shell
Accessory	3500	0.25	Tetrahedral
Facet	75	0.4	Shell
Nucleus pulposus	1	0.499	Tetrahedral
Interbody cage (PEEK)	4340	0.4	Tetrahedral
Screw (Titanium)	110,000	0.3	Tetrahedral

PEEK = polyetheretherketone.

Materials and methods

A three-dimensional (3-D) digital spine model was constructed using a spine model from Digimation (Saint Rose, LA, USA), which was a completely and morphologically accurate model of a healthy human spine from the atlas to the pelvis. The digital model was in the form of "IGES" or "parasolid" files, which served as input file for SolidWorks (Concord, MA, USA), a 3-D computer-animated design program for further geometrical modification. The SolidWorks model was then imported into the finite element analytical program ANSYS Workbench software (ANSYS Inc. Canonsburg, PA, USA) for quantitative analysis. Levels of L4—L5 were included in this study. Modifications were programmed to incorporate material properties and several contact surfaces, such as the facet joints.

The solid model of the spine was first modified to accurately simulate the structure of the vertebral bodies. Five distinct material profiles were used for the vertebra: cancellous bone, cortical bone, endplate, accessory and facet. The intervertebral discs were also constructed by two materials: annulus and nucleus. Material properties

Table 2 Parameter of annulus fibrosus. Data from the study by Wagner and Lotz.

Mu1	Alpha1	Mu2	Alpha2	Mu3	Alpha3	D1	D2	D3
−126.22	24.81	123.78	25.00	2.75	11.66	1.42	0	0

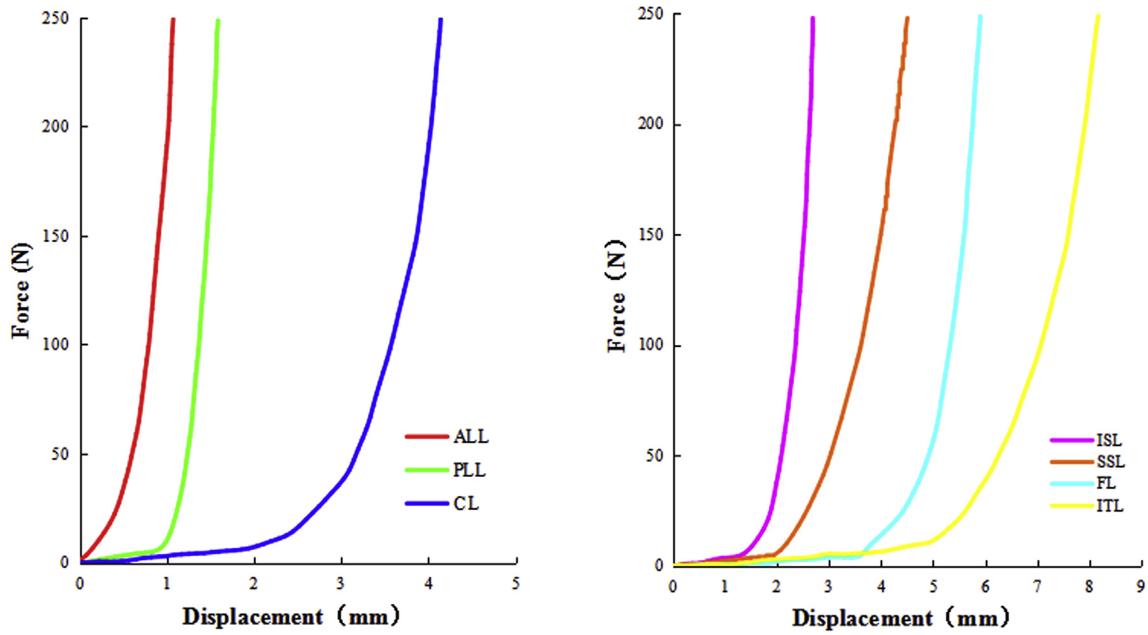

Figure 1 Force—displacement curve of ligaments.
ALL = anterior longitudinal ligament; CL = capasular ligament; FL = flavum ligament; ITL = intertransverse ligament; ISL = interspinal ligament; PLL = posterior longitudinal ligament; SSL = suprsaspinal ligament.

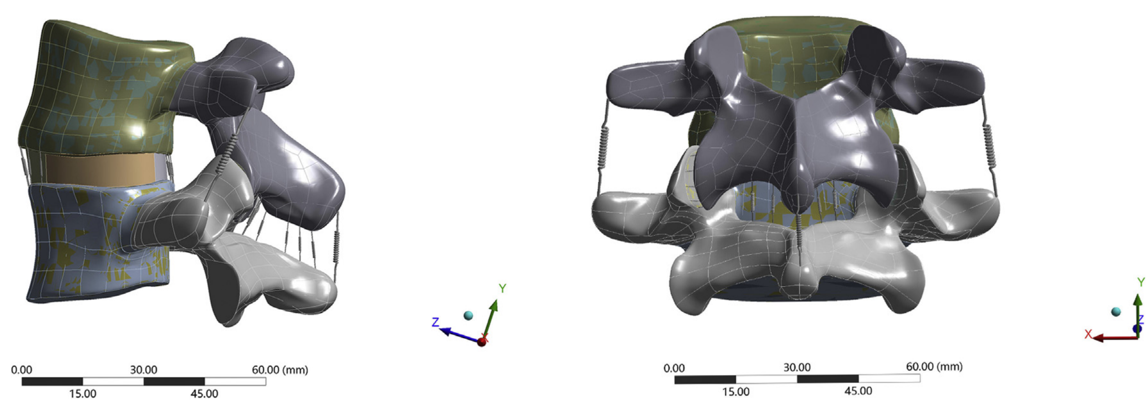

Figure 2 Intact lumbar spine of L4—L5 was established.

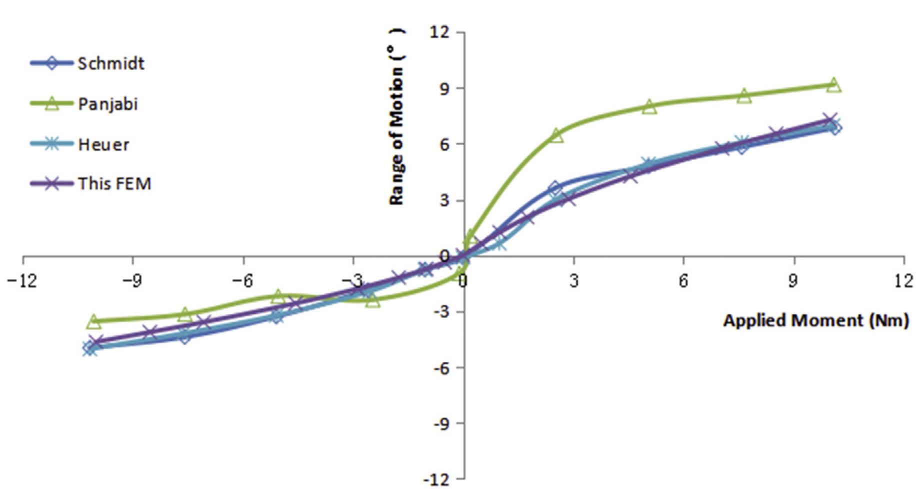

Figure 3 Range of motion of this intact model was compared with that in the previously published studies in flexion and extension.

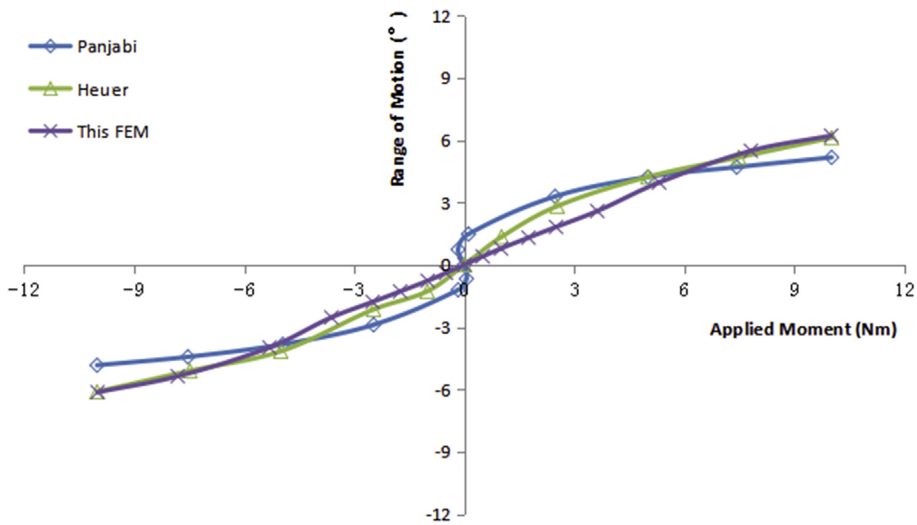

Figure 4 Range of motion of this intact model was compared with that in the previously published studies in lateral bending.

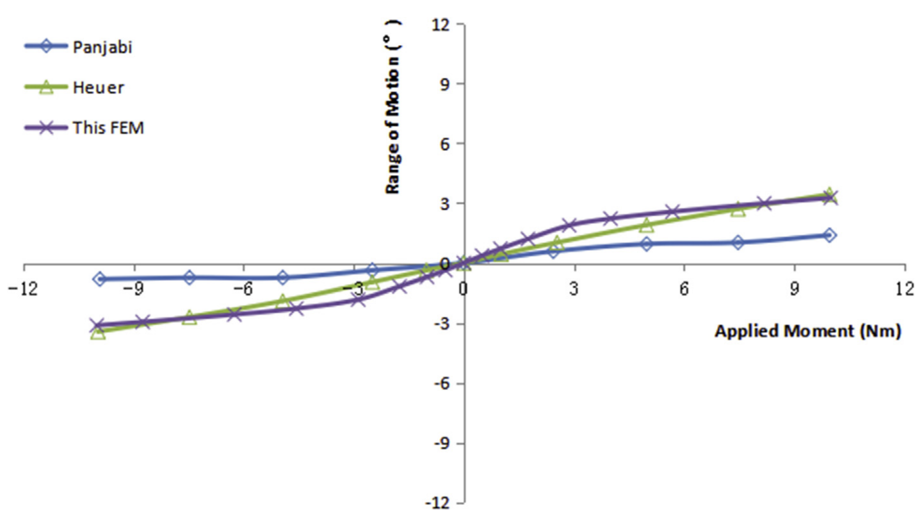

Figure 5 Range of motion of this intact model was compared with that in the previously published studies in axial rotation.

were obtained from previously validated models [18–22] and listed in Table 1. The annulus fibrosus was modelled by a hyperelastic constitutive law for the ground substance and by nonlinear springs oriented at about 30° to each other. Coefficients of the fifth-order Ogden hyperelastic formulation were determined from experimental data [19] and listed in Table 2. Ligaments were incorporated into the model in the form of tension-only spring elements, including anterior longitudinal ligament, posterior longitudinal ligament, flavum ligament, intertransverse ligament, interspinal ligament, supraspinal ligament and capsular ligament. According to previously published experiments [23–28], nonlinear force–displacement curves, which were defined as each ligament's reaction to different vertebral loading, were presented in Figure 1. The intact constructed model of L4–L5 was showed in Figure 2.

Model validation

The model was made up by 166,144 elements. With a preload axial compression of 500N, a pure moment up to 10 Nm was applied. Nonlinear behaviour of the finite element model was verified over the entire moment–rotation curve under the conditions of flexion, extension, lateral bending and axial rotation. The motion at the bottom was fixed in all directions. The rotation of the upper section of the segment was recorded and validated against the results of previously published studies and experimental results [27–29] for prediction accuracy.

Table 3 Comparison of screws' peak stress of two reconstructed models.

Moments	TPTD screw (MPa)	BPSS (MPa)
Flexion	182.58	103.16
Extension	272.75	129.74
Left lateral bending	133.01	120.28
Right lateral bending	137.36	134.62
Left axial rotation	155.48	180.84
Right axial rotation	150.50	169.76

BPSS = bilateral pedicle screw system; TPTD = transpedicular transdiscal.

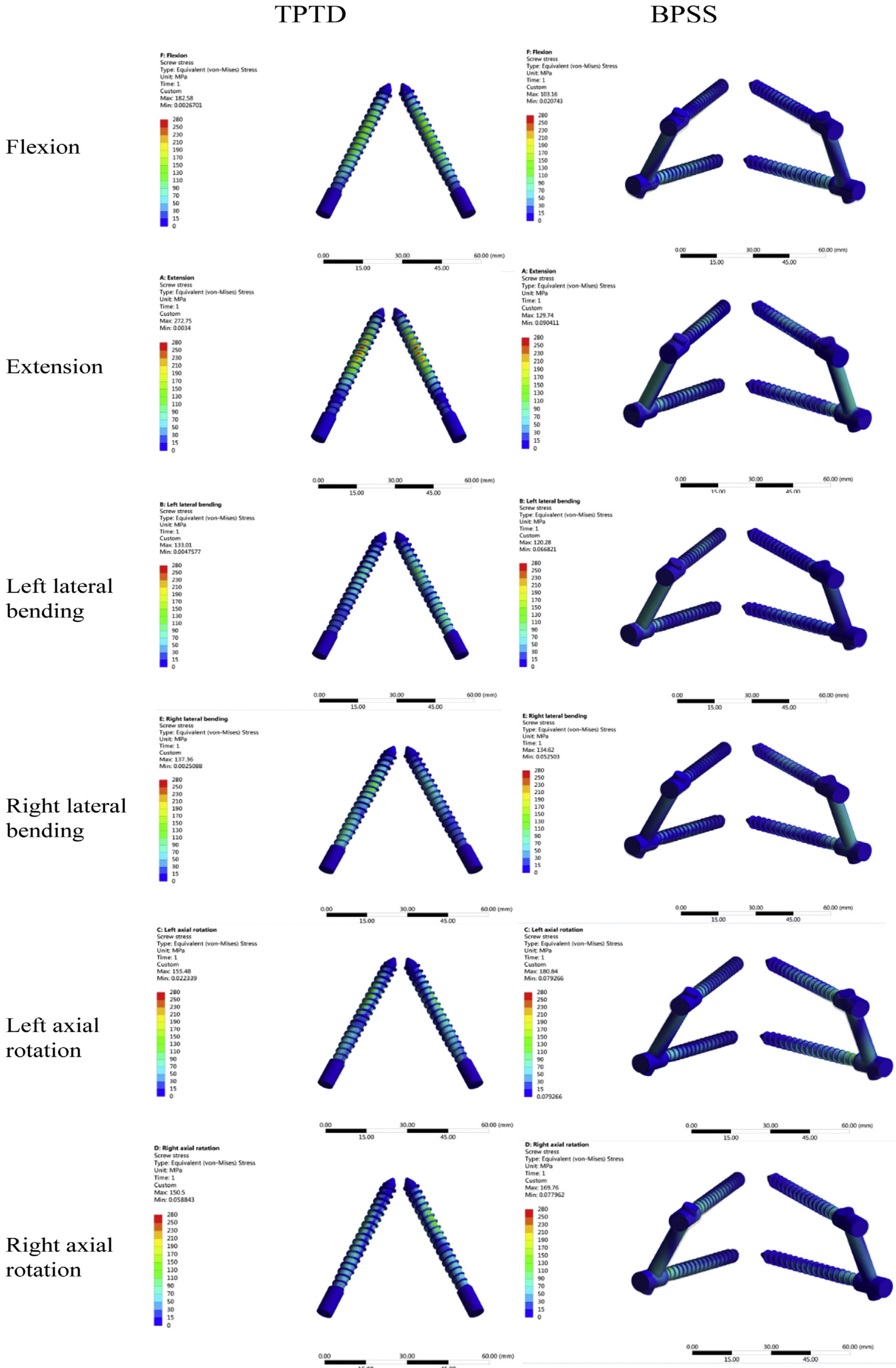

Figure 6 Comparison of stress contour plots for the screws of transpedicular transdiscal screw system and bilateral pedicle screw system.
BPSS = bilateral pedicle screw system; TPTD = transpedicular transdiscal.

Model of TPTD screw system

The finite element model was modified to simulate the surgical procedure to put the trapezium-shaped interbody cage at the L4—L5 level via a lateral approach. Two cylindrical screws were designed in ANSYS Workbench software and assembled into finite element model. Two screws were set to "tie" with the vertebra. After removal of the intervertebral disc, size dimension of preset position for the interbody cage was verified. According to this result, the substance of trapezium interbody cage was designed in CATIA (Dassault, Paris, French) based on the measurements mentioned previously. Then, the model of interbody cage was put into ANSYS Workbench software with optimal position in the vertebra. A finite sliding algorithm with a coefficient of friction of 0.4 was defined between the cage and endplate to allow any small relative displacements between the two contacting surfaces.

Model of BPSS

The posterior instrumentation consisted of transpedicular screws (55-mm long and 6-mm diameter) and longitudinal rods (45-mm long and 6 mm diameter) spanning between adjacent screws, which were designed in the ANSYS Workbench software and assembled into finite element model. Rigid fixation was simulated using a "tie" constraint at the following interfaces: pedicle screw and pedicle/vertebral body and pedicle screw and rod. The substance of the standard interbody cage was designed in CATIA accordingly. The model of interbody cage was positioned optimally in vertebra in the ANSYS Workbench software. The superfluous parts of the structure were cut. Same with TPTD screw system, the coefficient of friction between the cage and endplate was set as 0.4.

Boundary and loading condition

A motion protocol was defined for all reconstructive options and two operation lumbar spine models. The inferior surface of the L5 vertebra was immobilised throughout the load simulation. The nodes on the uppermost surface of the L4 vertebra were coupled to a reference node for load application. A bending moment of 7.5 Nm was applied to this reference node on the superior surface of the L4 vertebra to represent movements of flexion/extension, lateral bending and axial rotation. The ROMs and stress of screws of two models were tested and contrasted.

Results

Loaded with motions of flexion, extension, lateral bending and axial rotation, nonlinear behaviour was observed for the intact model. The finite element analysis of L4—L5 of the intact model indicated similar ROM compared with the *in vitro* biomechanical result of Heuer et al [29] and Schimdt et al [30] in flexion and extension, with only slight reduction in flexion for this intact model compared with the data of Panjabi et al [31], but not in extension (Figure 3). Under the condition of lateral bending, we found that our present model was consistent with the models of Heuer et al [29] and Panjabi et al [31] (Figure 4). The condition of axial rotation was consistent with that in the study by Heuer et al [29] (Figure 5).

Screws' stress analysis of two reconstructed models

For TPTD screw system, the maximum peak stresses were found in flexion and extension, with 182.58 MPa and 272.75 MPa, respectively, whereas the minimum peak stresses were found in left lateral bending and right lateral bending, with 133.01 MPa and 137.36 MPa, respectively (Table 3).

Stress contour plots for the screws of TPTD screw fixation and bilateral pedicle screw fixation system were shown in Figure 6. We found the peak stress of TPTD screw was presented in the contact surface between the screw and upper vertebra.

For bilateral pedicle screw system, the maximum peak stresses were in moments of left axial rotation and right axial rotation, with 180.84 MPa and 169.76 MPa, respectively. The minimum peak stresses of screws were in flexion and left lateral bending, with 103.16 MPa and 120.28 MPa, respectively (Table 3). We found that the peak stress was concentrated in the junctional area of screw cap and screw body for bilateral pedicle screws (Figure 6).

Comparison of ROM for two reconstructed models

The ROM of both reconstructed models decreased dramatically (Table 4). But, ROMs of BPSS were all slightly less than those of transpedicular transdiscal screw system under any condition of motion (Figure 7). The maximum ROM was at the condition of flexion and extension for TPTD screw system. For BPSS, the largest ROM was under the condition of flexion as 1.48°, whereas for other five conditions, ROM was all less than 0.75°.

Discussion

In our study, the tests were based on one function spinal unit. Both TPTD screw fixation and BPSS are used for lumbar

Table 4 Comparison of ROM of two reconstructed models.

Moments	TPTD model ROM (°)	BPSS model ROM (°)	Intact model ROM (°)
Flexion	1.92	1.48	5.21
Extension	2.12	0.42	3.74
Left lateral bending	1.10	0.35	3.97
Right lateral bending	1.11	0.38	4.05
Left axial rotation	0.90	0.74	2.39
Right axial rotation	0.87	0.75	2.54

BPSS = bilateral pedicle screw system; ROM = range of motion; TPTD = transpedicular transdiscal.

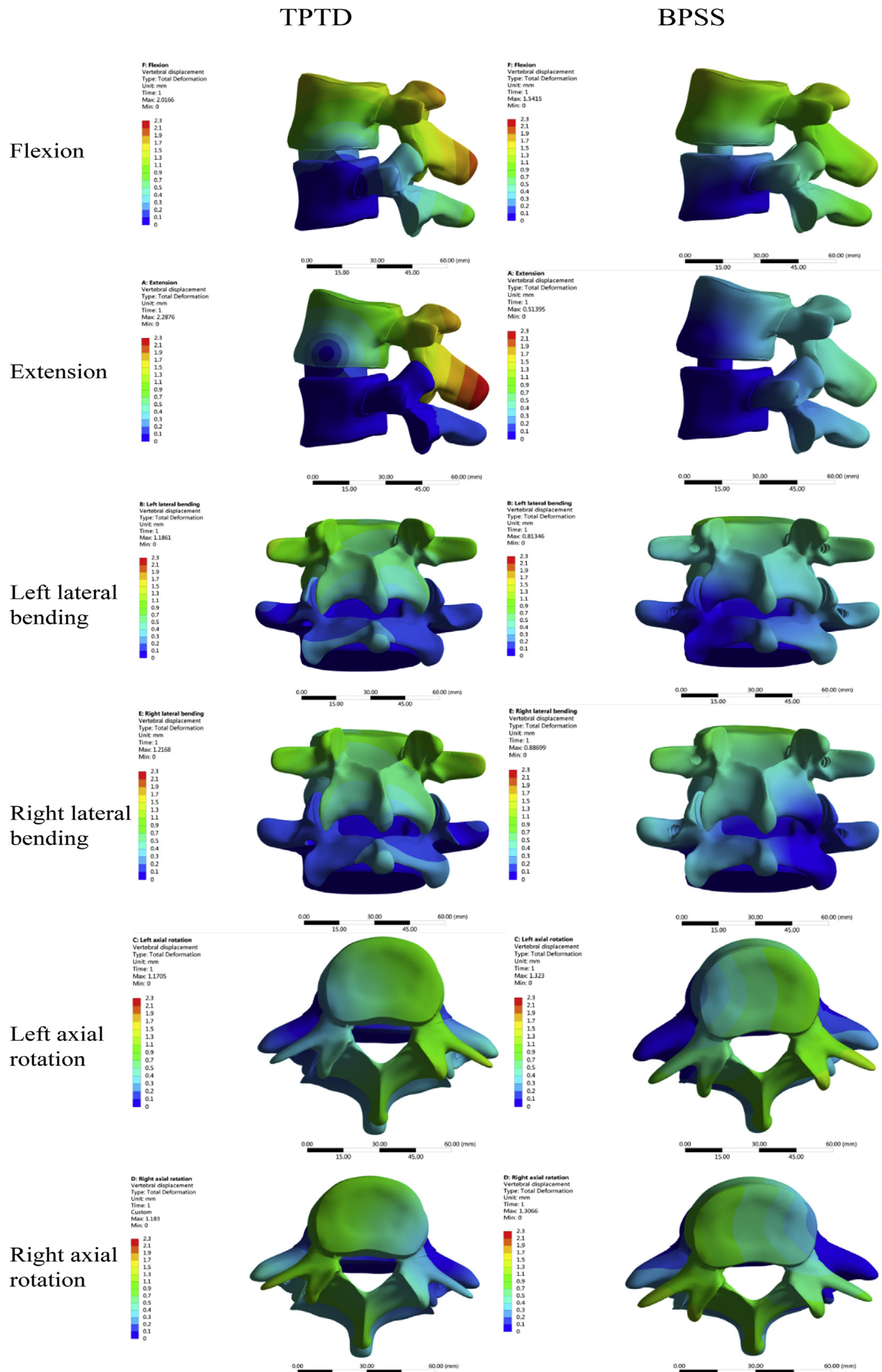

Figure 7 Comparison of ROM of transpedicular transdiscal screw system and bilateral pedicle screw system. BPSS = bilateral pedicle screw system; ROM = range of motion; TPTD = transpedicular transdiscal.

fusion; the fixation is used for temporary (about 3 months), and it is rigid fixation, but not semi-rigid fixation or dynamic fixation, which aimed to preserve the motion of indexed level and needed to compare the motion and stress of the adjacent levels [27]. The rigid fixed lumbar level will achieve interbody fusion at about 3 months after surgery. Theoretically, the motion and stress of the adjacent levels will be the same after interbody fusion of the indexed level among different fixation techniques; therefore, we did not compare the motion and stress of the adjacent levels in the present study. Our L4—L5 model was first validated similar with the results of published studies of *in vitro* investigation, including studies of Heuer et al [29], Schmidt et al [30] and Panjabi et al [31], proving the great simulation and feasibility of this model used for analysis.

After the validation study of the model of L4—L5 lumbar spine segment, our investigation established the model of TPTD screw with the trapezium-shaped interbody cage [32] and the model of BPSS with the standard interbody cage. To imitate the surgery operation more realistically, when placed with the interbody cage in the intervertebral space, the fibrous ring and nucleus pulposus were cut. And, two reconstructed models were both loaded with 7.5 Nm moments.

The maximum peak stress of TPTD screw system reached 272.75 MPa more than the maximum value in BPSS. Screws' stresses were mainly concentrated in the connective area of screws and upper vertebra, which remind us to strengthen this part of screws. We also found that under the condition of extension, the peak stress achieved the maximum for TPTD screw system. A previous cadaveric study had reported familiar results. In an *in vitro* compression investigation, St Clair et al [33] found that loaded with bending motion the screw was easy to pierce from the anterior part of upper vertebra. Another *in vitro* biomechanical investigation by Aghayev et al [15] reported that TPTD screw system had been proven with immediate stabilisation; however, the data of TPTD screw with the interbody cage were unavailable, which was investigated by our present study. Besides, we also provided detailed information about stress and ROM.

The ROMs were decreased dramatically for two reconstructed fusion models with screws and interbody cage compared with intact model under six angles of motions. However, the ROM decreased in the BPSS model was slightly more than that in the TPTD models; these results were similar to those of the cadaveric studies [15,32]. Our finite element analysis suggested a comparable stability for TPTD screw system with BPSS in axial rotation, slightly less stiffness in flexion, extension and lateral bending. But, both reconstructions can provide immediate stability for lumbar spine.

There were some advantages of finite element analysis used in our study. First, the stress condition of screw and internal vertebral structure can be quantified in the finite element model, which cannot be investigated in *in vitro* investigation. Second, easy availability and constancy of the finite element model allowed repeated test on it. Moreover, with finite element analysis, different surgical procedures can be designed and modified on it. With accurate measurement on it, the dimension of surgical measurements can be designed more reasonable. Finally, cost-effectiveness of finite element analysis was another significant superiority compared with *in vitro* biomechanical investigation. However, as a simulation technology, finite element model cannot completely imitate the condition of a complex spine structure. Some of them had to be simplified for valid calculating. Besides, the validation of the model had to rely on consistency with the data of *in vitro* biomechanical investigation.

Conclusions

Our finite element analysis suggested that the technique of TPTD screw fixation combined with interbody cage can provide stable biomechanical properties for lumbar spine. The decreased ROMs of flexion, extension and lateral bending were slightly more in the BPSS model than in the TPTD model, and ROMs of axial rotation were similar between the BPSS model and TPTD model. The screws' peak stress of TPTD screw focused on the L4—L5 intervertebral space region, and more caution should be put at this site for the fatigue breakage.

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Conflicts of interest

All authors report that there are no conflicts of interest related to the present article.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jot.2018.08.005.

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