TESSYS Technique With Small Grade of Facetectomy Has Potential Biomechanical Advantages Compared to the In-Out TED With Intact Articular Process: An In-Silico Study

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Research Article

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Abstract

**Background:** The facetectomy was reported as an important procedure in both in-out and out-in (i.e. transforaminal endoscopic spine system (TESSYS)) techniques in the transforaminal endoscopic discectomy (TED), and which was also related to the deterioration of postoperative biomechanical environment and related poor prognosis. Recently, the facetectomy was reported to be avoided in the modified in-out TED, but iatrogenic injury of annulus and related larger grades of nucleotomy can also be seen as risk factors for the prognosis deterioration. Meanwhile, above mentioned risk factors can be alleviated in TESSYS TED, and the grade of facetectomy can also be reduced in this surgery with the use of endoscopic dynamic drill.

**Methods:** To evaluate the risk of biomechanical deterioration and related postoperative complications of these two surgical modified strategies in TED, an intact lumbo-sacral finite element model and the corresponding model with adjacent segments degeneration have been constructed and validated, modified in-out and TESSYS TED have been simulated in these models. Then, the change of biomechanical indicators have been computed to evaluate the risk of postoperative complications in the surgical segment.

**Results:** Compared with intact FEA models, the tendency of biomechanical deterioration in TESSYS TED models was generally slight. By contrast, obvious biomechanical deterioration can be observed in models with modified in-out TED. The degenerative change in adjacent segments magnifies rather than alters the overall tendency of biomechanical change.

**Conclusions:** Modified TESSYS TED with a small grade of facetectomy has potential biomechanical advantages compared with the in-out TED with intact articular process (i.e. without facetectomy). The iatrogenic injury of annulus and larger grade of nucleotomy can be seen as risk factors for postoperative biomechanical deteriorations and complications in the surgical segment.

**Background**

Since the Kambin triangle was discovered [1], the transforaminal endoscopic discectomy (TED) has been promoted rapidly in the treatment of lumbar disc herniation (LDH) [2]. The facetectomy was reported as an important procedure in both in-out (i.e. Yeung endoscopic spine system (YESS)) and out-in (i.e. transforaminal endoscopic spine system (TESSYS)) techniques of TED [3–5], whose definition was the foramen enlargement by removing part of the superior articular process (SAP) and ligamentum structures 6–8. It was useful for the expansion of surgical field and the decompression of the exiting nerve root, especially for patients with the foramen stenosis [4, 9–12].

However, the zygapophyseal joint (ZJ) could guide the spinal motions, transfer a substantial part of the compressive load, bending and shearing moments (i.e. limit excessive motions) and resulting protect structures in the functional spinal unit (FSU) [13–20]. As a result, spinal load distribution could be changed pathologically after a large grade of facetectomy, resulting injury of the surgical FSU was a risk
factor of symptoms recurrence and further disc degeneration [16, 21–23]. Besides, ZJ is an important structure during the maintenance of spinal stability [13, 14, 24]. Instability in the surgical segment caused by facetectomy was also a risk factor for the biomechanical deterioration, resulting degeneration in the surgical FSU and poor long-term prognosis [19–22, 25]. These deductions were consistent with our published finite element numerical studies [26–28]. In which, larger grade facetectomy has been demonstrated to be associated with biomechanical deterioration and lumbar instability, and these changes may be related to spinal further degeneration and symptoms recurrence [27–29].

Considering the axial rotation will enhance the vulnerability of posterior annulus and the zygapophyseal joint (ZJ) could restrict the lumbar spinal motion under axial rotation, the iatrogenic injury of SAP in TED may also increase the risk of annulus tear, related symptoms recurrence and resulting acceleration of disc degeneration [17, 18, 24, 30].

To avoid the facetectomy in TED for patients without foramen stenosis, the standard YESS technique could be modified. Firstly, insert the cannula into the disc space trans Kambin triangle. Then, by pressing down the end of cannula and using different sizes of bending forceps, the herniated disc can be removed without any damage of SAP (i.e., without facetectomy), related risk of biomechanical deterioration and resulting postoperative complications can be avoided (Fig. 1). Facetectomy was an important surgical procedure in YESS technique [3, 5]. Therefore, the modified surgical technique was called optimized in-out, rather than YESS technique in the following statement. But the optimized in-out surgical strategy still has its original defects and which may also lead to poor clinical outcomes. Specifically, the risk of the recurrent lumbar disc herniation (RLDH) was reported to increase dramatically with the expansion of annulus tear (which may up to more than one-quarter when the size annulus tear larger than 6mm) [31–35]. More significantly, the strength of scar tissue in the annulus outer lamellae is not strong enough to prevent RLDH [36, 37]. Considering the diameter of our working cannula was 7.5mm (type WTS127502, Joimax International, Irvine, Calif) and its insertion will lead to iatrogenic annulus injury inevitably, a relatively larger grade of nucleotomy in the modified in-out TED seems necessary to prevent RLDH (Fig. 1) [3], but this surgical strategy also has its limitations.

Postoperative residual nucleus is still important during to maintenance of spinal biomechanical function [19, 38, 39], larger grades of nucleotomy may lead to the annulus stress pathological distribution and make it vulnerable to fatigue damage under cyclic loading [38–41], resulting annulus tears will accelerate disc degeneration. Besides, disc collapse could also be accelerated in this pathological process [16, 39, 40], related risk of lumbar instability will increase for the laxity of soft tissues, and the foramen stenosis incidence will also increase for the decrease of the foramen cross-sectional areas (CSA) during the collapsed of the surgical FSU without facetectomy [24, 25, 42]. As a result, higher risk of symptom recurrence can be observed in patients with larger grades of nucleotomy [16, 23]. Additionally, the collapse of the surgical segment and DD also lead to secondary spinal irregular loading transmission and which has been proved to increase the load of the ZJ cartilage and resulting risk of ZJ degenerative osteoarthritis, hypertrophy of articular process and resulting spinal stenosis [43–45]. In consequence, a large grade of nucleotomy, the remedial action to reduce the risk of RLDH caused by iatrogenic annulus
tear in the in-out technique may lead to greater potential risk of poor clinical outcome and lower satisfaction of patients after TED [32].

By contrast, as a remedial procedure of iatrogenic annulus injury, a large grade of nucleotomy was not necessary in TESSYS TED commonly. Specifically, considering the size of original annulus tear was usually smaller than 6 mm and the residual annulus tissue will not lead to serious clinical symptoms generally [46, 47]. Nucleotomy could be accomplished along the original annulus tear without any iatrogenic annulus injury. Besides, for patients with contained type of LDH (i.e. LDH with intact annulus), discectomy can be accomplished by using bipolar radiofrequency to make a small slit (less than 6mm) in the annulus, and extensive grades of nucleotomy is also unnecessary. Meanwhile, facetectomy can be limited by endoscopic dynamic drill for which could be accomplished precisely under direct version with its assistance. As a result, in our clinical practice, the grade of facetectomy can be restricted to less than one third generally for patients without foramen stenosis, and the cartilage and capsule of ZJ can also be protected (Fig. 1). More significantly, the controllable risk of postoperative spinal instability and biomechanical deterioration after endoscopic nucleotomy with small grades of facetectomy has been proved in our published studies [26–28].

On the basis of above theoretical and practical foundations, we can make a hypothesis that even if the iatrogenic injury of SAP can be avoided, compared with the in-out TED, TESSYS TED with small grade of facetectomy still has potential biomechanical advantages. To verify this hypothesis, the biomechanical effect of modified in-out and TESSYS TED have been computed in a validated three dimensional lumbo-sacral model. Considering LDH patients were mainly middle-aged and elderly, their original disc degenerative changes may have potentially impacts on the postoperative biomechanical environment [23, 48, 49], surgical simulations and finite element analyses have been accomplished in models with and without degeneration. To the best of our knowledge, published studies have not adequately clarified these issues.

**Methods**

**Model construction**

The intact finite element (FE) model from L3 to S1 has been constructed in our published studies [26, 28, 50]. Bone structures include cortical, cancellous, and posterior structures, nonbony components include the intervertebral disc and ZJ cartilages. IVD consist of the nucleus core, the surrounding annulus, and cartilage endplates [51, 52]. The thickness of the cortical and the endplates was set as 0.8 mm [48, 49, 53]. Ligaments and ZJ capsules were constructed by cable elements [50, 54]. Facet cartilages were defined by surface–surface contact elements and the gap between cartilages was set as 0.5 mm [48, 55]. In the construction of models with disc degeneration in segments adjacent to the surgical segment, the disc height was reduced to 67 %, the cross-sectional area of annulus was expanded by 40%, and material properties of annulus and nucleus were modified based on anterior published studies [23, 48, 49].

**Boundary and Loading Conditions**
Current models were set to be symmetric in the sagittal plane to increase the computational efficiency by computing the bending and axial rotation loading conditions of intact models unilaterally [27]. Different sizes of hybrid elements were set in FE models and the mesh was refined in thin structures and the structures with large deformation [27, 50, 56]. To ensure the computational credibility, a mesh convergency test was performed on the intact model by evaluating the change of maximum annulus shear stress, and the model was considered to be converged if the change of computational value less than 3%. All of freedom degrees were fixed under the inferior of S1, stress and moments were applied on the superior of L3 [50, 57], and the contact between facet cartilages was defined as frictionless [54, 57].

Model calibration and validation

During the model calibration process, the stiffness of ligamentum structures were slightly modified within the physiological range to reduce the difference between the computed biomechanical indicators with which from widely cited in-vitro studies [51, 57-62]. Then, to ensure the reliability of the calibrated model, multi-indicators model validation has been accomplished by comparing the computed range of motion (ROM), the intradiscal pressure (IDP) and the value of disc compression (DC) with which from in-vitro studies under different loading conditions [63-66].

Simulation of the modified in-out and TESSYS TED

The right side of L4-L5 segment was selected for the simulation of TED. TESSYS TED with a small grade of facetectomy was simulated according to the reported surgical technique and our clinical experience [573]. In which, a 3 mm incision was made on the annulus to simulate the annulus tear and its width was set as 1 mm. One-sixth of the nucleus around the incision was removed to simulate a small grade of nucleotomy. The vertex of facetectomy was located on the cranial tip of SAP, one-third of SAP and the ligamentum flavum (LF) were excised during this procedure (Fig. 2) [6, 7, 26, 50]. During the simulation of the in-out TED with intact SAP, the original annulus tear was set as the center of working cannula insertion, annulus in the surrounding 7.5 mm area was completely deleted to simulate the iatrogenic injury. One-third (twice the range of nucleotomy in the model with TESSYS technique) of the nucleus around the annulus tear was removed to simulate a larger range of nucleotomy (Fig. 3). Pathological changes caused by DD were simulated in the L3-L4 and L5-S1 segments, and the surgical simulation keep consistent in models with and without DD (Fig. 2). To simplify the following statement, FEA models in this study were named from model 1 to model 6 (Table. 1).

Table 1
## Results

### Model validation

The concept of computational accuracy (ACC) was presented in the figure. 4. In this study, ACC was greater than 90% except for the disc compression in L3-L4 segment. In which, the value of ACC was 85.2% and the difference between our computational result and the average value from in-vitro study was obviously less than one standard deviation [59]. Additionally, DD in segments adjacent to the surgical segment lead to the increase of IDP and the decrease of facet contact force (FCF) slightly in the surgical segment, this tendency was consistent with published studies [23, 49]. So we believe our models make good representation of real biomechanical environment.

### Biomechanical change in different models

Special emphasis should be placed on FCF. FCF was not been recorded in the flexion condition. Besides, cartilages in the bending side were contact, and the opposite side of cartilages were contact in the axial rotation condition. In other words, FCF under the left lateral bending, was the force on left facet cartilages, and when it comes to the FCF under left axial rotation, the force was recorded on the right side, and vice versa.

Biomechanical indicators in different models were presented in figure.5 to figure. 8. Generally, DD in adjacent segments will lead to the deterioration of biomechanical indicators in the surgical segment, however, the decrease of FCF and ROM can also be observed and the original biomechanical change tendency in different surgical models was not varied or amplified obviously in degenerated models. Compared with intact models, change in models after TESSYS TED was slightly under most of loading conditions. Most importantly, biomechanical deterioration can be observed in models after in-out TED compared with intact models and TESSYS TED models especially in the extension, bending and rotation conditions to the surgical side (i.e. right lateral bending and axial rotation).

### Summary table of named FE models

| Models without disc degeneration | Models with adjacent segments disc degeneration |
|---------------------------------|-----------------------------------------------|
| Intact model                    | 1                                              |
| Model after TED with in-out technique | 2                                              |
| Model after TED with TESSYS technique (annulus tear: 3mm) | 3                                              |

![Summary table of named FE models](image)
Discussion

The objective of this study

To evaluate the risk biomechanical deterioration and resulting postoperative complications in the surgical segment caused by the optimized in-out technique with intact SAP and TESSYS TED with a small grade of facetectomy, intact lumbo-sacral models with and without disc degeneration and corresponding models after these operations have been constructed and biomechanical indicators shortly related to lumbar degenerative diseases (LDD) have been computed and evaluated. Considering the importance of biomechanical environment for postoperative clinical outcomes has been repeatedly demonstrated [23, 50, 52], investigations for the biomechanical change caused by these two different surgical techniques in TED was of great significance for the reference of surgical strategy selection.

Notable points in the model construction process

Adjacent segments, rather than the surgical segment were selected for the construction of DD models. This model construction strategy was based on our clinical practice. As is mentioned above, DD was very common in TED patients. This nature degenerative change may not lead to serious clinical symptoms, but will adversely affect the biomechanical environment in adjacent segments [23, 48, 49]. Hence, the simulation of disc degeneration was meaningful for the evaluation of real postoperative biomechanical environment. Disc collapse during the process of DD lead to a reduction in the cross-sectional area in the Kambin triangle, and the risk of exiting nerve root injury in a degenerated disc will increase during the insertion of working cannula without facetectomy [67, 68]. As a result, LDH with narrow disc space can be seen as a contraindication for the application of modified in-out TED and the surgical segment has been excluded from the construction of degenerative change models.

Besides, although ZJ degeneration was shortly related to DD [43, 45, 58, 69], and some FE studies construct ZJ degenerative models by reducing the facet gap [48, 57], we still give up the construction of ZJ degeneration. The gap thickness of ZJ should be seen as a reflection of the cartilage wear, sclerosis and hyperplasia of subchondral bone [60, 70, 71], and this pathological process was difficult to simulate in the model construction. Specifically, the decrease of the facet gap by thickening the facet cartilage was completely contrary to the pathological change of ZJ degeneration. Besides, if the gap was reduced by thickening the bone tissue of articular process, the definition of material properties for sclerosis subchondral bone structures was also inaccurate for which was obviously differ from normal bone tissues [15, 72, 73], and the casual definition of material properties without reliable data will decrease the credibility of this study. Hence, we chose to construct DD models without the change of facet gap [49, 57].

Additionally, the grade of facetectomy in TESSYS TED models and discectomy in in-out TED models were set as one-third, this grade was consistent with the maximum one in our clinical practice. This modeling strategy was selected for facetectomy and nucleotomy were assumed to be main reasons for poor clinical outcomes after these operations respectively. Therefore, larger grades of these two procedures
should lead to more pronounced biomechanical deterioration and which could provide us a clear reference for the evaluation of these two techniques.

Clinical significance of biomechanical indicators

Disc collapse and DD acceleration in the surgical segment and resulting several kind of secondary pathological changes were most significant causes for the poor clinical outcome for patients after non-fusion lumbar surgery [33, 74, 75]. As is reported by Adam et. al, the injury of endplates and annulus can be seen as two different separately pathways in the DD process [21]. The maximum von-Mises stress and the strain energy of endplates were recorded to evaluate the risk of DD caused by the endplate lesion and ossification. Specifically, endplates play a key role in the pressure distribution, post operative abnormal stress concentration on endplates increases the risk of endplate lesions [21, 76, 77], resulting inflammatory response, autoimmune reaction and disc innervation can be seen as significant triggers for DD acceleration and increase risk of low back pain (LBP) [51, 78-80].

Besides, IVD was an avascular structure, and the most important pathway for its metabolism was the trans-endplate diffusion [81, 82]. According to the Wolff's law, the concentration of strain energy, a kind of compensatory reaction for the endplate stress concentration can be seen as a predicted factor for its ossification [83, 84], and resulting occlusion of trans-endplate diffusion pathway will lead to DD acceleration [43, 80, 85, 86]. Moreover, endplate injury caused by the abnormal stress concentration was closely associated with the disruption of the annulus and can also be reflected by the deterioration of biomechanical indicators on the annulus, especially in the post and post lateral part of annulus [21, 29, 82]. The concentration of shear stress and compressive stress have been proved to be related to different kinds of annulus tear and resulting DD, more significantly, to resulting discogenic LBP and RLDH [22, 23, 85]. Hence, we can speculate that above biomechanical indicators can be seen as credible predictors for the assessment of postoperative prognosis.

Meanwhile, the foramen stenosis was another vital reason for the clinical outcome deterioration, and special attention should be taken for models after in-out TED with intact SAP for the risk of foramen stenosis will get worse with disc collapse caused by a larger grade of disectomy in the surgical segment without foraminoplasty [74, 75, 87]. Noteworthy, the increase of FCF can not only be seen as a risk factor for the cartilage wear and resulting degenerative osteoarthritis of ZJ [15, 44, 73], a trigger of LBP [22, 25, 45], but also for the foramen stenosis considering a larger load will promote the osteogenic activity [43, 83, 88]. More importantly, disc collapse and degeneration in the surgical segment will lead to pathological stress concentration on ZJ cartilages and resulting further degenerative osteoarthritis and osteophytes formation in which [15, 45]. Besides, lumbar instability was also an important cause of prognosis deterioration after non-fusion surgery, and which have been proven to be related to LBP and further DD [86, 89, 90]. Therefore, ROM can be used not only as an indicator for model validation, but also for the assessment of postoperative complications. In a word, there was close interactions between different biomechanical indicators, and biomechanical deterioration will lead to a series of clinical symptoms and deterioration of prognosis.
Limitations

Firstly, ligaments were constructed by cable elements, and the simulation for the LF excision was accomplished by reducing its CSA. Cable elements can not stimulate the fold, the hypertrophy and the calcification of ligaments, and there pathological changes were reported to be vital risk factors for the spinal stenosis and nerve compression.

Meanwhile, as a common issue of FE studies, the proliferation of scar on the annulus and its biomechanical effects can not be evaluated. Considering that the size of annulus breakage was an important variable in this study, biomechanical changes caused by the formation of annulus scar tissue (although its strength proved not strong enough to stop RLDH) may also have its potential biomechanical impact on patients prognosis. Hence, current computational results should be recognized and discussed on the basic of the awareness of this defect and follow-up clinical study is still necessary for more definitive conclusions.

Conclusions

Based on above theoretical foundations and our computational results, it was not hard to make following conclusions. Biomechanical deterioration can be observed in models with optimized in-out TED without facetectomy (i.e. TED with intact SAP), especially in the extension, right bending and rotation conditions. Although the facetectomy was avoided, iatrogenic annulus breakage caused by the insertion of working cannula and a larger grade of nucleotomy for the prevention of RLDH provide this surgical method a potentially poor clinical outcome, and which was consistent with the report that larger grades of nucleotomy will lead to lower patients' satisfaction [32]. By contrast, the promotion of endoscopic dynamic drill in modified TESSYS TED (TED with a small grade of facetectomy), a kind of surgical design without extra injury of annulus and a large grade of discectomy, was proved to be advantageous biomechanically (Fig. 9).

Moreover, biomechanical deterioration can be observed in models with DD generally, and which was consistent with published reports [48, 49]. Although DD in adjacent segments did not obviously exacerbate the biomechanical deterioration in the surgical segment, the reported vicious cycle of DD can also be observed and which provide us the significance of this FE study from another perspective [21, 91]. Specifically, in this vicious circle, the deterioration of biomechanical environment caused by the unsuitable surgery may be continuously amplified and lead to disastrous prognosis. Therefore, the selection and optimization of surgical techniques based on the biomechanical FE study was of great significance.

Abbreviations

ACC: Accuracy
CSA: Cross-sectional areas
Ethics approval and consent to participate

Approval for the current study protocol (including the lumbar CT scan) was obtained from the ethics committees of Affiliated Hospital of Integrated Traditional Chinese and Western Medicine for Nanjing University of Chinese Medicine (2019LWKY015). We confirm that the subject signed the informed consent and submitted it to the ethics committee for review before the examination, and all methods were carried out in accordance with relevant guidelines and regulations.

Consent for publication

Not Applicable

Availability of data and materials

All the data of the manuscript are presented in the paper.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

LX and YMS contributed to the concept and design of the study, XYZ, ZXF and MNL contributed to the model construction, JCL and CX contribute to the finite element analysis, ZPX and NW drawn figures, JCL XC and XYZ wrote the manuscript, LX and YMS checked the manuscript, all authors read and approved the final manuscript.

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References

1. Kambin P: Arthroscopic microdiscectomy. Spine J 2003, 3(3 Suppl):60s-64s.
2. Pan M, Li Q, Li S, Mao H, Meng B, Zhou F, Yang H: Percutaneous Endoscopic Lumbar Discectomy: Indications and Complications. Pain Physician 2020, 23(1):49–56.
3. Hoogland T, Schubert M, Miklitz B, Ramirez A: Transforaminal posterolateral endoscopic discectomy with or without the combination of a low-dose chymopapain: a prospective randomized study in 280 consecutive cases. Spine (Phila Pa 1976) 2006, 31(24):E890-897.
4. Wu B, Zhan G, Tian X, Fan L, Jiang C, Deepti B, Cao H, Li J, Lian Q, Huang X et al: Comparison of Transforaminal Percutaneous Endoscopic Lumbar Discectomy with and without Foraminoplasty for Lumbar Disc Herniation: A 2-Year Follow-Up. Pain Res Manag 2019, 2019:6924941.
5. Yeung AT, Tsou PM: Posterolateral endoscopic excision for lumbar disc herniation: Surgical technique, outcome, and complications in 307 consecutive cases. Spine (Phila Pa 1976) 2002, 27(7):722–731.
6. Ruetten S, Komp M: Endoscopic Lumbar Decompression. Neurosurg Clin N Am 2020, 31(1):25–32.
7. Sivakanthan S, Hasan S, Hofstetter C: Full-Endoscopic Lumbar Discectomy. Neurosurg Clin N Am 2020, 31(1):1–7.
8. Xiong C, Li T, Kang H, Hu H, Han J, Xu F: Early outcomes of 270-degree spinal canal decompression by using TESSYS-ISEE technique in patients with lumbar spinal stenosis combined with disk herniation. Eur Spine J 2019, 28(1):78–86.
9. Choi G, Lee SH, Lokhande P, Kong BJ, Shim CS, Jung B, Kim JS: Percutaneous endoscopic approach for highly migrated intracanal disc hemiations by foraminoplastic technique using rigid working channel endoscope. Spine (Phila Pa 1976) 2008, 33(15):E508-515.
10. Henmi T, Terai T, Hibino N, Yoshioka S, Kondo K, Goda Y, Tezuka F, Sairyo K: Percutaneous endoscopic lumbar discectomy utilizing ventral epiduroscopic observation technique and foraminoplasty for transligamentous extruded nucleus pulposus: technical note. *J Neurosurg Spine* 2016, 24(2):275–280.

11. Choi KC, Shim HK, Park CJ, Lee DC, Park CK: Usefulness of Percutaneous Endoscopic Lumbar Foraminoplasty for Lumbar Disc Herniation. *World Neurosurg* 2017, 106:484–492.

12. Yang J, Guo C, Kong Q, Zhang B, Wang Y, Zhang L, Wu H, Peng Z, Yan Y, Zhang D: Learning curve and clinical outcomes of percutaneous endoscopic transforaminal decompression for lumbar spinal stenosis. *Int Orthop* 2020, 44(2):309–317.

13. Szkoda-Poliszuk K, Żak M, Pezowicz C: Finite element analysis of the influence of three-joint spinal complex on the change of the intervertebral disc bulge and height. *Int J Numer Method Biomed Eng* 2018, 34(9):e3107.

14. Adams MA: Biomechanics of back pain. *Acupunct Med* 2004, 22(4):178–188.

15. Brown KR, Pollintine P, Adams MA: Biomechanical implications of degenerative joint disease in the apophyseal joints of human thoracic and lumbar vertebrae. *Am J Phys Anthropol* 2008, 136(3):318–326.

16. Naserkhaki S, Jaremko JL, Adeeb S, El-Rich M: On the load-sharing along the ligamentous lumbosacral spine in flexed and extended postures: Finite element study. *J Biomech* 2016, 49(6):974–982.

17. Newell N, Little JP, Christou A, Adams MA, Adam CJ, Masouros SD: Biomechanics of the human intervertebral disc: A review of testing techniques and results. *J Mech Behav Biomed Mater* 2017, 69:420–434.

18. Chen C, Jia Z, Han Z, Gu T, Li W, Li H, Tang Y, Wu J, Wang D, He Q et al.: Quantitative T2 relaxation time and magnetic transfer ratio predict endplate biochemical content of intervertebral disc degeneration in a canine model. *BMC Musculoskelet Disord* 2015, 16:157.

19. Heuer F, Schmidt H, Claes L, Wilke HJ: Stepwise reduction of functional spinal structures increase vertebral translation and intradiscal pressure. *J Biomech* 2007, 40(4):795–803.

20. Heuer F, Schmidt H, Klezl Z, Claes L, Wilke HJ: Stepwise reduction of functional spinal structures increase range of motion and change lordosis angle. *J Biomech* 2007, 40(2):271–280.

21. Adams MA, Dolan P: Intervertebral disc degeneration: evidence for two distinct phenotypes. *J Anat* 2012, 221(6):497–506.

22. Clancy C, Quinn A, Wilson F: The aetiologies of Failed Back Surgery Syndrome: A systematic review. *J Back Musculoskelet Rehabil* 2017, 30(3):395–402.

23. Qasim M, Natarajan RN, An HS, Andersson GB: Damage accumulation location under cyclic loading in the lumbar disc shifts from inner annulus lamellae to peripheral annulus with increasing disc degeneration. *J Biomech* 2014, 47(1):24–31.

24. Mochida J, Nishimura K, Nomura T, Toh E, Chiba M: The importance of preserving disc structure in surgical approaches to lumbar disc hemiation. *Spine (Phila Pa 1976)* 1996, 21(13):1556–1563;
25. Schaller B: Failed back surgery syndrome: the role of symptomatic segmental single-level instability after lumbar microdiscectomy. *Eur Spine J* 2004, 13(3):193–198.

26. Li J, Zhang X, Xu W, Xi Z, Xie L: Reducing the extent of facetectomy may decrease morbidity in failed back surgery syndrome. *BMC Musculoskelet Disord* 2019, 20(1):369.

27. Li J, Xu W, Jiang Q, Xi Z, Zhang X, Wang N, Xie L, Liu Y: Indications Selection for Surgeons Training in the Translaminar Percutaneous Endoscopic Discectomy Based on Finite Element Analysis. *Biomed Res Int* 2020, 2020:2960642.

28. Li J, Li H, He Y, Zhang X, Xi Z, Wang G, Wang N, Xie L: The protection of superior articular process in percutaneous transforaminal endoscopic discectomy should decreases the risk of adjacent segment diseases biomechanically. *J Clin Neurosci* 2020, 79:54–59.

29. Adams MA, Roughley PJ: What is intervertebral disc degeneration, and what causes it? *Spine (Phila Pa 1976)* 2006, 31(18):2151–2161.

30. Hasegawa K, Kitahara K, Shimoda H, Hara T: Facet joint opening in lumbar degenerative diseases indicating segmental instability. *J Neurosurg Spine* 2010, 12(6):687–693.

31. McGirt MJ, Eustacchio S, Varga P, Vilendecic M, Trummer M, Gorensek M, Ledic D, Carragee EJ: A prospective cohort study of close interval computed tomography and magnetic resonance imaging after primary lumbar discectomy: factors associated with recurrent disc hemiation and disc height loss. *Spine (Phila Pa 1976)* 2009, 34(19):2044–2051.

32. Carragee EJ, Spinnickie AO, Alamin TF, Paragioudakis S: A prospective controlled study of limited versus subtotal posterior discectomy: short-term outcomes in patients with hemiated lumbar intervertebral discs and large posterior anular defect. *Spine (Phila Pa 1976)* 2006, 31(6):653–657.

33. Carragee EJ, Han MY, Suen PW, Kim D: Clinical outcomes after lumbar discectomy for sciatica: the effects of fragment type and anular competence. *J Bone Joint Surg Am* 2003, 85(1):102–108.

34. Stokes IA, Iatridis JC: Mechanical conditions that accelerate intervertebral disc degeneration: overload versus immobilization. *Spine (Phila Pa 1976)* 2004, 29(23):2724–2732.

35. Faulhauer K, Manicke C: Fragment excision versus conventional disc removal in the microsurgical treatment of hemiated lumbar disc. *Acta Neurochir (Wien)* 1995, 133(3–4):107–111.

36. Kim HS, You JD, Ju CI: Predictive Scoring and Risk Factors of Early Recurrence after Percutaneous Endoscopic Lumbar Discectomy. *Biomed Res Int* 2019, 2019:6492675.

37. Hampton D, Laros G, McCarron R, Franks D: Healing potential of the anulus fibrosus. *Spine (Phila Pa 1976)* 1989, 14(4):398–401.

38. O'Connell GD, Malhotra NR, Vresilovic EJ, Elliott DM: The effect of nucleotomy and the dependence of degeneration of human intervertebral disc strain in axial compression. *Spine (Phila Pa 1976)* 2011, 36(21):1765–1771.

39. Johannessen W, Cloyd JM, O'Connell GD, Vresilovic EJ, Elliott DM: Trans-endplate nucleotomy increases deformation and creep response in axial loading. *Ann Biomed Eng* 2006, 34(4):687–696.
40. Vresilovic EJ, Johannessen W, Elliott DM: Disc mechanics with trans-endplate partial nucleotomy are not fully restored following cyclic compressive loading and unloaded recovery. *J Biomech Eng* 2006, **128**(6):823–829.

41. Cannella M, Arthur A, Allen S, Keane M, Joshi A, Vresilovic E, Marcolongo M: The role of the nucleus pulposus in neutral zone human lumbar intervertebral disc mechanics. *J Biomech* 2008, **41**(10):2104–2111.

42. Kirkaldy-Willis WH, Wedge JH, Yong-Hing K, Reilly J: Pathology and pathogenesis of lumbar spondylosis and stenosis. *Spine (Phila Pa 1976)* 1978, **3**(4):319–328.

43. Ganbat D, Kim YH, Kim K, Jin YJ, Park WM: Effect of mechanical loading on heterotopic ossification in cervical total disc replacement: a three-dimensional finite element analysis. *Biomech Model Mechanobiol* 2016, **15**(5):1191–1199.

44. Kim HJ, Chun HJ, Lee HM, Kang KT, Lee CK, Chang BS, Yeom JS: The biomechanical influence of the facet joint orientation and the facet tropism in the lumbar spine. *Spine J* 2013, **13**(10):1301–1308.

45. Suri P, Miyakoshi A, Hunter DJ, Jarvik JG, Rainville J, Guermazi A, Li L, Katz JN: Does lumbar spinal degeneration begin with the anterior structures? A study of the observed epidemiology in a community-based population. *BMC Musculoskelet Disord* 2011, **12**:202.

46. Mahatthanatrakul A, Kotheeranurak V, Lin GX, Hur JW, Chung HJ, Kim JS: Comparative analysis of the intervertebral disc signal and annulus changes between immediate and 1-year postoperative MRI after transforaminal endoscopic lumbar discectomy and annuloplasty. *Neuroradiology* 2019, **61**(4):411–419.

47. Wang Y, Luo G, Wang J, Zhu M, Li C, Teng H: Early Postoperative Magnetic Resonance Imaging Findings After Percutaneous Endoscopic Lumbar Discectomy and Their Correlations with Clinical Outcomes. *World Neurosurg* 2018, **111**:e241-e249.

48. Chuang WH, Lin SC, Chen SH, Wang CW, Tsai WC, Chen YJ, Hwang JR: Biomechanical effects of disc degeneration and hybrid fixation on the transition and adjacent lumbar segments: trade-off between junctional problem, motion preservation, and load protection. *Spine (Phila Pa 1976)* 2012, **37**(24):E1488-1497.

49. Ruberté LM, Natarajan RN, Andersson GB: Influence of single-level lumbar degenerative disc disease on the behavior of the adjacent segments—a finite element model study. *J Biomech* 2009, **42**(3):341–348.

50. Li J, Xu W, Zhang X, Xi Z, Xie L: Biomechanical role of osteoporosis affects the incidence of adjacent segment disease after percutaneous transforaminal endoscopic discectomy. *J Orthop Surg Res* 2019, **14**(1):131.

51. Dreischarf M, Zander T, Shirazi-Adl A, Puttlitz CM, Adam CJ, Chen CS, Goel VK, Kiapour A, Kim YH, Labus KM et al. Comparison of eight published static finite element models of the intact lumbar spine: predictive power of models improves when combined together. *J Biomech* 2014, **47**(8):1757–1766.
52. Herren C, Beckmann A, Meyer S, Pishnamaz M, Mundt M, Sobottke R, Prescher A, Stoffel M, Markert B, Kobbe P et al: Biomechanical testing of a PEEK-based dynamic instrumentation device in a lumbar spine model. Clin Biomech (Bristol, Avon) 2017, 44:67–74.
53. Tsouknidas A, Sarigiannidis SO, Anagnostidis K, Michailidis N, Ahuja S: Assessment of stress patterns on a spinal motion segment in healthy versus osteoporotic bony models with or without disc degeneration: a finite element analysis. Spine J 2015, 15(3 Suppl):S17-s22.
54. Du CF, Yang N, Guo JC, Huang YP, Zhang C: Biomechanical response of lumbar facet joints under follower preload: a finite element study. BMC Musculoskelet Disord 2016, 17:126.
55. Schmidt H, Galbusera F, Rohlmann A, Zander T, Wilke HJ: Effect of multilevel lumbar disc arthroplasty on spine kinematics and facet joint loads in flexion and extension: a finite element analysis. Eur Spine J 2012, 21 Suppl 5(Suppl 5):S663-674.
56. Wang B, Hua W, Ke W, Lu S, Li X, Zeng X, Yang C: Biomechanical Evaluation of Transforaminal Lumbar Interbody Fusion and Oblique Lumbar Interbody Fusion on the Adjacent Segment: A Finite Element Analysis. World Neurosurg 2019, 126:e819-e824.
57. Chuang WH, Kuo YJ, Lin SC, Wang CW, Chen SH, Chen YJ, Hwang JR: Comparison among load-, ROM-, and displacement-controlled methods used in the lumbosacral nonlinear finite-element analysis. Spine (Phila Pa 1976) 2013, 38(5):E276-285.
58. Kim HJ, Kang KT, Son J, Lee CK, Chang BS, Yeom JS: 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(8):1841–1847.
59. Renner SM, Natarajan RN, Patwardhan AG, Havey RM, Voronov LI, Guo BY, Andersson GB, An HS: Novel model to analyze the effect of a large compressive follower preload on range of motions in a lumbar spine. J Biomech 2007, 40(6):1326–1332.
60. Woldtvedt DJ, Womack W, Gadomski BC, Schuldt D, Puttlitz CM: Finite element lumbar spine facet contact parameter predictions are affected by the cartilage thickness distribution and initial joint gap size. J Biomech Eng 2011, 133(6):061009.
61. Hsieh YY, Chen CH, Tsuang FY, Wu LC, Lin SC, Chiang CJ: Removal of fixation construct could mitigate adjacent segment stress after lumbosacral fusion: A finite element analysis. Clin Biomech (Bristol, Avon) 2017, 43:115–120.
62. Ottardi C, Galbusera F, Luca A, Prosdocimo L, Sasso M, Brayda-Bruno M, Villa T: Finite element analysis of the lumbar destabilization following pedicle subtraction osteotomy. Med Eng Phys 2016, 38(5):506–509.
63. Schmidt H, Heuer F, Drumm J, Klezl Z, Claes L, Wilke HJ: Application of a calibration method provides more realistic results for a finite element model of a lumbar spinal segment. Clin Biomech (Bristol, Avon) 2007, 22(4):377–384.
64. Schmidt H, Heuer F, Simon U, Kettler A, Rohlmann A, Claes L, Wilke HJ: Application of a new calibration method for a three-dimensional finite element model of a human lumbar annulus fibrosus. Clin Biomech (Bristol, Avon) 2006, 21(4):337–344.
65. Wilson DC, Niosi CA, Zhu QA, Oxland TR, Wilson DR: **Accuracy and repeatability of a new method for measuring facet loads in the lumbar spine.** *J Biomech* 2006, **39**(2):348–353.

66. Schilling C, Krüger S, Grupp TM, Duda GN, Blömer W, Rohlmann A: **The effect of design parameters of dynamic pedicle screw systems on kinematics and load bearing: an in vitro study.** *Eur Spine J* 2011, **20**(2):297–307.

67. Pfirrmann CW, Metzdorf A, Zanetti M, Hodler J, Boos N: **Magnetic resonance classification of lumbar intervertebral disc degeneration.** *Spine (Phila Pa 1976)* 2001, **26**(17):1873–1878.

68. Xin G, Shi-Sheng H, Hai-Long Z: **Morphometric analysis of the YESS and TESSYS techniques of percutaneous transforaminal endoscopic lumbar discectomy.** *Clin Anat* 2013, **26**(6):728–734.

69. Park WM, Kim K, Kim YH: **Effects of degenerated intervertebral discs on intersegmental rotations, intradiscal pressures, and facet joint forces of the whole lumbar spine.** *Comput Biol Med* 2013, **43**(9):1234–1240.

70. Ichchou L, Allali F, Rostom S, Bennani L, Hmamouchi I, Abourazzak FZ, Khazzani H, El Mansouri L, Abouqal R, Hajjaj-Hassouni N: **Relationship between spine osteoarthritis, bone mineral density and bone turnover markers in post menopausal women.** *BMC Womens Health* 2010, **10**:25.

71. O’Leary SA, Link JM, Klineberg EO, Hu JC, Athanasiou KA: **Characterization of facet joint cartilage properties in the human and interspecies comparisons.** *Acta Biomater* 2017, **54**:367–376.

72. Homminga J, Aquarius R, Bulsink VE, Jansen CT, Verdonschot N: **Can vertebral density changes be explained by intervertebral disc degeneration?** *Med Eng Phys* 2012, **34**(4):453–458.

73. Bellido M, Lugo L, Roman-Blas JA, Castañeda S, Caeiro JR, Dapia S, Calvo E, Largo R, Herrero-Beaumont G: **Subchondral bone microstructural damage by increased remodelling aggravates experimental osteoarthritis preceded by osteoporosis.** *Arthritis Res Ther* 2010, **12**(4):R152.

74. Barth M, Weiss C, Thomé C: **Two-year outcome after lumbar microdiscectomy versus microscopic sequestrectomy: part 1: evaluation of clinical outcome.** *Spine (Phila Pa 1976)* 2008, **33**(3):265–272.

75. Thomé C, Barth M, Scharf J, Schmiedek P: **Outcome after lumbar sequestrectomy compared with microdiscectomy: a prospective randomized study.** *J Neurosurg Spine* 2005, **2**(3):271–278.

76. Adams MA, Freeman BJ, Morrison HP, Nelson IW, Dolan P: **Mechanical initiation of intervertebral disc degeneration.** *Spine (Phila Pa 1976)* 2000, **25**(13):1625–1636.

77. Brayda-Bruno M, Albano D, Cannella G, Galbusera F, Zerbi A: **Endplate lesions in the lumbar spine: a novel MRI-based classification scheme and epidemiology in low back pain patients.** *Eur Spine J* 2018, **27**(11):2854–2861.

78. Fakouri B, Patel V, Bayley E, Srinivas S: **Lumbar microdiscectomy versus sequesterectomy/free fragmentectomy: a long-term (> 2 y) retrospective study of the clinical outcome.** *J Spinal Disord Tech* 2011, **24**(1):6–10.

79. Dolan P, Luo J, Pollintine P, Landham PR, Stefanakis M, Adams MA: **Intervertebral disc decompression following endplate damage: implications for disc degeneration depend on spinal level and age.** *Spine (Phila Pa 1976)* 2013, **38**(17):1473–1481.
80. Wang Y, Videman T, Battié MC: ISSLS prize winner: Lumbar vertebral endplate lesions: associations with disc degeneration and back pain history. Spine (Phila Pa 1976) 2012, 37(17):1490–1496.

81. Tomaszewski KA, Saganiak K, Gladysz T, Walocha JA: The biology behind the human intervertebral disc and its endplates. Folia Morphol (Warsz) 2015, 74(2):157–168.

82. Roberts S, Evans H, Trivedi J, Menage J: Histology and pathology of the human intervertebral disc. J Bone Joint Surg Am 2006, 88 Suppl 2:10–14.

83. Von Forell GA, Nelson TG, Samartzis D, Bowden AE: Changes in vertebral strain energy correlate with increased presence of Schmorl's nodes in multi-level lumbar disk degeneration. J Biomech Eng 2014, 136(6):061002.

84. Rajasekaran S, Babu JN, Arun R, Armstrong BR, Shetty AP, Murugan S: ISSLS prize winner: A study of diffusion in human lumbar discs: a serial magnetic resonance imaging study documenting the influence of the endplate on diffusion in normal and degenerate discs. Spine (Phila Pa 1976) 2004, 29(23):2654–2667.

85. Xiao L, Ni C, Shi J, Wang Z, Wang S, Zhang J, Lu A: Analysis of Correlation Between Vertebral Endplate Change and Lumbar Disc Degeneration. Med Sci Monit 2017, 23:4932–4938.

86. Park P, Garton HJ, Gala VC, Hoff JT, McGillicuddy JE: Adjacent segment disease after lumbar or lumbosacral fusion: review of the literature. Spine (Phila Pa 1976) 2004, 29(17):1938–1944.

87. Patriota GC: Re: two-year outcome after lumbar microdiscectomy versus microscopic sequestrectomy: part 2: radiographic evaluation and correlation with clinical outcome. Spine (Phila Pa 1976) 2008, 33(22):2481; author reply 2481.

88. Grosland NM, Goel VK: Vertebral endplate morphology follows bone remodeling principles. Spine (Phila Pa 1976) 2007, 32(23):E667-673.

89. Wu H, Peng J, Jin X: Internal Biomechanical Study of a 70-Year-Old Female Human Lumbar Bi-Segment Finite Element Model and Comparison with a Middle-Aged Male Model. Biomed Res Int 2019, 2019:9794365.

90. Eubanks JD, Lee MJ, Cassinelli E, Ahn NU: Prevalence of lumbar facet arthrosis and its relationship to age, sex, and race: an anatomic study of cadaveric specimens. Spine (Phila Pa 1976) 2007, 32(19):2058–2062.

91. Vergroesen PP, Kingma I, Emanuel KS, Hoogendoorn RJ, Welting TJ, van Royen BJ, van Dieën JH, Smit TH: Mechanics and biology in intervertebral disc degeneration: a vicious circle. Osteoarthritis Cartilage 2015, 23(7):1057–1070.

Figures
Figure 1

The schematic for the optimization of TED by two different strategies (ligamentum structures have been hided for the sake of brevity in schematic diagrams)
Figure 2

Intact 3D models in the current study

Figure 3

The surgical model construction and the corresponding imaging data
Model validation

Range of motions (°)

Flexion (8Nm) - Extension (6Nm)

L1-L4: ACC=95.67%  L4-L5: ACC=90.26%  L5-S1: ACC=97.30%

Lateral Bending (6Nm)

L1-L4: ACC=98.73%  L4-L5: ACC=95.85%  L5-S1: ACC=99.05%

Axial rotation (4Nm)

L1-L4: ACC=98.73%  L4-L5: ACC=95.85%  L5-S1: ACC=99.05%

Intradiscal pressure (KPa)

L1-L5 segment (7.5Nm)

L1-L4: ACC=98.09%  L4-L5: ACC=98.09%  L5-S1: ACC=96.20%

Disc compression (mm)

1200N vertical compression

L1-L4: ACC=98.13%  L4-L5: ACC=98.04%  L5-S1: ACC=98.03%

The formula of accuracy (ACC): \( ACC = \left\{ \frac{VAL_{\text{true}} - VAL_{\text{pred}}}{VAL_{\text{true}}} \right\} \times 100\% \)

VAL_{\text{true}}: The average value of biomechanical indicators measured by widely cited in-vitro study

VAL_{\text{pred}}: The value of biomechanical indicators computed by the intact FEA model in this study

Figure 4

Model validation
Figure 5

The variation of biomechanical indicators related to the “endplate type” disc degeneration F: flexion, E: extension, LB: left bending, RB: right bending, LAR: left axial rotation, RAR: right axial rotation. The corresponding meanings of model 1 to model 6 were shown in table 1.
Figure 6

The variation of biomechanical indicators related to the “annulus type” disc degeneration
Figure 7

The variation of biomechanical indicators related to ZJ degeneration and lumbar instability
Figure 8

The variation of CSA
Figure 9

The endoscopic vision of precise facetectomy by dynamic drill

Intact superior articular process  Facetectomy by dynamic drill under direct vision

Herniated nucleus  Enough operative space for discectomy

Different grades of facetectomy

Facetectomy was controllable under direct vision, So, unnecessary facetectomy can be avoided.