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Research article

Transforaminal lumbar interbody fusion (TLIF) surgery: A finite element analysis of open and minimally invasive approach on L4-L5 segment

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ABSTRACT

Background: To compare the effect of minimally invasive and open transforaminal lumbar interbody fusion (TLIF) approaches in fusing the L4-L5 segment and predicting the potential risk of adjacent segment degeneration (ASD).
Methods: A computed tomography scan image was processed and the three-dimensional model of the L1-L5 spine was reconstructed. The minimally invasive and Open TLIF finite element models were constructed. The models were analyzed using an axial compressive load (500 N) and physiological movements like flexion, extension, and lateral bending with a combined load and moment (150 N and 10 Nm). The ranges of motion (ROM), stress-strain distributions on the L4-L5 implanted segment and cranial adjacent soft structures were compared with the intact model.
Results: A substantially comparable drop in ROM was observed for both models due to implantation. The stress and strain distributions on the implanted segment of both models were nearly identical. The peak strain on the L4-L5 was higher than 0.007 for both models. The maximum stress and strain observed on adjacent segment soft structures, except for the annulus fibrosus of both the implanted models, were substantially higher than the intact structures.
Conclusions: The open and MI-TLIF approaches are effective in reducing ROMs. However, the higher stress and strain on the L4-L5 segment indicate the chances of bone failure. The higher stress and strain on the adjacent segment soft structures indicate the potential risk of ASD in both models. However, considering the lower intrusive nature of the MI-TLIF technique, it might be favoured over Open TLIF.

1. Introduction

Lumbar interbody fusion is an effective surgical procedure for treating severe degenerative lumbar disorders. Transforaminal

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Lumbar Interbody Fusion (TLIF) is a type of posterior lumbar fusion that has proven to be a reliable, safe, and effective technique that can help achieve significant clinical outcomes [1–4]. The TLIF technique helps preserve the contralateral posterior column structure, reduce soft tissue injury, maintain spinal biomechanical stability, and thus favouring early postoperative recovery [3,4].

With improvements in surgical technique and implants, the minimally invasive approach to performing TLIF surgery has gained popularity. Minimally invasive TLIF (MI-TLIF) involves significantly less soft-tissue and muscle disruption and has become the TLIF procedure of choice, especially for low-grade spondylolisthesis [5,6]. The MI-TLIF procedure for a single-level grade 1 degenerative lumbar spondylolisthesis has been reported to be associated with less disability, higher return to work, a better quality of life, and greater patient satisfaction when compared to Open TLIF [7,8]. The Open TLIF procedure requires a large midline incision with significant muscle stripping and retraction, leading to extensive soft tissue damage, including paraspinal muscle injury [9,10]. Even though this method offers a direct view of the surgical site, offering easier handling of complex anatomy, it often results in scarring, reduced muscle function, higher postoperative pain, more extended hospital stays and prolonged recovery periods. The patients may take months to regain full functionality. Meanwhile, in MI-TLIF, using tubular retractors or endoscopic tools to make smaller incisions helps minimize muscle disruption. This preservation of soft tissues leads to better postoperative muscle function, shorter hospital stays, less postoperative pain, and faster recovery times. However, it demands a higher surgical precision and skill.

Finite element (FE) analysis has been used widely to predict the effects of various fusion surgeries. It is possible to compare various surgical techniques by assessing the ranges of motion (ROM), the strain on the implanted bone, and the stress & strain on the adjacent soft structures. Various FE studies compared these parameters of other fusion surgical techniques on the implanted lumbar spine [11–13]. However, a comparison of the potential threat of adjacent segment degeneration (ASD) and the possibility of revision surgery between open and minimally invasive TLIF has rarely been investigated in the literature. The current study hypothesizes differences in the biomechanics of Open and MI-TLIF approaches in fusing the lumbar spine. The study evaluates the possible risk of ASD and compares the impact of the Open and MI-TLIF techniques in fusing the L4-L5 segment to verify this hypothesis. The L4-L5 segment is considered in the present investigation because of its significant clinical importance, vulnerability to degenerative alterations and occurrence of ASD [14,15]. The L4-L5 segment is one of the human spine's most mobile and load-bearing segments. It is known to be the most prevalent site for the degeneration of discs, herniation, and spondylolisthesis, leading to spinal fusion procedures due to the enormous mechanical stress it experiences [15,16]. Furthermore, its anatomical location next to the lumbosacral junction predisposes it to changed biomechanics after fusion, increasing the incidence of ASD at nearby levels. Understanding the biomechanical behaviour of the L4-L5 segment following fusion has become essential for enhancing surgical results and reducing postoperative problems.

2. Materials and methods

2.1. Finite element model

A computed-tomography (CT) scan image of a 34-year-old female subject (slices: 401, thickness: 1 mm; pixel size: 0.34 mm × 0.34 mm) was processed using MIMICS (Materialise Inc., Belgium) and the three-dimensional model of the L1-L5 was reconstructed. The full model included five vertebrae, endplates (bony & cartilaginous) and intervertebral discs (annulus fibrosus & nucleus pulposus) between them. The seven types of spinal ligaments were modelled using two-node tension-only link elements [17]. The model was meshed using a ten-node tetrahedral element, and the biomechanical evaluation was performed using ANSYS (ANSYS Inc, USA). The authors' previous study reported details of the lumbar spine model's reconstruction, validation, and verification [18]. Direct experimental validation was not feasible since the CT data used for modelling the lumbar spine is from a living subject. The FE models were indirectly validated by comparing the intact model ROM results with previously reported investigations [15,18–21]. The total ROM for

Table 1
Material properties used for the finite element analysis [22].

Components	Elastic modulus (MPa)	Poisson's Ratio
Vertebrae	$\mathbf{E} = 4730\boldsymbol{\rho}^{1.56}$ Where $\boldsymbol{\rho} = 0.022 + 0.00123$HU HU is Hounsfield Unit	0.3
Endplates		
Bony	12000	0.3
Cartilaginous	24	0.4
Intervertebral disc		
Annulus Fibrosus	8.4	0.45
Nucleus Pulposus	1	0.49
Ligaments [*Cross-Sectional Area*]		
Facet capsular [60 mm^2]	33	0.3
Interspinous [40 mm^2]	12	0.3
Supraspinous [30 mm^2]	15	0.3
Anterior Longitudinal [63.7 mm^2]	20	0.3
Posterior Longitudinal [20 mm^2]	20	0.3
Ligamentum Flavum [40 mm^2]	19.5	0.3
Intertransverse [3.6 mm^2]	59	0.3
IMPLANTS (Ti6Al4V)		
Rods, Screws & Cage	110,000	0.3

the intact L1-L5 was 14.3° in flexion, 12.51° in extension, and 12° in lateral bending. For the L3-L4 segment, the ROM was 4.2° in flexion, 4° in extension, and 3.56° in lateral bending. These results were comparable with the previously reported FE and experimental literature and served as a validation to the lumbar spine FE models [15,18–21]. This validated lumbar spine model was suitably modified to simulate Open and MI-TLIF approaches in the present study. The assigned material properties were similar to the authors' previous study [22] and are shown in Table 1.

2.2. Transforaminal lumbar interbody fusion (TLIF)

The finite element model of the intact and implanted models (L1-L5 and L4-L5 segment) is shown in Fig. 1. The TLIF models (Open and MI) were constructed by removing the left facet joint of the L4-L5 segment, part of the annulus fibrosus, associated ligaments and the nucleus pulposus. Both models' ligamentum flavum and posterior longitudinal ligament were detached from the L4-L5 segment. For the Open TLIF model, the left facet joint and the L4 left lamina portion were completely removed (Fig. 1c), whereas, for the MI-TLIF model, most of the L4 lamina part was left untouched (Fig. 1b). The part of the annulus fibrosus was removed to create a postero-lateral opening, followed by nuclectomy. The affected segment was stabilized using posterior fixation implants. A model of interbody cage ETurn™ (Icotec, Switzerland) was placed in the disc space. After creating four holes through the pedicles of the L4 and L5 vertebrae, percutaneous pedicle screws (4.5 mm × 40 mm) were inserted and connected with rods (4.5 mm × 40 mm), as shown in Fig. 1b and c. All the interfaces between implants and the vertebrae were assumed to be bonded and the facet joints were assigned a surface-to-surface frictional contact with a frictional coefficient of 0.1 [22]. The implants were modelled in SOLIDWORKS (Dassault Systems SOLIDWORKS Corp., USA), and the assigned implant material was Ti-6Al-4V (E = 110 GPa; ν = 0.3).

2.3. Loading and boundary conditions

The loading and boundary conditions were similar to the authors' previous study [18], where the superior endplate of the L1 vertebra was used to apply the loads and the L5 vertebra's inferior endplate was restricted in all directions. The analysis of the constructed models was performed using an axial load (500 N) and physiological movements (flexion, extension, and lateral bending) with a combined load and moment (150 N and 10 Nm). The ROMs, stress-strain distributions on the L4-L5 implanted segment and cranial adjacent soft structures were compared with the intact model to investigate the biomechanical effects of the fusion surgeries.

3. Results

3.1. Ranges of motion under applied loading and boundary conditions

The observed reduction in ROMs of Open and MI-TLIF compared to intact models under applied loading conditions is shown in Fig. 2. After the implantation, the ROMs of the L4-L5 segment were significantly reduced. The implanted segment of the MI-TLIF model had a higher restriction on ROM compared to Open TLIF during flexion. The observation was similar under extension as well. However, under lateral bending, the Open TLIF model experienced slightly higher motion restriction than MI-TLIF. Due to implantation, a substantially comparable drop in ROM was observed for the L1-L5 full segment of both models.

3.2. Stress and strain on implanted segments

The stress and strain distributions observed in the implanted and intact segment (L4-L5) are shown in Fig. 3. In the implanted models, the anterior region of the vertebral body was under higher stress during flexion and compression loading. However, the posterior region (below pedicles) was under higher stress during extension. Compared to the intact segment (L4-L5), the stress distribution was substantially different for both the implanted models. The strain within the core region of the implanted segment

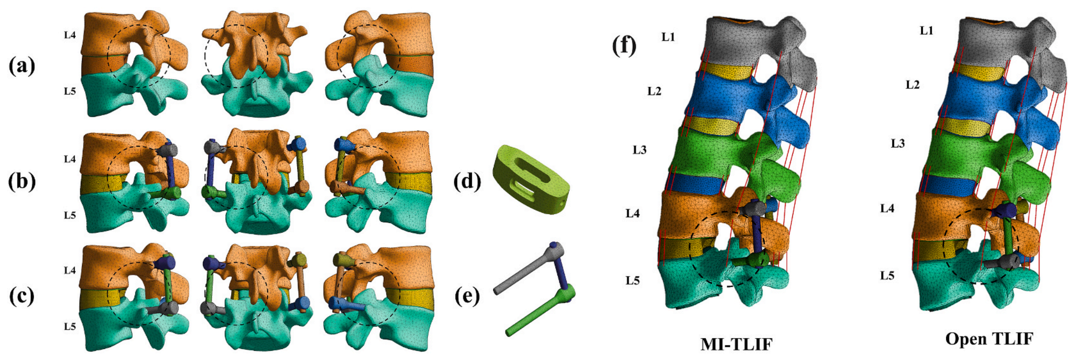

Fig. 1. Finite element models: (a) Intact L4-L5 segment, (b) MI-TLIF L4-L5 segment, (c) Open TLIF L4-L5 segment, (d) Cage, (e) Pedicle screw and rod system, (f) MI-TLIF and Open TLIF complete model with attached ligaments.

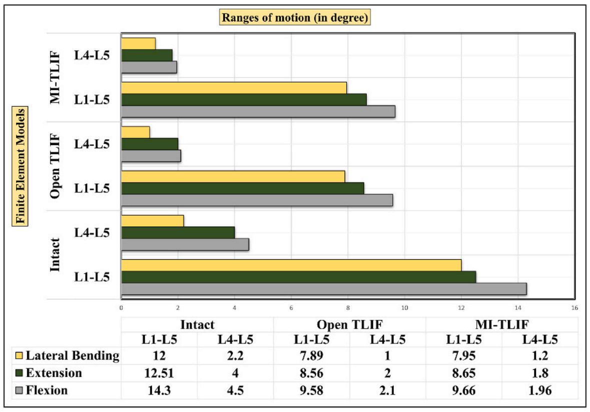

Fig. 2. Comparing the ranges of motion.

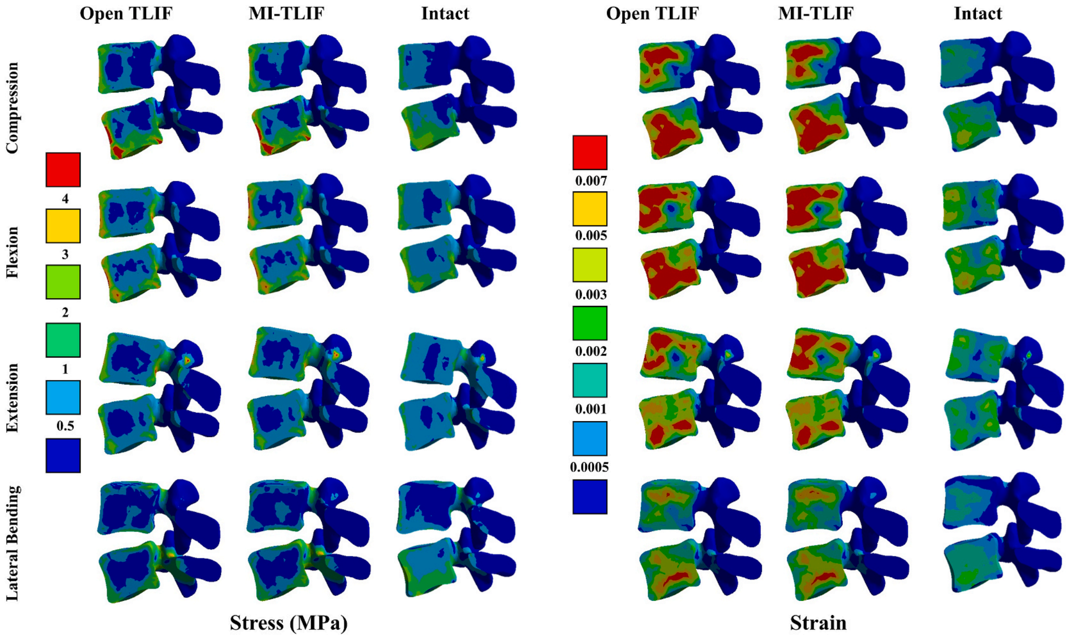

Fig. 3. Stress and strain distributions on the L4-L5 segment.

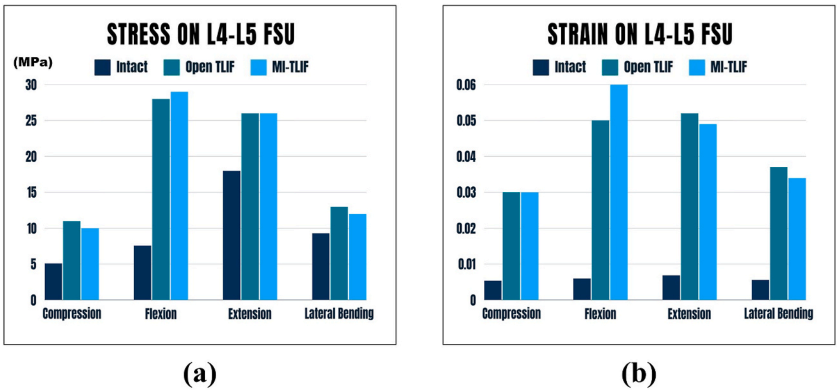

Fig. 4. Comparing the peak stress and strain on the L4-L5 segment.

exceeded 0.007 under all the loading conditions. The strain distributions for both implanted models were almost identical. However, it was substantially distinct from the intact model.

A graphical comparison of peak stress and strain on the implanted segments is shown in Fig. 4. The maximum stress and strain under compression on the MI-TLIF model was 10 MPa and 0.03, respectively. Meanwhile, the Open TLIF model had 11 MPa and 0.03. The maximum stress values for the MI-TLIF and Open TLIF models during flexion, extension, and lateral bending were 29 MPa & 28 MPa, 26 MPa for both, and 12 MPa & 13 MPa, respectively. Similarly, the strain values were 0.06 & 0.05, 0.049 & 0.052 and 0.034 & 0.037, respectively, for MI-TLIF and Open TLIF models. The highest stress and strain on the intact L4-L5 segment were well below those of implanted segments for all loading cases.

3.3. *Stress and strain on cranial adjacent segment*

The stress and strain on the cranial adjacent soft structures are shown in Figs. 5 and 6. Compared to the intact model, the maximum stress and strain observed on the endplates of both the implanted spine models were higher under all loading conditions (Fig. 5). However, the endplates of the implanted models exhibited negligible variation (<2 %) between them.

Under extension loading, the cranial adjacent annulus fibrosus of both the implanted models was less stressed than the intact model (Fig. 6a). The maximum stress under flexion loading was similar between the three models (Fig. 6a). Under compression, the maximum stress in the annulus fibrosus of the Open TLIF model was higher than both the intact and MI-TLIF models (Fig. 6a). Under lateral bending, the maximum stress in the annulus fibrosus of the Open TLIF model was lesser than the intact and MI-TLIF models (Fig. 6a). However, under all the loading situations, the maximum strain observed on the cranial adjacent annulus fibrosus of the implanted models was higher than the maximum strain on the intact model (Fig. 6b). The maximum stress observed in the cranial adjacent nucleus pulposus of both the implanted models under compression, flexion and extension loading were similar (Fig. 6c). However, under lateral bending, a difference in maximum stress was observed (Fig. 6c). The maximum strain observed in the cranial adjacent nucleus pulposus of both the implanted models was identical (Fig. 6d).

3.4. *Stress on cages*

The maximum stress observed on the cage of MI and Open TLIF model was 12.5 MPa and 13 MPa under compression, 26 MPa and 24 MPa under flexion, 19 MPa and 22 MPa under extension and 12 MPa and 9 MPa under lateral bending, respectively (Fig. 7).

4. Discussion

The current FE study compared the biomechanical alterations in an L4-L5 segment implanted using open and MI-TLIF surgical approaches. Additionally, the study investigated the effect of implantation on the soft structures of the cranial adjacent segment. Compared to the intact model, the ROM observed on both the implanted models was substantially reduced. The stress and strain distribution observed on the vertebrae of both the implanted models were nearly identical. Similarly, the maximum stress and strain observed on adjacent segment soft structures of both the implanted models except annulus fibrosus were substantially higher than the intact structures.

The reduction in ROMs exhibited by both the implanted models is higher than 50 % compared to the intact model (Fig. 2). This indicates that either an Open or MI-TLIF approach can be adopted to fuse a degenerated L4-L5 segment. Even though reduction in ROM

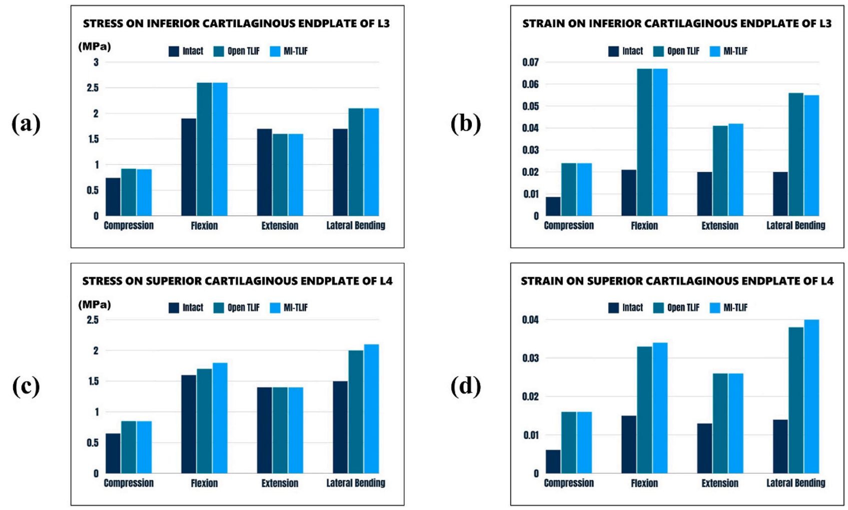

Fig. 5. Comparing the peak stress and strain on the adjacent endplates.

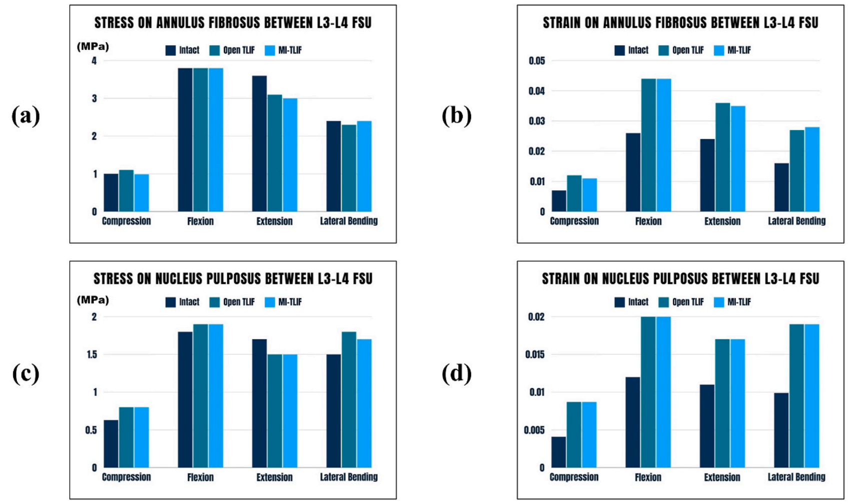

Fig. 6. Comparing the peak stress and strain on the adjacent disc (annulus fibrosus and nucleus pulposus).

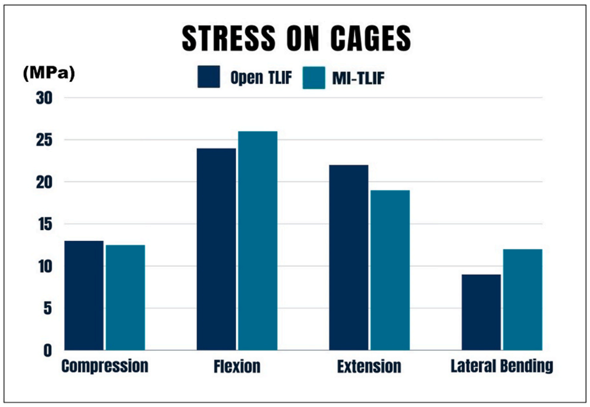

Fig. 7. Stress on the cage under different loading conditions.

is the objective of fusing the segments, it carries significant clinical consequences, especially those related to normal spine biomechanics and patient functionality. Fusion rigidly immobilizes the operated segment, redistributing the motion and loading at the adjacent segments. This biomechanical shift may result in increased stress and accelerated degeneration of adjacent levels (ASD), which may present with pain, disc herniation, or instability and may require further surgery [15,22,23]. Loss of flexibility also extends to everyday activities such as bending, rotating, or lifting. Besides that, the changed pattern of load-sharing increases stresses on non-fused segments, leading to implant loosening or failure. Further, reduced ROM compromises postural stability as reflected in impaired balance or abnormal gait and increased risk of falling. This procedure is usually traded off with general functional limitation, chronic pain, or diminished quality of life, especially in active patients. Regular follow-up is vital so that ASDs and other complications can be promptly identified and treated to ensure optimal long-term outcomes.

Considering the maximum restriction to ROM of the implanted segment, the MI-TLIF model shows better performance under flexion and extension loading (Fig. 2). A minor difference in ROM between the Open TLIF and MI-TLIF models may seem negligible at first glance. However, even minor variations in spinal biomechanics can have substantial implications over time, particularly regarding ASD. A retrospective follow-up study on 718 patients who underwent MI-TLIF surgery reported by Yuan C et al. [24] found that the incidence of ASD was 4.7 % and the average onset time was 62.7 ± 15.1 months, eventually leading to revision surgery. The study also reported that the symptoms alleviated over time. Another 5-year clinical follow-up study to compare ASD after Open and MI-TLIF in 121 patients has been reported recently [9]. In this study, 57 patients were treated with MI-TLIF, and 64 patients were treated with Open-TLIF. This study reported that the clinical effects of both patient groups were similar. However, the incidence of ASD was significantly lower for patients treated with MI-TLIF at 5-year follow-up. The marginally lower ROM in the MI-TLIF model of the present study (under flexion and extension) indicates slightly greater stabilization of the fused segment. This may reduce the compensatory motion or hypermobility at adjacent segments, potentially lowering the mechanical stress contributing to ASD. However, this slightly reduced flexibility may also lead to biomechanical changes in adjacent segments that accelerate postoperative degeneration over time [9,15,24,25]. The reduction in ROM for the Open and MI-TLIF model has been compared with the authors' previous study [18,22] and validated the present models. The reductions observed in this study are also comparable to various other FE studies on the lumbar spine [26,27]. This proves the correctness of the FE approach used for the present study.

The stress-strain distributions observed on the implanted segments (L4-L5) are higher than the corresponding intact segment (Fig. 3). However, the implanted models have no substantial difference in stress-strain distribution between them. The maximum stress-strain values observed for both the implanted models are similar. These observations imply a challenge in recommending Open or MI-TLIF surgical approaches over one another. According to Morgan et al. [28], the compressive yield strain limit of vertebrae is 0.007; however, the cancellous bone of the L4 and L5 vertebrae of both the implanted models of the present study is under a strain greater than 0.007 (Fig. 4). This may indicate the potential risk of failure of the implanted segments.

Several studies reported that there is always a risk of adjacent segment failure following fusion surgery [14,27,29]. Therefore, the present study examined both the implanted models' cranial adjacent soft structures and compared them with the intact model. The endplates of the cranial adjacent segment of both implanted models exhibited a substantial rise in stress and strain due to implantation (Fig. 5), except maximum stress under extension. The maximum strain observed in the cranial adjacent annulus fibrosus and nucleus pulposus of implanted models was higher than the intact model under all the loading cases (Fig. 6). The increase in stress on the adjacent cartilaginous endplate may result in its degeneration, followed by restriction to the smooth transfer of nutrients to the nucleus pulposus between the L3-L4 segment. This may lead to degeneration of the nucleus pulposus. The higher stress and strain on the nucleus pulposus (Fig. 6c and d) indicates the degeneration of the cranial nucleus pulposus. This is an indication of ASD in both the open and MI-TLIF models. The maximum stress observed on the cage (Fig. 7) of both models is lower than the yield stress limit of the Ti-6Al-4V (880 MPa). This demonstrates that implants are holding up under imposed loading circumstances.

The current FE study has certain limitations. The current analysis focusses solely on lamina resection, disc and ligament removal without addressing muscle disruption. Future studies may incorporate extensive muscle modelling to predict the effects of muscle disruption in segmental stability and risk of ASD. The study did not consider the musculoskeletal influences on the vertebra and the viscoelastic nature of the intervertebral disc. However, the FE models were validated by comparing the results with other experimental and similar FE studies. The predictions made in the study are wholly based on FE analysis. Future studies may also include experimental and clinical evaluations and long-term follow-up data studies to physically validate the current model's predictions.

5. Conclusion

This biomechanical analysis showed that the open and MI-TLIF approach could substantially reduce the ROM, compared to the intact model, under all the physiological loading conditions. However, the higher stress and strain on vertebrae compared to the intact model indicate the chances of bone failure. The higher stress and strain on the adjacent segment soft structures increase the risk of ASD in both models. Both the open and MI-TLIF approaches carry similar potential risks and capabilities. The ability to reduce the ROM was almost similar between the models. However, a slightly higher reduction in ROM was observed for MI-TLIF under flexion. The stress and strain distributions observed for the models were almost similar. However, the maximum stress and strain observed in the MI-TLIF implanted segment was slightly higher under flexion. These observations indicate that the biomechanical differences between Open TLIF and MI-TLIF surgical approaches are not substantial in fusing L4-L5 segment.

CRediT authorship contribution statement

Kishore Pradeep: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bidyut Pal:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Conceptualization. **Kaushik Mukherjee:** Writing – review & editing, Visualization, Validation, Resources, Conceptualization. **Gautam M. Shetty:** Writing – review & editing, Visualization, Validation, Resources, Conceptualization.

Ethical statement

Informed consent was obtained from the patient about using the image data (collected as a part of routine treatment) for reconstructing a three-dimensional spine model to be used for research purposes. The patient's anonymity was maintained throughout the study.

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None.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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