A Finite Element Analysis of the Effects of Different Internal Fixation Strategies and Cage Implantation Methods on the Biomechanics of the Lumbar Spine

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Research article

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Abstract

Objective: Providing the biomechanical evidences to the surgeons on the internal fixation strategy and Cage implantation method in minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) by the finite element analysis (FEA).

Methods: Firstly, based on the common MIS-TLIF surgical methods, three surgical models with different internal fixation strategies and Cage implantation methods were established. The surgical models simulated the physiological activities of the lumbar spine to evaluate the range of motion (ROM) of lumbar spine, the peak stress and the overall stress of the internal fixation system and Cage.

Results: The results of the study show that the ROM of the surgical model has decreased significantly under all working conditions, and the decrease range is between 71.07-97.53%. The peak stress of the internal fixation system range was 48.56 to 100.09 MPa in Model-A, 58.10 to 136.05 MPa in Model-B, and 83.26 to 189.81 MPa in Model-C. Especially in the three working conditions of left lateral bending (LLB), left rotation (LR), and right rotation (RR), the peak stress of the internal fixation system of Model-C is 1.80 , 2.07, 1.79 times of Model-A and 2.05 , 1.64, 2.28 times of Model-B. The peak stress of Model-C Cage is significantly lower than Model-A and Model-B under all working conditions.

Conclusion: Although the strategy of unilateral pedicle screw + lamina articular process screw + Cage horizontal implantation has the least Cage stress, there is a higher risk of internal fixation fail. Comprehensive evaluation, the surgical strategy of bilateral pedicle screw + Cage horizontal implantation has the best performance, and has the potential to become the standard implantation strategy of MIS-TLIF.

Introduction

Lumbar degenerative disease (LDD) is one of the leading causes of chronic low back pain[1], resulting in high medical costs, low back pain-related disability, loss of productivity, and substantial economic damage[2]. When the conservative treatment fails, interbody fusion is the standard surgical procedure in treating the refractory low back pain caused by the LDD [3–4]. Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) was first reported by Professor Foley in 2003[5], and it is widely used in treating LDD [6–8]. Compared with traditional open surgery, MIS-TLIF can significantly reduce the surgical approach damage and preserve the physiological function of muscle tissue to the maximum extent, which has become a major surgical method for the treatment of degenerative diseases of the lumbar spine [9–10]. What kind of internal fixation strategy and Cage implantation method MIS-TLIF can be used to achieve strong stability, thereby increasing the rate of intervertebral fusion, is a practical and important clinical problem. However, there is still a lack of relevant effective biomechanics research. Therefore, it is necessary to study the basic biomechanics of MIS-TLIF's internal fixation strategy and Cage implantation method.

Since the human lumbar spine has complex shapes and heterogeneous biological structures, it is still challenged in analyzing the related biomechanical properties. Some research utilizes the finite element model to analyze the human lumbar spine because the finite element models are not affected by many complicated clinical factors and can provide detailed data that the experimental methods cannot quickly obtain. Therefore, the finite element model is ideal for evaluating spinal biomechanics [11–12]. In this study, based on the current common clinical MIS-TLIF fixation strategy and Cage implantation method, three kinds of finite element surgery models were constructed using the finite element method. It aims to test the influence of different internal fixation strategies and Cage implantation methods on the biomechanics of the spine, and to provide a reference for the standardization of MIS-TLIF surgery.

Materials And Methods

Establishment of the intact L4-5 segment finite element models

According to the lumbar tomographic images of a healthy volunteer (male, 24 years old, 70 kg, 176 cm, no history of lumbar spine disease), with an 0.625 mm image interval (Philips Brilliance 64 Slice CT, Philips Medical Systems, Inc., OH, USA), and the data was saved in DICOM format. Then, these images were imported into Mimics Research 19.0 (Materialise, Inc.) software to preprocess the CT images and obtain the L4-5 preliminary three-dimensional geometric model. After that, the file (format: .stl) generated by Mimics software was imported into Geomagic Wrap 2017 (3D Systems, Inc.) software to optimize and smooth the model. Then the file with .stp format generated by the Gemoagic software was further imported into the SolidWorks2017 (Dassault Systemes, Inc.) software for combining and assembling the bones, annulus, nucleus pulposus, screws, and Cages, followed by generating a reconstructed model .X_T file. Finally, the .X_T file was imported into ANSYS V20.0 software (ANSYS, Inc.) for finite element analysis. The model utilized tetrahedral elements for finite element meshing. The number of nodes was 170900, including seven types of ligaments: anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligament flavum (LF), interspinous ligament (ISL), supraspinous ligament (SSL), intertransverse ligament (ITL) and joint capsule ligament (CL). According to the reference, the assignment of material property is fixed [13–14]. The Finally, the Young modulus, Poisson's ratio, cross area, and some other data (Table 1) of materials were inputted to finish the establishment of the intact L4-5 segment finite element model (Model-INT).

Table 1
Material Properties Used in the Present Finite-Element Model of the Lumbar Spine

Material properties	Young modulus, MPa	Poisson ratio, m	Cross section area, mm^2
Cortical bone	12000	0.3	-
Cancellous bone	100	0.2	-
Endplate	12000	0.3	-
Posterior bone	3500	0.25	-
Articular cartilage	25	0.25	-
Annulus fibrosus	6	0.40	-
Nucleus pulposus	1	0.50	-
ALL	7.8	-	22.4
PLL	1	-	7.0
LF	1.7	-	14.1
ITL	1	-	0.6
CL	7.5	-	10.5
ISL	1	-	14.1
SSL	8	-	10.5
Cage (PEEK material)	3500	0.3	
Screws and rods (Titanium alloy material)	110000	0.3	

Establishment of MIS-TLIF surgical models

According to clinical cases, MIS-TLIF uses unilateral nerve decompression, that is, intraoperative removal of the lower articular process of the L4 vertebral body and part of the upper articular process of the L5 vertebral body, ligamentum flavum, posterolateral fibrous annulus and all nucleus pulposus tissues. Retain the bony structure of the posterior column, supraspinal and interspinous ligaments, etc. Combining with the MIS-TLIF surgical implant equipment in our department, the experimental simulation of the intervertebral fusion Cage based on Z-Cage (WeGo Company, Shandong, China) modeling, and the sizes were Z-Cage (L×W×H=32×10×12mm), the material of the Cage was polyether ether ketone (PEEK). The simulated internal fixation system in the experiment was modeled by Premier (WeGo Company, Shandong, China). The length of screw was 45mm with diameter at 6.0mm. The length of connecting rod was 40mm with diameter at 5.5mm. The lamina articular process screws (Medtronic, USA) are selected with a length of 50mm and a diameter of 4.5mm.All the materials were made of titanium alloy.

The MIS-TLIF surgical model constructed according to the commonly used clinical internal fixation strategies and Cage implantation methods is: bilateral pedicle screw fixation + single fusion Cage horizontal implantation model (Model-A, Figure 1A-C), bilateral vertebral arch Root screw fixation + single fusion Cage oblique 45° implantation model (Model-B, Figure 1D-F), unilateral pedicle screw fixation + lamina articular process screw fixation + single fusion Cage horizontal implantation model (Model-C, Figure 1G-I). Because studies have found that the stability of unilateral pedicle screw fixation is poor [15], this study did not establish a model of unilateral pedicle screw fixation because of its clinical significance.

Loads and boundary conditions

The lower endplate of L5 was fixed, which means there was no displacement or rotation under the external force. A 500N preload was vertically applied to the upper endplate of L4 to simulate the upper body weight. Additionally, a 10N/m force was applied to simulate some physiological activities, such as the lumbar flexion (FL), extension (EX), and left lateral bending (LLB), right lateral bending (RLB), left rotation (LR), and right rotation (RR) [16–17]. Furthermore, the lumbar spine range of motion (ROM), the Von Mises peak stress of the internal fixation system and Cage under various working conditions were systematically evaluated.

Results

Verification of the Model-INT

In order to verify the reliability of the Model-INT, the Model-INT simulated six different types of lumbar motions with the 500 N preload force and 10 N/m torque. Then the ROM was measured, specifically, the ROM value of the Model-INT was FL (3.32°), EX (2.43°), LLB (2.66°), RLB (2.42°), LR (2.62°), and RR (1.59°). Comparing these results to the results from other references under the same conditions, similar trends in the ROM value of the intact L4-5 segment finite element model could be observed in this study and the results in the Chen WM et al. [18], Liu XY et al. [19], and Li KY et al [20]. This result confirmed the performance effectiveness of the Model-INT model, as shown in Figure 2.

Range of motion (ROM)

At different working conditions, the ROM of Model-INT, Model-A, Model-B, and Model-C were exhibited in Table 2. Comparing the three surgical models with Model-INT, it can be seen that the ROM of the surgical model has decreased significantly under all working conditions, and the decrease range is between 71.07-97.53%. Specifically, ROM of Model-A, Model-B, and Model-C decreased by 76.20%, 71.69% and 74.40% in FL, 97.53%, 96.71% and 93.00% in EX, 80.83%, 81.20% and 77.44% in LLB, 80.17%, 72.73% and 80.17% in

RLB, 85.50%, 82.44% and 84.73% in LR, 72.96%, 71.07% and 73.58% in RR, respectively. In particular, the decline in EX exercise was the most significant. Although the various surgical models show similar ROM under different working conditions, there are subtle differences in comparing the three surgical models by the average of the ROM change rate. The ROM change rate is shown as Model-A>Model-C>Model- B.

Table 2
Lumbar spine range of motion under each working condition of the four models

Direction of motion	Model-INT(°)	Model-A(°) [ROM ratio]		Model-B(°) [ROM ratio]		Model-C(°) [ROM ratio]	
FL	3.32	0.79	(76.20%)	0.94	(71.69%)	0.85	(74.40%)
EX	2.43	0.06	(97.53%)	0.08	(96.71%)	0.17	(93.00%)
LLB	2.66	0.51	(80.83%)	0.50	(81.20%)	0.6	(77.44%)
RLB	2.42	0.48	(80.17%)	0.66	(72.73%)	0.48	(80.17%)
LR	2.62	0.38	(85.50%)	0.46	(82.44%)	0.4	(84.73%)
RR	1.59	0.43	(72.96%)	0.46	(71.07%)	0.42	(73.58%)
Average value	2.51	0.44	(82.47%)	0.52	(79.28%)	0.49	(80.48%)

ROM ratio=(Model-INT-ModelA/B/C/D)÷Model-INT×100%

The peak stress and overall stress value of the internal fixation system.

The peak stress of the internal fixation system under different working conditions was presented in Figure 3A. The peak stress of the internal fixation system range was 48.56 MPa (EX) to 100.09 MPa (RR) in Model-A, 58.10 MPa (EX) to 136.05 MPa (RLB) in Model-B, and 83.26 MPa (EX) to 189.81 MPa (LR) in Model-C. In addition, the peak stress of Model-C was significantly higher than that in Model-A and Model-B under these five working conditions (FL, EX, LLB, LR and RR). Especially in the three working conditions of LLB, LR and RR, the peak stress of Model-C is 1.80 times (LLB), 2.07 times (LR), 1.79 times (RR) of Model-A and 2.05 times (LLB), 1.64 times (LR), 2.28 times (RR) of Model-B. The peak stress of the internal fixation system of Model-A is lower than that of Model-B and Model-C under the four working conditions of FL, EX, RLB and LR. The overall stress value of the internal fixation system is shown in Figure 3B. It can be seen that the overall stress of the internal fixation system in Model-C is higher than Model-A and Model-B in almost all working conditions, showing a trend similar to the peak stress.

Cage's stress cloud diagram, peak stress and overall stress value

Cage stress cloud diagrams of the three surgical models are shown in Figure 4. The peak stress of Cage is shown in Figure 5A. Comparing the peak stress of different models of Cage under the same working condition, it can be seen that the maximum peak stress of Model-A Cage are 47.86 and 40.29 MP in FL and LLB, the maximum peak stress of Model-B Cage are 14.64, 31.07, 32.64 and 32.89 MPa in EX, RLB, LR and RR. The peak stress of Model-C Cage is significantly lower than Model-A and Model-B under all working conditions. The overall stress of the three surgical model Cages is shown in Figure 5B. The overall stress of Model-B Cage is higher than Model-A and Model-C under all working conditions. Similarly, the overall stress of Model-C Cage is significantly lower than Model-A and Model-B under all working conditions.

Discussion

After more than ten years of development and clinical verification, MIS-TLIF has become a reliable surgical method for minimally invasive treatment of degenerative diseases of the lumbar spine [9, 21]. It is well known that achieving reliable intervertebral fusion will determine the long-term effect of surgery. Modern intervertebral fusion is mostly achieved by implanting an intervertebral fusion Cage (Cage). As a permanent implant in the human body, Cage plays an important role in promoting intervertebral bony fusion and maintaining early biomechanical stability [22]. At first, clinicians used two Cages to implant the intervertebral space [23]. The advantage is that the biomechanical stability is high, but the implantation will cause more bleeding, prolong the operation time, and increase the risk of dural tear and the cost of surgery. With the further study, scholars found that although the single Cage oblique implantation was not as biomechanically stable as two Cage implants, satisfactory clinical efficacy could be obtained, and the implantation process was simpler, the trauma was less, and the operation cost was lower[24–25]. However, with the wide application of Cage, the complications related to Cage have become increasingly prominent, such as Cage displacement, subsidence, non-fusion and other problems, which have not been effectively solved. It has been reported that Cage sinking and displacement may be caused by stress shielding [26]. Cage shape may also be an important factor leading to displacement. Zhao et al. [27] retrospectively studied Cage displacement in five spinal centers and found that the incidence of Cage displacement in rectangular Cage (3.11%) was significantly higher than that in renal Cage (0.28%). In addition, the position of Cage in the intervertebral space is an important factor affecting displacement. Currently, the Cage is generally implanted into the intervertebral space at an oblique angle of 45° in clinical. In recent years, some scholars began to advocate Cage placement horizontally in intervertebral space to reduce the risk of Cage displacement and subsidence [4, 28–29]. Theoretically, it is more difficult for the Cage to move when it is horizontally implanted because the Cage is parallelly placed against the posterior longitudinal ligament horizontally. Therefore, the Cage should be rotated if it is supposed to be removed from the original implant position. Clinically, fusion strategies and Cage implantation methods are mainly determined by the experience and habits of surgeons. Therefore, to provide some biomechanical evidence to surgeons in determining the fusion strategies and Cage implantation methods in MIS-TLIF, we conducted this finite element study.

The finite element method is widely used in the lumbar spine theoretical biomechanics, especially for spinal diseases and surgical curative effect analysis [30]. In this study, the stability of the model was evaluated by measuring the lumbar spine mobility in each model. By comparing Model-A and Model-C, it was found that both bilateral pedicle screw fixation and unilateral pedicle screw + lamina articular process screw fixation could significantly reduce lumbar motion, and both fixation strategies achieved good fixation strength and biomechanical stability, which was consistent with previous research conclusions [31]. The influence of Cage implantation position on biomechanical stability was analyzed, and the comparison between Model-A and Model-B showed that Cage placement horizontally in intervertebral space could maintain more spinal stability than Cage placement at an oblique angle of 45°. Theoretically, Cage intervertebral space horizontal placement has a larger end plate contact area, the larger the contact area, the greater the friction resistance between Cage and end plate, so better stability. Considering the fact that the lumbar gap is wide at the front and narrow at the back, it is difficult for Cage to contact the end plate when placed at an oblique angle of 45°, so the friction resistance between Cage and the end plate is reduced. The overall stability of bilateral pedicle screw fixation and horizontal fusion device implantation was optimal.

According to the test results in Figure 3, the fixation strategy of unilateral pedicle screw + lamina articular process screw bears greater peak stress and overall stress of the screw system. This may be closely related to the geometry of the internal fixation system in this model. It can be inferred that the risk of rod breakage is higher with this fixation strategy than with bilateral pedicle screw fixation if bone fusion is not achieved for a long time. Liu F et al. [32] found in a long-term follow-up study of different fixation strategies that the incidence of screw fracture in unilateral pedicle screw + laminar facet screw fixation was as high as 14.29% (4/28), significantly higher than that in bilateral pedicle screw fixation. Our research results also prove the risks of this fixed strategy.

The elastic modulus of polyetheretherketone fusion Cage is similar to that of normal human bone [33]. The results of this study found that although the maximum peak stress of Cage was 47.86 MP in FL of the Model-A, but it was much smaller than the yield stress of human cortical bone of 108 MPa [34]. Meanwhile, the overall stress of Cage placed at the intervertebral space parallel to the posterior longitudinal ligament was lower than that of Cage placed at an oblique angle of 45° under all working conditions. The results show that the use of Cage level placed in the intervertebral space does not increase the risk of subsidence. Since Cage is placed horizontally in the intervertebral space parallel to the posterior longitudinal ligament, it needs to rotate itself before exiting from the original implantation port. Therefore, the risk of Cage displacement and exit when placed horizontally in the intervertebral space is far less than when Cage is placed at an angle of 45°.

There are still some limitations in this study. The FE model is constructed by the CT images from healthy subjects without any spinal diseases. Therefore, the changes in the geometry of spines and implantations were not considered. This study does not evaluate the biomechanical changes in adjacent segments since intervertebral fusion could lead to adjacent segment degeneration (ASD). The paraspinal muscles are not considered in the whole investigation, which could slightly affect the stability of the lumbar spine.

In conclusion, according to the results of the finite element study, MIS-TLIF internal fixation strategy and Cage implantation mode have a profound impact on the biomechanics of the lumbar spine. Although the unilateral pedicle screw + facet screw strategy resulted in less surgical injury and more benefit, there was a higher risk of long-term rod breakage. The surgeon needs to be vigilant and choose carefully. The surgical strategy of bilateral pedicle screw fixation + fusion Cage horizontal implantation is relatively safe, suitable for clinical application, and is expected to become the standard implantation strategy of MIS-TLIF.

Abbreviations

MIS-TLIF：Minimally invasive transforaminal lumbar interbody fusion; FEA：Finite element analysis; ALL:Anterior longitudinal ligament; PLL:Posterior longitudinal ligament; LF:Ligament flavum; ISL:Interspinous ligament; SSL:Supraspinous ligament; ITL:Intertransverse ligament; CL:joint capsule ligament; FL:flexion; EX:extension; LLB:left lateral bending; RLB:right lateral bending; LR:left rotation; RR:right rotation; ROM:spine range of motion.

Declarations

Authors’ contributions

Han conceived and designed this study; Ren collected the data; Han wrote the manuscript; Zhang prepared tables. Ma prepared pictures. Mao and Tang revised this manuscript. All authors reviewed the final manuscript. All authors agreed to be accountable for all aspects of the work. Han and Ren contributed equally to this work and should be considered as equal frst authors. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

All data collected in this study have consent for publication.

Competing interests

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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Figures

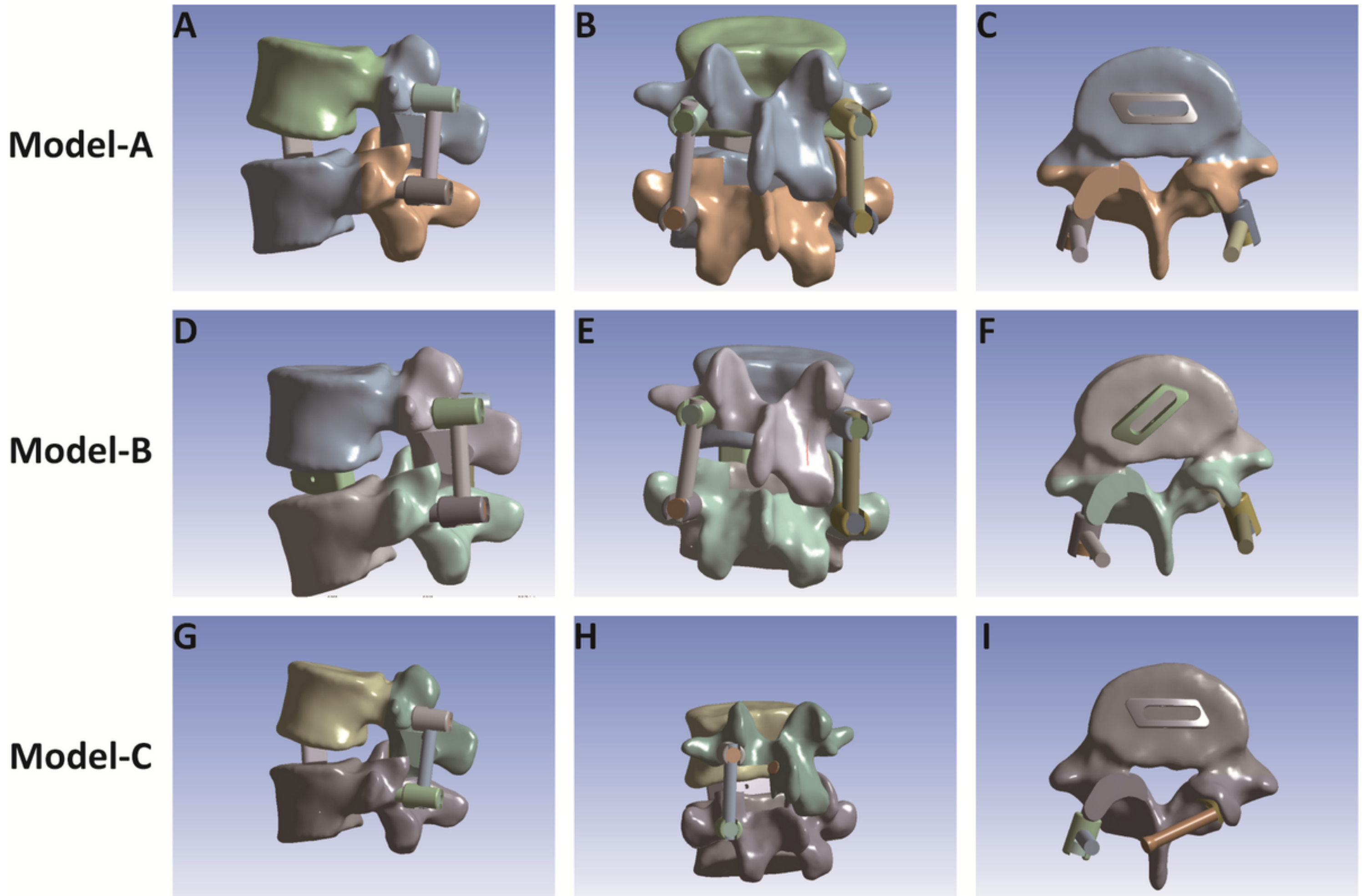

Figure 1

Effect picture of A-C single Cage horizontal implantation model; D-F Single Cage oblique 45° implantation model effect picture; G-I Two Cages vertical implantation model effect picture.

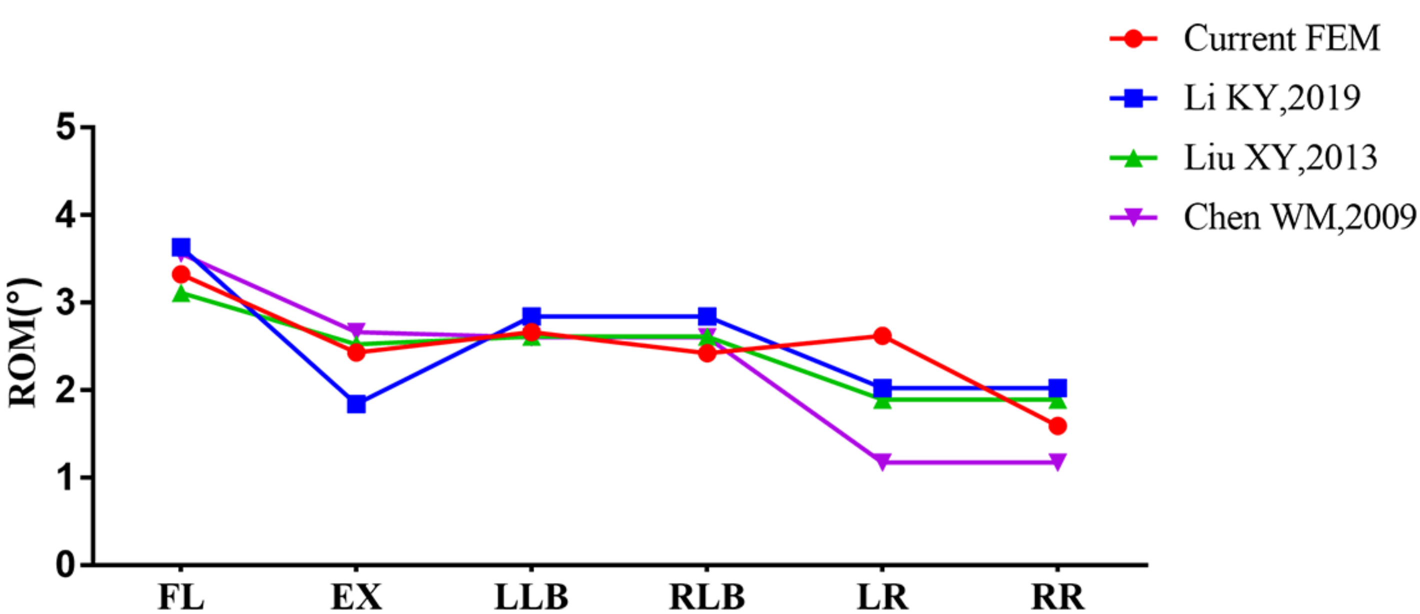

Figure 2

The range of motion (ROM) of the model in this study is compared with the results reported in the literature under the same conditions.

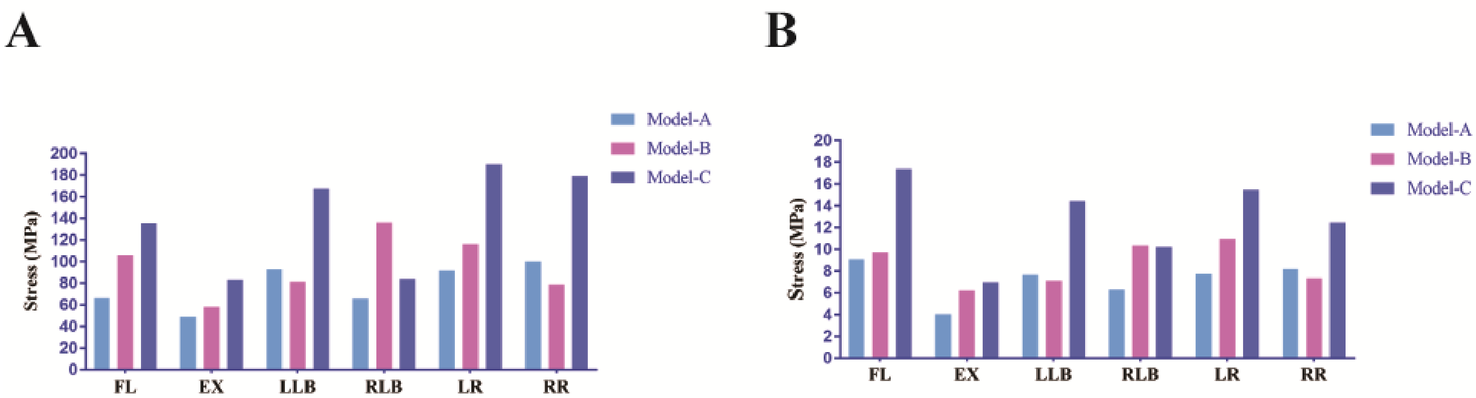

Figure 3

A The stress peak value of the internal fixation system of the three fusion models under different working conditions; B The overall stress value of the internal fixation system of the three fusion models under different working conditions.

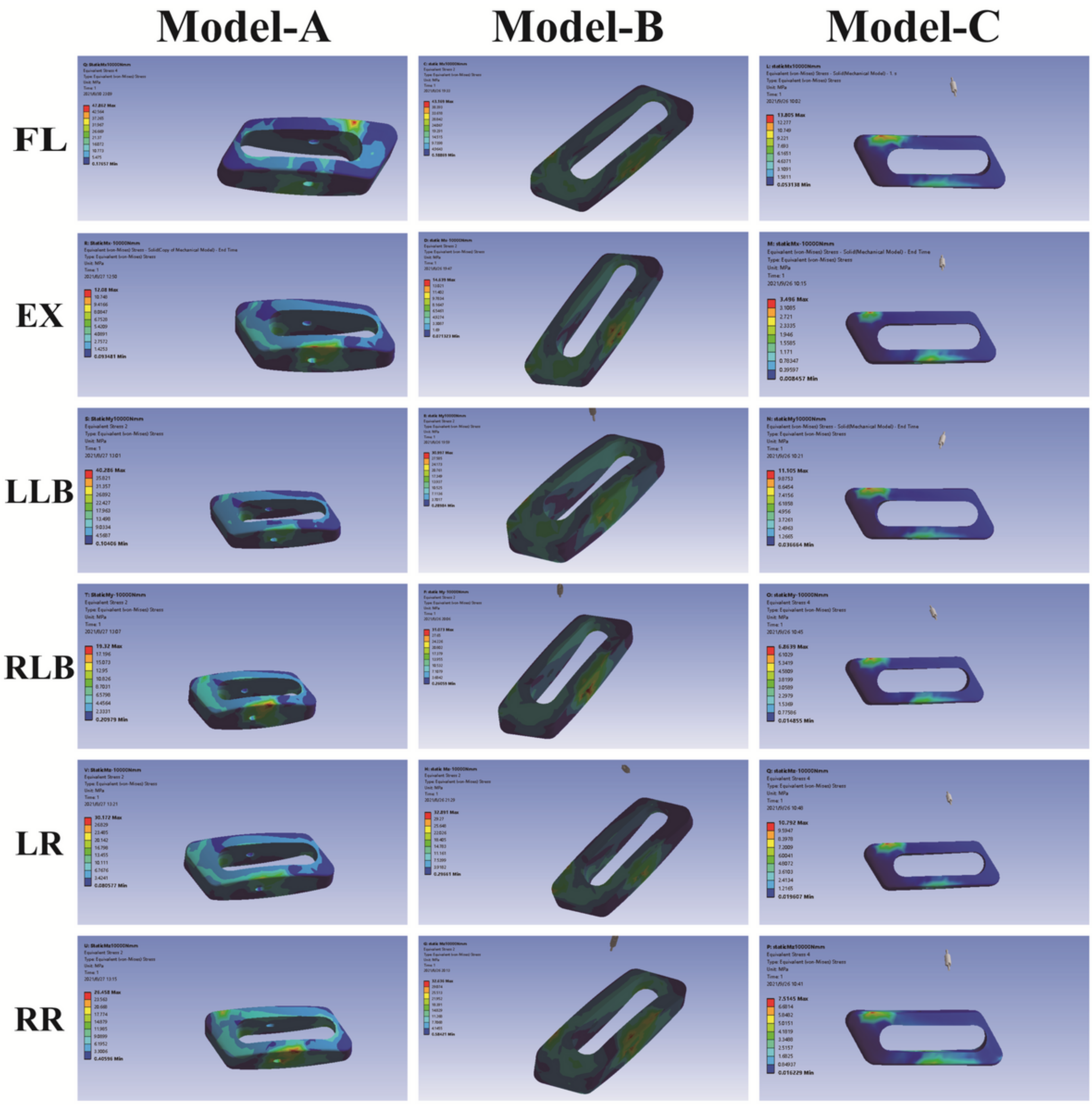

Figure 4

Cage stress cloud diagram of 3 models.

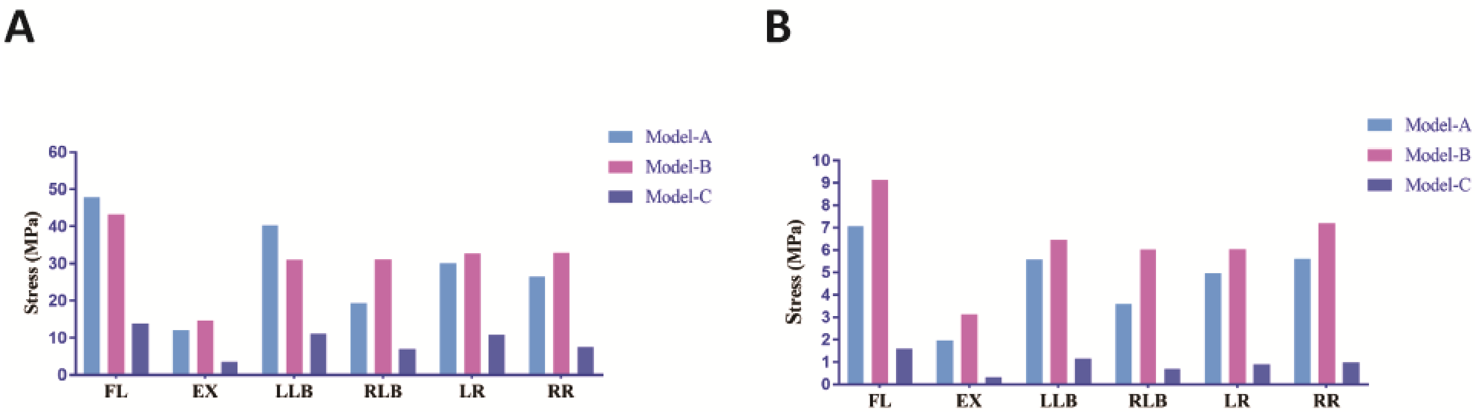

Figure 5

A: The peak stress of the Cage in 3 models; B The overall stress value of the Cage in the 3 models.