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ARTICLE

Research progress of finite element analysis in lumbar fusion surgery for lumbar degenerative diseases

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Abstract

Lumbar degenerative disease (LDD) refers to the normal strain of the body involving lumbar bone, ligament, intervertebral disc, thereby protruding lumbar intervertebral disc, slippage, spinal stenosis and other lesions. Lumbar fusion surgery has been proved to be an effective strategy for the treatment of LDD. At present, a variety of fusion methods such as anterior and posterior have been reported. This article aims to review and discuss the reported strategies of fusion surgery for LDD and related biomechanical studies and analyze the development and significance of the finite element method (FEM) in lumbar biomechanics. To investigate the influence of different surgical strategies on lumbar spine biomechanics from the perspective of biomechanics and to provide a reference for selecting clinical surgical strategies.

Keywords: Lumbar degenerative disease (LDD);Lumbar fusion surgery;Finite element method (FEM);Biomechanics

1. Introduction

1.1 Concept and introduction of LDD

LDD refers to lumbar instability, lumbar spondylolisthesis, lumbar spinal stenosis, lumbar disc herniation, and other lesions due to the normal strain of the body involving the bone, ligaments, and intervertebral discs of the lumbar spine. The lumbar spine plays a crucial role in maintaining the standard physiological shape and various movements of the human body and is the mechanical bearing hub of the upper and lower parts of the human body. The increase of age, combined with incorrect posture habits, lumbar intervertebral disc, bone tissue, and other degrees of degeneration. The most common clinical manifestations are low back pain and leg pain, affecting personal life and bringing a heavy economic burden to the family and society. Conservative treatment such as braking and physiotherapy is often used for mild diseases. When strict conventional treatment is ineffective, surgical treatment becomes a critical intervention method. Lumbar interbody fusion is a common and effective method for the treatment of LDD. Its prominent role is to restore the height and physiological curvature of the intervertebral space, decompress the cauda equina and nerve root tissue sufficiently and effectively and maintain the spine's stability. Compared with other spinal fusion techniques, interbody fusion has fewer postoperative complications and the occurrence of interbody pseudarthrosis, which is widely used in clinical practice. [1–3]

1.2 Concept and introduction of the finite element

The Finite Element Method (FEM) concept is initially proposed as an approximate solution to a differential and integral equation in mathematics. Due to the difficulty of solving the whole, the whole is decomposed into several subunits, and the solution of each subunit is solved. The solution of each subunit is combined to derive the approximate solution of the whole. Based on predecessors in the 1970 s, Hakim and others added the three-dimensional model of the lumbar ligament of the vertebral bodies, such as the accessory structure. Thus, the lumbar spine model is almost complete, and the team continues on a comprehensive model of the lumbar spine biomechanics of the static and dynamic simulation. Then, all kinds of lumbar spine finite element studies are conducted based on the study[4]. For a biomechanical analysis of the target spine using FEM, the current techniques usually obtain the CT data of the target spine segment-first and save it in DICOM (Digital Imaging and Communication in Medicine) format. The obtained DICOM format data was imported into Mimics 21.0 software. The extraction tool received the target segment contour according to the difference in the gray value of different tissues. Each layer of the contour image was processed by edge segmentation and filling holes to form a mask. The reverse 3D model reconstructed the mask to complete the initial model establishment[5]. After the preliminary model was established, the different tissue attributes were assigned the parameter values were given concerning the widely recognized research data in the industry, and then the mesh division and other optimization were carried out. The optimized model was then assembled according to the research needs to obtain the finite element model required for the study[6]. Before the experiment, the model must be debugged and verified, and the relevant verification parameters come from the literature data recognized in the industry. Conforms to the validation of the model, such as import ANSYS17.0 calculation software, set the boundary conditions and load, the load applied on the corresponding vertebral endplate surfaces, respectively, simulation segmental proneness, stretch, left and right lateral bending and rotation around the axial movement, may obtain each part of the spine biomechanics data related to the stress distribution and mobility. Using finite element analysis of spinal biomechanics can evaluate the biomechanics of the spine with relatively low cost and high efficiency. It is of great significance in the study of etiology, prevention and treatment, and reduction of postoperative complications and provides a reference for formulating surgical strategies[7, 8].

2. Application of FEM in lumbar biomechanics

2.1 Application of FEM in the biomechanics of anterior lumbar vertebrae

The lumbar vertebral body is the composition of the lumbar spinal motion unit framework. Wentao Yan[9] et al. through the use of lumbar vertebra CT data, lumbar spinal finite element model is established, under different axial pressure, conduct biomechanical validation tests, lumbar almost linearly relative displacement increases, consistent with experimental results in vitro biological mechanics, finite element model is applied to the analysis of the lumbar spine biomechanics is feasible. Many earlier studies suggested that the influence of spinal biomechanical strength was not only related to the cross-sectional area of the vertebra but also closely related to bone mineral density (BMD) [10]. Eswaran[11] et al. found that the position with the smallest cross-sectional area of lumbar cortical bone was the place with the most considerable load-bearing in cortical bone, accounting for up to 54%; the cancellous bone near the endplate carried 89% of the load. By FEM analysis, Liu Yingfan[12] et al. studied the pull-out resistance of pedicle screws under different BMD. The results showed that for every 10 mg/cm3 decrease in BMD, the axial pull-out force decreased by 11%, 23%, 43%, and 51%, respectively. It can be seen that BMD has an essential effect on the screw holding force.

2.2 Application of FEA in the biomechanics of the lumbar intervertebral disc

The intervertebral disc consists of the nucleus pulposus and annulus fibrosus. The annulus fibrosus comprised the outer collagen fiber and inner fibrocartilage bands. A highly aligned collagen fibers network within discrete laminates provides tensile properties that help support a multiaxial loading environment. The long-term intervertebral load caused by external or internal factors will lead to biomechanical changes in the lumbar spine, which is also an essential factor leading to lumbar degenerative diseases[13]. Studies have found that the cells and tissue structures in the intervertebral discs of mice were damaged to varying degrees by loading them[14]. Long-term loading of the intervertebral discs aggravated the irreversible damage to the intervertebral discs. Kroeber [15] exerted vertical compression on the intervertebral discs for 14 days, which resulted in a significant reduction in disc height and increased stromal cell necrosis. Xu Wenqiang [16]et al. studied the biomechanical effects of nucleus pulposus removal on the spine by the FEM. Digital simulation analysis was performed under six flexion, extension, lateral flexion, and torsion conditions.

2.3 Application of FEA in the biomechanics of facet joints

Facet joints are also an essential part of the functional unit of the spine. It has been reported that the biomechanics of the lumbar spine will be affected only when the articular process of the lumbar spine is wholly removed[17]. However, Zhou Yue [18]et al. believed that resection of facet joints by more than 50% would cause significant damage to the spine's stability, and patients would have accelerated spinal degeneration due to spinal instability after surgery. Woldtvedt[19]et al. found no significant correlation between the thickness of lumbar facet articular cartilage and the range of motion of the lumbar spine. Still, there was a significant correlation between the thickness of the lumbar facet articular cartilage and the stress load between the facet articular cartilage. Zhao Yong[20]et al. used fresh cadaveric specimens to resect L4/5 facet joints step by step, including 1/4, 1/2, 3/4, total, and no facet resection. CT scan was performed on five specimens after resection, and a three-dimensional finite element model was established according to CT data to analyze the changes in lumbar mechanical stability. The results clearly indicated that the Von Mises stress and the range of motion of the corresponding segment increased when the facet joint was removed more than half.

3. Lumbar fusion surgery and its related biomechanical research

3.1 Anterior lumbar intervertebral fusion (ALIF)

The ALIF technique was first proposed in the 1930s but was not popularized due to its high complication rate. In the past 30 years, clinicians have gradually accepted and widely used ALIF with the development of internal fixation technology. For ALIF, the patients were in the supine position, and the incision was selected as a midline transabdominal approach or retroperitoneal approach. The location of the operation involves the ureter, vas deferens, essential blood vessels, and other tissues, which need to be carefully identified during the process to prevent injury. Due to the preservation of the intact posterior spinal structure, this surgical procedure has minor damage to the spine's stability. The long-term follow-up of patients with lumbar spondylolisthesis has confirmed that ALIF has achieved good interbody fusion[21]. In particular, ALIF combined with internal fixation can maintain the spine's stability and reduce complications such as CAGE displacement and subsidence caused by local stress changes[22]. Although ALIF can achieve a certain therapeutic effect, the incidence of Adjacent segment degeneration (ASD) is high after surgery, which Lee[23] et al. reported at 37%, and 8.33% after reoperation. Some studies have found that ASD is caused by increased stress and activity changes in the main and adjacent segments[24, 25]. It is still controversial whether osteoporosis can affect the occurrence of ASD[26, 27]. Chenchen Zhang[28] et al. simulated the healthy group, the normal ALIF group, and the osteoporotic ALIF group by the FEM. They found that the osteoporotic ALIF group was closer to the biomechanical state of the healthy group than the normal ALIF group. These results suggest that osteoporosis can alleviate the adverse biomechanical phenomena after ALIF. However, due to the damage to the ureter, vas deferens, hypogastric plexus, and vital tissues, it has been reported that the incidence of retrograde ejaculation is due to hypogastric plexus injury in male patients after ALIF surgery is as high as 45%[29].

3.2 Posterior lumbar intervertebral fusion (PLIF)

According to the three-column spine theory, the anterior and middle columns bear 2/3 of the spinal load. PLIF has a good biomechanical performance due to minor damage to the anterior and middle columns and is the most widely used in China. PLIF patients were placed in the prone position, and conventional fluoroscopy was positioned before the operation. The posterior median incision was used to strip the spine's paraspinal muscles, expose the operating area, remove part of the lamina and ligament flavum, remove the nucleus pulposus tissue of the intervertebral disc, insert the CAGE, and then perform pedicle screw internal fixation. Zhang Zhenhui[30] et al. established two spinal fusion models of L4/5 spondylolisthesis: a. three-dimensional finite element analysis model of posterior lumbar fusion; B. Three-dimensional finite element model of posterolateral lumbar fusion.

By comparing the displacement distances of the two models under different loads, it was found that the displacement of the posterior interbody fusion group was smaller than that of the posterolateral lumbar fusion group, and posterior interbody fusion was considered to be more appropriate. Due to the significant damage to paravertebral muscles, PLIF is prone to residual low back pain after the operation. During the procedure, the dura and nerve roots are often pulled due to the need to expose the intervertebral disc, and dura rupture and nerve root injury may also occur. Okuda[31] et al. conducted a retrospective analysis of 251 patients after PLIF and showed that the neurological damage caused by the surgery was as high as 6.7%.Guan JunJie[32] et al were retrospectively analyzed the 60 cases of patients treated by PLIF average follow-up time of about 4.5 years; 11 patients were found to have the ASD, and the incidence of cephalic segment degeneration is higher than caudal, showing posterior intervertebral fusion and internal fixation lead to changes in the stress of the adjacent segment, the incidence of ASD is significantly increased. Although fusion surgery can enhance the stability of lumbar vertebrae, it is prone to the loss of motion of corresponding segments and adjacent vertebral lesions. Osteoporosis and Whole Body Vibration (WBV) risk factors for ASD. Zhang Renwen[33]et al. established PLIF models of osteoporosis and normal bone by using the FEM, a sinusoidal vertical load of 5Hz and 40N was applied to the L1 upper surface of each model to simulate the vibration load, the results showed that the dynamic response curve and maximum value of the osteoporosis PLIF model were higher than that of the normal bone PLIF model, but the difference was small and negligible. Wei Fan[34]et al. simulated PLIF and TLIF under WBV by the FEM and showed that TLIF resulted in increased internal fixation stress of the pedicle corresponding to the fusion segment, and the anterior endplate of the PLIF fusion vertebral body had better contact force with the fusion device. Mou Xiuping[35] et al. prospectively compared the clinical effects of posterior fusion surgery (PLIF) and Dynesys dynamic stabilization system in treating lumbar spondylolisthesis in patients with grade 1 lumbar spondylolisthesis. They found that the Dynesys system was superior to the PLIF group in terms of VAS scores at the same follow-up time. However, the difference was not statistically significant, and the Dynesys system was superior to the PLIF group in global lumbar motion.

3.3 The intervertebral foramen in the lumbar intervertebral fusion (TLIF)

TLIF is based on PLIF. Removing nucleus pulposus tissue, decompression of nerve roots, and bone grafting fusion are mainly performed through the intervertebral foramen. Therefore, it is necessary to remove the inferior articular process of the upper vertebral body and the superior articular process of the lower vertebral body to expose the intervertebral foramen fully. TLIF has good biomechanical stability after spinal surgery because it does not need to remove the lamina behind the vertebral body, and the posterior structures such as interspinous ligament and supraspinous ligament can be preserved[36]. A prospective study compared PLIF with TLIF. The mean follow-up time was 30.5 months, and the results showed that TLIF had apparent advantages in operation time and blood loss[37]. There is controversy over whether TLIF is a unilateral or bilateral internal fixation. Zhijing Zhang[38]et al. used bovine lumbar specimens to compare the biological differences between unilateral and bilateral TLIF internal fixation and found that the data were not statistically significant.

However, Divya V[39] et al. found that for single-level TLIF, bilateral posterior fixation provided more excellent biomechanical stability than unilateral internal fixation. When bilateral pedicle screws were used, the shape and number of intervertebral implants did not appear to have much effect on segmental stability. The study also found that oblique placement of a Cage and bilateral posterior pedicle screw fixation can minimize the posterior fixation and stress on the endplate and provide a better biomechanical effect. Lu Xiao[40] et al. established TLIF surgical models with fusion devices of different heights using the FEM. Through biomechanical experiments, it was found that with the increase of the height of the fusion device, the ROM and maximum disc stress of the adjacent segment also increased, suggesting that the height of the fusion device should not exceed 2mm in the original intervertebral space during TLIF.

All surgical specialties are developing toward minimally invasive surgery in order to ensure the therapeutic effect while minimizing the harm to patients and better prognosis, spine surgery is no exception. Minimally invasive by the intervertebral foramen in the lumbar intervertebral fusion (minimally invasive transforaminal lumbar interbody fusion, MIS - TLIF) was put forward in 2003; the main advantage of using a small incision to insert a special kind of pipes, The intervertebral foraminal visual field was exposed through the channel, and the intermuscular approach was adopted without stripping too many paravertebral muscles. Partial facet joint resection could decompress the nerve root and remove the nucleus pulposus tissue[41]. To evaluate the effect of MIS-TLIF, the patients who underwent MIS-TLIF were followed up for up to 5 years, including VAS score, JOA score, ODI score, and interbody fusion rate. The results showed no significant difference in clinical efficacy between the two groups[42-44]. In the past, single-level decompression was usually fixed with four screws and two rods. Recently, a hybrid fixation system (ipsilateral pedicle screw + contralateral translaminar screw fixation) was reported. The new internal fixation system has the advantages of short operation time and simple operation[45].

3.4 Lateral lumbar intervertebral fusion (LLIF)

Pimenta[46]first proposed the technique of LLIF in 2001. LLIF adopts a retroperitoneal approach to remove the nucleus pulposus tissue and decompress the nerve root by separating the psoas muscle and exposing the surgical site. LLIF technique preserves important spinal structures such as anterior longitudinal ligament and posterior longitudinal ligament, so the spinal biomechanics is good after surgery. Fan Wei[47]et al. established three fusion finite element models of ALIF, LLIF, and TLIF, applied a sinusoidal axial load of 40 N to the L1 vertebral body at a frequency of 5 Hz to simulate the driving scene in daily life and conducted the instantaneous dynamic analysis. The study found that LLIF is better than the other two methods in the contact force between the cage and the endplate and the stress of the internal fixation device. The larger cage of LLIF may be the main reason for its advantage. Teng Lu[48] et al., using FEM analysis, found that the stress on the endplate of the LLIF cage was significantly less than that of TLIF and OLIF, indicating that the LLIF cage had a lower incidence of subsidence and was superior to TLIF and OLIF in maintaining segmental stability and intervertebral height. There are different methods of internal fixation during LLIF. The biomechanical analysis of different internal fixation methods by FEM shows that the bilateral pedicle screw internal fixation model shows better biomechanical performance than other internal fixation methods[49].

3.5 Oblique lumbar interbody fusion (OLIF)

In 2012, Silvestre[50] et al. first reported the OLIF technique, which can be considered an improvement of the ALIF technique because OLIF has a wide operating field and can be inserted into a larger cage, which is more conducive to vertebral fusion and stability. Fifty patients with lumbar spondylolisthesis who underwent OLIF were followed up for six months, the results showed that OLIF was superior to TLIF in operative time, blood loss, length of hospital stay, and ODI score[51]. Agarwal[52] et al. found that stand-alone OLIF had a good clinical effect in 55 patients who were followed for up to 10 years. However, Tempe[53] et al. found that sinking the fusion apparatus was a common complication of stand-alone OLIF in long-term postoperative follow-up. Through biomechanical analysis by the FEM, Shuyi ZHANG[54] et al. found that stand-alone OLIF mobility and the stress of the fusion apparatus were large, which might be a reason for fusion sinking. Shengjia Huang[55]et al. through the FEM analysis, that stand-alone OLIF technology significantly reduces the activity in all directions, and the technology has a certain stability. However, the fusion of the upper and lower end plate under stress is also bigger, signal fusion subsidence risk, OLIF joint posterior internal fixation can provide better spinal biomechanics, it can improve the occurrence of complications such as sink of fusion apparatus. By using finite element method, Sun Ke[56]et al. found that OLIF fusion device placement combined with pedicle screw fixation compared with fusion device placement alone, because the pedicle screw can bear part of the stress, the stress of the facet joint is relatively smaller, and the incidence of degeneration is smaller, and the risk of fusion device sinking can also be reduced. However, the internal fixation methods in OLIF have been controversial, such as the pedicle screw technique and single lateral screw combined with facet screw fixation. The finite element study by Guo Huizhi[57] et al. showed that bilateral pedicle screw fixation technology had good biomechanics in the fixed segment range of motion, the maximum stress of the cage, and the internal fixation stress.

4. Summary and Prospect

The incidence of lumbar degenerative diseases is increasing year by year. Due to the change in modern life patterns, it is developing younger, which not only causes trouble to individual life but also causes a significant economic burden to society. Fusion surgery plays an essential role in treating lumbar spine-related diseases. Although it has been widely used, there are still many related problems to be solved. Most of the complications after lumbar spine surgery are caused by the biomechanical changes of the lumbar spine, so the biomechanical study of the lumbar spine is an important content of medical development. For the accuracy of biomechanical experiments, previous research methods are usually carried out in fresh cadavers. However, with the strict regulation of laws and ethics, corpses are increasingly difficult to obtain, limiting the development and progress of biomechanical research to a certain extent. However, at the same time, the finite element method in the study of lumbar biomechanics is becoming more and more in-depth, and the finite element method plays an essential role in the selection of clinical, surgical procedures and the preliminary evaluation of postoperative effects. For common postoperative complications, finite element analysis to establish different models for comparative analysis can determine the complications' cause. The advantages of the finite element analysis method, such as simplicity, convenience, low cost, and repeatability, have been widely recognized by spinal biomechanics researchers.

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