Three-dimensional finite element analysis of lumbar vertebra loaded by static stress and its biomechanical significance

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Objective: To explore the mechanical behavior of lumbar spine loaded by stress and provide the mechanical basis for clinical analysis and judgement of lumbar spine fracture classification, mechanical distribution and static stress.

Methods: By means of computer simulation method, the constructed lumbar spine three-dimensional model was introduced into three-dimensional finite element analysis by software Ansys 7.0. The lumbar spine mechanical behavior in different parts of the stress loading were calculated. Impact load is 0-8000 N. The peak value was 8000 N. The loading time is 0-40 minutes. The values of the main stress, stress distribution and the lumbar spine unit displacement in the direction of main stress were analyzed.

Results: The lumbar spine model was divided into a total of 121 239 nodes, 112 491 units. It could objectively reflect the true anatomy of lumbar spine and its biomechanical behavior and obtain the end-plate images under different stress. The stress distribution on the lumbar intervertebral disc (L₃-L₄) under the axial, lateral flexion and extension stress, and the displacement trace of the corresponding processus articularis were analyzed.

Conclusion: It is helpful to analyze the stress distribution of lumbar spine and units displacement in static stress loading in the clinical research of lumbar spine injury and the distribution of internal stress.

Key words: Lumbar vertebrae; Models, anatomical; Stress, mechanical


As an important human load-bearing structure, the lumbar spine has a variety of clinical manifestations because of its complex physical structure. And that is mainly related to congenital physical structure of the lumbar vertebrae and its load bearing in the whole spine. The mechanical load can aggravate low back pain and disc degeneration.₁,₂,₃ Therefore, in clinic, many methods of bone fusion or non-fusion fixation are applied to achieve anatomical reduction and fixation, thus increase three-dimensional stability of the spine.₄,₅ Using the three-dimensional numerical analysis and biomechanical testing technology to calculate and test the state of stress and deformation of the spine under the actual stress, is an effective way to obtain mechanical changes under a variety of fixations. This study attempted to further investigate the mechanical behavior of lumbar spine by adopting three-dimensional modeling and finite element method.

METHODS

Materials

The following materials were used in the study: the pelvis of an adult female volunteer at the age of 39 years, three-dimensional model of individual lumbar spine, Dell precision 650 workstation, model construction Simpleware software, Ansys 7.0 software, Windows XP operating system, Siemens SOMATOM Volume Zoom CT machine (Siemens, Germany) and refrigerator.

Experimental procedure

Three-dimensional finite element model of lumbar spine was constructed and tested according to the previous study.₅,₇ In order to include the entire lumbar spine in the existing calculation model, the characteristics of material and all geometric contact points, as well as a clear definition of discrete segments, were of great importance, because the stress transferred between different points of lumbar spine fully depended on their...
locations. Lumbar spine model had been simplified into 8 regions to avoid painting a lot of exact surrounding points and simplify the tissue.

**Loading direction of static stress** Stress was loaded on the three-dimensional solid models of the lumbar spine above and below the human body.

**Load-time curve** At the 10 nodes of three-dimensional lumbar spine model, the stress was averagely distributed up to down in the axial direction. The peak power was 8000 N. The rising time was 4 minutes and the falling time was 12 minutes. Then distribute medially the power to 10 nodes of the lumbar spine in three-dimensional model. The loading direction was from the below to the site impacting the sacrum. The peak power was 8000 N. The rising time was 10 minutes and the falling time was 30 minutes (Figs. 1-2). The material properties of each module were set as follows: strain rate $\varepsilon = 0.1$, Poisson's ratio $\gamma = 0.3$.

**RESULTS**

**Stress loading on the anterior lumbar spine**

**Von Mises stress distribution** The three-dimensional finite element model of lumbar spine was constructed (Fig.3). Von Mises stress was distributed along the lumbar spine (Fig. 4). Within the first 10 minutes, the stress was distributed mainly along the articular process, and in the next 10 minutes, the vertebral body undertook a greater stress.

**Von Mises stress-time curve** Ten minutes after stress loading, the maximum element of Von Mises stress was E174454, consisting of the nodes 49051, 49035, 49034 and 49052, while the minimum element was E179946, consisting of the nodes 23562, 23467, 23559 and 23557. The contact element of the lumbar spine under stress was E106889, a tetrahedral unit consisting of the nodes 30878, 30859, 30876 and 29362. The Von Mises stress - time curves of these three element in the process of impacting are shown in Fig.5. It demonstrated that the stress of E174454 did not reach their peak at the peak of load, however, it got to the peak at 11 minutes after loading.

**Stress loading on the sacrum**

**Von Mises stress-time distribution** Von Mises stresses distribution of the lumbar vertebra is shown in Fig.6. In 0-20 minutes, the main stress was conducted longitudinally, and the stress did not reach the peak at 10 minutes. However, 20 minutes later, the stress was conducted towards the sacroiliac joint, lumbar vertebrae and other parts and the stress distribution was obvious.

**Von Mises stress-time curve** By three-dimensional finite element method, we drew the stress-time curve of the maximum force element at the peak impact (Fig.7).

**DISCUSSION**

Traditionally, lumbar spine biomechanical experiments were carried out on cadavers and each internal fixation used the bones from a cadaver, causing inconvenience to the experiment. The existing methods of numerical analysis and finite element method are beneficial to solve this problem. Many scholars do the finite element study on models, however, because of the complex structure of the human body, the process of modeling looses a lot of information on bone structure. Based on the Dicom standard digital medical images, this study used thin-slice CT scanning technology to obtain more accurate CT images. The direct use of Simpleware three-dimensional modeling software to read image data effectively reduced the influence of anthropic factors, greatly decreased the workload, avoided the loss of original data and improved the speed of modeling, so as to construct the three-dimensional finite element model of lumbar vertebrae and endplates, nucleus pulposus and anulus fibrosus. However, due to the nonvisualization of other soft tissues in CT scan, it should be noted that some manual operations are needed to construct soft tissue structures. For example, a variety of ligaments were added into the Ansys. Because most of biological materials are anisotropic viscoelastic materials, it takes a lot of calculation to simulate mechanical properties of biological structures.

The accuracy of the model can be influenced by a lot of factors, including grid division, the size, shape and numbers of elements, the distinction between assumption and actual conditions and so on. Therefore, the evaluation of finite element model and experimental results depends on the above factors to a large extent. The three-dimensional finite element model of the lumbar spine in this study is analyzed as follows: (1) grid
division. The distribution of three-dimensional finite element was consistent with force condition, i.e. the sites with higher stress gradient have a relatively dense grid distribution. The areas with complex anatomical structure have dense grids and the grid shape is complicated, which indicates that the anatomical change of lumbar spine frequently occurs in those areas. Meanwhile, those areas have high incidence of fracture because of stress concentration. (2) Element number. The proper number of elements of lumbar model should be decided. From the perspective of finite element, the more elements, the higher accuracy. However, the more elements require more complex calculation, which a common computer cannot afford. But less elements will cause the error between its overall mechanical characteristics and the actual situation. (3) Vertebrae selection. Geometric shape of the lumbar spine and properties of the model are related to many factors, including age, gender, loading direction, strain rate, force conditions, etc. It is necessary to select the lumbar vertebrae with typical features because the biomechanical properties are different in individuals.\(^{7,8}\)

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**Fig. 1.** Load-time curve of the lumbar spine model with the stress being loaded in the axial direction.

**Fig. 2.** Load-time curve of the lumbar spine model with the stress being loaded at the sacrum.

**Fig. 3.** Front view and back view of three-dimensional model of lumbar spine.

**Fig. 4.** Von Mises stress distribution of the lumbar spine in the process of stress loading.

**Fig. 5.** Von Mises stress-time curve.

**Fig. 6.** The distribution of Von Mises stress at the sacrum.

**Fig. 7.** The maximum stress-time curve at the peak impact.

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In practical analysis, the materials used for lumbar spine model are assumed to be isotropic, continuous-distributed and linear elastic materials. The results demonstrated that the stress distribution of lamina terminalis is reasonable in axial compression, lateral bending and flexion, which is mainly consistent with clinical manifestations. The distribution and magnitude of discomanometry are important indicators to evaluate...
fusion and non-fusion stabilization. It is reported in literature that needle or ring pressure transducers are placed in intervertebral disc.\textsuperscript{11-12} However, it can not obtain the stress distribution of the whole interface. Using pressure-sensitive adhesive films, we can directly observe the pressure and stress distribution of the intervertebral disc when the spine is loaded in various directions. The application of digital image processing technology can improve the automation and precision of measurement. How to use the finite element method for the biomechanical study of lumbar spine is challenging because of complex geometric structure, the deformations to a large degree, multimer conjunction, and the provision of \textit{in vivo} stress for each conjunction. Moreover, the real mechanical analysis of the lumbar vertebra needs the construction of intervertebral disc / ligament structure, so the detailed mathematical description of materials is necessary. Early finite element model of lumbar spine is only one-dimensional description, which adds the intervertebral disc into the model (single elastic). With one-dimensional elastic element, intervertebral disc material is considered as a simple load-extension relationship (usually nonlinear). The three-dimensional model greatly reduces the complexity of research and simplifies the biomechanic analysis.

In conclusion, this study successfully established a three-dimensional finite element model containing the intervertebral disc tissue, accurately simulated the anatomy of human lumbar spine and reflected the biomechanic features. However, it is the first step to comprehensively understand biomechanic changes of the spine. An ideal model will provide a reliable method for further research and contribute to the related biomechanic research of the lumbar spine.

REFERENCES


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