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Establishment of a Finite Element Model for the Cervical Spine with Spring Muscle Units

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Abstract: The accelerated pace of modern life has led to an increasing number of people suffering from cervical spondylosis. Traditional research methods for cervical spondylosis are limited by ethical and material constraints, but finite element models can effectively address these issues during the research process. In this paper, a finite element model of C0-C7 vertebrae was reconstructed based on CT scan data, and finite element models of intervertebral discs, ligaments, muscles, and other anatomical structures were added and combined. The reconstructed cervical spine finite element model is highly realistic in shape and has good similarity, making it suitable for cervical spondylosis research.

Keywords: Cervical Spine; Finite Element Model; Biomechanics.

1. Introduction

Due to China's large population base and increasingly serious aging problem, the population suffering from various cervical diseases has reached an alarming level. Cervical disease not only affects individuals' quality of life but also imposes a heavy burden on society. Preventing, treating, and rehabilitating cervical diseases require significant social investment. Traditional experimental types and methods have greatly limited cervical disease research due to considerations such as experimental materials, research depth, and ethical morality. Finite element software can display model deformation and stress information, thereby better studying stress and strain in complex structures such as the cervical spine, intervertebral discs, and muscles. In cervical biomechanics research, finite element analysis plays a significant role in areas such as postoperative mechanical changes, intervertebral disc degeneration, and ligament injuries [1-3].

In 1983, Williams [4] described a special five-sided continuous element that effectively maintained the stability of the cervical spine under lateral and frontal accelerations by treating the C1 vertebra and head as rigid bodies connected by deformable elements. The head-neck model established could well reflect the dynamic behavior of the head and neck in frontal and lateral impacts. In 1991, Saito [5] et al. used displacement increment method based on finite element analysis combined with composite materials and cross-element theory to simulate the deformity after cervical or cervicothoracic laminectomy. However, the simple geometry of the cervical spine model resulted in differences between the mechanical distribution in the conclusions and actual results. In 1998, Yang [6] et al. used MRI to establish a more complex finite element model of the head and neck, taking into account passive muscle forces in the simulation analysis. In 2014, Wang [7] et al. established a human finite element model of the skull (C0) and spine (C1-T1), obtained the kinematic characteristics of live motion of the head and neck through photonic systems, and used it for verification of the finite element model. In 2015, Zafarparandeh [8] et al. developed two finite element models of the cervical spine C2-C7. One model was based on the precise geometric structure of the cervical spine (asymmetric model), while the other model was a symmetrical model about the sagittal plane. The predicted range of motion for the main and coupled movements of the model was compared with experimental data from all motion planes published under full range loads. In 2017, Diao [9] et al. conducted biomechanical research on the cervical spine using multibody dynamics. They objectively established a comprehensive multibody dynamics model of the cervical spine, combined with force-related kinematics (FDK) methods, and studied the effect of soft tissue deformation on joint load prediction. In the same year, Manickam [10] et al. simulated joint degeneration by changing the direction of the facet joint at the C5-C6 level, analyzed the model using finite element analysis, and concluded that handling small joint orientation may be an anatomical risk factor for intervertebral disc degeneration or small joint degeneration. In 2021, Correia [11] aimed to develop a closed-loop controller for neck muscle activation in contemporary male HBM based on known reflex mechanisms, and evaluated the comparison between this method and current open-loop controllers in a range of collision directions and severity levels. Establishing a finite element model is the basis for pathological analysis of cervical spine disease. Below is the establishment of a finite element model with spring muscle units.

2. Materials and Methods

2.1. Three-dimensional Point Cloud Model of the Vertebrae

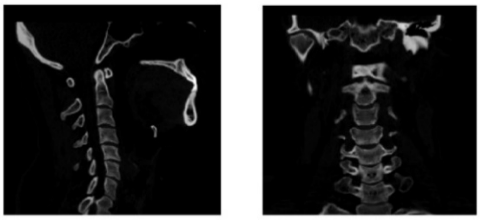

Figure 1. Shows the coronal (left) and sagittal (right) views of the neck CT scan of a research subject

A healthy 23-year-old male of Han ethnicity with no history of cervical spine disease underwent a CT scan of his neck using a 16-slice spiral CT scanner (Siemens SOMATOM Scope). The scan produced 345 CT images with a thickness of 0.75mm. The DICOM format data of the CT images were imported into Mimics 21.0 software, and coronal and sagittal views of the neck were obtained as shown in Figure 1.

Mimics software reconstructs a 3D model based on the gray values of each frame image. As tissue density varies, the gray values of different parts in the CT scan images also vary. Generally, the higher the tissue density, the higher the gray value and the clearer the image. The software has default bone (CT) gray values, but after several attempts, more accurate gray value ranges were selected for gray value extraction. Based on the actual anatomy and position, the erase and fill commands were used to modify the layers of vertebrae in the selected gray values and ensure that the gray values of the image could be docked with those of the previous and next images without discontinuity. From the CT images, it can be clearly seen that the boundary contour of the vertebrae is prominent, while the internal gray value of the vertebrae is low and difficult to extract. Vertebrae are divided into cortical bone and cancellous bone according to their material properties. Cortical bone is relatively hard, and cancellous bone is relatively soft. Cortical bone wraps around cancellous bone and protects it. To distinguish between the two types of vertebrae with different material properties, layering of cortical and cancellous bone needs to be performed on the model, which requires further processing of the vertebrae. Using 3D calculation tools, various independent geometric entities were reconstructed into 3D point cloud models.

2.2. Cervical Vertebrae NURBS Surface Model

During the CT scanning process, instrument vibration can cause significant noise in the output images, which seriously affects the accuracy of the raw data from CT scans. This can result in inaccurate representation of the true morphology of the vertebrae and cause rough surfaces, holes, and self-intersections in the model. Although a 3D image appears to have been formed, the actual 3D image data is not continuous, resulting in a noisy image. Therefore, it is necessary to repair and refine the reconstructed model.

The 3D point cloud model of the vertebrae obtained using Mimics is imported into Geomagic software for optimization and removal of instrument noise. The Mesh Doctor tool is used to remove rough surfaces and repair non-conforming surfaces, such as self-intersecting surfaces, non-manifold edges, and highly reflective edges. After repairing with Mesh Doctor, the model still appears relatively rough and requires further optimization. Removing spikes can eliminate rough spikes on the surface, and the smoothing level should not be set too high, as excessive removal of spikes can result in significant differences between the surface and the actual vertebrae. Then, the fast-smoothing function is used to make the triangle sizes on the model uniform. Taking the atlas vertebra as an example, the comparison of the modified model before and after noise removal is shown in Figure 2.

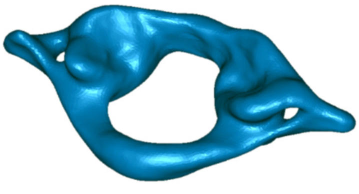

Figure 2. Image of the completed repair of the cervical vertebrae model

To improve the accuracy of weak areas in the skeletal structure, the initial model's triangle mesh size needs to be reduced by subdividing the global model mesh and increasing the number of triangles, resulting in a more even distribution of triangle layout. This step is used to repair noise in the corresponding vertebral point cloud model, as shown in Figure 2 for C1-C7 vertebral repair comparison results.

Geomagic detects contour lines based on changes in curvature, but the software's automatically generated contour lines are often messy. To address this issue, this study smoothed out the contour lines using reference to the solid vertebral model. CT data in point cloud form was used in the above steps, and the smooth surface visualized was due to Geomagic's algorithm converting the point cloud data into a visual surface; fundamentally, it remains individual data points. Thus, the point cloud needs to be converted into NURBS surfaces. NURBS surfaces are a mathematical representation method consisting of multiple NURBS curves connected to form a surface with high-order derivative continuity, capable of generating high-quality smooth surfaces. The NURBS surface model can be exported in standard format for integration with other software.

In the process of building a finite element model of the vertebrae, fitting the NURBS surface is crucial. Based on the smoothed contour lines, a grid is constructed, with the grid lines serving as guide lines for the NURBS surface, influencing the quality of the mesh partition. Finally, the NURBS surface is fitted and exported as a repaired and improved model. While Geomagic provides an automatic surfacing command that can generate contour lines, surface patches, and grids with simple operation, this command is only suitable for models with simple structures. Given the complex structure of the vertebrae, manual processing is necessary to generate ideal NURBS surfaces.

2.3. Establishment of a Model for Neck Soft Tissues

2.3.1. Intervertebral Disc Model

To reconstruct the intervertebral disc, a model of the annulus fibrosus and nucleus pulposus can be created. However, attempts to use CT scan data to create a point cloud model resulted in significant geometric differences between the reconstructed model and the actual anatomical position of the disc. Therefore, the authors chose to use Solid works software to rebuild the disc model based on its anatomical position, filling the space between two adjacent vertebrae. The resulting model perfectly matched the contours of the corresponding vertebrae.

2.3.2. Ligament and Cartilage Model

Ligaments were represented in the finite element model using spring elements, while the small joints that limit rotation and lateral bending were modeled with attached cartilage. The method used to create these models was similar to that used for the intervertebral disc model.

2.3.3. Muscle Tissue Model

From the perspective of muscle function, skeletal muscles can be divided into passive and active muscles. Passive muscles do not actively generate force and do not directly participate in movement, while active muscles can contract to generate force and directly participate in bodily movement.

Current finite element models of the cervical spine with muscles use spring elements to simulate muscle tissue. This type of muscle can roughly simulate passive muscles but lacks the volume collision that muscles should have. Some models are based on MRI data to create solid muscle models, which are more accurate because they come from human data. However, these models are primarily used for research in stress analysis related to car safety collisions, and there is relatively little research on stress analysis of muscle tissue.

Based on anatomical structures, spring elements were established on the vertebrae finite element model to represent muscle tissue. Build muscles have Sternocleidomastoid, Trapezius, Semispinalis capitis, Erector spinae capitis, Rectus capitis posterior minor, Rectus capitis posterior major, Obliquus capitis superior, Obliquus capitis inferior, Longus colli, Rectus capitis anterior, Scalene muscles, Levator scapulae, Serratus anterior, Trapezius, Sternocleidomastoid, and Semispinalis capitis. The resulting model is shown in the figure 3.

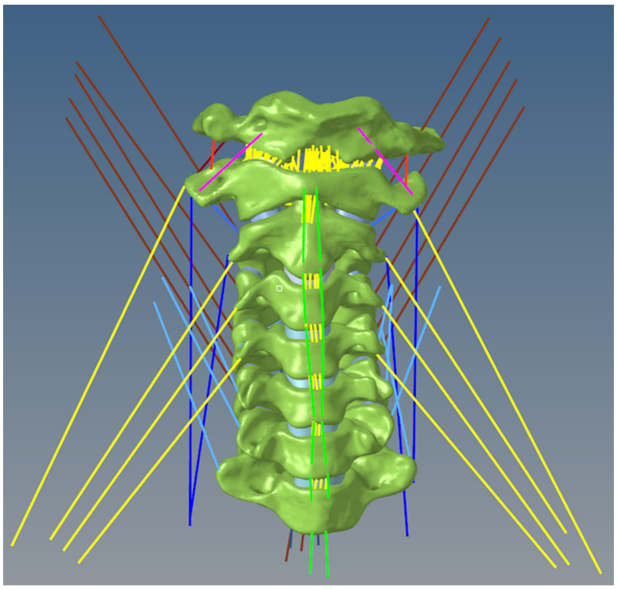

Figure 3. Finite element model of the cervical spine with spring-mass muscle units incorporated

3. Summary

This article describes the process and method of establishing a finite element model of the entire cervical vertebrae with muscle tissue in a healthy adult male. The process of establishing the finite element model is divided into three parts: creating the solid model, creating the finite element model, and pre-processing the finite element model. The model includes C0-C7 vertebrae, ligaments, articular cartilage, intervertebral discs, and muscles. The intervertebral disc-vertebra and muscle-vertebra connections share common nodes in the model. The model maintains a high degree of geometric similarity in appearance, which greatly restores the true geometric shape of the vertebrae and indirectly ensures the effectiveness of model verification. Next, it can be imported into finite element analysis software for mechanical analysis.

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