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Establishment of a three-dimensional finite element model of severe kyphotic deformity secondary to ankylosing spondylitis

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Abstract

Objective: To establish a three-dimensional (3D) finite element (FE) model of ankylosing spondylitis (AS) kyphosis that is a digital platform for further studies.

Methods: A 30-year-old man with AS kyphosis underwent computed tomography transverse scanning from T1 to the sacrococcyx. The images were imported into Mimics® 17.0 software to establish a 3D model of the posterior spine, which was then imported into Studio Geomagic 2013 software. Posterior spine convex geometry was established on the 3D geometric model for subsequent optimization of image processing. Unigraphics NX 8.5 produced the spinal kyphosis surface model. Modeled calcification of ligaments and partial resection of useless sacral bone were added. The model was imported into ANSYS 15.0 FE analysis software. Ligaments were added. Parameters were set to generate a 3D FE model of AS.

Results and Conclusion: A 3D FE model of AS was successfully established, providing a reliable digital platform for subsequent biomechanical analysis.

Keywords

Ankylosing spondylosis, kyphosis, biomechanics, finite element analysis

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Introduction

Convex spinal ankylosis is a severe complication of ankylosing spondylitis. It can cause severe kyphotic deformity and limit the respiratory capacity and kinetic ability of the patient.[1] It is often necessary to use a surgical approach to treat ankylosing

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spondylitis deformity.[2] Although various techniques have been proposed to generate a suitable operative method in such situations, controversy remains concerning the best operative technique. Although radiography, computed tomography (CT),[3–5] and magnetic resonance imaging (MRI) provide two-dimensional (2D) images of the patient anatomy, the information is often not sufficient to help design a precise operative technique for the individual patient. Since the 1970s, the development of the finite element (FE) method and advances in three-dimensional (3D) modeling and biomechanics have enabled 3D analysis for spinal surgery. A complete 3D FE model could help simulate osteotomy, perform biomechanical analysis, aid preoperative planning, and guide surgical performance.

In this study, we collected CT images of a volunteer with convex ankylosing spondylitis. We applied computer-aided engineering software to establish the structural integrity of tonic convex spondylitis and then constructed a 3D FE model for further analysis of convex spinal biomechanics to provide a reliable model.

Methods

Patient

The ethics committee of the Sixth Affiliated Hospital of Xinjiang Medical University approved this study. After acquiring patient consent, full-length, positive, lateral MRI scans of the spine were performed. The patient was a 30-year-old man (height 170 cm, weight 75 kg). After ruling out the possibility of other abnormalities of the spine and spinal cord, he was diagnosed with ankylosing spondylitis.

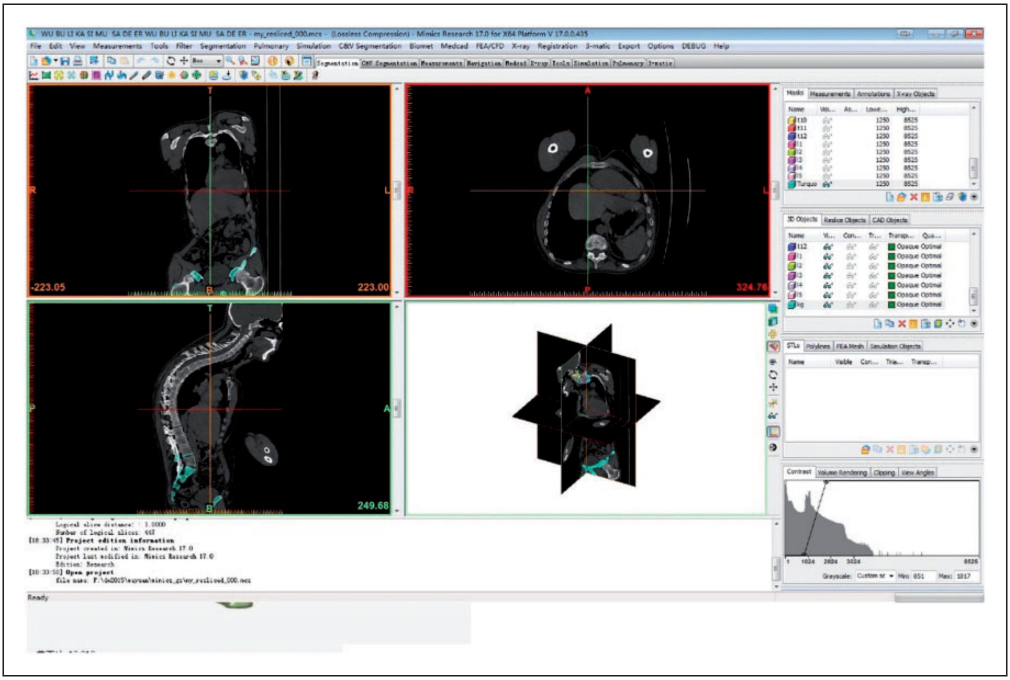
Hardware and software

The Dell Precision T7600 desk workstation with a Toshiba/Aquilion ONE 320 CT device was used in the current research. The software Mimics® 17.0 (Materialise, Leuven, Belgium) was used for reconstruction of CT data and to generate a medical model of the triangular structure. The output data were transformed to other forms of data in a personal computer. Studio Geomagic 2013 (3D Systems, Rock Hill, SC, USA) was used to read in the Mimics® 17.0 output data, transform the model data package, check for errors and optimize the data, and rebuild the non-uniform rational basis spline (NURBS) surface model. Unigraphics NX 8.5 software (Siemens PLM Software, Plano, TX, USA) was used to adjust the position between the components, divide them into a segmentation model, assemble the model, and perform the surgical simulation. ANSYS Workbench 15 (ANSYS Inc., Canonsberg, PA, USA) was used for material assignment, applying the load, setting the contact relationship, dividing the mesh, and establishing and analyzing the 3D FE model.

Establishment of the 3D FE model

Acquisition of CT data. Data were acquired using a Toshiba Aquilion™ ONE line 320-row dynamic volume CT thin-layer scanner (Toshiba Medical Systems Inc., Tustin, CA, USA), with an acquisition interval of 1 mm. Reconstructed specifications were a thickness of 0.5 mm, flat resolution of 512 × 512 pixels, 0.873 mm/pixel 2D CT images of 2434 pieces, saved as Digital Imaging and Communication in Medicine (DICOM) format files.

3D reconstruction of CT images. Mimics® 17 Medical Professional was applied for 3D reconstruction of CT images. The image command was used to import the 3D reconstruction data while preserving the CT Image in DICOM format, manually adding the coronal and sagittal sections (Figure 1). Variations in the gray-scale values with different organization were found in the image. The difference in



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        Logical slice distance: : 1.0000
        Number of logical slices: 447
[18:33:45] Project edition information
        Project created in: Mimics Research 17.0
        Project last modified in: Mimics Research 17.0
        Edition: Research
[18:33:50] Open project
        file name: F:\dx2015\aurum\mimics_gs\my_resliced_000.mcs
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Figure 1. Importing the computed tomography image into Mimics software.

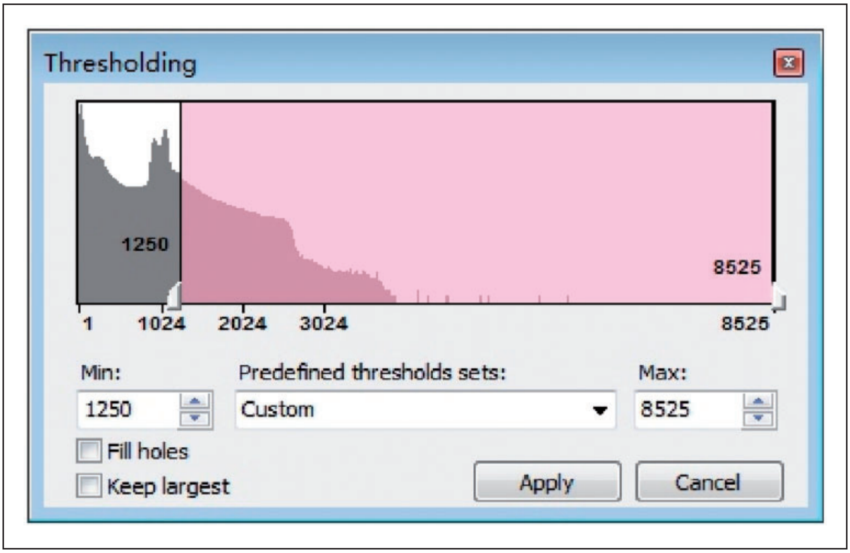
gray-level texture between the gray mutations was not obvious, however, so we used enhanced articulation of the CT images and adjusted the CT threshold parameter.

To establish the position of each vertebral body, we needed to adjust the imaging thresholds to 1250 (minimum) and 8525 (maximum) (Figure 2). We then used the Edit Masks with the Erase command to remove irrelevant image data and the Calculate command to obtain a preliminary 3D model (Figure 3). The initial vertebral body model was then exported and saved as an STL file.

Surface reconstruction model of the spine. The model was imported in STL format to Geomagic Studio 2013 software, allowing us to inspect the surface model for crisscrosses, tiny channels, or other artifacts (e.g., noise) and repair the triangles in the mesh structure. The smooth function was used to optimize the surface, remove sharp edges, and create a model for FE modeling in light of the various components used in the surface reconstruction function to establish the NURBS surface. The surface model of the spine was saved in IGES file format (Figure 4).

Setting up the NX8.5 spinal entity model. After importing the established spine surface model, we generated a complete model of the spine using the software entity function to remove any useless sacral entity modeling, establish a plan for loading C1 at the top, and facilitate force settings. We then used the curve and sketch functions, connecting the model's calcified ligaments between the vertebral bodies. We thus completed the 3D model of convex ankylosing spondylitis.

Establishment of the 3D FE model. After importing the established 3D model of convex ankylosing spondylitis into FE software ANSYS workbench 15.0, we divided the FE meshing and added the intervertebral



Min: 1250

Predefined thresholds sets: Custom

Max: 8525

☐ Fill holes

☐ Keep largest

Figure 2. Vertebral threshold.

Figure 3. Preliminary vertebral body three-dimensional model.

Figure 4. Spine surface model.

Table 1. Structural parameters.

Structure	Modulus (MPa)	Poisson's ratio
Cortical bone	12,000	0.3
Cancellous bone	500	0.3
Intervertebral disc	12,000	0.3
Ligament	12,000	0.3

disc and ligament structures described in the literature. This step was necessary because ankylosing spondylitis patients develop protruding intervertebral discs and serious ligament ossification.[6] Using cortical bone of the same material parameters as presented herein, the result was a complete 3D FE model of convex ankylosing spondylitis.

Setting the material properties. The material properties were set as indicated in Table 1.

Figure 5. Three-dimensional finite element model of convex ankylosing spondylitis.

Results

After convex 3D FE analysis, a model of ankylosing spondylitis was successfully established that included 7 cervical vertebrae, 12 thoracic vertebrae, 5 lumbar vertebrae, the sacral vertebrae, intervertebral discs, and spinal ligaments. The model was divided into 10 nodes with 398,370 tetrahedron units and 668,538 nodes (Figure 5).

Discussion

Kyphosis is a common deformation of the complex 3D space in patients with ankylosing spondylitis. Deformation in those patients could occur in both sagittal and coronal planes. Because of its complex 3D structure, conventional imaging methods such as radiography, CT, and MRI fail to provide sufficient information for establishing a surgical strategy.[7–9]

FE analysis is a discretization method used in numerical calculations (e.g., matrix mechanics, mechanics of elasticity) in the field of development and application. The finite element method (FEM) combined with modern techniques of spinal surgery has resulted in rapid developments in the field. Belytschko et al.[10] were the first to apply the FEM to spinal biomechanics research. Aubin *et al.*[11] used the FEM for the first time in the study of scoliosis. Since the beginning of the 21st century, the FEM has led to rapid developments in the field of spine surgery, with publications by Pitzen *et al.*[12] and Sadegh and Tchako[13] in 2000 demonstrating how FE analysis could be applied to studying the cervical spine.

Because of the complex anatomical structure of the human spine, preliminary studies are necessary to analyze the load distribution and the complexity of the biomechanics to obtain comprehensive information. The FEM can be used to summarize the structure of the spine in terms of mathematics, material performance, load, and boundary conditions by changing the parameters to observe the combined effect. This information increases our understanding of mechanical changes involved in physiological and pathological processes in the spine. In addition, computer simulation can be used to create conditions closer to normal, making the results more credible. The FEM not only can simulate lifelike vertebrae and intervertebral discs, it can rotate the ligaments and muscles to join the model. In addition, modeling of external loads and implants can be added for biomechanical testing. The FEM has become an important tool in current research into biomechanics of the spine.

The current study was based on the principle of reverse engineering. Using Toshiba/Aquilion ONE line 320-row dynamic volume CT with thin-layer scanning, a volunteer patient with convex ankylosing spondylitis was scanned using a CT interval of 1 mm and scan data reconstruction thickness of 0.5 mm. The 3D structure of the medical model was captured using Mimics® 17.0 software, and the data were imported into Geomagic Studio 2013 software for further modification. Unigraphics NX 8.5 software was then used to create a segmenting model by assembly, simulating the operation, and finally ANSYS 15.0 software to establish the FE model. The model was created based on data from the most advanced domestic 320-row spiral CT, with a reconstruction thickness of only 0.5 mm, and a 64-row small difference.[14]

Using a 320-row instrument allows use of a reduced scanning time and shortens the scan time interval. Based on the powerful advantages of 320-row CT, we established a 3D model that closely resembled human anatomy. The established 3D FE model realistically resembles ankylosing spondylitis, similar to that of the human body.

The 3D modeling software Mimics® 17.0 has been adopted internationally as mainstream modeling software that accepts input data from various scanning techniques such as CT and MRI. Once the 3D model is established for editing, the output can be used for a general computer-aided design to establish a realistic 3D model, which can then be imported into ANSYS software for FE analysis. Using our convex model under different constraints and different loads to simulate the human body, we concluded that, for the human body in different biomechanical states, ANSYS 15.0 is powerful software for 3D FE analysis. It has powerful functions and is easy to operate. Thus, it has become the most popular FE analysis software to date.

The application prospects of this technique must take into consideration that the human spinal anatomy is highly complex. Ankylosing spondylitis with kyphosis causes variation from the normal structure, in both 2D and 3D fields, resulting in a large difference from the normal structure and increasing the difficulty associated with surgical performance. In this study, the medical modeling software Mimics® 17.0 was used to establish the protrusion after creating the 3D model. It has high geometric similarity with the actual entity, and a computer-aided design of the protrusion can be made part of the 3D model. There are many osteotomy techniques for correcting the deformity, including pedicle subtraction osteotomy (PSO) and vertebral column resection/vertebral column decancellation (VCR/VCD). The traditional osteotomy is performed using the paper-cutting method.[15]

The current study applied FE analysis to surgical treatment of a spinal deformity. FE analysis has been applied increasingly more often in the surgical field in recent years. For treatment of the patient in the current study, a medical model established by Mimics software could be directly input into ANYSYS FE analysis software. A 3D FE model was built, and a variety of osteotomy techniques and their biomechanical characteristics were simulated on the model. Based on the experimental data, the best osteotomy method was designed preoperatively for this patient, increasing the possibility of successful surgery.

This study is a preliminary exploration of the application of information technology on spinal osteotomy. Because the 3D convex structure of the spine affected by ankylosing spondylitis is extremely complicated, any model must take into account the disc and possible severe ligament ossification, which makes determining the material properties difficult. Because of the lack of experimental data regarding the protrusion associated with ankylosing spondylitis, the model of the material parameters was constructed based on selected, similar data. Because the properties of the ligament and severe intervertebral disc ossification were unknown, we used the same parameters as for the vertebral body. Thus, the mechanical properties of the model were unavoidably affected by these similarities.

Conclusions

A novel 3D FE model of complete ankylosing spondylitis can provide a reliable digital platform for surgical planning and biomechanical analysis in patients with kyphotic deformities secondary to ankylosing spondylitis.

Authors' contribution

Aikeremujiang. Muheremu: statistical analysis and writing the paper; Hui Li: data collection; Wei Tian: study design, selection and recruiting patients.

Declaration of conflicting interests

The authors declare no conflicts of interest.

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