Computer simulation of idiopathic scoliosis initiated by local asymmetric growth force in a vertebral body

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Abstract

Scoliosis is defined as an appreciable lateral deviation with axial rotation in the normally straight vertical line of the spine. Idiopathic scoliosis is a deformity which develops during a period of rapid growth and reduces after skeletal maturity. As a biomechanical approach to scoliosis, this paper presents a computer simulation method to examine the hypothesis that local asymmetric growth in a vertebral body might initiate scoliosis deformities of the spinal column.

1 Introduction

The human spine is a complex structure which composed of many vertebrae and intervertebral discs, and has three parts of cervical, thoracic and lumbar region. The normal geometry of it is frontal straight and physiological sagittal curvature which shows kyphosis in the thoracic region and lordosis in the lumbar region. One of the most serious disease of the spine is scoliosis, which is characterized as a lateral deformity of spine in frontal plane. Scoliosis is a three dimensional spinal deformity and defined as an appreciable lateral deviation with axial rotation in the normally straight vertebral line of the spine. In particular, idiopathic scoliosis is a deformity which develops during a period of rapid growth and reduces after skeletal maturity. The definite cause of it, however, is unknown yet, in spite of numerous clinical studies. Many researchers have been reported that an evidence of asymmetric growth in spinal components was responsible for causing scoliosis; asymmetric growth in the vertebrae (Roaf [1]), in the upper arm (Dangerfield et al. [2]) and in the rib (Stokes et al. [3], Agadir et al. [4]). These observation of asymmetries implicate asymmetric growth in etiology of scoliosis. However, they did not establish that asymmetric growth is
the primary cause of the spinal and other asymmetries, nor do they define the precise kinematic and kinetic mechanisms responsible for the observed changes. Therefore, the biomechanical aspects of curve development and mechanism of scoliosis were analyzed by finite element modeling techniques. Stokes et al. [5] have presented a finite osseo-ligamentous structural model of human thorax, in order to analyze the asymmetric growth of the rib cage.

This paper presents a three dimensional finite element skeletal structure model of the whole human spine which is composed of a spinal column from thoracic to sacrum with a rib cage. This model is analyzed to examine the hypothesis that local asymmetric growth in a vertebral body might initiate scoliosis deformities of the spinal column.

2 Methods

2.1 Three Dimensional Structural Modeling of The Whole Spine
The normal skeletal spine model was constructed with three dimensional isoparametric solid elements, which consists of the vertebrae and the intervertebral discs of the thoraco-lumbar region from T1 to L5, the sacrum, the rib pairs 1-10, sternum, costal cartilages, and the joint capsules. The initial geometry of the model was created by reflecting the data of many anatomical features; the physiological curves of the spinal column in the sagittal plane, the
complex shape of vertebrae and rib pairs with level to level variations. Fig.1 shows the overall geometry of the model in frontal and sagittal view. This model has a total elements of 2002. Each vertebral body has the substructures of cortical and cancellous bone. Each intervertebral disc has the substructures of annulus fibrosus and nucleus pulposus.

Material properties are much difficult to determine, because of known non-linearity, inhomogeneity etc. of biological tissue. Therefore, linear elastic properties of each component in this model were taken from the reference data in many published papers. Table 1 lists the Young's modulus E (MPa) and the Poisson ratio $\nu$ at each structural part. Sacrum, lamina, spinal process, rib and sternum were modeled by cortical bone tissue. Facet joint and costovertebral joint were modeled by a solid element having lowest elastic modulus to represent an articular tissue. Costcartilage was modeled by a cartilage tissue.

2.2 Growth Analysis

It can be assumed in a macroscopic and mechanical aspect that growing a living tissue is analogy to deforming with increasing a volume. Then, a stress may occur in the living tissue to be deformed itself. The stress is considered as growth force.
stress which induces self-swelling and acts as external work to outer tissue. To simplify these phenomena in this analysis, growth force was defined as an equivalent external load acting at nodal points in an element where growth stress occurred.

The purpose of this analysis is to investigate the effect of local asymmetric growth force on the curve configuration of scoliosis. Therefore, the growth deformation of only spinal column was analyzed by applying a growth force at cortical bone on the lower and upper surfaces of vertebral bodies. The force was tensile and was always applied for the axial direction on local coordinate system set in a vertebral body. Bony growth deformation induced by growth force was defined as permanent deformation, which was analyzed by introducing the constitutive laws of incremental stress-plastic strain which permits the volume change in a loading direction. The material matrix representing the relationship between stress and plastic strain is unknown under growth deformation. Therefore, the [D] matrix of elasticity was used without the values of Poisson ratio on axial direction of cortical bone in a vertebral body. These values were 0.1. This computational procedure is analogous to a rigid-plastic analysis which is often used in a metal forming analysis.

The configuration of scoliotic spine with a single thoracic curve was simulated in this analysis. Since it was observed that actual scoliotic spines with a single thoracic curve often had the apical vertebra of T8 vertebra [6], the asymmetric growth force was applied at T8 vertebral body only. At the other vertebrae except for T8, uniform growth force was applied to be deformed symmetrically. Fig.2 shows both distribution of uniform and asymmetric growth force applied at a vertebral body. The maximum force in the distribution of asymmetric growth force was located at a anterior region of T8 vertebra (Case 1), antero-lateral right (Case 2), right (Case 3), postero-lateral right (Case 4), posterior (Case 5) and left (Case 6). All rotations and three translations were constrained at sacrum and T1 vertebra of upper and lower bound in the model (a). In the less constrained model, all rotations and only vertical translation were permitted at T1 vertebra (b).

2.3 Method of Computer Simulation
The solution was obtained by using the ANSYS three dimensional finite element package (ANSYS, Inc., Houston, PA). Linearity of both material properties and geometry of small displacements were assumed. In order to simulate geometric non-linearity due to large displacements, the model was calculated in reiteration with increments of varying growth force. Fig.3 shows a flow chart of this calculation. This calculation starts from setting initial geometry of the model. Local coordinate systems in each vertebral body are set up. Next, one vertebral level to apply growth force is selected at random. If T8 vertebra is selected, asymmetric growth force is applied to it. If the other vertebra, uniform growth force is applied. End constraints are determined and the model is analyzed in succession. Therefore, the geometric data of the model deformed is obtained, and is replaced as initial geometry for next step calculation. This loop is iterated. 1 step is the calculation that growth force is loaded in one vertebral body. 1 cycle is iterated in
Initial geometry → Replacement of geometry data

Set up local coordinates at each vertebral body

Select at random one vertebral level which applies growth force. (one by one)

T8 vertebra
Asymmetric growth force

Other vertebra
Uniform growth force

Boundary condition

Calculation: at growth force in one vertebral body

Results: deformed geometry

Figure 3: Flow chart of the calculation

16 steps, which means one round calculation from T1 to L5 vertebra in the whole spine. The increment magnitude of uniform growth force was defined as an equivalent value of external load when height of the model increased in 1% at 1 cycle iteration. On the other hand, the maximum force in local asymmetric distribution was 2 times of uniform force. The calculation was carried out until 5 cycles of 80 steps. The run time for one solution cycle was 90 min when run on an HP-712/80 work station (Hewlett-Packard, Palo Alto, CA).

3 Results and Discussion

A typical configuration of scoliosis is shown in Fig. 4. The data of a subject of scoliosis with a single thoracic curve was measured by using the method which was proposed by the authors [6]. The ordinate of the figure indicates nondimensional spinal height from sacrum (h/H), where H is height of upper surface at T1 vertebra. The left side figure in Fig. 4 shows the displacement of scoliotic spine in frontal view. The middle one is the displacement in sagittal view, and the right is rotation angle of each vertebra. It is clear that the clinical configuration of scoliosis has the vertebral lateral deviation on the right, the disappearance of physiological sagittal curve, and the appearance of vertebral axial rotation. Moreover, the maximum rotation occurred at T8 vertebra.

The result of the computer simulation due to growth analysis was obtained
at each condition of asymmetric growth force. The result of Case 1 is shown in Fig. 5, where the maximum asymmetric growth force was located in the anterior region of T8 vertebral body. Roaf [1] pointed out thus asymmetric growth induced a morphological feature of scoliosis. In this figure, however, no lateral deviation but back deviation appears. There is also no vertebral rotation. These results are much different from the clinical configuration shown in Fig. 4. Case 2 is at maximum growth force in the antero-lateral right region. Slightly lateral deviation occurred on the right. However, no deviation and no vertebral rotation appeared. Case 4 is at maximum growth force in the postero-lateral right region. Lateral deviation occurred on the left. Forward deviation and vertebral rotation occurred. The result shows an opposite deformation of clinical configuration. However, because this model has symmetric geometry, the opposite result of this case can be obtained at maximum growth force in the postero-lateral left region, which is similar to the clinical configuration.

Case 6 is at maximum growth force in the left region, and is shown in Fig. 6, where T1 is constrained in three direction. Large lateral deviation occurred on the right. It should be noted that the deviation appeared in the opposite side of the region applied the maximum force. Moreover, sagittal deviation decreased and much vertebral rotation occurred. These results simulated well the characteristics of clinical configuration. When T1 constraint is free in only axial direction, the result at the same loading condition of case 6 was also obtained that the lateral deviation and vertebral rotation became much greater than in Case 6.

If the axial asymmetric growth force was applied to the lateral region from the left to the posterior in T8 vertebral body, the deformation from the normal spine was similar to the configuration of typical scoliosis with thoracic curve. Namely, scoliosis with a single thoracic curve might be induced by the maximum asymmetric growth force applied at the zone in T8 vertebral body shown in Fig. 7. In addition, T1 constraints of free in only axial direction induced greater lateral deviation and vertebral rotation as a scoliotic spine.

Figure 4: A clinical configuration of idiopathic scoliosis with a thoracic curve
4 Conclusion

From the computer simulation with the structural model of whole spine, the effect of varying distribution of growth force and the end constraints were investigated on the deformation from the normal spine. Therefore, this model could simulated the modulation of growth in the osseous tissues, as well as a single thoracic scoliosis curvature convex toward the lateral direction with axial rotation, as seen in typical scoliosis deformities.

Figure 5: Results of computer simulation, when the maximum force of asymmetric growth force was located at the anterior region in T8 vertebral body.

Figure 6: Results of computer simulation, when the maximum force of asymmetric growth force was located at the left region in T8 vertebral body.
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Reference


Figure 7: The zone where the maximum vertical growth force is applied in T8 cross section to induce the configuration of scoliosis.