

TRABECULAR REMODELING SIMULATION OF A VERTEBRAL BODY WITH A FIXATION SCREW USING VOXEL FINITE ELEMENT MODELS

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Abstract. *A three-dimensional simulation of trabecular surface remodeling was performed to investigate the basic effects of a fixation screw on the trabecular structural changes in a vertebral body. Voxel-based finite elements were used to construct computational models of the bone and screw for an entire vertebral body with the screw and for the bone-screw interface. The remodeling simulation for the entire vertebral body showed that the implantation of the fixation screw caused changes in the mechanical environment in the cancellous bone, leading to trabecular structural changes at the cancellous level. The effect of the screw on trabecular orientation was greater in the regions above and below the screw than on that in front of the screw. In the case of the bone-screw interface, the trabecular structural changes depended on the load applied to the screw. It was suggested that bone resorption predicted in the pull-out loading case would be a candidate cause of loosening of the screw. The results indicate that the effects of the implanted screw on the trabecular structural changes would be more important for longer-term fixation.*

1. INTRODUCTION

Biomechanical view points are necessary for proper fixation of a screw implanted to a vertebral body to avoid loosening of the fixation screw and to obtain mechanical stability of the spinal structure. It has been suggested that changes in the bone structure due to remodeling as well as bone fatigue fracture [1,2] play an important role in the loosening of the screw. However, few studies have focused on mechanical bone remodeling in the vertebral body with the screw. The purpose of this study is to investigate effects of a fixation screw on the three-dimensional trabecular structural change in a vertebral body by using voxel-based finite element models of trabecular surface remodeling [3]. First, a remodeling simulation is conducted for an entire vertebral body to examine the effects of the implanted screw on structural changes at the cancellous level. Second, the trabecular microstructural changes adjacent to the bone-screw interface are simulated to investigate the relationships between loosening of the screw and the applied loads to the screw. Third, important mechanical factors in the implantation of the screw are discussed from the simulation results in respect of mechanical bone remodeling.

2. METHODS

2.1 Model of an Entire Vertebral Body with a Fixation Screw (Model E)

A pedicle screw used in total *en bloc* spondylectomy for a vertebral tumor [4] was considered as the example of a screw for spinal fixation. Assuming symmetry with respect to the central sagittal plane, a half model of an entire human L3 vertebral body with a fixation screw (model E) was created using about 0.79 million voxel-based finite elements, as shown in Fig. 1(a). This model consisted of cortical bone, cancellous bone, and the fixation screw. The size of the vertebral body was 50 mm in diameter in the bilateral and anteroposterior directions, and 25 mm in height in the axial direction. The X_1 axis was set to correspond to the bilateral direction, the X_2 axis to the anteroposterior direction, and the X_3 axis to the axial direction. The trabeculae at the initial stage, which was taken from the result of a remodeling simulation for a normal vertebral body, was aligned along the axial direction according to compressive loading due to the body weight, as shown in the $X_2 - X_3$ and $X_1 - X_3$ cross sections in Fig. 1(a). The screw was set to 4 mm in diameter and 50 mm in length of which 24 mm was implanted into the vertebral body. The size of each element was $250\mu\text{m}$.

As a boundary condition for the vertebral body under compressive loading due to the

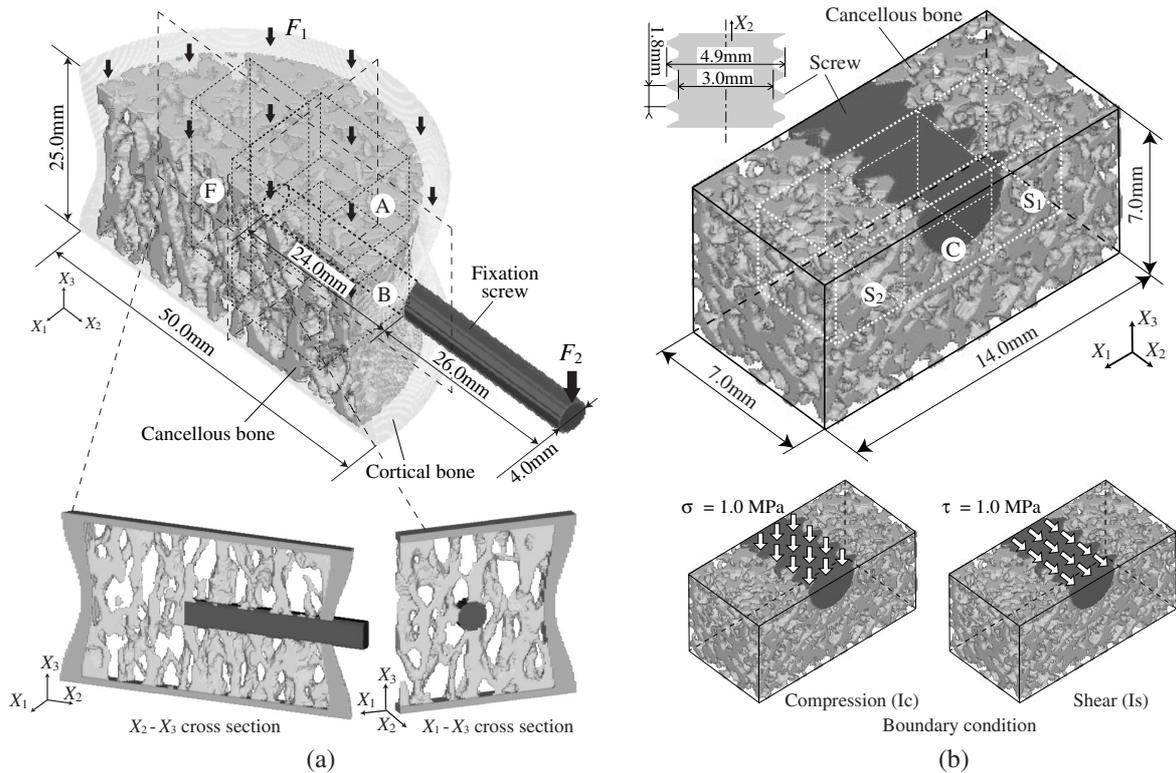


Figure 1. Voxel-based finite element models for trabecular surface remodeling simulation: (a) entire vertebral body with a fixation screw (model E); (b) cancellous bone adjacent to the bone-screw interface (model I) under compressive loading (case Ic) and shear loading (case Is).

body weight, uniform compressive displacement U_3 was applied to the upper plane at $X_3 = 25$ mm to apply the total loads $F_1 = 588$ N, and the lower plane at $X_3 = 0$ mm was fixed. Displacement constraint U_3 was used instead of force constraint F_1 to save computational time in the large-scale finite element method. Bending load $F_2 = 58.8$ N was applied to the end of the screw as a load transferred from a fixation device, as shown in Fig. 1(a). The bone and screw were assumed to be homogeneous and isotropic materials, and Young's modulus E and Poisson's ratio ν were set as $E_b = 20$ GPa and $\nu_b = 0.3$ for the bone, and $E_s = 200$ GPa and $\nu_s = 0.29$ for the screw assumed to be stainless steel [5]. The marrow was considered as a cavity, and neglected in the finite element analysis.

2.2 Model of Bone-Screw Interface (Model I)

The trabecular structure adjacent to the bone-screw interface is important for proper fixation of the screw to cancellous bone. As a model of the bone-screw interface, a $7 \times 7 \times 14$ mm³ cancellous bone hexahedron was created (model I) using about 0.91 million voxel-based finite elements, as shown in Fig. 1(b), the size of each voxel being 70 μ m. The cancellous bone part of model I was filled with ring-like shaped trabeculae assuming that the initial trabecular structure was isotropic, as shown in Fig. 1(b). The external and root diameters of the screw were 4.9 mm and 3 mm, respectively, and the pitch was 1.8 mm. The coordinate axes were set as shown in Fig. 1(b), in which the X_2 axis corresponded to the screw axis.

Assuming the screw to be subjected to the body weight and pull-out loading, two simple loading cases for compressive loading (Ic) and shear loading (Is) were considered in the remodeling simulation, as shown in Fig. 1(b). As a boundary condition, a uniform compressive displacement along the X_3 axis was applied to the upper surface of the screw in case Ic, and a uniform shear displacement along the X_2 axis was applied in case Is. Each of these displacements was controlled to apply an apparent stress of 1 MPa on the upper plane of the screw, as shown in Fig. 1(b). The displacement constraint was used instead of the actual stress to save computational time in the finite element analysis, as in the case of model E. On the bottom and side planes of cancellous bone, shear-free boundary conditions were applied, that is, the displacements perpendicular to the plane were fixed.

2.3 Voxel Simulation Method for Trabecular Surface Remodeling

Trabecular structural changes for models E and I were simulated based on a rate equation of trabecular surface remodeling in which the remodeling was assumed to be driven by local nonuniformity of equivalent stress [3]. The model parameters in the remodeling model were set constant as threshold values $\Gamma_u = 1.0$ and $\Gamma_l = -1.25$, and sensing distance $l_L = 2.5$ mm for model E, and $\Gamma_u = 1.5$, $\Gamma_l = -1.88$, and $l_L = 700$ μ m for model I. The trabecular morphological changes by remodeling were accomplished by repetitive cycles of a large-scale finite element analysis and the removal/addition of voxel elements from/to the trabecular surface. For the condition of the bone-screw interface in the stress analysis, it was assumed that tensile loading perpendicular to the interface was not transferred from the screw to the bone.

The simulation result was evaluated for regions F (in front of the screw tip), A (above the screw), and B (below the screw) for model E, as shown in Fig. 1(a), and for regions C (below the screw), S₁ (on the negative side of the X_1 axis), and S₂ (on the positive side of the X_1 axis) for model I, as shown in Fig. 1(b). Fabric ellipsoid was measured as an anisotropic structural parameter in these regions. The degree of structural anisotropy was

defined as the ratio of maximum principal value H_1 to minimum value H_3 of the fabric ellipsoid, and trabecular orientation angle Θ_i ($i=1,2,3$) was defined as the angle between maximum principal direction n^{H_1} of the fabric ellipsoid and the coordinate axis X_i . With model I, contact area S between the bone and screw threads, which was normalized by initial contact area S_0 , was measured to investigate the structural changes of trabeculae adjacent to the screw threads.

3. RESULTS

3.1 Structural Changes at Cancellous Level due to Implantation of the Screw

In the case of the entire vertebral body with a fixation screw (model E), the trabecular structure adapted to the mechanical environment that had been changed due to the implanted screw, as shown in Fig. 2. The effects of the fixation screw were greater in regions A and B

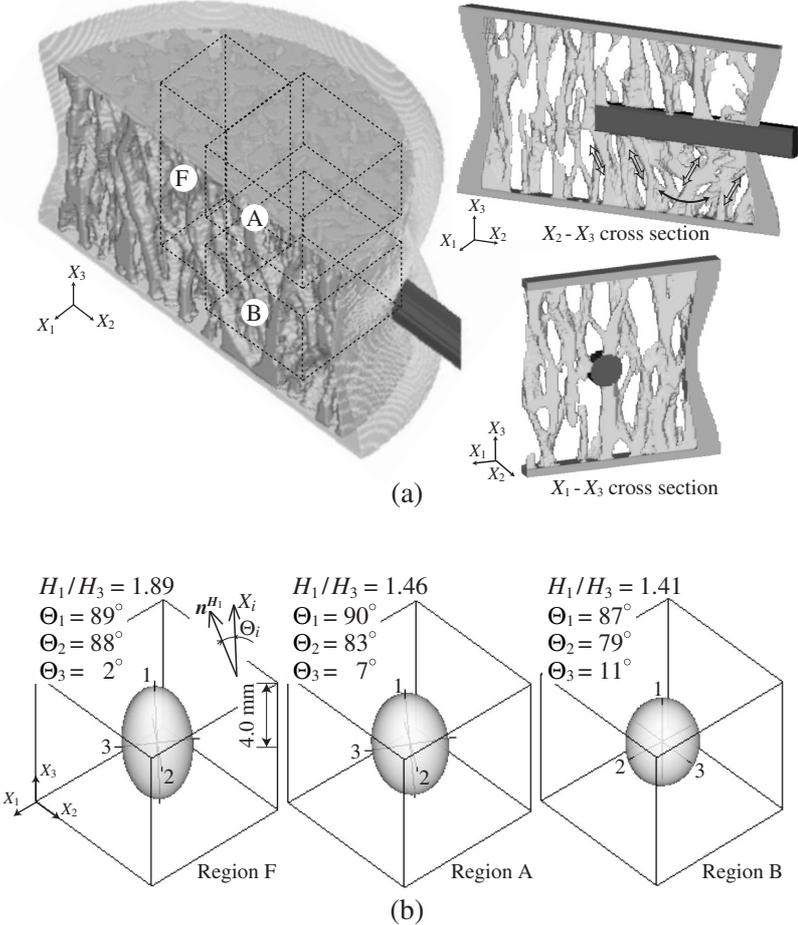


Figure 2. Trabecular structural changes in a vertebral body with a fixation screw (model E) predicted by trabecular surface remodeling simulation: (a) three-dimensional image and cross sections; (b) fabric ellipsoids of the trabecular structure in regions F, A, and B.

than in region F, because the loading applied to the end of the screw was supported mainly by the pedicle part including regions A and B. The trabeculae in the central cancellous region and in front of the screw were mainly subjected to the body weight.

In region F, the trabeculae grew thick in the axial direction and resorbed in the transverse direction due to compressive loading of body weight, as shown in the $X_2 - X_3$ and $X_1 - X_3$ cross sections in Fig. 2(a). Degree of structural anisotropy H_1/H_3 and trabecular orientation angle Θ_i ($i = 1, 2, 3$) were $H_1/H_3 = 1.89$ and $(\Theta_1, \Theta_2, \Theta_3) = (89^\circ, 88^\circ, 2^\circ)$. The structural parameters and fabric ellipsoid shown in Fig. 2(b) indicated the trabeculae in region F oriented along the axial direction.

Degree of structural anisotropy H_1/H_3 and trabecular orientation angle Θ_i were $H_1/H_3 = 1.46$ and $(\Theta_1, \Theta_2, \Theta_3) = (90^\circ, 83^\circ, 7^\circ)$ in region A, and $H_1/H_3 = 1.41$ and $(\Theta_1, \Theta_2, \Theta_3) = (87^\circ, 79^\circ, 11^\circ)$ in region B. Structural parameter H_1/H_3 was smaller in these two regions than in region F, and Θ_3 was larger. This result shows that the trabecular structure was more distributed in regions A and B than in region F. For example, the trabeculae in region B were formed from both the screw tip and the pedicle to the lower cortical shell, as indicated by the unfilled arrows in the $X_2 - X_3$ cross section shown in Fig. 2(a). Part of these trabeculae were connected with each other to configure an arcuate structure, as indicated by the filled arrow in the $X_2 - X_3$ cross section shown in Fig. 2(a).

3.2 Structural Changes of Trabeculae adjacent to Bone-Screw Interface

In the case of the bone-screw interface (model I), the isotropic trabecular structure, as shown in Fig. 1(b), changed to the anisotropic one, as shown in Fig. 3. As a result of the remodeling driven by stress nonuniformity on the trabecular surface, the obtained trabecular structure depended on the applied loads to the screw.

In the compressive loading case (Ic), degree of structural anisotropy H_1/H_3 and trabecular orientation angle Θ_i ($i = 1, 2, 3$) were $H_1/H_3 = 1.24$ and $(\Theta_1, \Theta_2, \Theta_3) = (86^\circ, 90^\circ, 4^\circ)$ in region C, $H_1/H_3 = 1.23$ and $(\Theta_1, \Theta_2, \Theta_3) = (54^\circ, 90^\circ, 36^\circ)$ in region S₁, and $H_1/H_3 = 1.22$ and $(\Theta_1, \Theta_2, \Theta_3) = (65^\circ, 88^\circ, 25^\circ)$ in region S₂. These results show that structural orientation Θ_i was different in each region, although degree of structural anisotropy H_1/H_3 was similar. Corresponding to the structural parameters, the trabeculae were aligned along the compressive loading direction below the screw, as indicated by arrows in the $X_2 - X_3$ cross section shown in Fig. 3(a), and radially formed from the screw, as indicated by arrows in $X_1 - X_3$ cross section shown in Fig. 3(a).

In the shear loading case (Is), degree of structural anisotropy H_1/H_3 and trabecular orientation angle Θ_i were $H_1/H_3 = 1.17$ and $(\Theta_1, \Theta_2, \Theta_3) = (85^\circ, 12^\circ, 79^\circ)$ in region C, $H_1/H_3 = 1.12$ and $(\Theta_1, \Theta_2, \Theta_3) = (52^\circ, 88^\circ, 38^\circ)$ in region S₁, and $H_1/H_3 = 1.15$ and $(\Theta_1, \Theta_2, \Theta_3) = (78^\circ, 12^\circ, 90^\circ)$ in region S₂. The smaller values for H_1/H_3 than those in case Ic indicate a more distributed trabecular structure, as shown in the $X_1 - X_3$ cross section in Fig. 3(b). Some of trabeculae below the screw, however, were aligned in the directions oriented 45 degrees according to shear loading, as indicated by arrows in the $X_2 - X_3$ cross section shown in Fig. 3(b).

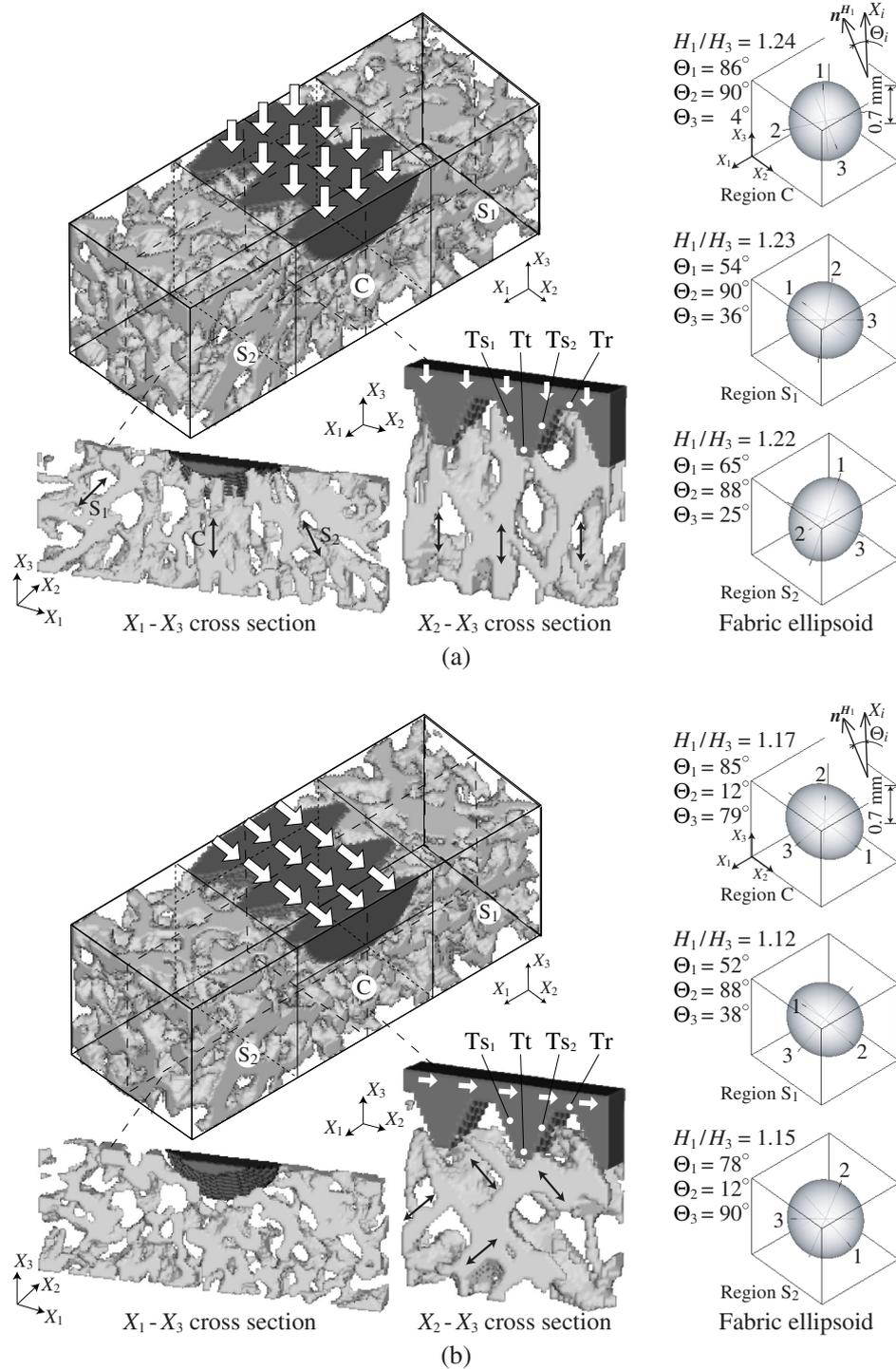


Figure 3. Trabecular structural changes adjacent to the bone-screw interface (model I) predicted by trabecular surface remodeling simulation: (a) compressive loading (case Ic); (b) shear loading (case Is).

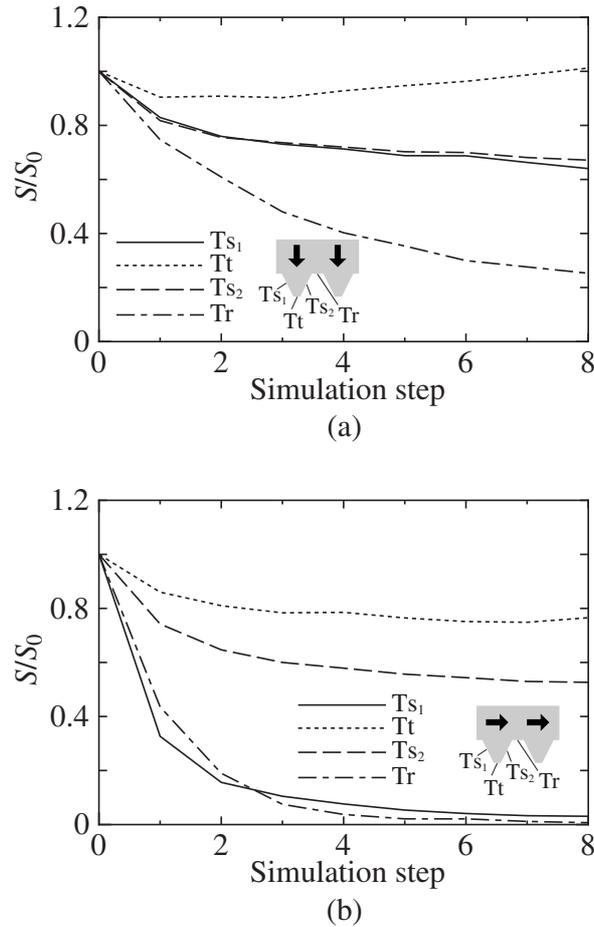


Figure 4. Change in contact area between the screw threads and trabeculae under (a) compressive loading (case Ic) and (b) shear loading (case Is).

The change in contact area S/S_0 is shown in Fig. 4. In case Ic, contact area S/S_0 increased at the top of the screw threads (Tt), as shown in Fig. 4(a). Contact area S/S_0 decreased on both the sides (T_{s1} and T_{s2}) and at the root (Tr), indicating bone resorption. In case Is, contact area S/S_0 decreased in the entire area due to bone resorption, as shown in Fig. 4(b). The decrease rate of the contact area S/S_0 at the root (Tr) and on the tensile side (T_{s1}) was higher than that at the top (Tt) and on the compressive side (T_{s2}), and contact area S/S_0 at Tr and T_{s1} became zero in the final state.

4. DISCUSSION AND CONCLUSIONS

It has been suggested that Trabecular structural changes due to mechanical bone remodeling are important for proper fixation of a bone implant such as a hip joint stem in the proximal femur [6] and a dental implant in the mandible [7]. The remodeling simulation with model E for an entire vertebral body with a fixation screw shows that the trabecular orientation was

changed in regions above (A) and below (B) the screw, as indicated in Fig. 2. Although the loading applied to the screw was only one tenth of the body weight, the trabecular structure adapted to the mechanical environment that had been changed by the implanted screw. This result indicates the influence of the fixation screw on the trabecular structural changes in the vertebral body.

In the remodeling simulation with model I for the bone-screw interface, the trabecular structure changed according to the load applied to the screw, as shown in Figs. 3 and 4. While the trabeculae remained near the screw threads in the compressive loading case (Ic), the bone was resorbed on the tensile side (Ts₁) and at the root (Tr) of the threads in the shear loading case (Is). These results show that the load applied to the screw is a critical factor in bone resorption at the bone-screw interface, and that the pull-out loading is a candidate cause of screw-loosening by remodeling. In addition, the degree of bone resorption obtained by the simulation depended on the site of the screw threads, indicating that the screw threads play an important role in loosening of the fixation screw due to remodeling.

These results have not yet been compared with experimental results because no data have been reported about the trabecular structural changes in a vertebral body with a fixation screw. The results obtained in this study, however, are consistent with the bone remodeling phenomenon that has been observed around other bone implants in terms of the structural adaptation. The simulation method with a voxel model is effective in predicting remodeling phenomena in individual cases because a voxel model of the bone structure can be easily constructed from medical image data. This voxel-based simulation method will therefore enable us to test various combinations of bone and spinal fixation screw, and provide useful information for choosing the screw type.

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