Compressive Strength Evaluation of Osteoporosis Vertebra by Finite-Element Analysis Based on Patient-Specific Models

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INTRODUCTION

In almost every cases of diagnosis for vertebral osteoporosis, quantitative value of bone is measured two-dimensionally, such as, bone mineral density is measured by DXA or bone mass density is measured by ultrasound. That kind of diagnosis is not sufficient to evaluate risk of compression fracture of vertebrae, because it does not evaluate mechanical strength of vertebrae directly. Mechanical strength of vertebra depends on its shape, cortical bone thickness, density distribution of cancellous bone, material properties of bone tissue, and so on. All of the factors related to mechanical strength of vertebra are inherently individual. Patient-specific mechanical analysis is required to evaluate vertebral fracture risk in clinic. Computational models of vertebrae were constructed by using CT images of osteoporosis patients and finite-element analyses of the individual vertebra models were carried out in this study. Several models of female lumbar vertebra were constructed for different ages. Ultimate fracture load obtained by finite-element analyses with compressive loading condition were compared each other, and influence of vertebra strength due to osteoporosis was considered.

MATERIALS AND METHOD

X ray CT images were taken from three osteoporosis patients who visited to the orthopedic clinic of the university hospital and a healthy volunteer. All of the patients are Japanese female. Their age and bone mineral density of L1 vertebra measured by DXA are shown in table 1 with condition of the disease. L1 vertebra was focused on, because it was located near the inflection point of spine and favorite site of osteoporosis fracture. Interval of CT section of L1 vertebra was set as 1mm. Mechanical Finder (RCCM Co.) is computer software for bone strength analysis considering individual bone shape, cortical thickness and bone density distribution. Patient-specific finite-element models of L1 based on CT images were obtained by using this software as shown in figure 1. Thin shell elements were used to

<table>
<thead>
<tr>
<th>Sign</th>
<th>Age</th>
<th>BMD [g/cm³]</th>
<th>Condition</th>
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<tbody>
<tr>
<td>A</td>
<td>59</td>
<td>1.043</td>
<td>Normal</td>
</tr>
<tr>
<td>B</td>
<td>84</td>
<td>0.865</td>
<td>Slight Osteoporosis</td>
</tr>
<tr>
<td>C</td>
<td>64</td>
<td>0.667</td>
<td>Osteoporosis</td>
</tr>
<tr>
<td>D</td>
<td>71</td>
<td>0.435</td>
<td>Severe Osteoporosis</td>
</tr>
</tbody>
</table>

Table 1 Age, BMD of L1, and condition of osteoporosis of the patients.

Fig.1 Patient-specific finite-element models of L1

Fig.2 Bone density distribution of the patient-specific FE models except for cortical shell elements.
represent thin cortical bone on the surface. Figure 2 shows bone density distribution of the models except for the cortical shell elements. Young's modulus and strength of each solid element is given one by one calculating from bone mass density and CT value. Relationship between the mechanical properties and bone mass density obtained by past studies (e.g., Carter 1977) was used in the calculation. Simple compressive loading was considered in the analyses, that is, bottom surface was fixed and uniform pressure was applied to upper surface of vertebra. Non-linear finite-element analyses considering bone fracture process were carried out with incremental loading condition. If principal stress over the local strength of an element, constitutive equation of the element is changed considering a crack initiated along orthogonal direction to the principal stress (e.g. Kwak 1990).

RESULTS AND DISCUSSION

An example of crack propagation process on the cortical surface is shown in figure 3 for the case of model C (osteoporosis). In cortical bone surface, crack was initiated at anterior midpoint of the vertebra, and the crack was propagated widely around anterior surface. Small fracture of cancellous bone arose from anterior side at lower load, and the fracture part grew to posterior side with increasing of load, then breakdown of the vertebra occurred when the fracture extended over circumference. Ultimate fracture load is defined as load at last increment just before breakdown, because finite-element analysis is not able to continue after breakdown. Figure 4 shows ultimate compressive fracture load of the models versus bone mineral density (BMD) measured by DXA. Positive correlation is observed between BMD and the ultimate fracture load. BMD obtained by DXA seems effective index for osteoporosis diagnosis in mechanical viewpoint, even though it is not mechanical property and measured two-dimensionally.

SUMMARY

Compressive strength of osteoporosis vertebrae was analyzed by finite-element method for patient-specific models based on CT images, in this paper. Ultimate fracture load obtained by the analyses decrease depending on bone mineral density measured by DXA.

REFERENCES


Fig.3 Crack propagation process on the cortical surface in bone fracture analysis of model C. Fractured finite-elements are shown with total load F.

Fig.4 Ultimate compressive fracture load of the models versus bone mineral density measured by DXA.