Prediction of Vertebral Strength Under Loading Conditions of Daily Life Using a CT-Based Finite Element Method

INTRODUCTION: Osteoporotic vertebral fractures occasionally occur slowly and asymptomatically, that appear to be caused by loading on the spine during activities of daily living that exceed the vertebral strength of the osteoporotic individual. The most common type of vertebral fracture is reportedly wedge-shaped fracture caused by axial and bending loads. To assess the strength of osteoporotic vertebrae, evaluating vertebral strength under loading as experienced during daily living is important, particularly forward bending. The purpose of the present study was to evaluate differences in predicted fracture strength of vertebral bodies among different loading conditions occurring during activities of daily living using patient-specific finite element (FE) analysis (FEA), which provides accurate prediction of bone mechanics under loading reported by Imai et al

PATIENTS AND METHODS: Subjects comprised 41 female patients (mean age, 69.4 years; range, 51-88 years) with postmenopausal osteoporosis according to the guidelines for osteoporosis as proposed by the Japanese Society of Osteoporosis (2006 ed.). No subjects had any previous history of disease or use of drugs affecting bone metabolism. The second lumbar vertebra (L2) was examined in these patients, and subjects with previous L2 fracture were excluded. With ethics committee approval, computed tomography (CT) of L2 was performed after obtaining informed consent from each patient. CT of L2 was obtained using a slice thickness of 2 mm with a calibration phantom. CT data were transferred to the workstation, and bone area of the L2 vertebral body was extracted from each scan. FE mesh models were then generated using the advancing front method. An FE model was created with 2-mm tetrahedral elements. Triangular elements with a thickness of 0.4 mm were attached to the model surface. Mechanical Finder software was used to extract bone area and for FE analyses. To allow for bone heterogeneity, mechanical properties of each element were computed from the Hounsfield unit value. Ash density of each voxel was determined from the linear regression equation created from the equations proposed by Keyak et al (1998). The minimum Young’s modulus of each triangular plate was set as 10 GPa. Poisson’s ratio of each element was set at 0.4, as used in previous papers. A uniaxial compressive load with uniform distribution was applied on the upper surface of the vertebra, with all elements and all nodes of the lower surface completely restrained. Loading configurations for erect standing and forward bending as described by Pollintine et al. (2004), were modified and adopted for analysis. Load distribution was divided into three parts: anterior; middle; and posterior. The ratio of load magnitude for each part was assigned on the assumption that the middle part bore the average load magnitude of the anterior and posterior parts. Ratios were thus 19:31:41 for erect standing and 59:48:38 for forward bending. Load was applied on the upper end plate vertically and the lower end plate was fully restrained (Fig. 1).

Figure 1: Load and boundary conditions in each model.

Nonlinear analysis was performed using the Newton-Raphson method with a post-yield modulus of 0.05. The ratio of ultimate stress to yield stress was assigned as 0.8. The element crack in tension was defined as occurring when maximum principal stress exceeded element ultimate stress. However, in compression, we introduced both yield and failure. Yield in compression was defined as occurring when Drucker-Prager equivalent stress exceeded element yield stress. Failure in compression was then defined as occurring when the negative value of maximum principal strain exceeded 10,000 microstrain. Fracture load was defined as the load when at least one element failed. Predicted fracture load in each of the erect standing and forward bending configurations was calculated and compared to that under uniaxial compression. Predicted fracture sites under each loading configuration were also identified. To analyze differences in distribution of fracture sites depending on differences in loading configuration, the whole vertebral body was divided into 3 parts in an antero-posterior direction and 3 parts in a crano-caudal direction, for a total of 9 parts. Pearson’s correlation analyses were performed. Paired analyses among the three groups were performed using the Friedman multiple comparison test. Analysis of differences in distributions of predicted fracture sites was performed using the χ² test for all loading configurations. Distributions of the distribution was analyzed by Ryan’s method. Differences were considered significant for values of P<0.05.

RESULTS: Mean fracture load was 3062 N under uniaxial compression (range, 883-5688 N), 2918 N in erect standing (range, 883-5492 N) and 2693 N in forward bending (range, 883-5296 N). The linear regression equation relating fracture load in erect standing to that under uniaxial compression was expressed as y = 0.8912x + 19.332 (R=0.9522, P=0.0001) (Fig. 2 a). Likewise, the equation relating forward bending to uniaxial compression was y = 0.7033x + 55.071 (R=0.8342, P=0.0001) (Fig. 2 b). Mean fracture load was significantly lower in forward bending than under uniaxial compression (P=0.00017).

The distribution of predicted fracture sites is shown in Figure 3 for each of the loading configurations. In the crano-caudal direction, fracture sites tended to be located in the upper third of the vertebral body under all loading configurations. In the antero-posterior direction, the antero-superior part was the most frequent fracture site in forward bending, with 76% of all sites. For both erect standing and uniaxial compression, the middle-superior part was the most frequent site (Fig. 3). Under all loading conditions, significant differences existed in the distribution of predicted fracture sites. Using Ryan’s multiple comparison, the antero-superior part was the most frequent fracture site in forward bending (P<0.005).

Figure 3: Distributions of predicted fracture sites under each of the loading configurations. Figures were expressed as percentages.

DISCUSSION: Fracture loads in erect standing and forward bending were highly correlated with those under uniaxial compression, however, the correlation between forward bending and uniaxial compression was moderate. Strength in forward bending was significantly lower than uniaxial compression according to Friedman analysis. Thus, when evaluating risk of vertebral fracture, assessment of predicted fracture load would need to be independently determined under each of the loading conditions to fully evaluate fracture risk during activities of daily living. Strength under uniaxial compression is clearly not representative of strengths under other loading configurations. If loading configurations under which the vertebrae are most vulnerable clearly not representative of strengths under other loading configurations. If loading configurations under which the vertebrae are most vulnerable may be able to be prevented by instructing patients to avoid such postures in activities of daily living. In any case, assessment of fracture risk using a patient-specific CT-based FE method could contribute to preventing vertebral fracture by allowing instruction of patients with predicted high risk to avoid various risky postures during activities of daily living.