Introduction:
Hip fractures are the most serious complication of osteoporosis and have been recognized as a major public health problem. Prevention of hip fracture is a high-priority issue because of the rapid increase in the number of elderly people in Japan. In elderly persons, hip fractures occur as a result of increased fragility of the proximal femur due to osteoporosis. It is essential to precisely quantify the strength of the proximal femur in order to estimate the fracture risk and plan preventive interventions. Clinically available methods of estimating bone strength include bone densitometry techniques such as DXA or pQCT, and imaging procedures such as X-ray or CT. These techniques evaluate regional bone density and morphology, which are partly related to fracture risk, but they are of limited value for quantifying structural strength. Therefore, it is necessary to develop a noninvasive method for accurate quantitative structural analysis that incorporates information on both morphology and bone density in a three-dimensional distribution. CT based finite element analysis, which incorporates information on both the three-dimensional architecture and bone density distribution, could possibly achieve precise assessment of the strength of the proximal femur.

The purpose of this study was to create a simulation model that could accurately predict the strength of the proximal femur using a CT based finite element method and to verify the accuracy of our model by load testing using fresh frozen cadaver specimens.

Materials and Method:
Eleven right femora with no skeletal pathology were collected within 24 hours of death from 5 males aged 30 to 90 years (average age: 56.8 years) and 6 females aged 52 to 85 years (average age: 71.5 years). Bone specimens were stored at -70°C after each step of the protocol. Frozen specimens were trimmed with a handsaw at 14 cm distal to the midpoint of the lesser trochanter and the proximal part of each specimen was used for the experiments. After thawing, trimmed specimens were cleaned of all soft tissues (Cody et al., 1999). We attached total of 11 circular fiducials with a radius of 5 mm and a width of 1.5 mm made of epoxy resin sheet, comprising three for the femoral head, four for the trochanteric region, and four for the diaphysis. The femora were immersed in water and axial CT scans were obtained with a slice thickness of 3 mm and a pixel width of 0.398 mm using Aquilion Super 4 (Toshiba Medical Systems Co., Tokyo, Japan, 120 kVp, 75 mAs, 512×512 matrix), as well as a calibration phantom containing hydroxyapatite rods.

A quasi-static compression test of each femur was conducted. The proximal femur was slanted at 20 degrees in the coronal plane to simulate adduction and a quasi-static load was applied at a rate of 0.5 mm/min after all fiducials were removed (Keyak et al., 1998). A dental resin cap was molded and placed on the femoral head to apply a uniform compressive load. The distal diaphysis (with a length of 5 cm) was embedded in a wood metal. Eight strain gauges (KFG-1-120-D17, Kyowa Electronic, Tokyo, Japan) were attached to the surface of the diaphysis and the trochanteric region of each specimen with adhesive cyano-acrylate, and four strain gauges (SKF-22358; Kyowa Electronic) were attached to the cortical surface of the femoral neck. The magnitude of the load and the cross-head displacement were recorded. Strain at the gauge attachment sites was measured. Then the maximum and minimum principal strains were calculated at each of the gauge sites. The measured yield load was defined as the load at the end of the plateau of the constant load rate on a load rate increment versus time curve, which corresponded with the end of the linear increase of the load on a load displacement curve. The measured fracture load was defined as the value where the load increment rate per time reached zero. To identify the site of attachment for each strain gauge and the cap, image of the specimens were taken with a digital camera. The CT data were transferred to a workstation and 3D finite element models were constructed from the CT data using Mechanical Finder software (Mitsubishi Space Software Co. Ltd., Tokyo). Trabecular bone and the inner portion of cortical bone were modeled using 3 mm linear tetrahedral elements, while the outer cortex was modeled using 3 mm triangular plates (0.4 mm thick). On average, there were 92,541 tetrahedral elements and 5,194 triangular plates. To allow for bone heterogeneity, the mechanical properties of each element were computed from the Hounsfield unit value. The ash density of each voxel was determined from the linear regression equation derived by relating the Hounsfield unit of a calibration phantom to its equivalent ash density. The ash density of each element was set as the average ash density of the voxels contained in that element. Young’s modulus and the yield stress of each tetrahedral element were calculated using the equations proposed by Keyak et al. (1998) and Keller (1994). Poisson’s ratio of each element was set as 0.4. Boundary conditions were applied to the finite element model to represent the mechanical testing. To identify the loading sites and constrained sites, as well as the strain gauge sites, in a finite element mesh model, we matched a 2D image of each specimen with the corresponding 3D finite element model. To perform this registration process, we utilized a fiducial-based system (Russakoff et al., 2003). Nonlinear finite element analysis was performed by the Newton-Raphson method. Each element under compression was assumed to yield when their Drucker-Prager equivalent stress reached the element yield stress. Failure was defined as occurring when the minimum principal strain of an element was less than -10,000 microstrain. Each element under tension was assumed to fail when the maximum principal stress exceeded the ultimate tensile stress. To allow for the nonlinear phase, the mechanical properties of the elements were assumed to be bi-linear elastoplastic, and the post yield modulus was set as 0.05. Yield was defined as the point where at least one solid element yielded, and fracture was defined as occurring when at least one shell element failed. The maximum and minimum principal strains at 50% of the experimental yield load were calculated. To assess the accuracy of the analysis, Pearson’s correlation analysis was used to evaluate correlations between the predicted and measured values of the yield and fracture loads, and the maximum and minimum principal strains.

Results: The results were illustrated in Fig. 1-4

Discussion:
Excellent accuracy was obtained in predicting the yield and fracture loads, and the maximum and minimum principal strains of the proximal femur. The CT based finite element method we adopted in this study could be applicable for clinical use.

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