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Prediction of apparent material properties of human femoral cancellous bone using finite element method

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ABSTRACT

Age related bone fractures caused by the reduction of mechanical performance of cancellous bone (CB) reflect tremendous sociological and economic implications on aging population. Knowledge of the apparent mechanical properties (AMP) of CB of human, in vivo would enhance understanding of these important orthopedic pathologies and generate strategies for prevention and treatment. Computational modeling of CB could be a potential method to predict the AMP with uses of the advanced imaging technique such as CT. It is well known that the morphology of CB was changed by anatomic site, age, and pathology such as osteoporosis. As a result, there is tremendous variation in CB failure stresses. Even in a human, the average strength per site could vary from 2 MPa in the vertebrae to over 7 MPa in the distal femur. With considering the aging effects, the strength of CB decreases about 7 % per decade for the human proximal femur from ages 20 to 100 and almost 11 % per decade for human vertebrae. The variations in the strength of CB are caused by the changes of the morphology, mainly in volume fraction. Recently, it has been accepted that the strength of CB caused by the altered mechanical properties of trabecular tissue by osseo-pathology. As a result, it can be understood that the AMP of CB are varied by the morphology such as volume fraction and architecture, and the trabecular tissue properties. For full considerations of the morphology and trabecular tissue properties of CB, high-resolution finite element (FE) models based on imaging techniques at resolutions have been used for analyzing the CB. Although previous studies using the high-resolution FE model showed successful potential for predictions of apparent biomechanical properties of CB, the models had intrinsic errors due to mostly assumed mechanical properties of trabecular tissue. A study [1] showed an agreement for predicted apparent properties of CB based on the assumption that the trabecular tissue had yield strains of cortical bone. However, it is still unknown that the strength of human CB could be predictable using the high-resolution FE model. In this study, it was hypothesized that the strength of human CB in an interested anatomic site can be obtained by a high-resolution FE model. Importantly, it was also assumed that the trabecular tissue properties of the model were similar to those of macro-level cortical bone adjacent to the interested site. A total of 6 cylindrical

human proximal CB samples from a fresh cadaver (male, 30 years with the death of brain tumor) were obtained based on the trabecular trajectory. To minimize the testing artifacts, the samples had 6 mm in diameter and 12 mm in length. There was no chemical treatment for the samples to prevent any changes in biomechanical properties. Then, the samples were scanned by a micro-CT (Skyscan-1076, SKYSCAN, Belgium) with resolutions of 21 μm by 21 μm in the plane and of 35 μm in the longitudinal axis. By using a threshold, then, segmentation regions composed of trabeculae were obtained by removing bone marrow. The FE models composed of tetrahedral elements (10 nodes) were generated from the images on a specified threshold and volume of interest (Fig. 1). The size and number of the elements were 108 μm and about 110k for each sample. A bilinear constitutive model with asymmetric yield strain [1] was applied to trabecular tissue. The elastic modulus, Poisson's ratio, and yield strain of the trabecular tissue were set as 5.8 GPa, 0.3, and 0.4 %, respectively, based on the experiments performed on the human proximal femoral cortical bone adjacent to the site that CB samples were obtained. Then, the FE models were subjected a quasi-static loading up to a deformation of 0.36 mm. The interfaces between the loading platens and the ends of the samples were treated as the contact condition without the frication. The analyses were performed using ABAQUS™ with the Newton-Raphson method. Figure 1 shows the comparison with the stress-strain relationships obtained from the experiments and FE analyses for the human proximal cancellous samples. The predicted and measured apparent elastic moduli of the samples were 501 ± 108 MPa and 499 ± 165 MPa, respectively. The predicted and measured apparent yield strains were 0.95 ± 0.21 % and 0.9 ± 0.36 %, respectively. Thus, the proposed model using the constitutive equation [1] and the adjacent apparent biomechanical properties of human cortical bone could be applicable to predict the intact apparent mechanical properties of human cancellous bone. Since it has reported that the trabecular tissue shows anisotropic elastic behavior, a further study is required to understand the effects in the future.

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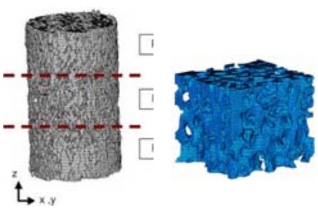

Figure 1

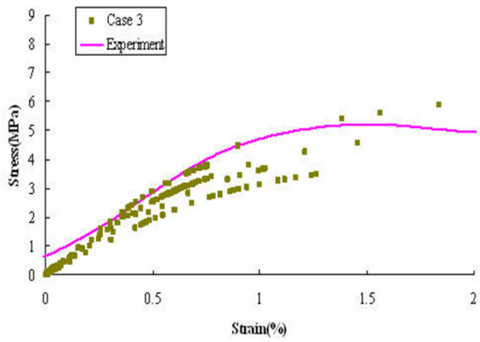

Figure 2

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