Finite Element Analysis Of Osteonecrosis Of The Femoral Head And Material-characteristics Measurement Of Osteonecrosis

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Introduction: Idiopathic osteonecrosis of the femoral head (ION) is an intractable disease that often results in complete joint destruction secondary to collapse of the necrotic region. Collapse of necrotic region in such cases causes hip pain, and may thus potentially result in disorder of the range of motion of joints as well as gait disturbance. Thus, most patients with collapse of the femoral head eventually require surgical treatment. Although the probability of collapse according to the classification of types of ION has been clarified, it is difficult to predict the progressive collapse of the femoral head. Thus, we hypothesized whether the prognosis of every case could be predicted, and initiated research involving finite element analysis (FEA) to confirm this hypothesis. To investigate the mechanisms of collapse in ION, we used FEA to examine which part of the femoral head was the key point of a collapse. In the present study, we aimed to perform FEA in cases of ION by using the findings of computed tomography (CT) and magnetic resonance imaging (MRI), and attempted to predict the progressive collapse of the femoral head in a case of ION.

In addition, by using human femoral heads that were obtained from patients with femoral head of osteonecrosis who underwent total hip arthroplasty (THA), we measured the material-characteristics of osteonecrosis. So we believe that we will be able to perform FEA more exactly by using more exact material-characteristics of osteonecrosis.

Methods: FEA of osteonecrosis

In total, 10 hips of 9 patients (male, 6; female, 3) diagnosed with ION based on MRI findings were assessed in the present study and underwent CT and MRI. The average age of the patients was 41.9 years (range, 17-83 years). The cause of ION was related to steroid use in 7 hips and alcohol in 3 hips. The patients were recruited to perform a three-dimensional FEA using the Mechanical Finder software (version, 6.1; Research Center of Computational Mechanics, Inc.) between October 2011 and July 2013. Based on the CT and magnetic resonance images, the finite element mesh of the acetabulum, femoral head, cartilage, and osteonecrotic area was found to comprise approximately 300,000 elements. The acetabulum and femoral head were produced using CT images, whereas cartilage was produced from the femoral head using CT images that were expanded by 1.4 times. The necrotic region was produced from magnetic resonance images and piled up manually (Figure 1).
With regard to the characteristics of the material in the necrotic lesion, the material characteristics value was computed from the CT value based on the dynamic experimental data of the formula described by Keyak et al., and the values for necrosis of the femoral head described by Brown et al. were used. The Young’s modulus of the necrotic region that was used was 28% of the value of the Young’s modulus of normal bone tissue, whereas the Poisson’s ratio the necrotic lesion was set to 0.15 times that in normal bone tissue. In all analyses, the distal end of the femur was completely constrained and a load of 620 N was applied from the direction of gravitational force towards the proximal region of the pelvic bone. For analysis, stress distribution was evaluated in each case in the necrotic region.

Material-characteristics measurement of osteonecrosis

One femoral head was obtained from patients with non-traumatic femoral head osteonecrosis who underwent THA in our hospital. A total of 6 cubic bone cores measuring 8×5 mm were obtained from the specimen along the longitudinal axis of the femoral head. The core samples underwent mechanical testing using a universal testing machine. The material-characteristics of osteonecrosis such as elastic (Young’s) modulus were measured.

Results: In all cases, concentration of stress was noted along the border of the necrotic region, and the potential initiation point of collapse could be identified (Figure 2).

Figure 2.
The area of maximum stress was different in each case. These areas were likely to be the initiation point for collapse in ION.

Mechanical testing showed that the elastic modulus of osteonecrosis were 0.6 and 0.9 MPa, and that of normal bone tissue were 5.1, 6.2, 39, and 158 MPa, respectively. The elastic modulus of the osteonecrosis showed the prominent low value as compared with the normal bone tissue as a result of material-characteristics measurement (Figure 3).

Figure 3.
Discussion: In the present study, we performed FEA using CT and MRI, and attempted to predict the progressive collapse of the femoral head in each case of ION. Motomura et al. analyzed 30 consecutive surgically removed femoral heads histologically, and reported that collapse consistently involved a fracture at the lateral boundary of the necrotic lesion in all of the femoral heads. Histologically, the fractures occurred at the junction between the thickened trabeculae of the reparative zone and the necrotic bone trabeculae. They found that collapse began at the lateral boundary of the necrotic lesion.

In the present study, concentration of stress was observed along the border of the necrotic lesion, and this portion was suggested to be the potential initiation point for collapse based on the results of FEA. However, the area experiencing maximum stress was different in each case. The difference in the stress distribution may be a result of morphological influences, such as necrotic lesion size, or an effect of the Young's modulus. However, a common feature in the stress distribution was that the stress was concentrated along the border. Thus, we believe that the area where the maximum stress is noted depends on the differences in the abovementioned parameters (morphology or Young's modulus).

However, the model has certain problems such as whether the stress distribution along the border of the necrotic lesion changes with the material characteristics within the necrotic lesion, the form of the acetabulum or the position of the leg, and differences in the loading condition at the femoral head. If these problems are solved and a more accurate simulation can be performed, we believe that progressive collapse in each case can be accurately predicted.

Significance: We performed FEA in cases of ION of the femoral head using CT and magnetic resonance images and attempted to predict the progressive collapse of the femoral head in cases of ION. Concentration of stress was noted along the border of the necrotic lesion, which was likely to be the initiation point for collapse in cases of ION of the femoral head.
We performed material-characteristics measurement of osteonecrosis. The elastic modulus of the osteonecrosis showed the prominent low value as compared with the normal bone tissue as a result of material-characteristics measurement.

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