Stress Analysis of Femoral Stems on Non-Cemented Total Hip Replacement

- A Three-Dimensional Finite Element Analysis -

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-Abstract-

Three dimensional numerical model based on the finite element method(FEM) were developed to predict the mechanical behavior of hip implants. The purpose of this study is to investigate the stress distribution of two types of cementless total hip replacement femoral component -a straight stem and a curved stem, and to compare their effect on the stress shielding between two types by three dimensional finite element method. The authors analyzed von Mises stress in the cortex & stem and compared the stress between the straight and the curved stem.

In comparison of stresses between two different design of femoral stem, there was 25% more decrease of stress in straight stem than curved stem in the medial cortex at proximal region. The straight stem had consistently much lower stresses than the curved stem throughout the whole medial cortex with maximum 70% reduction of stress. However, there was little change in stress between nature and 2 implanted femur throughout the lateral cortex. Stress of femoral stem was much higher in the straight stem than the curved stem up to 60%. The straight stem had more chance of stress shielding and a risk of fatigue fracture of the stem compared with the curved stem in noncement hip arthroplasty. In design of femoral stem still we have to consider to develop design to distribute more even stress on the proximal medial cortex.

Key Words : Straight Stem, Curved Stem, Stress Shielding, Finite Element Method, Noncement hip arthroplasty

INTRODUCTION

Stress related changes in proximal femur after total hip replacement are common[2,6,7]. These changes may be compatible with excellent function and longevity of the implant for the patients. In areas where excessive micromotion occur, the prosthesis may separate from bone and promotes the growth of a fibrous tissue membrane, which may play a role in the long term stability of the prosthesis[21]. Reduction in stresses around Proximal femoral stem when compared to the natural situation(stress-shielding phenomenon) leads to bone resorption and may accelerate the loosening process[5,10]. Hence an accurate evaluation of interface behavior and stress field in the bone implant system may be important for better understanding of clinical situations and improving THA design.

The current available cementless femoral stems can be classified into two types in respect to their design: the straight stem and the curved(anatomic) stem. Clinically subjective assessment of radiograph, and dual energy X-ray absorptiometry have been used to estimate the bone loss. Experimental methods have also been extensively used to study the alternation of stress and strain field associated with the implantation of cementless or cemented prosthesis. However, complete evaluation of load transfer including stress distribution in the bone remains difficult to assess experimentally because the main draw back of the experimental stress analysis is the lack of information inside the bone. Hence recently three dimensional numerical models based on the finite element method(FEM) were developed to predict the mechanical behavior of hip implants[9,17]. However, there is controversy as to the importance of stem design on bone loss of femur after THA.

The purpose of this study is to investigate the stress distribution of two different types of cementless total hip replacement femoral component-a straight stem and a curved stem, and to compare their effect on the stress shielding between two types by three dimensional finite element method. For this study, the authors developed 3 models of three dimensional finite element which are straight stemmed femur, curved stemmed femur and natural proximal femur without inserting femoral stem which was used as a natural femoral stress.

Material and Methods

The geometry of the finite element mesh generated in this study was taken from the 2 same sized identical synthetic femurs in which a straight stem and a curved stem with porous coated surface on the proximal one third of the prosthesis had been implanted. 13 sections were cut from the top of greater trochanter to the tip of femoral stem level with Diamond wheal cutter to visualize accurately the change of cross sectional area for their three dimensional complex geometry of femur and femoral stems, and measured the cortex and cancellous areas. The calibrated date from each sections was used as input into AUTOCAD™ to make three dimensional surface model.In addition, geometry of the femoral stems was defined by measuring their main data by Vernian Calipers and input to AUTOCAD™ to generate three dimensional surface model. These cross sectional data of the geometry stored in AUTOCAD™ was converted into IGES format, which can be input into the Hypermesh™ as preprocessor of finite element model, and three dimensional finite element models was developed(Fig. 1). The finite elements used in this meshes were three dimensional linear 8 node solid brick elements and in some areas where the change of geometry was sharp, 6 node wedge element was used. The finite element model used 1174 nodal points and employed 1179 elements for the straight stemmed femur and 1564 nodal points with 885 elements for the curved stemmed femur. Since the cortical shell in many parts of the greater and lesser trochanter was as thin as the width of a single trabeculae, we did not model the cortex as a continuous ring in the proximal region of the femur. Contact between the bone and prosthesis was simulated using three dimensional linearly interpolated contact elements available in MARC™. At the bone metal interface, two coincidental nodes were generated where a single node would normally be used. One node was used with prosthesis and the other node was used in the bone element definition. The frictional coefficient was chosen $\mu=1.73$ in areas between bone and porous coating of prosthesis and $\mu=0$ in the remaining other areas of the prosthesis, which was suggested by Keaveny and Bartel[11](Fig. 2). Boundary condition in which all the medial nodal points at all directions and the lateral nodal points at only Z-direction was constrained at the bottom of femur. The loads applied to the prosthesis head and the greater trochanter were transformed into mesh coordinate system according to measurement by Davy et al[4]. Thus, applied compressive load on the prosthesis in simulating single leg stance was -495N, -400N, and -994.5N in the X, Y and Z-coordinates of the mesh, respectively. The tensile load applied on the greater trochanter was 319N, 552N, -159N in the X, Y, and Z-coordinates of the mesh, respectively. These loads correspond to a 68kg weight patient simulating single leg stance gait. We analysed von Mises stress including normal shear stress on the bone and compared the stress for the 2 types of femoral stem geometry.

RESULTS

This study analyzed von Mises stress in the cortex and stem, and compared the stress between the two types of straight and curved stem. In natural femur, the stress of medial cortex was 3 MPa as a minimum at the cut surface of calcar of femur and then sharply increasing linearly to 11 MPa within the 20 mm below the calcar cut surface. The maximum stress of 17 MPa was reached about 60 mm below the calcar cut surface along the medial cortex. In cases of femoral stem implanted femur, the straight stem had 8 MPa and the curved stem had 10.5 MPa on the calcar-collar contact region, where in contrast, the natural femur was 3 MPa(Fig. 3). However, there was sharp decrease of stress from just below the collar to within 25mm of the prosthesis in both types of femoral stem. Compared with natural femur, the magnitude of stress was only 10% to 50% of natural femur. In comparison of stresses between two different design of femoral stem, there was 25% more decrease of stress in straight stem than curved stem in the medial cortex at proximal region. The straight stemmed femur had consistently much lower stresses than the curved stem throughout the whole medial cortex at maximum 70% reduction of stress(Fig. 3). However, there was little change in stress between nature and 2 implanted femur near the greater trochanter throughout the lateral cortex(Fig. 4). Stress of femoral stem was much higher in the straight stem than the curved stem up to 60%(Fig. 5).

DISCUSSION

The present models were designed to analysis stress distribution and micromotion at the bone-stem interface in THA, in addition to the classical stress distribution in bone-implant system. Use of three dimensional model is suitable to simulate more realistic loading cases such as stair climbing or the single leg stance gait, which are combination of compression, flexion, and torsion. These three loading play fundamental roles in the evaluation of the stress and mainly the bone implant relative micromotion. For analysis of the stress with the present models, we adopted the loading type of Davy et al[4], who measured the forces across the hip joint during a number of common daily activities with the first month after total hip arthroplasty. We applied loading in assumption of 68kg weight with assuming single leg stance gait.

The present result showed that in natural femur, the von Mises stress of the medial cortex at cut surface of the calcar was 3 MPa, which was the minimum value along the entire medial cortex. In contrast, the stress on the same area of medial cortex was very high ranged 8 MPa to 10.5 MPa in both straight and curved stemmed femur. This can be explained by the stress concentration because the area is the calcar-collar contract point by the existence of collar of both stem. After passing the areas of calcar-collar contact, there happened drastic decrease of stresses in both straight and curved stem in comparison with natural femur especially in the proximal medial cortex. This sharp decrease of stress could be explained by so called "stress shielding". After extracting the stress shielding from the results obtained by Huiskes[9] for Osteonics femoral collarless stem, we observe consistent stress shielding pattern when compared to their report. The author especially focused our attention to the stress change of the proximal medial cortex to compare the degree of stress shielding between the two different design; straight stem and curved stem(Fig. 4). There was 25% more decrease of stresses in the straight stem than the curved stem in the proximal medial cortex within 20mm below the calcar cut surface, which was main concerns in this study. Down to 20mm below the calcar surface there also happened more reduction of stresses throughout the entire medial cortex in the straight stem and in some area there was 70% decrease of stress in comparison with the curved stem. So far, we could not compare our results of two designs to those obtained by others because we cannot find any direct comparative stress analysis between two designs of stem.

There are several factors influencing the degree of stress shielding on the femoral cortex. One of the factors is the material property of the stem used. The use of titanium rather than cobalt-chrome offered a lesser degree of stress shielding on the proximal medial cortex because Young's modulus of elasticity of the titanium is approximately one half that of cobalt-chrome[2,10]. Experimental studies in dogs indicated that the use of titanium stem led to better preservation of bone stock in the proximal femur that did the use of stem of a similar design of cobalt-chrome. The other major factor influencing stress shielding effect is the use of large diameter stem, which are expected to cause more pronounced bone loss by stress shielding[7]. This is because the axial rigidity of the implant increase directly with the cross-sectional area or square of the stem diameter, and flexural rigidity increase directly with the area moment of inertia of fourth power of the stem diameter. Our present model was applied the same Young's modulus and the same size of diameter of titanium to both straight and curved stem to eliminate such a bias as material property and size of the stems. However, comparison of our stress distribution with those reported in previous studies is relatively difficult since the geometry of FEM model and loading and boundary condition are different from ours. So the results of stress shielding effect for the two types of design of stem was compared with clinical results which compared between straight and curved stem with dual energy x-ray absorptiometry. Kilgus et al[13] found at 5 years on average 35% loss of bone mineral density in the medial neck in Anatomic Medullary Locking prosthesis, but this stem was made of cobalt chrome alloy. Collier et al[3] reported the physiologic stress loading prosthesis showed a near physiologic strain pattern in the proximal femur with strain levels within 10% normal level. In contrast, Anatomic Medullary Locking prosthesis reduces strain in the medial cortex of neck by 60% to 70%. However, Kelly et al[12] found complete contact between the prosthesis collar and calcar of medial femoral neck was essential to decrease loss of bone density in any type of stem.

Collier[3] reported the degree of proximal bone loss found their study correlated with the degree of stress shielding. More stress shielding effect in straight stem obtained in this present FEM study had good correlation with the clinical results that the straight stem had more loss of proximal bone density by using dual energy X-ray absorptiometry. The stress of femoral stem itself was much higher in straight stem than curved stem and the results suggested that the straight stem is subject with a much higher risk of fatigue failure of the prosthesis in noncemented arthroplasty.

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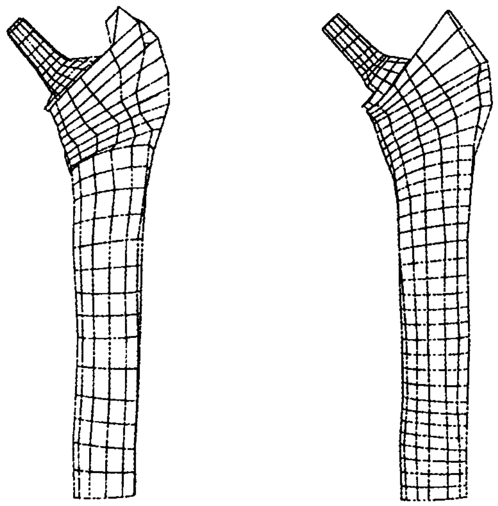

Fig. 1. Finite element models

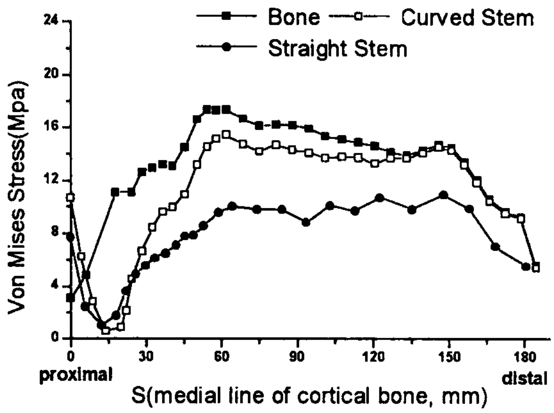

Fig. 3. Von Mises stress along the medial cortex of femoral

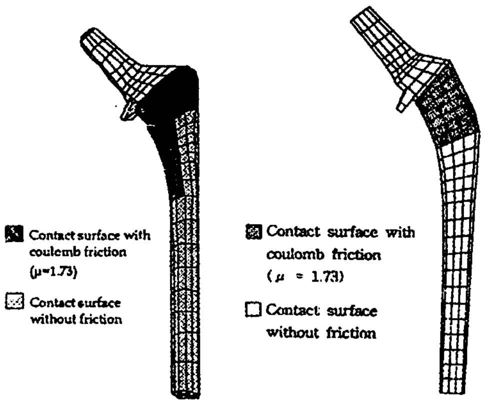

Fig. 2. Contact Surface of femoral stem

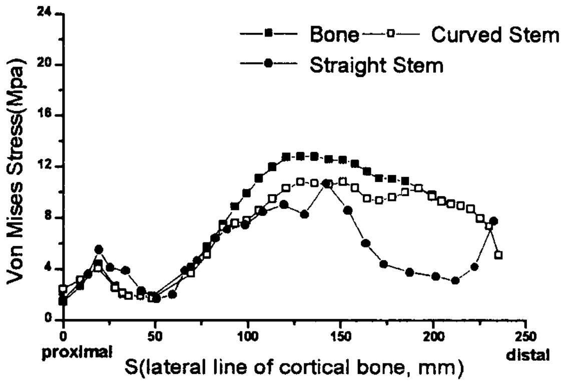

Fig. 4. Von Mises stress along the lateral cortex of femur

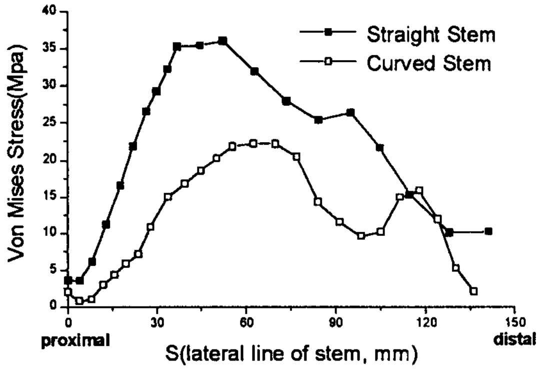

Fig. 5. Von Mises stress along the stem