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# Stress Analysis of PS Type Knee Prostheses under Deep Flexion*

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**Abstract**

3-D finite element models of two kinds of Stryker's PS type knee prostheses, Scorpio Superflex and NRG, were constructed using their CAD data with use of a nonlinear spring model and an analytical load data for deep squatting. Superflex model was formerly used in TKA, and NRG model is the latest version with a modified design of Post. Stress analysis was then performed by an explicit finite element method under continuous flexion motion from 0 to 135 degree. It was shown that only the condylar surfaces of the femoral component and the tibial insert contacted each other from 0 to 60 degree flexion for both the models, and the stress concentration in NRG was a little higher than that in Superflex. The simulation results also exhibited that severe stress concentration was generated at Post of the tibial UHMWPE insert due to Post/Cam contact. This kind of stress concentration may result in damage and failure of Post. It was shown that the design modification applied to NRG effectively reduced the stress concentration of Post.

***Key words***: Total Knee Arthroplasty, UHMWPE Insert, Deep Flexion, Finite Element Analysis

## 1. Introduction

Total knee arthroplasty, TKA, is applied to patients with severe osteoarthritis, and in general, QOL of the patients is dramatically improved after TKA. Although the function of knee prosthesis is being improved through design modification, there are still some demands for knee prosthesis such as higher durability of tibial insert and deeper flexion angle to fit Japanese life style, for example, 150 degree for kneeling on a tatami mat. It is therefore needed to understand the detail of movements of the knee after TKA, and such information should be reflected to the design of knee prosthesis. It is however very difficult to understand the detail of TKA knee motion because of its complex movements characterized as a combination of flexion, external and internal rotation and roll-back. Fatigue fracture and severe wear of tibial inserts are sometimes reported, and they are thought to be caused by the stress concentration under such complex knee motions.

PS type knee prosthesis is known to be used in a type of TKA where anterior and posterior cruciate ligaments are removed. PS type prosthesis is characterized by the existence of Post-Cam structure to stabilize the knee movement through the Post-Cam contact. In this type of prosthesis, failure and wear of Post of the tibial insert are important problems and therefore, there is a demand for understanding the stress state of the tibial insert during knee motion. Under such circumstances, three-dimensional finite element method (FEM) has been utilized to characterize the 3D stress state of knee prosthesis.

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In the previous studies of FEM simulations of TKA, most of them were aimed to analyze stress states under walking conditions with shallow flexions [1,2-5,8], and a few attempts have been made to analyze stress state under deep flexion [9-11]. Morra and Greenwald performed a deep flexion analysis of TKA, however, their work was limited to a certain deep flexion angle under simple loading condition [9]. On the contrary, the author's group developed simplified 3D FEM models using CAD data of knee prosthesis clinically used, and investigated effects of deep knee flexion and internal rotation on the stress state of the tibial inserts [10,11]. In these studies, however, the movement of the tibial inserts of the FEM models was completely restricted and, for example, roll-back behavior in the PS type model was introduced compulsory by moving the femoral component [11].

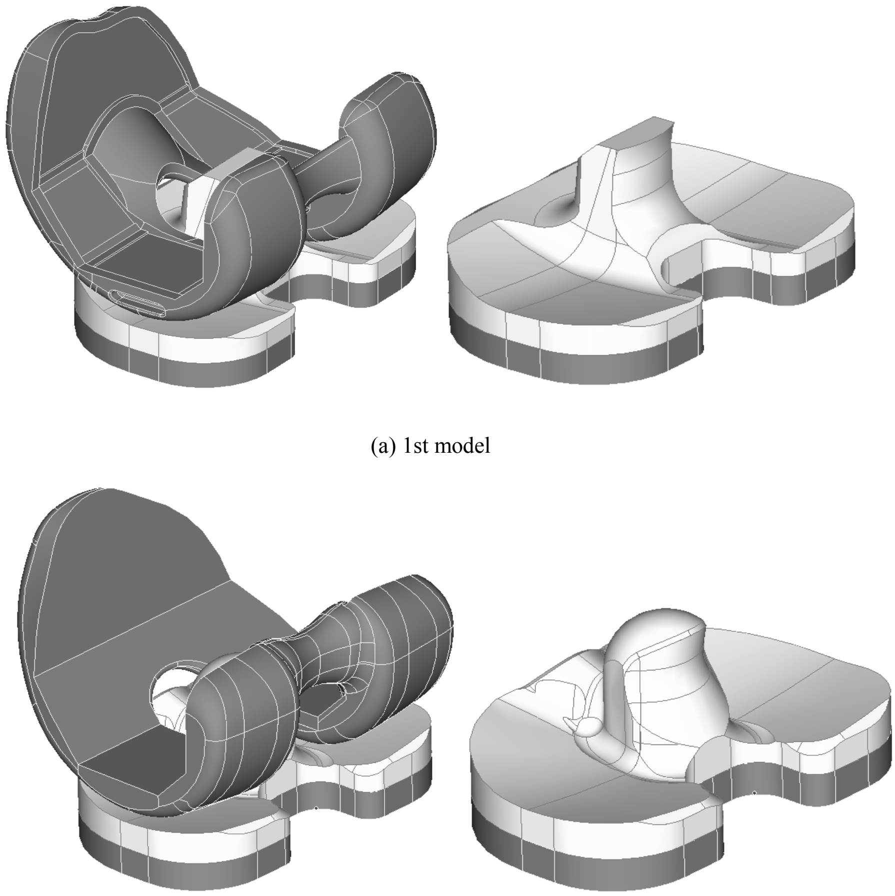
The aim of the present study is therefore to reproduce more natural roll-back behavior using a simple FEM model of PS type knee prosthesis, and to characterize the stress states of two different types of PS type knee prostheses with different Post and Cam design under deep flexion. 3D FEM models of the knee prostheses were developed from their CAD data. Nonlinear spring model and load data for deep squatting were utilized to simulate more precise knee motion than the motion previously analyzed [11]. Effects of wide range of flexion on the stress state of the condylar surfaces and Post of the tibial inserts were then assessed using the analytical results, and the 1st and the 2nd were compared to characterize the effect of the design modification on reduction of stress concentration and improvement of flexion angle.

## 2. Development of Finite Element Models

In this study, two different types of PS type knee prosthesis, Stryker Scorpio Superflex and Scorpio NRG, were analyzed to examine the effects of the design difference on the stress distribution in the tibial inserts. Superflex is called the 1st model and NRG the 2nd model, thereafter. The 2nd model, which is clinically used currently, can be recognized as a modified version of the 1st model, and especially, the shape of Post and Cam were redesigned to reduce stress concentration. Post of the 2nd has more round shape than that of the 1st, and the contact surface area of Cam to Post was modified to be larger in the 2nd than in the 1st. 3D-FEA models of the 1st and the 2nd consisting of femoral component, tibial component and tibial insert were constructed from their CAD data obtained from the manufacturer. In this modeling, the tiny parts of the femoral component and the stem of the tibial components were removed prior to finite element meshing in order to avoid extremely small meshes and reduce the number of meshes. It is noted that those removed parts were carefully chosen so that the removal did not affect on the simulation results. The simplified models of the PS type prostheses are shown in Fig.1.

Finite element meshed models are shown in Fig.2. The numbers of the nodes and the elements are 21958 and 89322 for the 1st model and 28254 and 121604 for the 2nd model, respectively. The material constants used in the analysis are shown in Table 1. The tibial insert originally made from UHMWPE (Ultra High Molecular Weight Polyethylene) was assumed to be an elastic-plastic material and to follow the von Mises yield criterion. The nonlinear stress-strain relationship experimentally obtained is shown in Fig.3 [7]. The femoral component made from Co-Cr alloy and the tibial component made from Ti alloy are much stiffer than UHMWPE, and therefore, assumed to be rigid body in order to reduce computational time. The friction coefficient between the femoral component and the tibial insert was chosen to be 0.04 [5]. It was assumed that the back surface of the tibial insert was perfectly connected to the top surface of the tibial component and therefore, the both surfaces possessed the nodes in common.

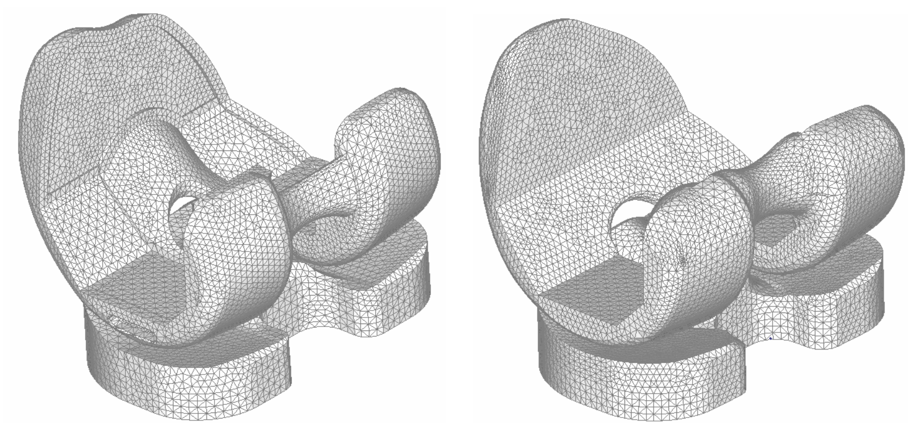
In a PS type knee prosthesis attached in a real human knee, reaction and frictional force are generated on the condylar and Post surfaces during motions. In this TKA knee, these forces are balanced with the tensions of the soft tissues existing around the knee; as a result,



(a) 1st model

(2) 2nd model

Fig. 1 FEA models of two kinds of PS type knee prostheses.



(1) 1st model (2) 2nd model

Fig. 2 FEA mesh models of PS type knee prostheses.

Table 1 Material constants for FEA.

| Parts | Material | Density (kg/m$^3$) | $E$ (MPa) | ν | $\sigma_Y$ (MPa) |
|---|---|---|---|---|---|
| Tibial insert | UHMWPE | 940 | 880 | 0.4 | 16 |

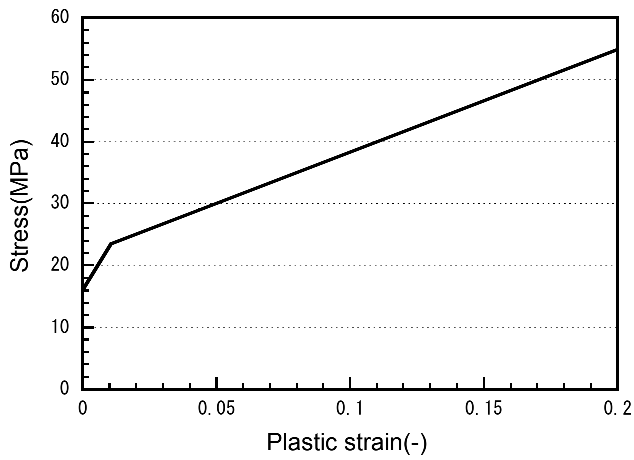



Fig. 3 Bi-linear relation of stress-plastic strain curve of UHMWPE.

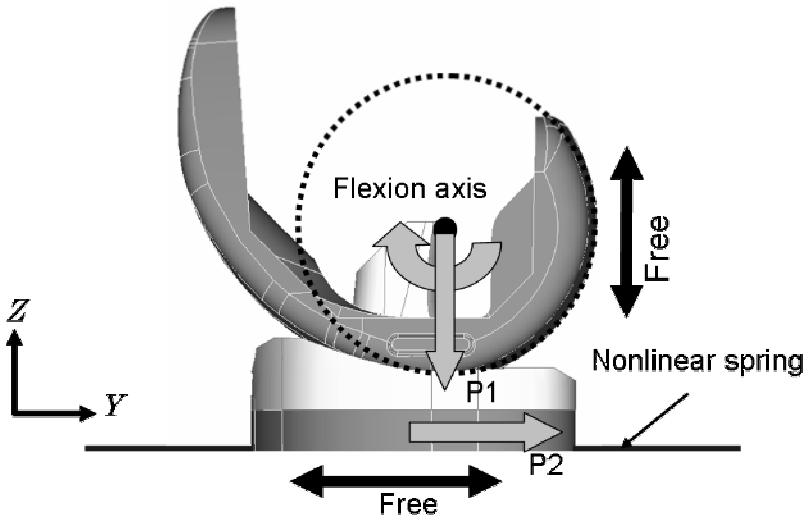



Fig. 4 Boundary conditions of the TKA model.

for example, roll-back motion occurs. In the present FEA models, a nonlinear spring model was utilized to express these motions in TKA [8]. Two spring elements were attached in the front of the tibial component and the two in the back as shown in Fig.4. The nonlinear force -displacement relation is given by

$$F = 0.18667d^2 + 1.3313d \quad (1)$$

where $F$ and $d$ are force and displacement, respectively. It is noted that this nonlinear relation was experimentally determined from a knee with removed anterior and posterior cruciate ligaments [8].

In the most of real knees, internal rotation tends to take place during flexion, and it was reported, for example, that 7 degree of internal rotation occurs at a deep flexion angle of about 135 degree [12]. In the present analysis, however, only flexional motion was considered in order to make the effect of the Post-Cam contact on the stress distribution clearer. The axis of flexion was assumed to be located in the center of the circle which coincides with the shape of the condylar surface of the femoral component (see Fig.4). For the femoral component, only the displacement in Z-direction was free and the displacements in X- and Y-directions were fixed. On the other hand, the tibial component was able to move freely in Y-direction and fixed in X- and Z-directions.

Load data used as the mechanical boundary condition was referred from the reference 2 in which load data for rapid deep squatting was analytically obtained using 2 dimensional model of human knee considering muscular forces. The load P1 and P2 were applied to the femoral component in the vertical direction (Z-direction) and to the tibial component in the horizontal direction (Y-direction), respectively. The relationship between the load data and the flexion angle were shown with the body force used in the analysis in Fig.5.

A commercially available pre-processor FE-MAP was used to develop those 3D FEM models including solidification from the surface data, meshing and setting up of the boundary conditions. A commercial explicit finite element code LS-DYNA was then utilized as solver, and a post-processor LS-POST was used to analyze the FEM results.

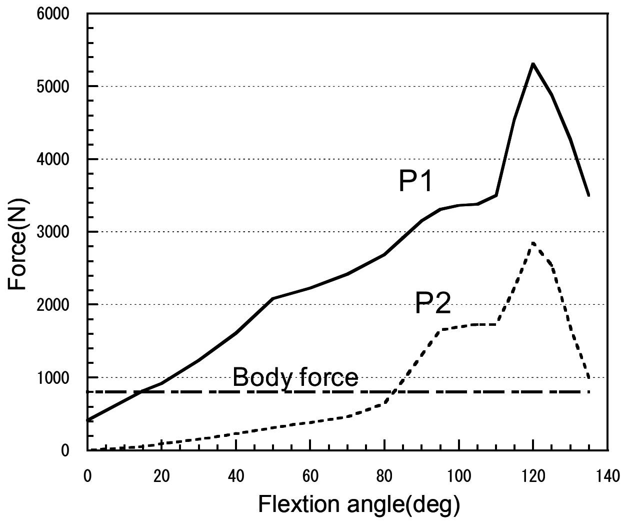



Fig. 5 Force-flexion angle relations used as mechanical boundary condition.

## 3. Results and Discussion

### 3.1 Mises equivalent stress distribution

Von Mises equivalent stress distributions of the tibial insert at 45 and 120 degrees of flexion are shown in Fig.6. At 45 degree, stress concentration occurred only on the condylar surfaces, and the maximum stress values of the 1st model and the 2nd model were 11.2 MPa and 17.6 MPa, respectively, indicating that the 2nd exhibited higher maximum stress than the 1st under the same boundary condition. The contact between Post and Cam did not take place at this angle. Larger stress concentration occurred on both the condylar and Post surfaces at 120 degree of flexion. The maximum stress values were 73.0 MPa for the 1st and 48.9 MPa for the 2nd, indicating that stress concentration was effectively reduced in the 2nd at deep flexion angle. It is also noted that the location of stress concentration on the condylar surfaces moved toward the back (Y-direction) as flexion proceeded from 45 to 120 degree, suggesting that roll-back movement was generated. The dependence of the displacement of the spring element on flexion angle is shown in Fig.7. The positive direction coincided with the negative Y-direction in Fig.4. There was no displacement generated up to about 60 degree and the displacement rapidly increased after 60 degree and the final displacement was approximately 12 mm. The difference between the two models was almost negligible. The displacement at the flexion angles greater than 60 degree corresponded to the displacement of the tibial component in the negative Y-direction, that is, so-called roll-back behavior in TKA.

Mises equivalent stress distributions in the cross-sectional areas of the tibial inserts at 120 degree of flexion are shown in Fig.8. It is clearly seen that the stress concentration region with the highest stress level of 40-50MPa was much wider in the 1st model than in the 2nd model. It is also interesting to see that for the 2nd, the highest stress concentration region was located inside of Post, suggesting that the possibility of delamination failure at this point.

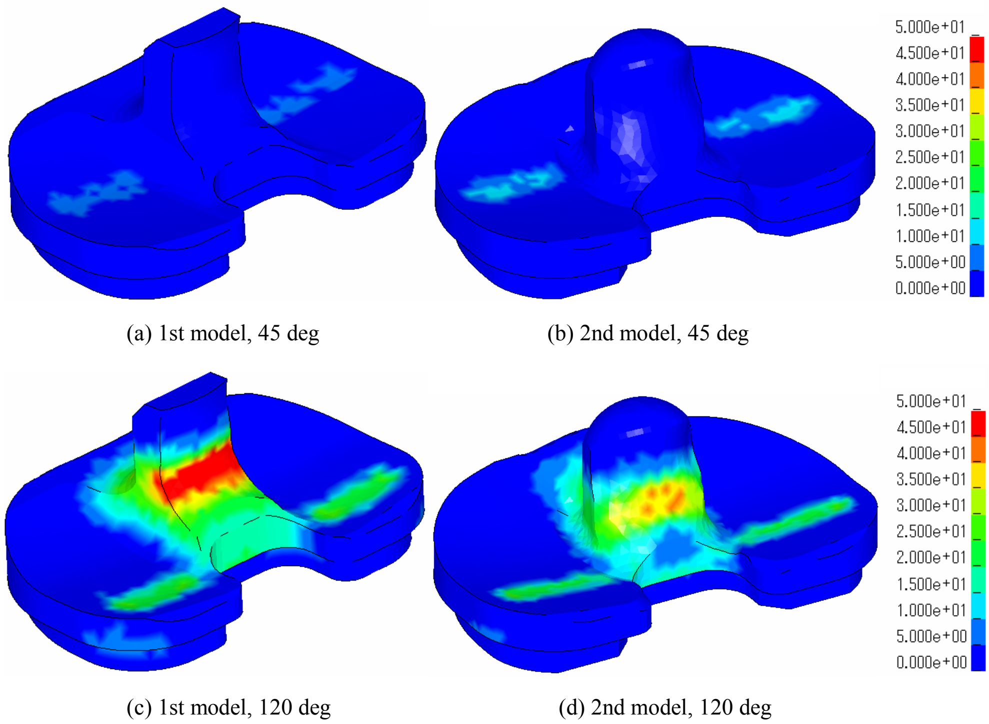



Fig. 6 Equivalent stress distribution on the surface of tibial insert (unit: MPa).

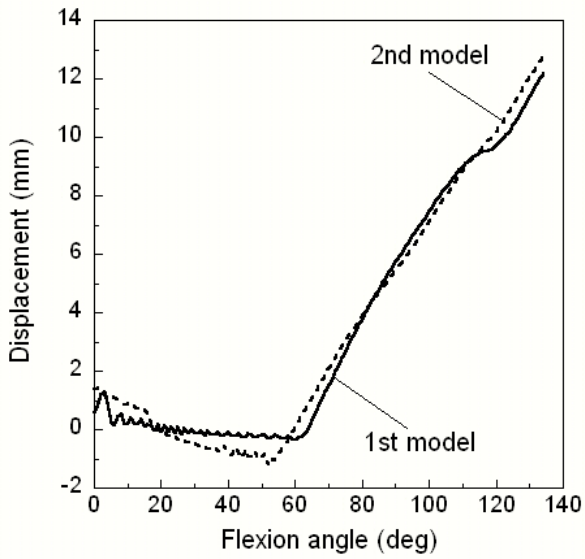
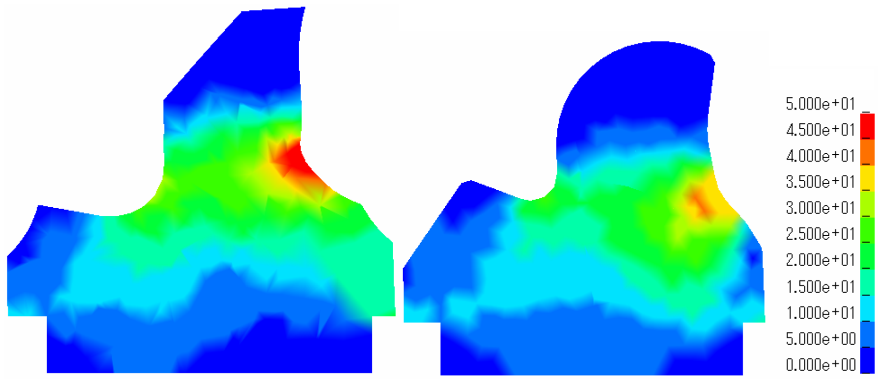



Fig. 7 Dependence of displacement of spring model on flexion angle.

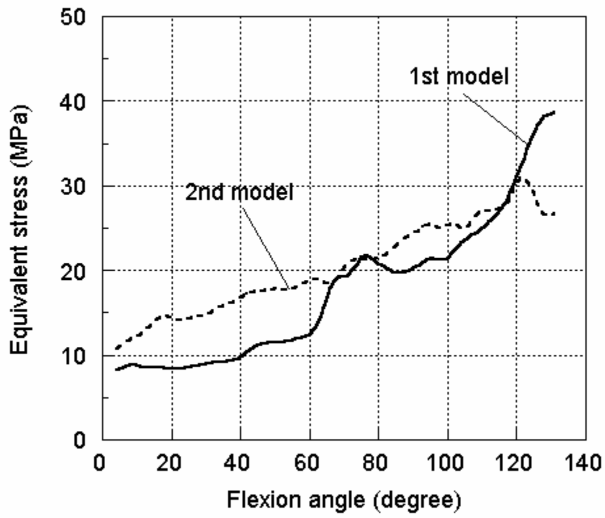
### 3.2 Dependence of maximum equivalent stress on flexion angle

The dependences of the maximum equivalent stress values on flexion angle on the condylar surface and Post of the tibial inserts are shown in Fig.9. For the condylar surfaces, the maximum stress of the 2nd model was larger than that of the 1st model at flexion angles smaller than 60 degree. On the other hand, the 1st exhibited larger stress at angles greater than 120 degree, however the difference was not so large compared to the Post stress discussed later. The slope of the frontal condylar surface of the 2nd was designed to be a little gentler than that of the 1st; therefore, the contact area between the condylar surfaces of the femoral component and the tibial insert became smaller in the 2nd, resulting in the higher stress at angles smaller than 60 degree. The slope of the rear condylar surface of the 2nd was almost the same as that of the 1st and therefore, the difference of the stress became

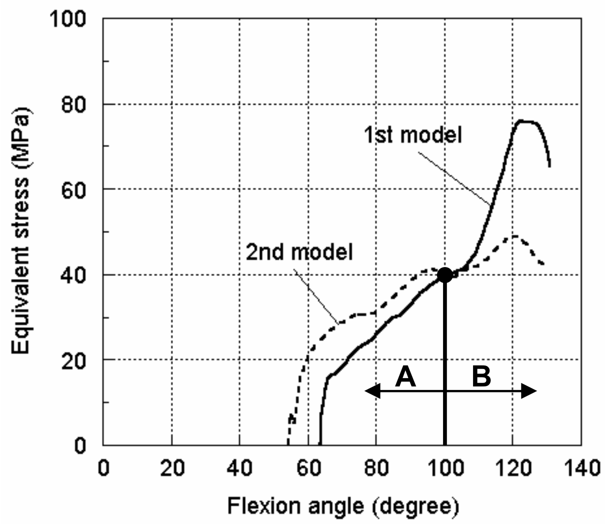



(a) 1st model (b) 2nd model

Fig. 8 Stress distribution in the cross-sectional area of tibial insert at 120 degree of flexion (unit: MPa).




(a) condyle surface




(b) Post surface

Fig. 9 Maximum equivalent stress history on the surface of tibial insert.

small. It was found that the contact between Post and Cam started at 64 degree in the 1st; on the contrary, the contact started at 54 degree in the 2nd. This difference was caused by the difference of the Post shape, i.e., Post of the 2nd was much larger than that of the 1st as a result of the shape modification. The Post surface stress of the 2nd was higher than that of the 1st up to 100 degree (region A in Fig.9(b)); on the contrary, at flexion angles greater than 100 degree (region B), the 1st exhibited higher Post stress than the 2nd. The rapid increase of the Post stress of the 1st in region B is related to higher stress concentration due to smaller contact area between Post and Cam in the 1st than in the 2nd.

### 3.3 Effect of design modification on deep flexion motion

It was found from these analytical results discussed above that the design modification, especially Post and the surrounding region of Post, applied in the model change from the 1st model to the 2nd model effectively reduced stress concentration in Post and the surrounding region. This kind of reduction of stress concentration generally corresponds to reduction of the reaction force generated by the Post/Cam contact during deep flexion. Such reduction of the reaction force generally implies the decrease of resistance for deep flexion and therefore, the 2nd model is considered to be more suitable for deep flexion motion than the 1st model. In order to further confirm the superiority of the 2nd model, it is needed to analyze and compare the stress states under more complicated boundary conditions including flexion, rotation and lift-off.

## 4. Conclusions

3D FEM models of two different types of Stryker's PS type knee prostheses, the 1st model (Scorpio Superflex) and the 2nd model (Scorpio NRG), clinically used worldwide were constructed from their CAD data. Stress states of the two models were analyzed and compared under a condition of deep knee flexion by using the explicit finite element method. The conclusions are summarized as follows:

(1) A simplified 3D-FEA model of PS type knee prosthesis for deep knee flexion analysis was developed for the first time by using nonlinear spring model and load data for deep squatting. High stress concentration due to the Post-Cam contact was reasonably expressed at deep flexion angles and furthermore, roll-back behavior was well simulated by introducing the nonlinear spring model.

(2) Post surface stress of the 2nd model was higher than that of the 1st model up to 100 degree flexion; on the contrary, at flexion angles greater than 100 degree, the 1st model exhibited much higher Post stress than the 2nd model. This is due to higher stress concentration created by smaller contact area between Post and Cam in the 1st model than in the 2nd model.

(3) The modification of Post shape conducted in the designing process of the 2nd model effectively reduced the stress concentration at deep flexion angles. This kind of stress reduction is thought to correspond to the reduction of reaction force, indicating that the resistance to deep knee flexion is lower in the 2nd model than in the 1st model.

(4) The developed FEA model can easily be extended to express more complicated knee motions such as rotation and lift-off through modification of the boundary conditions. Further study on stress analysis under deep knee bending conditions using these models will give us some ideas towards new design concepts for knee prosthesis specially suiting to Japanese lifestyle.

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