Stress Analysis of the Proximal Tibia using Finite Element Method after Unicompartmental Knee Arthroplasty

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Abstract

**Background:** Because the indications for UKA are limited, the number of patients who have undergone this procedure is small, and it is therefore difficult to decide the acceptable range of variation in the details of this surgical procedure on the basis of the available clinical data. The objective of the present study was to determine the factors affecting the stress distribution of the proximal tibia after UKA.

**Methods:** The two-dimensional finite element analysis in the proximal tibia was employed to assess the following four factors: 1) Two types of implants, all-ultra-high molecular weight polyethylene (UHMWPE) type and metal backed type, 2) post-operative alignment, 3) coverage of tibial bone, 4) level of the tibial osteotomy.

**Results:** In the cases of varus alignment, high stress and large deformation was observed on and beneath the implant. In the cases of valgus alignment, stress concentration was seen at the lateral portion of tibial tray. In comparison with the standard model, the stress concentration was observed at the medial edge of the medial condyle in a narrow coverage model. Comparing to the standard model, the stress distribution in a low osteotomy level model did not differ markedly from that in the standard model. Metal
backed implants were shown to provide better stress distribution than UHMWPE implants in this study.

**Conclusions:** The proper postoperative alignment must be achieved in UKA. The osteotomy level should be set at the cancellous bone close to the joint line, and maximum bone stock should be preserved.

**Key words:** 2-dimensional finite element analysis (2D-FEA), unicompartmental knee arthroplasty (UKA), tibial implant, alignment
Introduction:

Unicompartmental Knee Arthroplasty (UKA) is a superior procedure compared to bicompartamental or tricompartmental total knee arthroplasty (TKA) having advantages of maintaining normal knee kinematics, while maintaining a functional range of motion and preserving bone stock, the anterior and posterior cruciate ligaments, as well as patello-femoral joint and opposite compartment. However, even with these advantages, UKA is still a procedure with some controversies regarding its efficacy and indication. There have been some reports of good results clinically at the early stage of the development of this procedure\textsuperscript{1, 2}, but there have also been reports of less successful results with deterioration such as implant breakage and loosening.\textsuperscript{3, 4} These failures come from a variety of factors including misjudgment of patient selection, postoperative malalignment, and poor implant design with inadequate thickness and without metal backing. In recent years, with UKA indication strictly controlled and with improvement of implant design including metal backing,\textsuperscript{5, 6} there have been many reports of successful outcomes.\textsuperscript{1, 2} The reasons for mechanical failure of UKA have been reported to be the following: 1) technical failure such as varus positioning of the implant and overcorrection
of the postoperative leg alignment, 2) design and material of the element, 3) errors in the selection of patients such as severe varus deformity, involvement of patello-femoral joint, pan-arthritis such as rheumatoid arthritis and chondro-carcinosis, ligament insufficiency, severe obesity, high activity, osteoporosis and others. A study regarding the alignment of limb in patients having UKA reported positive effects when the mechanical axis was at the center or slightly medial to the center of the knee.\textsuperscript{7} Many reports cautioned against overcorrection which leads to excess load in the lateral compartment and early failure.\textsuperscript{8} The stress to the implant with inadequate postoperative alignment works as shear stress and causes loosening to both varus and valgus knees.\textsuperscript{9} Due to the limited number of cases of UKA, it is difficult to determine the acceptable alignment range in detail for this procedure from the clinical data available. The finite element method (FEM) has made structural analysis possible under all conditions by the use of computer simulation and is often used to optimize the structural design of implants. Advanced application of FEM has been used in the area of artificial joint analysis in the field of orthopedic surgery. Many of the studies on FEM, which are mainly focusing on TKA, have shown consistency between simulated results and actual clinical results. The purpose of the
current study was to elucidate the factors affecting the stress distribution over the proximal tibia after UKA. In order to accomplish this, FEM was employed to analyze 4 elements based on the characteristics of heterogeneous and anisotropic material properties of cancellous bone in proximal tibia: 1) two types of implants; all-ultra-high molecular weight polyethylene (UHMWPE) type and metal-backed type, 2) post-operative alignment, 3) coverage of tibial bone, and 4) level of the tibial osteotomy.

Methods:

In order to study the stress distribution in proximal tibia under load, two-dimensional FEM was performed for varus alignment with under correction (Fig. 1-a), for neutral alignment (Fig.1-b), and for valgus alignment with over correction (Fig.1-c). The morphology of this model was obtained from the data previously published in literature. Two types of analysis were performed on each alignment model: 1) Linear analysis of rigid interface of stable implants, and 2) Non-linear analysis (Fig.1-d) with application of gap element under the presence of loosening. The mean trabecular orientation (Fig. 2-a), and the distribution of Young’s modulus in the mean trabecular orientation angle of
cancellous bone (Figure 2-b) were calculated based on numerical analysis of a soft X-ray photo of a sliced proximal tibia previously reported. Figure 3 shows the material properties of cancellous bone, cortical bone, UHMWPE and metal (Co-Cr-Mo).

In a non-liner model, to avoid dispersal of analysis, two truss elements were positioned on the medial and lateral sides of the tibia for stability of model (Young’s modulus is 10-6MPa). The frictional coefficient of gap element was 0, and the Young’s modulus of gap element was at 10-6MPa. The gap element was set only to transmit compression force. Figure 4 shows the conditions of loading and boundary for the model of the proximal tibia after UKA. The load was applied to the neutral alignment; the vertical stress over implant was applied to varus alignment, and the shear stress was applied to the valgus alignment. The load in non-linear analysis was increased gradually in 10 steps. The distal ends of all models were constrained in X-Y direction, and the side plate enabling these analyses to consider hoop stress was applied over cortical bone. Cosmos/m (version 2.7) was used for analysis.
Results:

“Stress Distribution in Different Postoperative Alignments”

Figure 5 indicates von Mises’ equivalent stress distribution with deformation (x10) in linear analysis and Figure 6 indicates von Mises’ equivalent stress distribution with deformation (x10) in non-linear analysis. In case of varus alignment, high stress and large deformation was observed on and beneath the implants, and this was a more obvious trend in UHMWPE type. In cases of valgus alignment, concentration of stress was observed at the lateral portion of the tibial tray, and this was a more obvious trend in non-linear analysis.

“Stress Distribution in Different Coverages of Tibia”

Figure 7-a and d indicate von Mises’ equivalent stress distribution with deformation (x10) for narrow coverage of the tibia. In comparison to the standard model (Fig.7-b,e), the narrow coverage model has concentration of stress at the medial edge of the medial condyle. There were no stress distribution differences found in other parts.
“Stress Distribution at Different Levels of Tibial Osteotomy”

Figure 7-c,f indicate von Mises’ equivalent stress distribution with deformation (x10) at low osteotomy level UKA. In comparison to the standard model, the stress distribution in this model did not have remarkable differences.

“Evaluation of Cancellous Bone Beneath the Implant”

Figure 8 indicates von Mises’ equivalent stress of element in cancellous bone beneath the implant. In comparison to metal backed type, the stress concentration can be observed at around the peg in any alignment in UHMWPE type UKA (Fig.8-a). In the model with loosening (Fig.8-b), stress concentration can be observed at both the medial side of the peg and the lateral portion of the tibial tray, and the stress to the central side of the implant was reduced. In cases of low osteotomy level UKA and narrow coverage UKA, stress was high at the medial edge of the medial condyle.
Discussion:

Finite element method (FEM) has been used for various mechanical analyses of materials and structures since its first utilization for structural analysis of aircraft by Turner et al. in 1956.\textsuperscript{10}

In the field of orthopedics, FEM was introduced as “a new method to analyze mechanical behavior of skeletal parts” by Brekelmans et al.\textsuperscript{11} In recent years, FEM has been used for examining the causes of prosthetic mechanical problems such as loosening and sinking of the tibial component of TKA and also evaluating and optimizing the design of prostheses. General agreement can be found in reports comparing various designs that all-plastic tibial components result in higher stress to bone and cement than metal backed types.\textsuperscript{14} Many reports have shown that the longer the central stem is, the less the stress to proximal trabecular bone,\textsuperscript{12,15} and the similar result can be found in components with larger surface areas.\textsuperscript{16} Clinical results also back up these results from finite element analysis in TKA. Therefore, FEM can be considered effective to predict mechanical issues of implants, the fixation mechanism and also the acceptable range of errors.

The mechanical failure of UKA has been reported with the following causes: 1) technical
failure such as varus positioning of the implant and overcorrection of the postoperative leg alignment, 2) design and material of the element, 3) errors in the selection of patients such as severe varus deformity, involvement of patello-femoral joint, pan-arthritis such as rheumatoid arthritis and chondro-carcinosis, ligament insufficiency, severe obesity, high activity, osteoporosis and others. In the present study, the design and material of implant, the positioning of implant and the postoperative alignment, which can be simulated using FEM, were investigated.

In regard to metal backing and the thickness of implant, Marmor and Shurley et al. reported that 6mm tibial component without metal backing has a tendency for deformation and loosening. Knutson et al. reported that plastic deformation of a thin tibial component will not only deform the proximal surface of the component but also introduce deeper deformation eventually. Ryd et al. reported by using roentgen stereophotogrammetric analysis that cold flow can be observed in all 9 to 12 mm thick UHMPWPE implants but not in metal backed types. In the present study, it has been proven that metal backing has advantages in stress distribution similar to the results of analyses in TKA.
In the study of limb alignment of patients who had UKA, good results were found when the mechanical axis was centered as stated before. Alignment during UKA procedure is corrected not only by the removal of osteophytes and balancing of the soft tissues but also by means of the thickness of the implant. As a conclusion, when the implant becomes too tight with over correction, the extreme high pressure transmits to the opposite side of the component and subluxation could occur. The present study suggests that under correction will introduce higher stress concentrations in the underlying cancellous bone than in neutral alignment and over correction will introduce stress concentrations at the eminence of the tibia and the underlying bone of the lateral portion of the tibial tray where the bone density is low. The width of the implant is assumed not having almost any effect on stress distribution, and this assumption is similar to the result of finite element analysis of TKA. Clinically, the coverage of implant has almost no effect on sinking and loosening in TKA. However, the stress concentration being observed at the medial edge of the medial condyle in this study suggests a high probability that loosening will occur from this area.

A severe varus deformity is a contraindication for UKA, as the osteotomy line of the
tibia should not reach cortical bone. The present study indicates that an osteotomy line close to cortical bone would cause stress concentration to the cancellous bone around the cortical shell. Therefore, it is advised to preserve maximum bone stock in UKA just as in TKA.

For the models with loosening, stress concentration was observed at both the medial side of the peg and the lateral portion of the tibial tray. This result suggested that if loosening once occurs, then loosening and bone destruction would extend from that area to others.

It is obvious with these results that the accuracy in the operative procedure of UKA with careful consideration of indication is very important.

This study has several limitations. There may be many factors that remain to be defined with finite-element analysis. In the present analysis, material connections such as prosthesis-bone interfaces and UHMWPE-metal tray junctions were assumed to be rigidly bonded. Loading conditions were also defined to be static. These conditions had to be simplified, and are not equivalent to actual conditions. Therefore, boundary and loading conditions should be established in future studies. The highly complicated geometry of knee joint and component design should be also simplified to provide a basis
of better mechanical understanding.

Conclusions:

Two-dimensional finite element model was utilized for analysis of stress distribution in the proximal tibia after UKA. In this study, metal backed implants had superior stress distribution compared with UHMWPE implants. For UKA, the proper postoperative alignment must be achieved. The osteotomy line should be set at the cancellous bone close to the joint line with good mechanical property and also as much bone stock as possible should be preserved.

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Figure Legends

Fig. 1 Finite element mesh: a) Varus alignment due to under correction (688 nodal points, 650 elements). b) Neutral alignment (685 nodal points, 644 elements). c) Valgus alignment due to over correction (704 nodal points, 662 elements). d) Non-linear model using gap element (neutral alignment, 708 nodal points, 687 elements).

Fig. 2 Mechanical properties of cancellous bone: a) Mean trabecular orientation. b) Distribution of the Young's modulus of the cancellous bone.

Fig. 3 Material properties in FEM.

Fig. 4 Loading and boundary conditions: a) Varus alignment b) Neutral alignment c) Valgus alignment

Fig. 5 Von Mises' equivalent stress distribution in linear analysis with deformation (x10). (Difference of the alignment):
   a) Metal-backed type UKA in varus alignment
   b) Metal-backed type UKA in neutral alignment
   c) Metal-backed type UKA in valgus alignment
   d) UHMWPE type UKA in varus alignment
   e) UHMWPE type UKA in neutral alignment
   f) UHMWPE type UKA in valgus alignment

Fig. 6 Von Mises' equivalent stress distribution in non-linear analysis with deformation (x10). (Difference of the alignment):
   a) Metal-backed type UKA in varus alignment
   b) Metal-backed type UKA in neutral alignment
   c) Metal-backed type UKA in valgus alignment
   d) UHMWPE type UKA in varus alignment
   e) UHMWPE type UKA in neutral alignment
   f) UHMWPE type UKA in valgus alignment
Fig. 7  Von Mises' equivalent stress distribution in linear and non-linear analysis with deformation (x10) Difference of the coverage and the level of osteotomy Line:
   a) Narrow coverage (Linear analysis)
   b) Standard (linear analysis)
   c) Low level cutting (linear analysis)
   d) Narrow coverage (non-linear analysis)
   e) Standard (non-linear analysis)
   f) Low level cutting (non-linear analysis)

Fig. 8  Von Mises’ equivalent stress of the cancellous bone beneath implant.
   a) Difference of alignment (linear analysis)
   b) Difference of alignment (non-linear analysis)
   c) Difference of alignment (mean ± SE)
   d) Difference of the coverage and the level of osteotomy line (linear analysis)
   e) Difference of the coverage and the level of osteotomy line (non-linear analysis)
   f) Difference of the coverage and the level of osteotomy line (mean ± SE)
Fig. 1
Fig. 2
Fig. 3

Young's modulus (MPa)

- UHMWPE: 500
- Co-Cr-Mo: 200,000
- Cortical bone: 15,000
- Cancellous bone:
  - a: 3,000
  - b: 2,000
  - c: 1,000
  - d: 800
  - e: 500
  - f: 300

Poisson's ratio: 0.3
Fig. 4
Fig. 5
Fig. 6

(a) (b) (c) (d) (e) (f)
Fig. 7
Fig. 8