The optimal alignment of the tibial implant in unicompartmental arthroplasty using 3-dimensional finite analysis

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Abstract

Background: Unicompartmental knee arthroplasty (UKA) has been becoming popular over the last decades for its good outcome. On the other hand, several accompanying complications have been reported. Tibial implant alignment is considered to be one of the important causes of these complications. There have been some reports about it, but an optimal alignment of the tibial implant is still controversial. The purpose of this study was to observe the changes in stress distribution in the proximal tibia after UKA at various tibial implant alignments by using 3-dimensional finite element analysis.

Methods: A 3-dimensional finite element model was created with CT-DICOM data of a medial osteoarthritic knee. The change in stress distribution of tibial implant alignment in the coronal plane (middle position, varus 5°, valgus 5°) and in the sagittal plane (0°, 5°, 10°) under the conditions of loose boundary between implant and bone and no loosening condition was observed using 3-dimensional finite element analysis.

Results: With no loosening, high stress distribution was observed at the lateral rim of the subchondral bone in the varus alignment model, and the high stress distribution was moving from anterior to posterior with the posterior tilting from 0° to 10°. With loosening, high stress distribution was observed at the proximal tibial medial cortex in the valgus alignment model.
Conclusions: In UKA, optimal alignment of the tibial implant might be at the middle position in the coronal plane and at the posterior inclination similar to each patient’s original inclination in the sagittal plane to reduce complications.

Key words: 3-dimensional finite element analysis (3D-FEA), unicompartmental knee arthroplasty (UKA), tibial implant, alignment
**Introduction**

In the past, discouraging results in unicompartmental knee arthroplasty (UKA) had been reported\(^1\). Recently, UKA has regained popularity due to improved surgical technique and implant design, and appropriate surgical indication. UKA has gained advantages in rapid postoperative recovery and good kinematics because of benefits in its less invasive surgical technique in preserving bone stock and bilateral cruciate ligament, and offers favorable patient satisfaction in recent years\(^2,3\). On the other hand, tibial implant loosening and subsidence and tibial medial condyle fracture are reported as complications of UKA\(^4,5\). One of the causes of these complications is the tibial implant alignment, but there are few reports on the optimal alignment. The optimal alignment of the tibial component in UKA remains controversial.

The purpose of this study was to investigate the influence of established tibial implant alignment in the coronal and sagittal planes on stress distribution in the proximal tibia using 3-dimensional finite element analysis (3-D FEA) and to determine an optimal alignment of the tibial implant in UKA.

**Materials and Methods**

**3-D finite element model**
A 3-D finite element (3-D FE) model was created with CT-DICOM data of a medial osteoarthritic knee (Fig.1). Informed consent for publication has been obtained from the patient. The lateral femorotibial angle of that case was 180°, and the tibial posterior inclination was 7°. The morphology of this model was relatively typical in literature. The model was consisted of 48,800 second-ordered tetrahedral elements with Mimics Ver.21 (Materialise). The average length of the elements was 0.8 ± 0.02 mm. The shape of the tibial component was also reproduced from a commercially available design, Persona Partial Knee (Zimmer-Biomet, Warsaw, US) of around 45 mm × 19.9 mm diameter. We assumed elasticity of each material and set Young's modulus and Poisson's ratio in Table. 1 based on literature.

**Alignment and load**

The alignment of the tibial implant was set in the coronal plane (middle position, varus 5° and valgus 5°) and in the sagittal plane (0°, 5°, 10°). The implant inclination angle was chosen in accordance with the study by Chtellard et al. The analysis model was completely fixed at the end of the distal tibia, and a total 1,500 N load was equally applied on both condyles parallel to the axis of the tibia. In this research, the interface between the tibial component and the cutting surface was defined as two different conditions. Thus, the ideal fixation for which the sufficient time had elapsed after
surgery was assumed for the bonded interface. Conversely, the loosening condition was expressed as the contact-only (zero friction) setting in the finite element software.

**Analysis**

Von Mises stress is a value which shows tensile or compressive stress on a given material which is loaded in multidirection. This was used to determine whether bone will yield or not when evaluating the stress distribution of the bone which is anisotropic and heterogenous\(^9\). Because it was thought that the loosening of the tibial implant of UKA was due to the collapse of the subchondral bone below it\(^10\), the changes of the stress distribution at the subchondral bone of the osteotomy region was analyzed. In addition, the change of stress distribution in the tibial proximal medial cortex was analyzed, because it was thought that the fracture of the tibial medial condyle is finally completed by the failure of the tibial proximal medial cortex. Abaqus Ver.6.3 (Fujitsu) was used for analysis.

**Results**

**Non-loosening condition**

The tibial component alignment was changed in the coronal plane, and the Mises equivalent stress of the subchondral bone under the tibial implant was observed in the
absence of loosening.

In the varus 5° model, a higher stress concentration at the subchondral bone under the lateral rim of tibial implant was observed compared to the middle position and valgus 5° model. On the other hand, a lower stress distribution was observed at the anterior cortex and the anterior subchondral bone of the keel in the middle position model. And a lower stress distribution was observed at the posterior cortex and the posterior subchondral bone of the keel in the valgus 5° model. (Figs. 2 and 3).

Changing the alignment of the sagittal plane, a high stress distribution was moving from anterior to posterior with the posterior inclination from 0° to 5° and then 10°. Especially in the posterior inclination 0° model, high stress concentration was observed at the anterior cortex (Figs. 2 and 4).

On changing the alignment of the coronal and sagittal planes, stress distribution in the medial cortex of the proximal tibia did not change.

**Loosening condition**

In the loosening condition, change of stress distribution in subchondral bone was observed, but there was no clear trend of stress distribution. In the valgus 5° model, a higher stress concentration was observed at the medial cortex of the proximal tibia than in the other models (Fig. 5).
**Discussion**

In the past, some stress analyses of proximal tibia after UKA using FEA were reported. Inoue et al.\(^4\) reported that the varus alignment is preferable from the view of the prevention of the fracture of the tibial medial condyle after UKA. On the other hand, Sawatari et al.\(^11\) and Iesaka et al.\(^12\) reported that valgus alignment is preferable to get a satisfactory stress distribution using analysis of subchondral bone under the tibial component. Zhu et al.\(^13\) reported that the middle position is best. Thus, the optimal alignment of the tibial implant in UKA is still controversial.

In the present study, the stress contribution of the proximal tibia was analyzed by varying the coronal and sagittal alignments of the tibial implant. In the absence of loosening, a tendency to have higher stress on the lateral rim than the medial rim under the implant overall was observed. On changing the coronal alignment in the absence of loosening, a high stress concentration was observed at the subchondral bone under the lateral rim of the tibial implant in the varus 5° model. It was assumed that the cause of this phenomenon was that medial inclination of the tibial implant moves the implant inward. From this, it appears that the tibial implant in the varus alignment should be avoided.
On the other hand, the high stress distribution at the subchondral bone under the lateral rim under the tibial implant moved from anterior to posterior with the posterior inclination from 0° to 5° and then 10°. In particular, a higher stress distribution was observed at 0° alignment. The greater possibility of subsidence of the tibial implant may occur in the less posterior inclination. Many reports have suggested that recreating the original posterior inclination of the tibia leads to good outcomes (Sawatari et al.\textsuperscript{11}, Franz et al.\textsuperscript{14}, Taylor et al.\textsuperscript{10}). Also, it was reported that the positioning of the tibial implant in a too little or excessive posterior inclination leads to implant loosening or subsidence (Chtellard et al.\textsuperscript{8}, Iesaka et al.\textsuperscript{12}). Therefore, considering that the original posterior inclination of the tibia in this study’s 3D-FE model was 7°, it might be appropriate to reproduce the original posterior inclination in the tibia. However, the analysis of the posterior inclination which simulated the reproduction in vivo was considered to be difficult with a high number of elements including the anterior cruciate ligament.

In the loosening condition, remarkable changes in the stress distribution in the subchondral bone under the tibial implant were observed. It was suggested that the tibial implant was in unstable condition, but there was no clear trend of stress distribution. Meanwhile, a stress concentration was observed at the proximal medial cortex of the
tibia in the valgus model, which was presumed to be likely to lead to tibial medial condyle fracture.

From the results of the stress distributions in the subchondral bone in the coronal alignment, the coronal inclination of the tibial implant was considered to be desirable from the middle position to a mild valgus position. However, the risk of tibial medial condylar fracture might increase, if high stress concentration occurred at the tibial proximal medial cortex in the case of loosening and the valgus model. It was presumed that the middle position is the optimal alignment to reduce postoperative complications from the reduction of the possibility of the loosening and subsidence of the tibial implant and tibial medial condyle fracture.

There is much intervention of elements other than the alignment of the tibial implant for the determining the optimal sagittal plane alignment, thus, it is difficult to conclude what it should be only with this research. However, it is suggested that it is desirable to reproduce the mild posterior inclination of the original tibia similar to past reports.

This study has several limitations. First, the equilibrium state in vivo could not be reproduced under the restriction of soft tissues such as ligaments. Second, the load conditions were parallel to the bone axis of the tibia, equal load was applied to both condyles, and the position of the lower limbs and the whole leg alignment were not
taken into account. Third, the data of the tibia is only one case, so it is not universal.

Fourth, this study provides no clear direct relationship between its results and clinical results including survival rates. However, our conclusion coincide with the clinical outcome reported in the past\textsuperscript{6,8,15,16}.

In the future, more accurate studies may be necessary. However, this is the first article to declare the optimal coronal and sagittal alignment of the tibial implant in UKA analyzing with 3-D FEA.

In conclusion, a 3D-FE model was used to analyze the changes in stress distribution in the proximal tibia while changing the alignment of the tibial implant in UKA at the coronal and the sagittal planes. It was inferred that the optimal alignment of the tibial implant in UKA was the middle position in the coronal plane and the original posterior inclination in the sagittal plane.

\textbf{Acknowledgements:} We are grateful to Mr. Lawrence J. Frumson for checking the English grammar of this manuscript.

\textbf{Conflict of interest:} The authors have no competing interest and funding to disclose with regard to the subject matter of this manuscript.
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Fig. 1. Finite element model

Fig. 2. Von Mises stress distributions on the subchondral bone of the bone-implant interface from above after removal of the tibial implant (non-loosening model).

Fig. 3. Von Mises stress distributions on the subchondral bone of the bone-implant interface (posterior inclination 5°, non-loosening model)

Fig. 4. Von Mises stress distributions on the subchondral bone of the bone-implant interface (middle position, non-loosening model)

Fig. 5. Von Mises stress distributions on the medial cortex of the proximal tibia (Posterior inclination 5°, loosening model)
Fig. 1
Fig. 2

**Backward**

**Medial**

Posterior inclination 0°

Varus 5°

Middle

Posterior inclination 5°

Valgus 5°

Lateral

Posterior inclination 10°

**Forward**
Fig. 3

- MPa
- Varus 5°
- Middle
- Valgus 5°

Anterior cortex | Anterior keel | Posterior keel | Posterior cortex

0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
Fig. 5

Varus $5^\circ$  Middle  Valgus $5^\circ$
Table 1  Material property

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<tr>
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<th>Young’s modulus (GPa)</th>
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<td>Tibial implant (Ti-6AL-4V)</td>
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<tr>
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<td>Cancellous bone</td>
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