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■ KNEE

The effects of kinematically aligned total knee arthroplasty on stress at the medial tibia

A CASE STUDY FOR VARUS KNEE

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Objectives

Little biomechanical information is available about kinematically aligned (KA) total knee arthroplasty (TKA). The purpose of this study was to simulate the kinematics and kinetics after KA TKA and mechanically aligned (MA) TKA with four different limb alignments.

Materials and Methods

Bone models were constructed from one volunteer (normal) and three patients with three different knee deformities (slight, moderate and severe varus). A dynamic musculoskeletal modelling system was used to analyse the kinematics and the tibiofemoral contact force. The contact stress on the tibial insert, and the stress to the resection surface and medial tibial cortex were examined by using finite element analysis.

Results

In all bone models, posterior translation on the lateral side and external rotation in the KA TKA models were greater than in the MA TKA models. The tibiofemoral force at the medial side was increased in the moderate and severe varus models with KA TKA. In the severe varus model with KA TKA, the contact stress on the tibial insert and the stress to the resection surface and to the medial tibial cortex were increased by 41.5%, 32.2% and 53.7%, respectively, compared with MA TKA, and the bone strain at the medial side was highest among all models.

Conclusion

Near normal kinematics was observed in KA TKA. However, KA TKA increased the contact force, stress and bone strain at the medial side for moderate and severe varus knee models. The application of KA TKA for severe varus knees may be inadequate.

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Keywords: Total knee arthroplasty, Kinematic alignment, Contact stress, Finite element analysis, Computer simulation

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Article focus

- Little biomechanical information is available about kinematically aligned (KA) total knee arthroplasty (TKA).
- A simulation program was used to analyse the kinematics and the kinetics for varus knee models with the KA and mechanically aligned TKA.
- The contact stress on the tibial insert, the stress to the resection surface and medial tibial cortex, and the bone strain at the medial side were examined by using finite element analysis.

Key messages

- The contact force, stress and bone strain at the medial side were increased in the moderate and severe varus models with KA TKA.
- The application of KA TKA for severe varus knees may be inadequate because of the increased contact force, stress and bone strain at the medial side.

Strengths and limitations

- A computer simulation program was able to estimate the kinematics and kinetics for various conditions.
- The study was restricted to only one bone model for each deformity.
- Other implant designs may exhibit different kinematics and contact status.

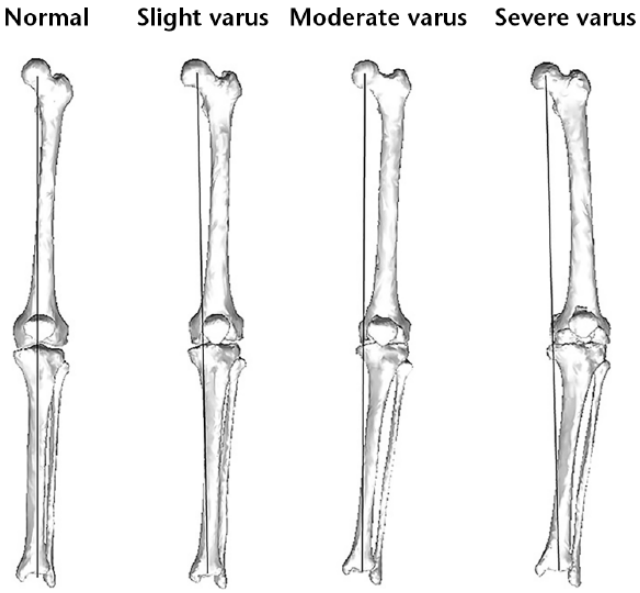

Fig. 1

Bone models constructed from CT data. The limb alignment was 0°, 6° varus, 10° varus, and 15° varus for the normal, slight varus, moderate varus, and severe varus models, respectively.

Introduction

Total knee arthroplasty (TKA) has been successfully performed for patients with end-stage knee osteoarthritis with the aim of relieving pain and improving function. Owing to its success, current patients receiving TKA are younger and more active than those in the past.[1,2] However, a lower satisfaction rate has been reported for patients undergoing TKA (81%) than for those undergoing total hip arthroplasty (THA) (89%).[3] In other clinical studies, up to 20% of patients have reported dissatisfaction with the outcomes after TKA.[4]

Previously, TKA has been mainly carried out based on the mechanical alignment of the limb (mechanically aligned (MA) technique). After surgery, the mechanical axis passes through the middle of the knee joint, which may be beneficial for equal weight distribution. One of the drawbacks of this technique is that it changes the natural angle and level of the joint line because the medial tilt of the joint line for normal knees is ignored.[5] Therefore, MA TKA may cause abnormal kinematics, and subsequent poor patient satisfaction.

Recently, a new modification in the surgical technique of TKA (kinematically aligned (KA) technique) was proposed.[6-8] The goal of this technique is to achieve pre-arthritic alignment for each individual patient and to restore the natural angle and level of the joint lines. Better pain relief, better range of movement, and better post-operative functions have been reported after a short follow-up period.[6,9] However, it remains uncertain whether KA TKA can be applied for all patients. It has been reported that pre-arthritic alignment in numerous populations is not "neutral";[10] some patients with pre-operative moderate to severe varus limb alignment would still have varus alignment after KA TKA. In biomechanical studies, post-operative varus alignment is reported to cause overload on the medial side.[11-13] Little biomechanical information is available about varus alignment as a possible result of KA TKA.[14] Therefore, a biomechanical study using actual patients' data is required to simulate post-operative stresses and bone strain on the medial side as a case study.

The purpose of this study was to investigate the kinematics, contact forces, and contact stress and bone strain after KA TKA and MA TKA by using a computer simulation. The models were made from the computed tomography (CT) data of a normal volunteer and patients with different limb alignments (slight, moderate, and severe varus deformity). We hypothesised that the KA TKA would reveal near normal kinematics, but that KA TKA would apply greater contact force and contact stress on the polyethylene insert and on the resected surface of the tibia at the medial side and bone strain at the medial side, especially in the severe varus deformity model.

Materials and Methods

In the current study, one knee model with straight alignment from a healthy volunteer and three different osteoarthritis models were constructed for analysis (Fig. 1). The healthy volunteer was a 28-year-old man without any knee symptoms or knee injuries. From 120 patients who underwent TKA from 2014 to 2015, three patients, whose hip-knee-ankle (HKA) angle was 5° ±1°, 10° ±1°, and 15° ±1° varus, respectively, were selected for the analysis. The height, weight, and age were matched. Appropriate Institutional Review Board approvals and informed consent from all participants was obtained. The slight, moderate, and severe varus knee deformity models were constructed by using the data of a 72-year-old male patient with 6° varus of the HKA, a 72-year-old female patient with 10° varus of the HKA, and a 72-year-old female patient with 15° varus of the HKA, respectively. Each bone was separated into the cortical bone area and the cancellous bone area based on the CT value of 250 (Mimics 16.0; Materialise HQ, Leuven, Belgium) for finite element analysis (FEA). Separation was carried out based on the CT value for each patient.

In MA TKA, the conventional measured resection technique was applied to all bone models. In the coronal plane, the femoral and tibial components were virtually positioned perpendicular to the mechanical axis of the femur and tibia, respectively. In the axial plane, the femoral component was implanted parallel to the transepicondylar axis. The tibial component was implanted according to the anteroposterior axis of the tibia, as previously reported.[15] After implantation, the mechanical axis of the lower limb passed through the centre of the knee joint for all models.

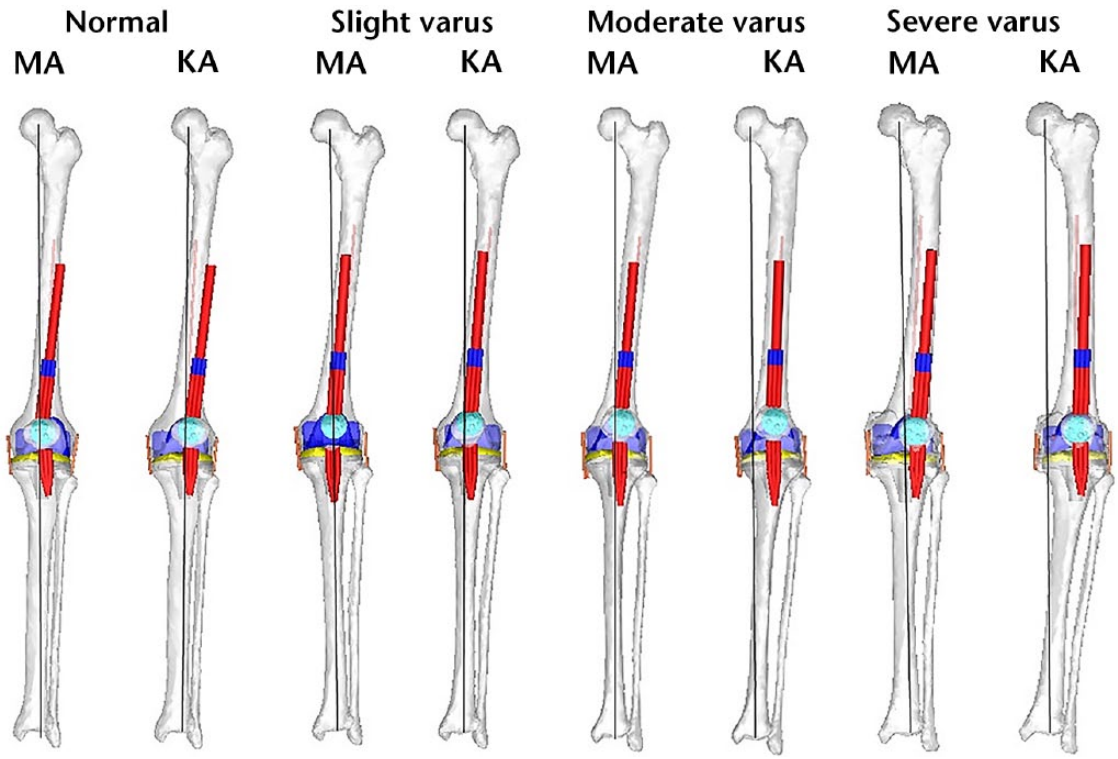

Fig. 2

Bone models after implantation with the mechanically aligned (MA) and kinematically aligned (KA) techniques.

In KA TKA, the distal femur and the proximal tibia were cut to restore the natural angle and the level of the joint lines for each bone model, as suggested by Howell et al.[6,7] In the coronal plane, cartilage wear was corrected at the medial side with 2 mm for the femur and 2 mm for the tibia of the osteoarthritis models. Then, the femoral and tibial components were implanted tangent to the estimated surface of the distal femur and the proximal tibia, respectively. In the axial plane, the femoral component was implanted tangent to the medial and lateral condyles of the posterior femur. Cartilage wear was not considered at the posterior femur because the wear of the posterior cartilage was minimal.[16] The technique for the internal-external rotation of the tibial component was to set the anteroposterior axis of the tibial component parallel to the major axis of the nearly elliptical boundary of the lateral tibial condyle, as also proposed by Howell et al.[7] After implantation, the HKA angles were 0°, 2° varus, 6° varus, and 10° varus for the normal, slight varus, moderate varus, and severe varus models, respectively (Fig. 2).

The medial and lateral tibiofemoral contact force was estimated with a patient-specific dynamic musculoskeletal modelling system (LifeMOD/KneeSIM 2010; LifeModeler Inc., San Clemente, California), which contained the medial and lateral collateral ligament, posterior cruciate ligament, quadriceps muscle and tendon, patellar tendon, and hamstring muscles. In previous biomechanical studies, this simulation program has been validated to secure the appropriate estimation of contact points and contact forces.[17,18] The origins of the insertion points and the stiffness were determined from the relevant anatomical studies, which were identical for both techniques.[19-23]

A fixed-bearing cruciate-retaining total knee prosthesis (NexGen CR-Flex; Zimmer Biomet Inc., Warsaw, Indiana) was implanted for the analysis. The appropriate implant size was size E for the femoral component, size 5 for the tibial component, 29 mm for the patellar component, and 10-mm thickness for the polyethylene insert for all bone models. A squatting activity was simulated with a weight-bearing deep knee bend by using an Oxford-type knee rig. A constant vertical force of 4000 N was applied at the hip and loaded on the knee joint. The knee model was flexed from full extension to 130° of knee flexion, and then back to full extension. The kinematics and kinetics, including the relative 3D positions of the femoral and tibial components and the medial and lateral tibiofemoral forces, were calculated. The anteroposterior positions and the axial rotation were measured using the coordinate system of the tibial component. The anterior direction and the external rotation of the femoral component were denoted as positive.[24] The maximum and average tibiofemoral forces were analysed.

The contact stress on the tibial insert and the stress applied to the resection surface and medial tibial cortex were examined by using 3D FEA for each bone model. Moreover, the strain of the cortical and cancellous bone

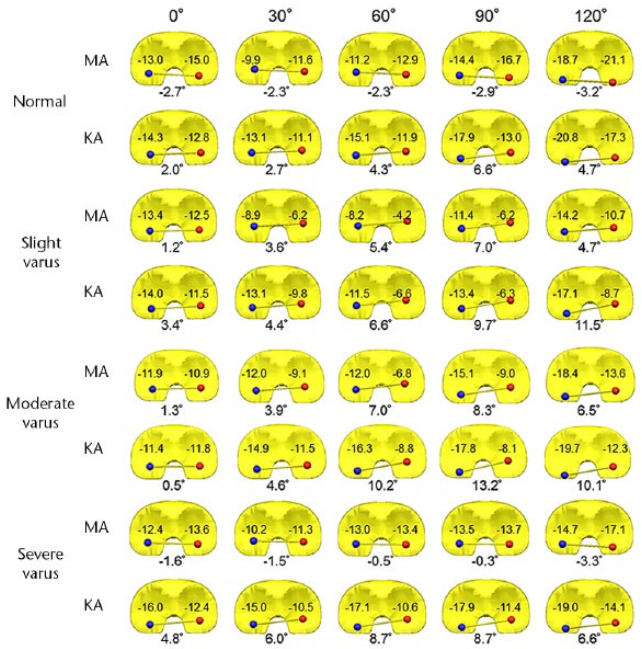

Fig. 3

Contact position relative to the tibial component and the axial rotation for each model. Red and blue dots indicate the medial and lateral facet centre positions, respectively (MA, mechanically aligned; KA, kinematically aligned).

was analysed at the medial side. FEA was carried out with ANSYS Workbench (ANSYS Inc., Canonsburg, Pennsylvania). The contact stress on the polyethylene and the stress to the tibia were analysed when the medial contact force was at maximum. The tibia was fixed, and the femoral component was constrained to only move in a vertical direction. The 3D positions of the tibia, tibial component, tibial insert, and femoral component were acquired from the simulation program, and then medial and lateral tibiofemoral contact forces were applied vertically in the FEA. The femoral and tibial components were directly positioned on the bony surface, and cementless fixation was simulated in the current study. Concerning the interaction between parts, the tibial component was bonded to the tibia, and the cancellous part of the tibia was also bonded to the cortical parts. The femoral and tibial components analysed were a Cobalt-Chrome-Molybdenum alloy and a Titanium alloy, respectively. The Young's modulus of the femoral and tibial components was set at 240 and 111 GPa, respectively. The analysed tibial inserts were nonlinear elastoplastic materials.[25] Nonlinear elastic material definitions for the polyethylene were adopted. The yield strength of polyethylene was 20 MPa. The tibial bone was separated into the cortical and cancellous parts, the Young's modulus of which was 13.4 GPa and 0.83 GPa, respectively.[26,27] Both parts were analysed as linear elastoplastic models. The mesh of the femoral component and the tibial insert were generated based on 10-node quadratic tetrahedral elements sized at 0.8 mm. The mesh of tibial tray and the cortical and cancellous bone were generated sized at 1.0 mm. The generated mesh of the femoral component, tibial insert and tibial component contained 43 908, 35 846, and 28 676 elements, respectively. The mesh of the cortical bone and cancellous bone for each patient, on average, contained 42 644 and 36 063 elements.

Results

The translation at the lateral side from 0° to 120° of knee flexion was -6.0 mm, -3.1 mm, -8.3 mm, and -3.0 mm for KA TKA in the normal, slight varus, moderate varus, and severe varus models, respectively, whereas the respective corresponding values were -5.7 mm, -0.8 mm, -6.5 mm, and -2.3 mm for MA TKA. The axial rotation for KA TKA was -2.7°, 8.1°, 9.6°, and 1.6° in the normal, slight varus, moderate varus, and severe varus models, respectively, whereas the respective corresponding values were -0.5°, 3.5°, 5.2°, and -1.7° for MA TKA (Fig. 3). In all bone models, the amount of posterior translation at the lateral side and external rotation in the KA TKA models were greater than in the MA TKA models.

The maximum and average tibiofemoral contact forces at the medial side in the severe varus model with MA TKA were the highest of all such values measured (Fig. 4, Table I). When comparing the maximum contact forces between MA TKA and KA TKA, a greater increase was observed in the severe varus model (12.6% increase) than in the normal knee model (6.3% increase) for KA TKA.

The contact stress on the polyethylene exceeded the yield strength for all models. The contact stress on the tibial insert in KA TKA was lower than that in MA TKA for the normal knee model. For the slight varus model, the result was similar between KA TKA and MA TKA. For the moderate and severe varus models, the maximum contact stress with KA TKA was increased by approximately 47.3% and 41.5%, respectively (Fig. 5).

The stress on the resection surface in KA TKA showed slight increases of 8.9% and 4.0% in comparison with MA TKA for the normal and slight varus knee models, respectively. For the moderate and severe varus knee models, the maximum stress in KA TKA increased by 24.8% and 32.2%, compared with that in MA TKA (Fig. 6). The stress to the medial tibial cortex in KA TKA was greater than that in MA TKA for all bone models. In the KA TKA models, the maximum stress increased with greater varus deformity. For the severe varus knee model with KA TKA, the stress to the medial tibial cortex was the highest (29.2 MPa) among all models, with a 101.3% increase in comparison with the normal bone model with KA TKA (14.5 MPa) and a 53.7% increase in comparison with the severe varus bone model with MA TKA (19.0 MPa) (Fig. 7).

The difference in the strain for the cortical bone at the medial side was relatively small in MA TKA models.

Table I. Maximum and mean contact forces for each model

		Medial contact force (N)		Lateral contact force (N)	
		Maximum	**Mean**	**Maximum**	**Mean**
Mechanically aligned	Normal	1760	944	1568	678
	Slight varus	1996	869	1376	745
	Moderate varus	1929	872	1168	749
	Severe varus	2156	1047	1485	771
Kinematically aligned	Normal	1870	760	1539	887
	Slight varus	2087	933	1485	780
	Moderate varus	2105	971	1197	712
	Severe varus	2428	1202	1233	755

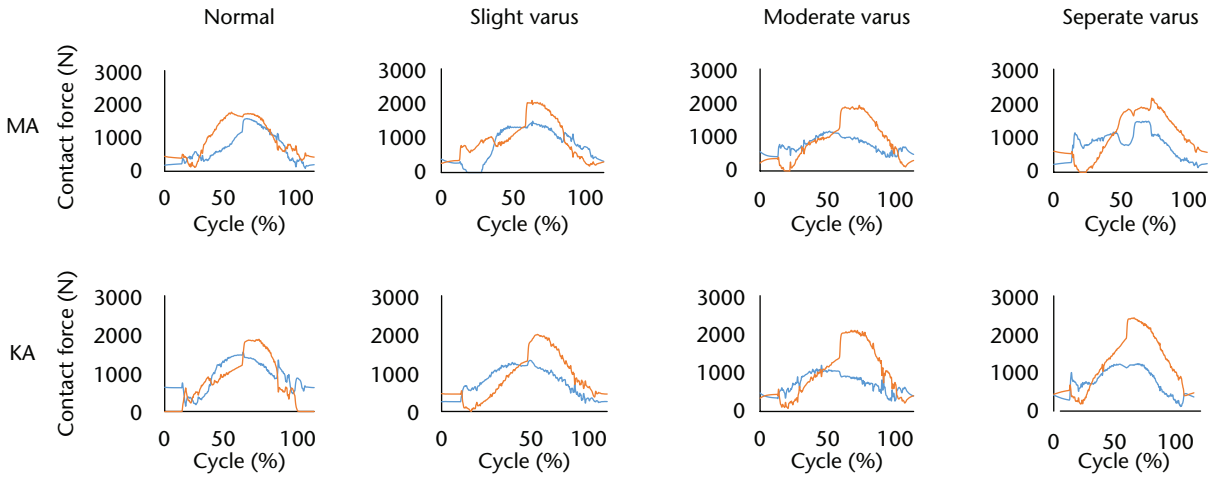

Fig. 4

Contact forces for each model. Red and blue lines indicate the medial and lateral contact forces, respectively (MA, mechanically aligned; KA, kinematically aligned).

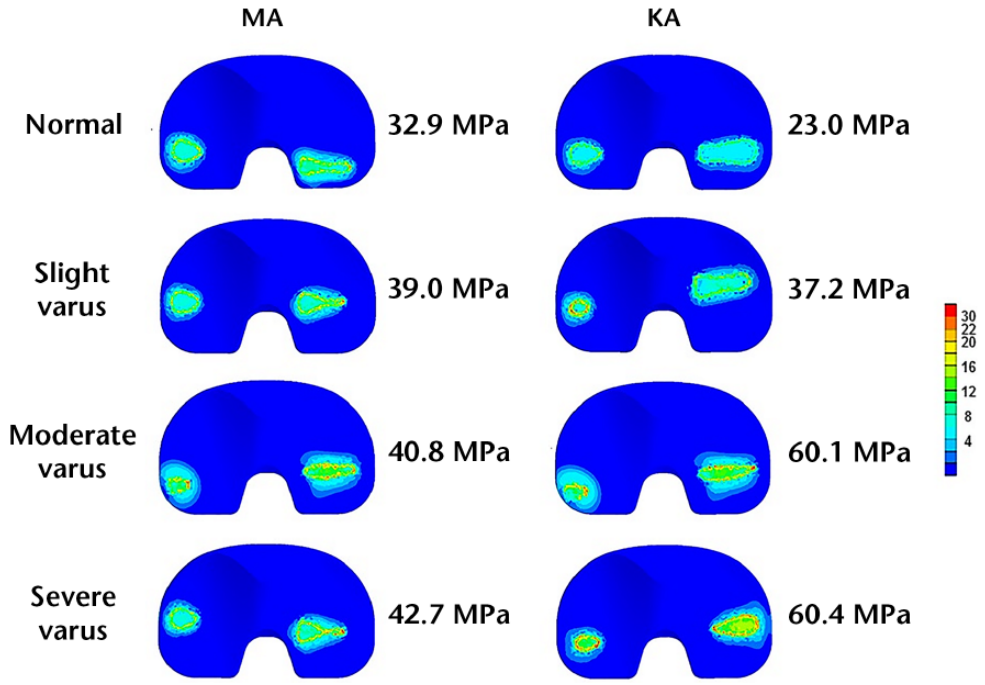

Fig. 5

Contact stress on the tibial insert with the mechanically aligned (MA) and kinematically aligned (KA) techniques. Right side on the figure indicates medial condyles.

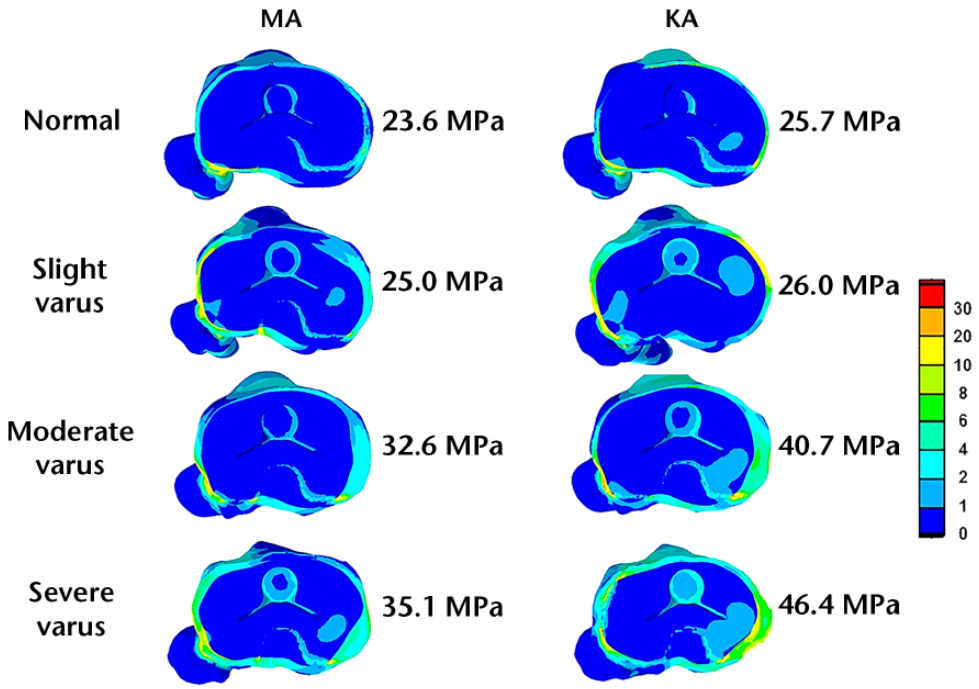

Fig 6

Stress on the resected surface of the tibia with the mechanically aligned (MA) and kinematically aligned (KA) techniques. Right side on the figure indicates medial condyles.

However, the cortical strain became higher with more varus alignment in KA TKA models. Comparing the cortical strain in MA and KA TKA, the strain was higher in KA TKA for all bone models. For the severe varus knee model with KA TKA, the cortical strain was maximal among all models (Fig. 8). The strain for the cancellous bone at the medial side showed similar trends but higher strain than that of the cortical bone. The highest cancellous strain was observed at the distal area to the cut surface in the severe varus knee model with KA TKA (Fig. 9).

Discussion

KA TKA has been suggested to improve clinical results and patient satisfaction after TKA. However, concerns about varus alignment still remain after KA TKA.[6,7] In the current study, the kinematics and kinetics of KA and MA TKA were analysed using a simulation program and FEA. Near normal kinematics was observed in KA TKA regardless of bone deformity. However, the stresses at the polyethylene and the tibial bone, and bone strain at the medial side were increased, especially in the severe varus model with KA TKA. KA TKA might be inappropriate for patients with severe varus deformity because of the overload to the polyethylene insert and the tibia at the medial side.

This is the first study to evaluate the influence of preoperative knee deformity on knee kinematics and kinetics after KA TKA. Despite substantial advances in implant design and the surgical techniques for TKA, some patients have indicated unfulfilled expectations.[3] Previously, TKA was conducted by using the MA method, which may change the limb and knee alignment from normal, resulting in poor clinical outcomes.[28] Recently, several clinical studies with the KA technique have reported achieving better pain relief, function, and range of movement.[6,7,9] In the current study, more normal knee kinematics was observed in KA TKA. Near normal knee kinematics with KA TKA might lead to better clinical results.

In the current study, the contact force at the medial side and the medial contact stress on polyethylene were increased when the overall limb alignment was varus. In previous biomechanical studies, TKA for varus malalignment was shown to increase the medial contact forces and the contact stress on the polyethylene insert.[29-31] With FEA, the increase in maximum contact stress was higher with greater varus alignment.[30] Similar results were obtained in a cadaver study with a knee simulator, in which a tibial malposition of 3° or more in varus can greatly alter the distribution of pressure and the load between the medial and lateral compartments.[31] In a recent FEA study, shifting the alignment to varus configurations led to an increase of stress in the medial region, and the loading effect was greater when changes in alignment were induced by the tibial component orientation.[29] The findings of the current study agree with those of previous biomechanical studies.

The stress to the tibial resection surface and medial tibial cortex, and the strain to the cortical and cancellous bone were also analysed by FEA in the current study. In the normal and slight varus knee models, the stress to

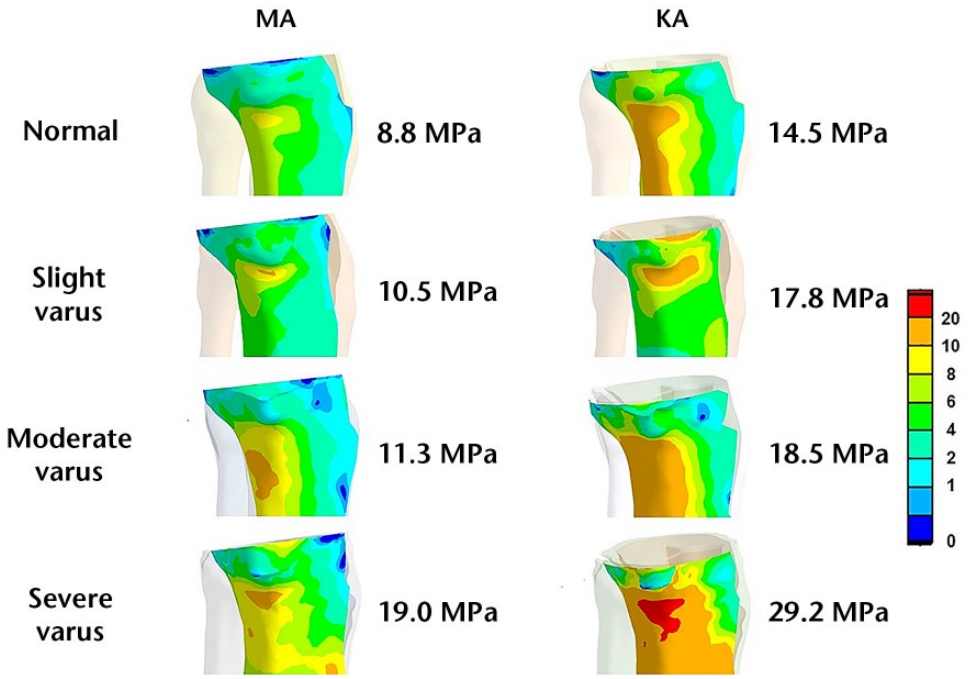

Fig. 7

Stress to the medial tibial cortex with the mechanically aligned (MA) and kinematically aligned (KA) techniques.

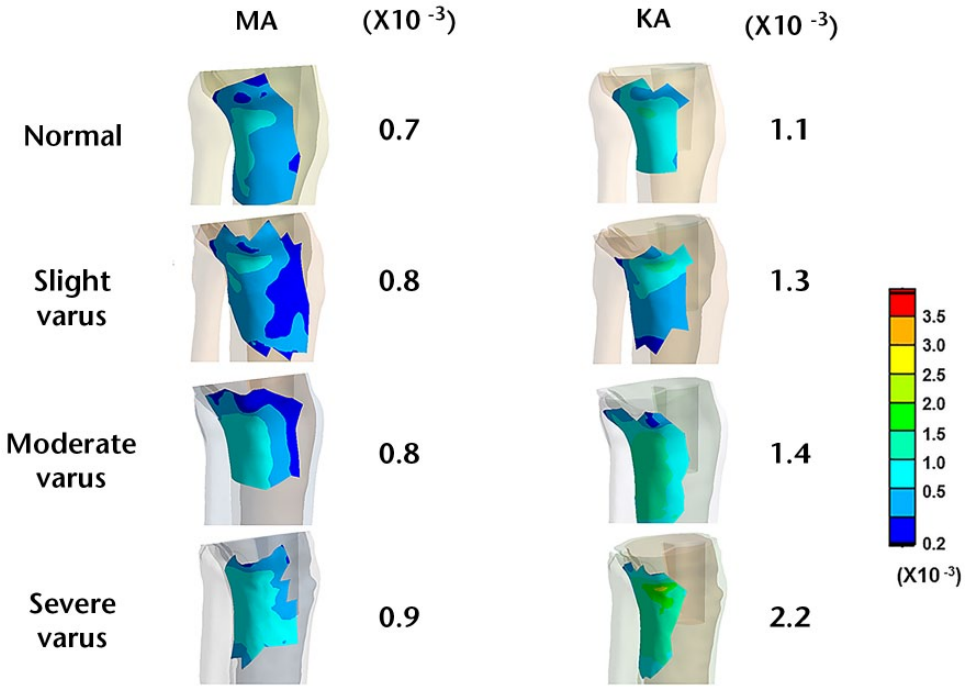

Fig. 8

Strain to the medial tibial cortical bone with the mechanically aligned (MA) and kinematically aligned (KA) techniques.

the resection surface and to the medial tibial cortex was increased slightly for KA TKA. For these bone models, KA TKA had relatively small effects on the contact mechanics; thus, this surgical technique might not negatively affect long-term durability of the prosthesis for patients with slight varus deformities. In moderate and severe varus knee models, the contact stress on the tibial insert, the stress to the resection surface and to the medial tibial cortex and the bone strain at the medial side for KA TKA were considerably increased compared with MA TKA.

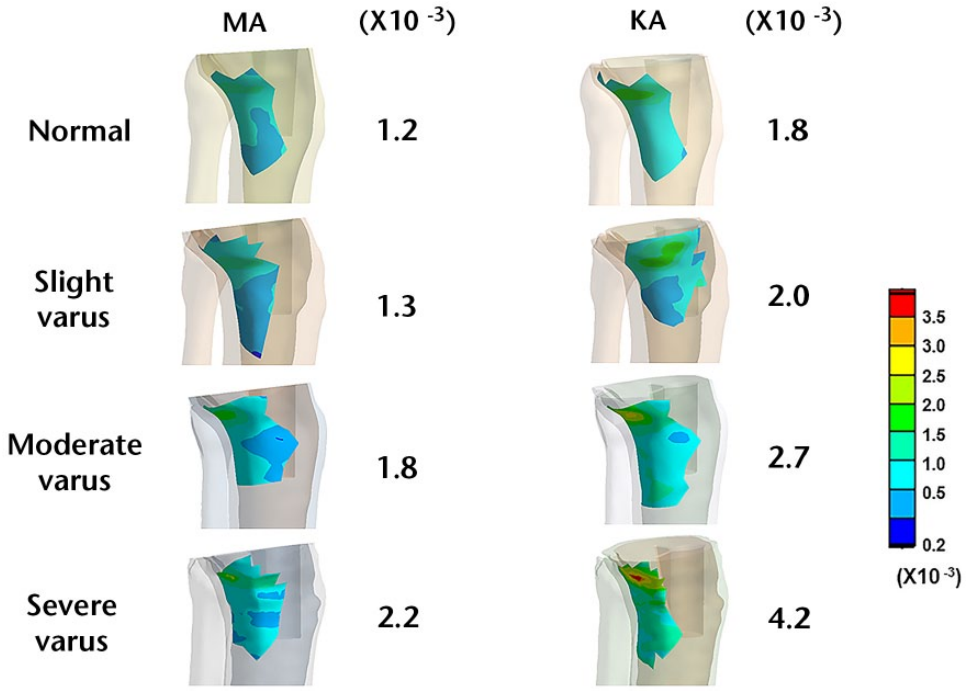

Fig. 9

Strain to the medial tibial cancellous bone with the mechanically aligned (MA) and kinematically aligned (KA) techniques.

For these patients, the KA technique might induce excessive polyethylene wear, medial tibial collapse, and early component loosening after the long-term follow-up.

In a short-term survivorship analysis of a KA technique, the varus alignment of the limb, including the tibial component, did not adversely affect implant survival or function.[9,32] This technique aims to restore pre-arthritic alignment by slightly correcting articular deformity, so severe varus patients would be expected to have post-operative varus alignment. In clinical long-term follow-up studies, varus malalignment was associated with a higher failure rate.[11,12] Failure was most likely to occur if the orientation of the tibial component was < 90° relative to the tibial axis and the orientation of the femoral component was ≧ 8° of valgus (failure rate, 8.7%).[12] Therefore, varus alignment after KA TKA might lead to poor long-term durability. We cannot make definitive clinical recommendations for KA TKA, however, the current study clearly shows that applying KA TKA for all patients has some risks for implant failure. At the very least, post-operative alignment should be simulated from pre-operative radiographs before KA TKA, and some technical modification should be necessary to avoid excessive post-operative varus alignment after KA TKA.

This study has several limitations. First, the number of samples analysed was small because it was a case study to analyse the effects of KA TKA. A total of four different bone models were evaluated with different alignments, thus, most patients with a varus deformity could be assigned to one of these bone models. Secondly, all bone models except for the normal knee model were constructed from actual patients undergoing TKA. The slight difference in morphology, especially for the tibia, might have an influence on the stress and bone strain to the medial tibia.[33] As the models were patient-specific and have not been validated because they are living patients and not cadaveric material, it might be difficult to conclude that differences in bone stress are due purely to implant alignment and not to differences in bony anatomy. Thirdly, the implant used had a multiple radius femoral component with a fixed-bearing cruciate-retaining polyethylene; thus, other implant designs such as a single radius femoral component, mobile-bearing polyethylene, and posterior-stabilised polyethylene might exhibit a different contact status. Fourthly, the femoral and tibial components were directly positioned on the bony surface to simplify the calculation, and cementless fixation was simulated, although most TKAs are actually cemented. The stress on the resection surface and bone strain might be different in the cemented TKA. Finally, correction of cartilage wear was 4 mm (2 mm femur, 2 mm tibia) for simplicity, and the differences in angular deformity were maintained. However, bone loss was not considered in KA TKA models. Pre-disease anatomy may not be represented, especially in the severe varus model, because the patients with severe varus deformity may have considerable bone loss.

In conclusion, KA TKA could restore near normal kinematics compared with MA TKA, regardless of bone deformity. KA TKA increased the contact stress on the tibial insert, the stress to the resection surface and to the

medial tibial cortex, and the bone strain at the medial side in an FEA severe varus knee model. The application of KA TKA for severe varus knees might be inadequate because of increasing risks for failure.

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Author Contribution

- S. Nakamura: Data analysis, Drafting the article.
- Y. Tian: Acquisition of data, Drafting the article.
- Y. Tanaka: Acquisition of data, Data analysis.
- S. Kuriyama: Data analysis, Interpretation of data.
- H. Ito: Conception and design of the study, Interpretation of data.
- M. Furu: Interpretation of data.
- S. Matsuda: Conception and design of the study, Interpretation of data, Final approval.

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- None declared