



Lecture

Medial tilting of the joint line in posterior stabilized total knee arthroplasty increases contact force and stress

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ABSTRACT

Background: Kinematically aligned total knee arthroplasty is based on the concept to represent the pre-morbid joint alignment with cruciate-retaining implants, characterized by medial tilt and internal rotation. However, kinematic and kinetic effects of kinematically aligned total knee arthroplasty with posterior-stabilized implants is unknown. The purpose of this study was to examine the effect of medial tilting of the joint line with posterior-stabilized implants.

Methods: A mechanical alignment model, and medial tilt 3° and 5° models were constructed. Knee kinematics and contact forces were simulated using a musculoskeletal computer simulation model. Contact stresses on the tibiofemoral joint and the post area were then calculated using finite element analysis.

Findings: From 0° to 120° of knee flexion, greater external rotation of the femoral component was observed in medial tilt models (−0.6°, 1.8° and 4.2° in mechanical alignment, medial tilt 3° and medial tilt 5° models, respectively). The peak contact stresses on the tibiofemoral joint and the post area at 120° of knee flexion were higher in medial tilt models. The peak contact stresses on the post area in medial tilt 3° and 5° models were 2.2 and 3.8 times greater than that in mechanical alignment model, respectively.

Interpretation: Medial tilting of the joint line causes greater axial rotation even with posterior-stabilized implants, which can represent near-normal kinematics. However, medial tilting of the joint line in total knee arthroplasty with posterior-stabilized implants may have a higher risk for polyethylene wear at the tibiofemoral joint and post area, leading to subsequent component loosening.

1. Introduction

Total knee arthroplasty (TKA) is a widely accepted procedure. However, it has been reported that patient satisfaction after TKA is not as high as that after total hip arthroplasty, suggesting that there is a need to improve the procedure (Bourne et al. 2010a; Bourne et al. 2010b). A technique called kinematically aligned (KA) TKA has been recently proposed, which is characterized by medially tilted joint line and internal rotated femoral component (Howell et al. 2013b; Howell et al. 2013c; Howell et al. 2013d; Howell et al. 2015). This method seeks to restore pre-morbid joint levels and angles after TKA. Recently, a randomized controlled study demonstrated that KA TKA resulted in better pain relief, postoperative function, and range of motion than mechanically aligned (MA) TKA (Dossett et al. 2014). In several studies, however, no differences were observed in function and patient reported outcomes between two techniques (Waterson et al. 2016; Young et al. 2017).

Most of the previously published clinical and biomechanical studies evaluating KA TKA were performed with cruciate-retaining (CR) implants (Dossett et al. 2014; Howell et al. 2013b; Howell et al. 2013c; Howell et al. 2013d; Howell et al. 2015; Ishikawa et al. 2015). In a biomechanical analysis, greater femoral rollback and more external rotation of the femoral component were observed in KA TKA than MA TKA; this may explain the better clinical results and patient satisfaction observed in previous clinical studies (Dossett et al. 2014; Ishikawa et al. 2015). However, contact stress at the patellofemoral and tibiofemoral joints was considerably increased with KA TKA, leading to concerns regarding its long-term durability.

In addition, limited data exists on the clinical and biomechanical effects of KA TKA with posterior-stabilized (PS) implants. Previous studies have shown that the kinematics of PS TKA is different from that of CR TKA, and the differences in post-cam design have a significant impact on postoperative knee kinematics (Dennis et al. 2003; Dennis et al. 2004; Nakamura et al. 2014a; Nakamura et al. 2014b). However,

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the kinematic impact of the joint line tilting in PS TKA is unknown. PS implants also have peculiar problems with their post-cam mechanism, including fracture of the post, anterior impingement, and excessive polyethylene wear (Bellemans et al. 2012; Clarke et al. 2004; Mauerhan 2003; Puloski et al. 2001). Unlike CR implants, it is necessary to check the impact of the medial joint line incline on contact mechanics of the post-cam area in PS implants to avoid post-related problems.

Tibiofemoral knee kinematics and contact forces were evaluated using a computational knee simulation model. In addition, contact stresses on the tibiofemoral joint and post area were assessed using finite element (FE) analysis. The purpose of this study was to compare the kinematic and kinetic outcomes of two medial tilting (MT) models with those of MA model in PS TKA, and determine whether the medial tilting of the joint line in PS TKA is appropriate. It was hypothesized that MT model would show near-normal knee kinematics, but that the stresses on the tibiofemoral joint and post area would be greater in MT models than MA model.

2. Methods

A musculoskeletal computer simulation was used to evaluate the results of the various alignment techniques. This model provides dynamic simulation of the knee (LifeMOD/KneeSIM 2010; LifeModeler Inc., San Clemente, CA, USA), including tibiofemoral and patellofemoral contact, lateral collateral ligament (LCL), medial collateral ligament (MCL), elements of the knee capsule, quadriceps muscle and tendon, patellar tendon, and hamstring muscles (Fig. 1). The LCL is considered to be a single fiber bundle, whereas the MCL consists of the anterior and posterior bundles (LaPrade et al. 2005; Sugita and Amis 2001; Warren et al. 1974). All ligament bundles were modeled as nonlinear springs with material properties obtained from a previous report (Blankevoort et al. 1991). The proximal attachment points of the LCL and MCL were defined as the most prominent points of the femoral epicondyles. Their distal attachment points were defined as the tip of the fibular head, and the midpoint between the tibial attachments of the anterior and posterior bundles, respectively. The stiffness coefficients of the LCL and MCL (anterior and posterior bundles) were determined to be 59, 63, and 63 N/mm, respectively; the initial strain of each ligament was determined based on the results of previous cadaver studies (Harner et al. 1995; Robinson et al. 2005; Sugita and Amis 2001).

The KneeSIM program uses implant geometry to analyze the performance of the femoral, tibial, and patellar components, as well as the polyethylene inserts, under a variety of conditions. This program has been validated in previous biomechanical studies, and is able to estimate individual in vivo knee kinematics and contact forces (Mizu-Uchi et al. 2015; Tanaka et al. 2016). In the current study, the model parameters for a fixed-bearing, posterior-stabilized, and total left knee (NexGen LPS-Flex; Zimmer, Warsaw, IN, USA) were imported into the program, and tested during a simulated weight-bearing deep knee bend as described previously (Kuriyama et al. 2014). The femoral component of the implant had a multi-radius, asymmetrical condyle design. During movement, the hip joint was allowed to flex and extend to slide vertically, whereas the ankle joint was allowed free translation in the mediolateral direction, and free varus-valgus and axial rotation. A 4000 N load was applied at the hip; its active driving elements were the forces of the quadriceps and hamstring muscles. The simulation was driven by a controlled actuator arrangement similar to a physical machine. A closed-loop controller applied tension to the quadriceps and hamstrings to match the firing of a prescribed flexion angle at each point; co-contraction between these muscles was defined. The models were subjected to a 4.5-s cycle of a squat motion (0°–130° flexion).

Implantation of the prosthesis was performed using virtual bones of the left knee. The implant sizes were size F for femoral component and size 5 for tibial insert, which were determined to match the size of the virtual bones in the model. For the MA TKA model, the femoral component was aligned perpendicular to the mechanical axis of the femur

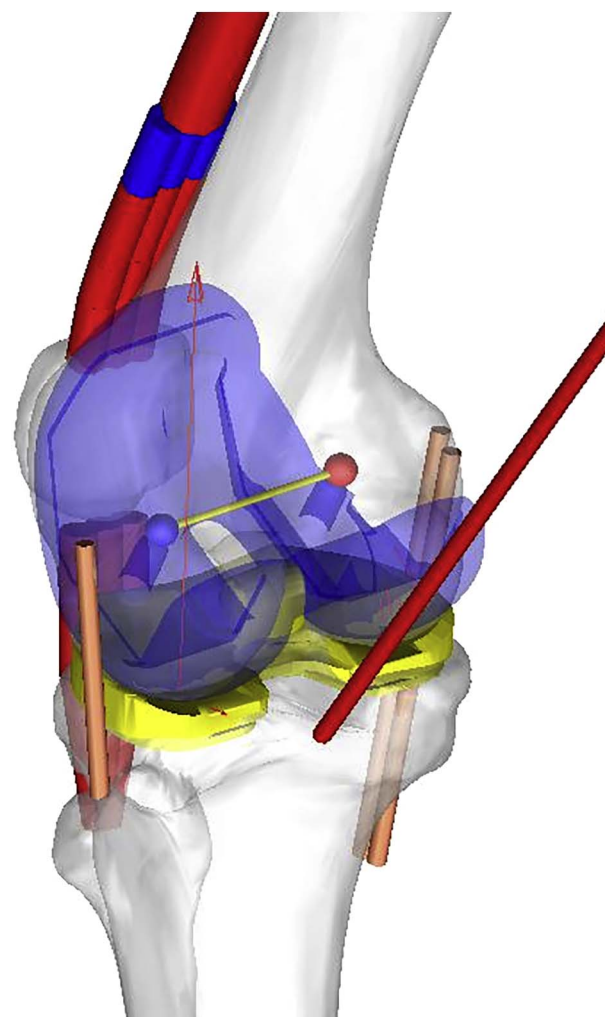


Fig. 1. The KneeSIM model. Red bars indicated quadriceps and hamstrings muscles, and orange bars indicated MCL and LCL. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in the coronal plane, and parallel to the distal anatomical axis of the femur in the sagittal plane. The tibial component was aligned perpendicular to the mechanical axis of the tibia with 7° of posterior tibial slope. The rotational alignments of the femoral and tibial components were determined based on the femoral transepicondylar axis and tibial anteroposterior axis, respectively (Akagi et al. 2004). MT models with different joint obliquity were created based on the MA model. To compare the mechanical alignment, the joint obliquity was determined to be 3° and 5° based on clinical data for KA TKAs (Dossett et al. 2014; Howell et al. 2013a; Howell et al. 2013c; Howell et al. 2013d). In the coronal plane, the femoral component in the MT 3° and 5° models was tilted 3° and 5° valgus coronally, respectively, compared with MA TKA. The tibial component in the MT 3° and 5° models was also tilted 3° and 5° varus. In the axial plane, the femoral component in both MT models was internally implanted by 3° to be tangent to the medial and lateral condyles of the posterior femur, compared with MA TKA. The tibial component in both MT models was also internally rotated by 3° to match the femoral component rotation.

All kinematic measurements were performed at 0°, 30°, 60°, 90°, and 120° of knee flexion. The medial and lateral centers of the femoral condyles were used as geometric reference points, as previously described (Morra et al. 2008). The axial rotations of the femoral component were determined relative to the tibial component. Contact forces were simulated at the anterior and posterior post area, as well as the medial and lateral polyethylene (Fig. 2). The position of the

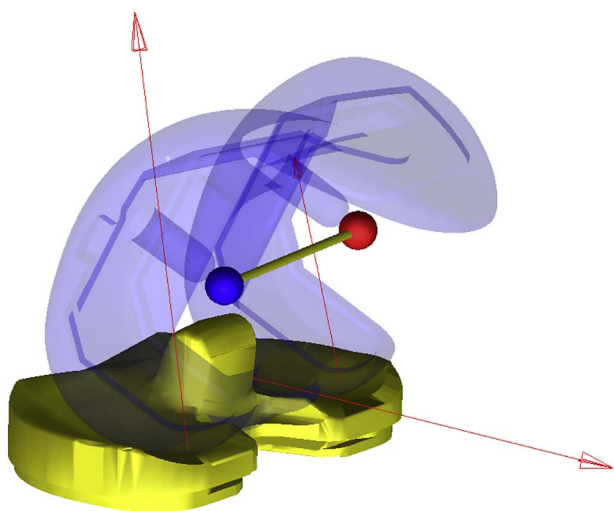


Fig. 2. The tibiofemoral forces were calculated as medial and lateral forces on the tibial insert, and the post/cam contact force was calculated as a single force on the post.

components, and the magnitude and direction of each force, computed by the computer simulation at 0°, 30°, 60°, 90° and 120° of knee flexion, were used in the FE analysis. Contact stresses on the medial and lateral polyethylene, and the anterior and posterior post area against the femoral component interfaces were calculated using three-dimensional FE analysis. FE simulations were performed using the ANSYS Workbench ver. 12.0.1 (ANSYS, Inc., Canonsburg, PA, USA). Young's modulus of the femoral component was set to 240 GPa, which is consistent with data for Co-Cr-Mo alloy femoral components. The tibial insert was modeled as nonlinear elastoplastic materials, as described in a previous study (Kurtz et al. 1999). The mesh of the femoral component and tibial insert were generated based on 10-node quadratic tetrahedral element. At first, a finite element analysis was performed at mesh size of 2.0 mm, and then the mesh size was lowered by 20%. Finally the mesh size of 0.8 mm was adopted so that the difference of the stress level provided by analysis converged in less than 5%. The generated mesh of the MA model at 0° of knee flexion contained a total of 203,676 nodes as a result of 118,036 total elements; the generated mesh of the other models almost had the same number of nodes and elements.

3. Results

All three models exhibited anterior translation of the femoral component relative to the tibia during the early flexion phase, and then posterior translation with knee flexion (Fig. 3). From 0° to 120° of knee flexion, medial anteroposterior translation was −15.1 mm, −14.8 mm, and −8.8 mm in MA, MT 3°, and MT 5° models, respectively. The corresponding values at the lateral side were −14.7 mm, −16.1 mm, and −11.9 mm, respectively. Posterior translation at the lateral side was greater than that at the medial side in the MT models, whereas posterior translation at the medial side was greater in the MA model. A normal axial rotation pattern was observed in both MT models from 0° to 120° of knee flexion, whereas the femoral component rotated internally in the MA model (−0.6°, 1.8°, and 4.2° in the MA, MT 3°, and MT 5° models, respectively). The angular rotation of the femoral component at 120° knee flexion was greater in the MT models than in the MA model (2.4°, 7.2°, and 9.0° in the MA, MT 3°, and MT 5° models, respectively).

In both MT models, lateral tibiofemoral contact forces were greater than medial tibiofemoral contact forces from 100° to 120° of knee flexion (Fig. 4). The anterior post came in contact with the femoral box at knee extension in the MA and MT models. The posterior post then began to come in contact with the femoral cam at approximately 100° in all three models. The anterior post-cam contact forces at 0° were

similar across the models (Fig. 5). The posterior post-cam contact forces during deep knee flexion were greater in the MT models than in the MA model. No contact was observed at the lateral post at any flexion phase for all models.

The peak contact stresses from 0° to 90° of knee flexion were low and almost similar among all models in the FE analyses of the tibiofemoral joint (Fig. 6). At 120° of knee flexion, the contact stresses in the MT TKA models were applied at more medial regions of the polyethylene insert, compared with the MA model. The peak contact stresses were also higher in the MT 3° and 5° models than in the MA model.

In the FE analyses of the post, the peak contact stresses were similar at 0° of knee flexion across the models (Fig. 7-A). At 120° of knee flexion, the peak contact stresses were observed at the posteromedial corner of the post in all models (Fig. 7-B). In addition, the peak contact stresses in the MT models were greater than that in the MA model. The peak contact stresses in MT 3° and MT 5° models were 2.2 and 3.8 times greater than those in the MA model.

4. Discussion

Tibiofemoral knee kinematics, contact forces, and contact stresses on the tibiofemoral joint and post area in MT and MA TKA with PS implants were determined using a computer simulation model and FE analysis. The amount of posterior rollback and axial rotation of MT models were greater than that of the MA model. Medial tilting of the joint line in PS TKA may be beneficial to achieve near-normal knee kinematics. In terms of contact force and stress however, lateral contact forces and forces on the posterior post were greater during deep flexion in the MT models. The contact stress on the posterior tibial post calculated in the FE analysis was much higher in MT models than MA model. Medial tilting of the joint line in PS TKA may result in a shorter longevity because of higher contact force and stress.

Howell et al., recently proposed the KA TKA technique (Howell et al. 2013b; Howell et al. 2013c; Howell et al. 2013d; Howell et al. 2015). KA TKA is based on the concept of achieving premodular joint level and angle, where the femoral component is placed in a slightly valgus and internal rotated position, and the tibial component is placed in a slightly varus and internal rotated position. Recently, a randomized controlled study has shown that KA TKA resulted in better pain relief, postoperative function, and range of motion than MA TKA (Dossett et al. 2014). On the contrary, other randomized control trial reported that there were no statistically significant differences in function one year post-operatively and patient reported outcome scores two years postoperatively (Waterson et al. 2016; Young et al. 2017). However, the concept of KA TKA has only been applied in patients with CR TKA. There has been no clinical or biomechanical analysis about the effects of KA TKA with PS implants.

In a computer simulation study, Ishikawa et al. reported that KA TKA with CR implants had better close-to-normal knee kinematics than MA TKA (Ishikawa et al. 2015). Nishio et al. reported that an intraoperative medial pivot kinematic pattern positively influenced patient-reported outcomes, suggesting that achieving normal knee kinematic patterns in TKA contributes to better clinical results (Nishio et al. 2014). These studies supported the mid-term good functional results of KA TKA reported by Howell et al. In the current study, the tibiofemoral kinematics was simulated for MT models and MA model in PS TKA, which showed that the posterior rollback and femoral external rotation during knee flexion were greater in MT models than in the MA model. These results suggest that KA may contribute to near-normal knee kinematics even with PS implants.

In the current study, the lateral contact force and stress on the tibiofemoral joint at 120° of knee flexion were higher in the MT models than in the MA model, although similar contact force and stress were observed, except in deep flexion range. This is almost the same result reported by a previously published computer simulation study of KA

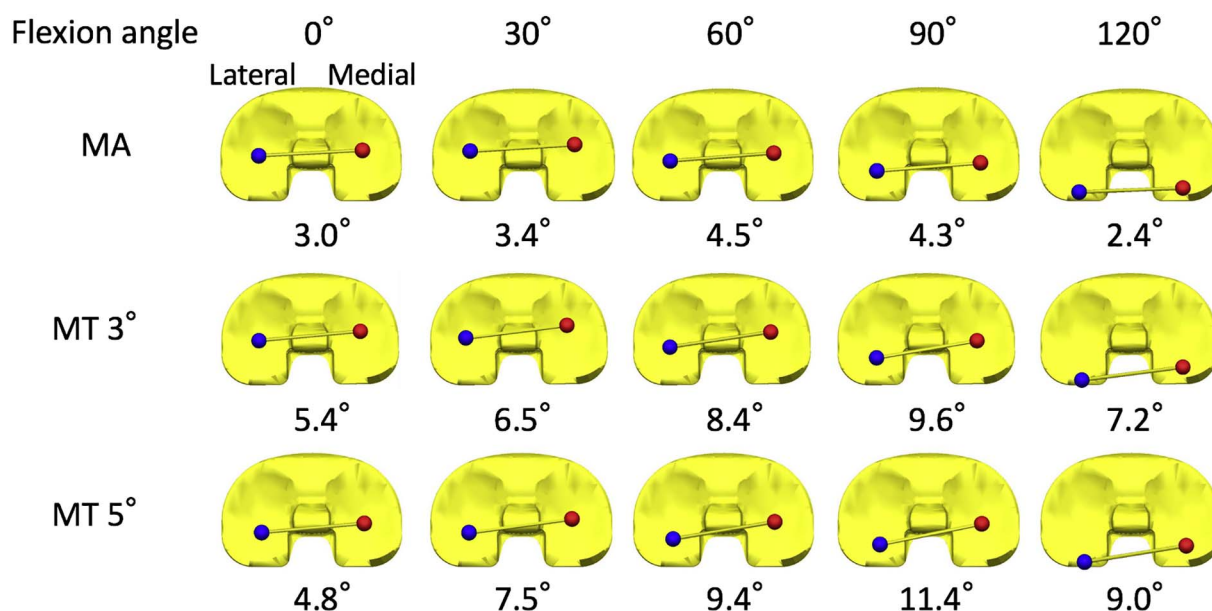


Fig. 3. The anteroposterior positions and rotational angles of the femoral reference axis at 0°, 30°, 60°, 90° and 120° of knee flexion in the three models. (MA: mechanical alignment, MT: medial tilt).

TKA with CR implants (Ishikawa et al. 2015). In addition, the femoral component in MT models was positioned medially relative to the tibial component due to medial tilting, which may have caused the medial shift of the contact area and subsequent unequal contact between the femoral component and the polyethylene. This may explain the increased tibiofemoral contact stress observed in deep knee flexion.

The fracture of the polyethylene tibial post is one of the severe complications of TKA with PS implants (Lee et al. 2009; Mauerhan 2003). Lee et al. reported the case of a patient with a nontraumatic fracture of the tibial polyethylene post that occurred 3 years after TKA with NexGen LPS-Flex (Lee et al. 2009). In another retrieval study, reported burnishing and surface deformation on the anterior surface of the post were reported (Dolan et al. 2011). In the current study, the contact forces and stresses of the anterior post at knee extension were similar among all models. In KA TKA, there were concerns that the medial border of the lateral condyle collided with the lateral aspect of the post because of the medial tilt of the joint line. However, the

collision with lateral condyles at the lateral side of the post was not detected in either MT models or the MA model at any positions. Medial tilting of the joint line in PS TKA seemed to have less effect on the risk for wear at the anterior and lateral post.

In a mechanical study measuring the contact areas and stresses at the posterior post in PS implants, very high contact stress was observed at the post-cam mechanism when the tibial component was rotated (Nakayama et al. 2005). In another mechanical study analyzing recent modified post-cam designs, none of the prostheses exhibited consistently low contact stresses throughout flexion (Akasaki et al. 2008). In the current study, contact stress on the posterior portion of the tibial post at 120° of knee flexion was much higher in the MT 5° model than in the other two models. The larger femoral rotation angle during deep knee flexion in the MT 5° model may have caused the higher contact stress.

This study has several limitations. First, a single implant design was used in the current study. Other implants with different designs may

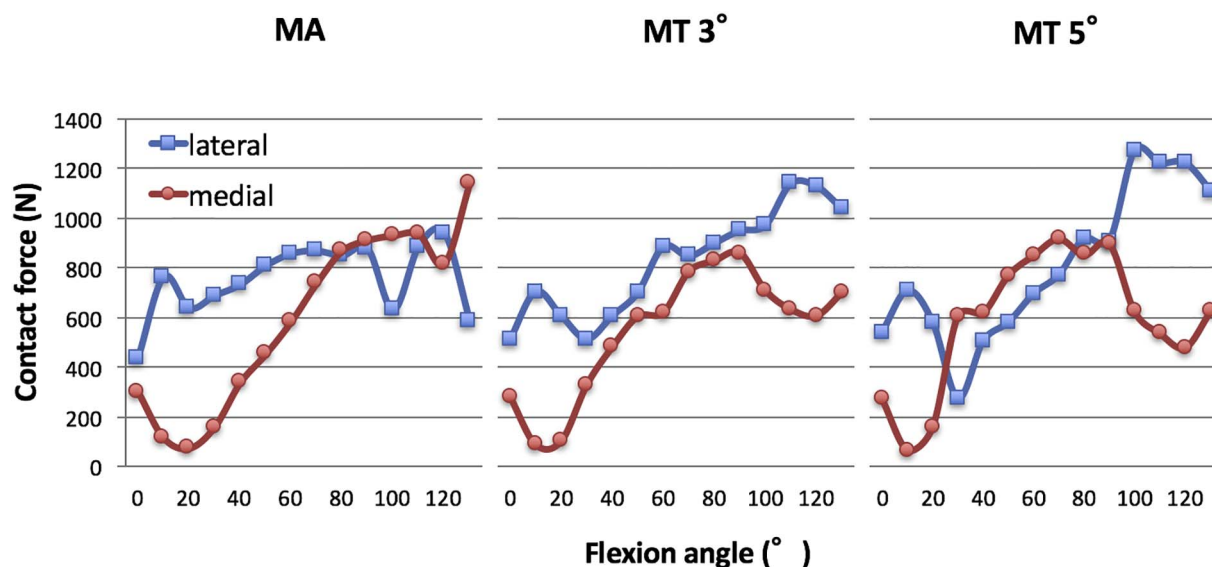


Fig. 4. Diagrams showing the tibiofemoral contact forces from 0° to 130° of knee flexion in the three models. (MA: mechanical alignment, MT: medial tilt).

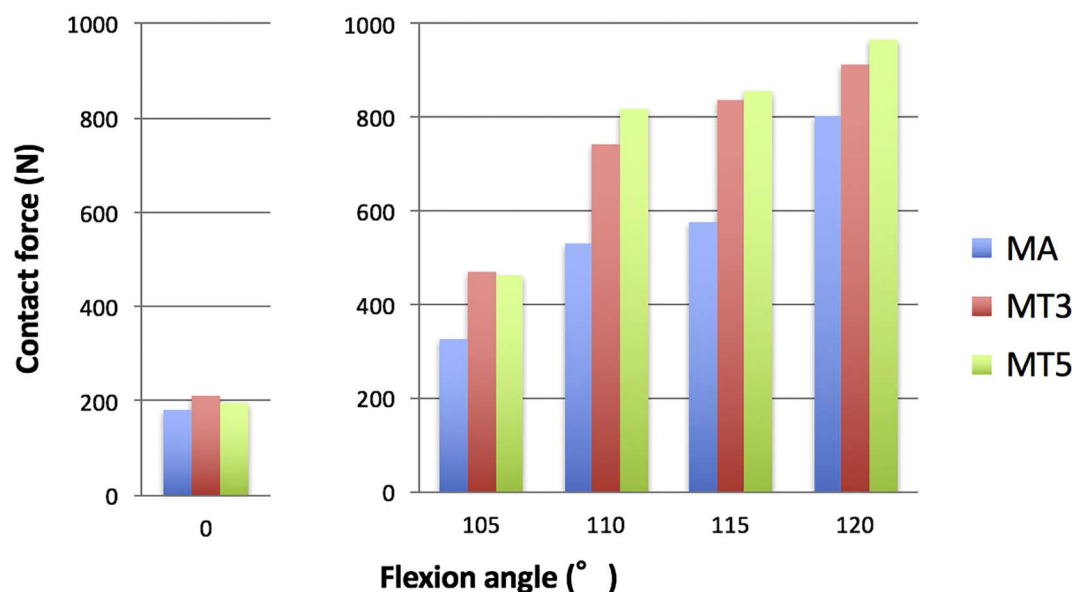


Fig. 5. The anterior post/cam contact forces at 0° of knee flexion (left) and the posterior post/cam contact forces during deep knee flexion (right) in the three models.

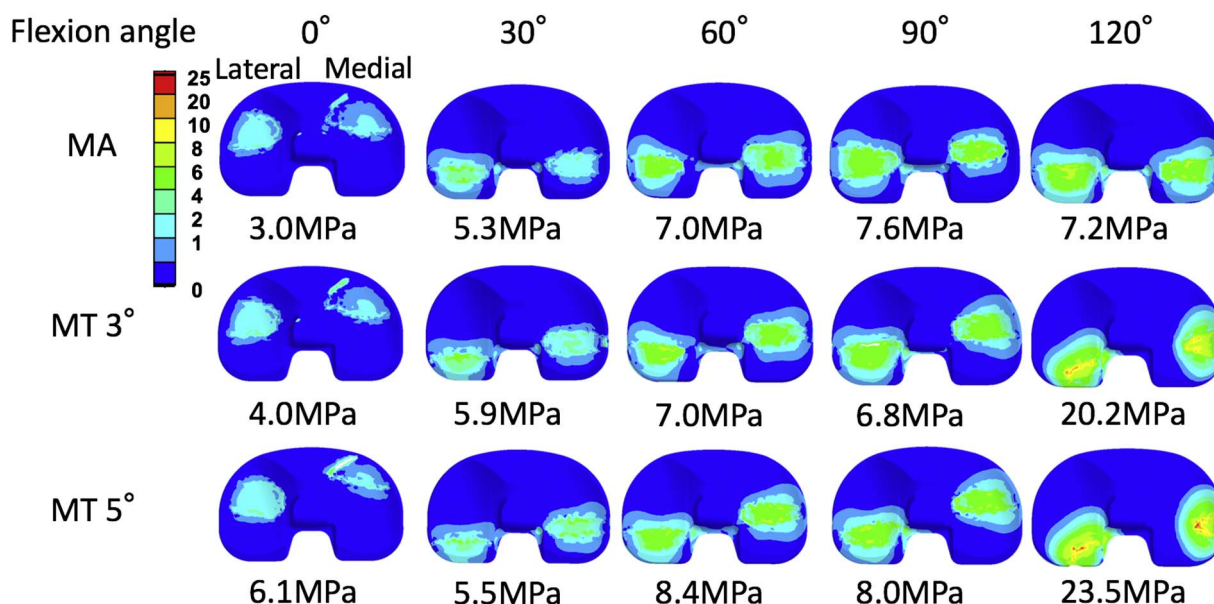


Fig. 6. The contact stresses on the tibiofemoral joint at 0°, 30°, 60°, 90° and 120° of knee flexion in the three models. The values of the each peak contact stress are shown. (MA: mechanical alignment, MT: medial tilt).

have shown different kinematics and contact status. Second, several designs of post-cam mechanism exist. The shape and design of the post-cam mechanism could have affected the kinematics patterns (Dennis et al. 2003; Dennis et al. 2004; Huang et al. 2006). Moreover, the shape and design of post-cam mechanism could have influenced the contact stress of the post-cam mechanism (Akasaki et al. 2008; Nakayama et al. 2005). Therefore, the results of the current study cannot be applied to other post-cam designs. Third, we simulated only one type of motion in the knee—deep knee bending—with computed models applying 4000 N. Other types of motion, such as gait, or the force applied may have shown a different tendency of the kinematics and contact status with MT models. In a gait activity, increase of contact stresses on the tibiofemoral joint and the post area may be small by medial tilt of joint line, because the flexion angle of the knee during gait is less than that during deep knee bend. Fourth, the maximum stress on the post area were considerably high for all models. The edge of the post might lead to these results in the static finite element analyses. Therefore,

comparison between the stress on the post and the stress on condylar contacts could be inappropriate, although comparison between condylar contacts and between the post-cam contacts seemed to be proper. Finally, a computational model cannot reproduce all inherent soft tissue conditions. In other soft tissue conditions, the kinematics and the contact status may be different.

5. Conclusions

Medial tilting of the joint line in PS TKA showed a greater external rotation of the femoral component. These results suggest that KA TKA can achieve near-normal knee kinematics, which may lead to better functional outcomes. However, lateral contact forces and stresses on the posterior portion of the post increased considerably in the medial tilt models in PS TKA. This may lead to significant complications, including excessive polyethylene wear and loosening. KA technique with PS implants may have the potential to achieve near-normal knee kinematics

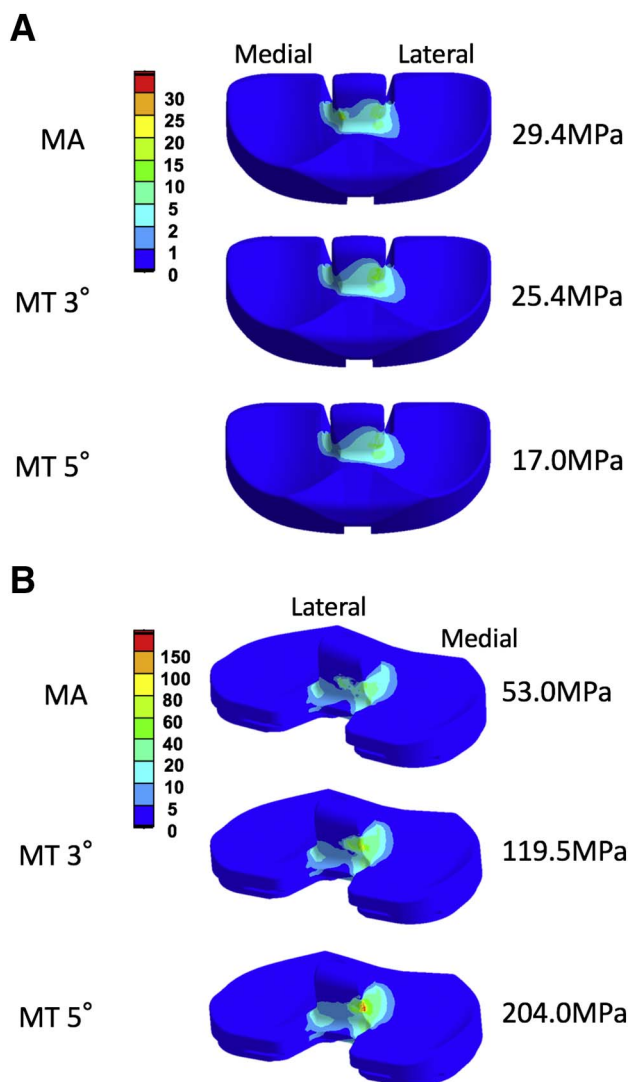


Fig. 7. The contact stresses on the post in the three models. The values of the each peak contact stress are shown. (MA: mechanical alignment, MT: medial tilt) A: The anterior portion of the post at 0° of knee flexion. B: The posterior portion of the post at 120° of knee flexion.

and better functional outcomes. However, this technique may have a negative impact on implant durability, because of higher contact force and stress.

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