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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 premorbid 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 premorbid 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 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.

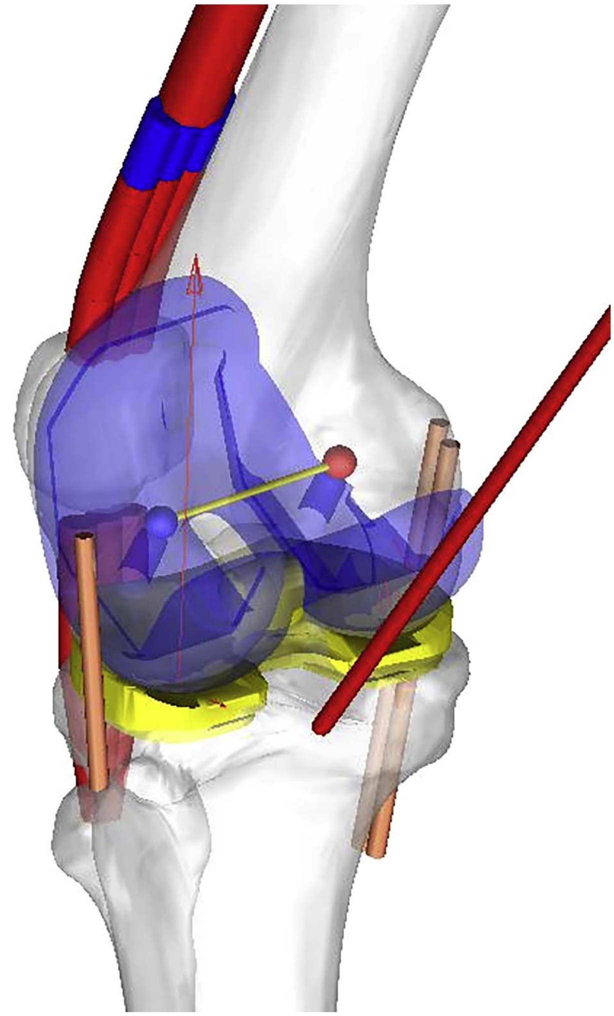

Fig. 1. The KneeSIM model. Red bars indicated quadriceps and hamstrings muscles, and orange bars indicated MCL and LCL. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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