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Comparison of the biomechanical effect of posterior condylar offset and kinematics between posterior cruciate-retaining and posterior-stabilized total knee arthroplasty

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ABSTRACT

Background: The effect of the changes in the femoral posterior condylar offset (PCO) on anterior–posterior (AP) translation and internal–external (IE) rotation in cruciate-retaining (CR) and posterior-stabilized (PS) total knee arthroplasty (TKA) remains unknown. The purpose of this study was to compare the kinematics in CR and PS TKA with respect to the difference in prosthetic design and PCO change through a computational simulation.

Methods: We developed three-dimensional finite element models with the different PCOs of ±1, ±2 and ±3 mm in the posterior direction using CR and PS TKA. We performed the simulation with different PCOs under a deep knee bend condition and evaluated the kinematics for the AP and IE in CR and PS TKA.

Results: The more tibiofemoral (TF) translation in the posterior direction was found as PCO translated in posterior direction for both CR and PS TKA compared to the neutral position. However, the change of the AP translation with respect to the PCO change in CR TKA was greater than PS TKA. The more TF external rotation was found as PCO translated in the anterior direction for both CR and PS TKA compared to the neutral position. However, unlike the TF translation, the TF rotation was not influenced by the PCO change in both CR and PS TKA.

Conclusion: The PCO magnitude was influenced by a postoperative change in the kinematics in CR TKA although a relatively smaller effect was observed in PS TKA. Hence, surgeons should be aware of the PCO change, especially for CR TKA.

1. Introduction

Pain relief and achieving a functional range of motion (ROM) are paramount in achieving success after total knee arthroplasty (TKA). Although TKA leads to a remarkable improvement in the knee function of patients who suffered from osteoarthritis (OA), restoring the pre-diseased ROM in a knee joint is not practically possible [1].

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Many potential factors must be considered. Among the several factors that influence the final postoperative mobility score, preoperative mobility probably has the greatest influence [2,3]. Although the severity of the joint disease and its etiology may have some influence, many other factors, such as the polyethylene (PE) insert design and the retention of the posterior cruciate ligament (PCL), may also affect the ROM. In addition to these factors, the surgical techniques performed, especially in bone resections, are likely to influence the postoperative range of mobility. Among these surgical factors, the changes in the posterior condylar offset (PCO), posterior tibial slope angle, joint line height (JLH), femoral roll back, PCL tension, gap balancing and patellar tracking have been evaluated and analyzed in previous studies [4–7].

A previous study reported that the anterior tibial translation during flexion could be a factor in restricting the maximum flexion by a posterior impingement of the PE insert against the back of the femur [5]. The study defined a parameter termed "PCO" and showed that a decreased posterior condylar offset PCO in a cruciate retaining (CR) TKA could be a causative factor in flexion limitation after TKA [5]. Although the PCO can be controlled by intraoperative bone resections, there is postoperative variability in the posterior translation of the femur in CR TKA because of the differences in TKA implant manufacturers/designs, confounding variables (e.g., soft tissue contractures and PCL integrity, which are difficult to control in vivo) and sample size [8]. However, that the change in the PCO provides an identical biomechanical effect in CR and posterior stabilized (PS) TKA remains controversial [9–11]. Many previous studies focused on whether the PCL is retained or sacrificed. Several clinical and biomechanical references have also been provided [11–15]. However, to the best of our knowledge, no study has evaluated the effect of the change in the PCO on the anterior–posterior (AP) translation and internal–external (IE) rotation in CR and PS TKA.

In the present study, the strength of the computational simulation using a single subject is that the effects of the component alignment within the same subject could be determined without the effect of variables, such as weight, height, bony geometry, ligament properties and component size [16]. Therefore, this study aimed to determine the kinematic changes with respect to the PCO change under a deep knee bend condition in CR and PS TKA. We evaluated the AP translation and the IE rotation in the tibiofemoral (TF) joint. Moreover, we hypothesized that while it was relatively low in PS TKA, a greater effect exists in the kinematics for CR TKA with respect to the PCO change.

2. Materials and methods

The model used herein included features based on a validated finite element (FE) model for a knee joint in a previous study [17–19]. A three-dimensional (3D) non-linear FE model of a normal knee joint was developed using data from computed tomography (CT) and magnetic resonance imaging (MRI) scans of a healthy 37-year-old male subject. The CT and MRI models were developed with slice thicknesses of 0.1 mm and 0.4 mm, respectively. The medical history of the subject did not reveal any musculoskeletal disorders or related diseases arising from a malalignment in the lower extremity, thereby indicating a healthy knee joint.

The reconstructed CT and MRI models were combined with a positional alignment of each model using commercial software, Rapidform (Version 2006; 3D Systems Korea Inc., Seoul, South Korea), to model the bone structures as rigid bodies using four-node shell elements [20]. The major ligaments were modeled using nonlinear and tension-only spring elements [21,22]. The ligament insertion points were made with respect to the anatomy from the MRI sets of the subject and the descriptions based on previous studies [23–25].

To develop the changed PCO models, the surgical simulation of a TKA was performed by two experienced surgeons. Computer-assisted design models of both CR and PS designs from the Genesis II Total Knee System (Smith & Nephew, Inc., Memphis, TN, USA) were virtually implanted in the bone geometry. Size 7 and 5–6 devices were selected for the femoral component and the tibial baseplate based on the dimensions of the femur and the tibia, respectively.

The femoral component was aligned in a neutral position, such that the distal bone resection was perpendicular to the mechanical axis of the femur, and the anterior and posterior resections were parallel to the clinical epicondylar axis in the transverse plane. The tibial default alignment was rotated by 0° relative to the AP axis. Meanwhile, the coronal alignment corresponded to 90° relative to the mechanical axis.

A PCO model identical to that of the original subject was developed, followed by the changed PCO model. The femoral component position was adjusted in the anteroposterior direction to avoid notching of the anterior cortex as per the standard surgical protocol. Seven models were developed with −3, −2, −1, 0, +1, +2 and +3 mm in the posterior direction (Figure 1). This corresponds to the lowest point of a PE insert in the articular surface adjacent to the lowest points of the femoral articular surfaces in the extension.

Contact conditions were applied in the femoral component, PE insert and patellar button in TKA. The coefficient of friction between the PE material and metal was selected as 0.04 for consistency with the explicit FE models proposed in the previous studies [26]. The femoral component, PE insert, tibial component and bone cement were made of cobalt–chromium–molybdenum (CoCrMo) alloy, ultra-high-molecular-weight-polyethylene (UHMWPE), titanium (Ti6Al4V) alloy and poly (methyl methacrylate) (PMMA), respectively. In a manner similar to that in the previous studies, the materials were assumed to be homogeneous and isotropic in this case, except for the PE insert [26–30]. The PE insert was modeled as an elastoplastic material. With respect to the UHMWPE, the yield strength and the ultimate tensile stress corresponded to 17 MPa and 33 MPa, respectively [26]. A cement layer was considered with a constant penetration depth of three millimeters into the bone based on a test for different cementing techniques at the femoral and tibial resection surfaces in contact with the femoral and tibial components, respectively [31,32]. The interfaces between the prosthesis and the bone were rigidly fixed by considering the cement used [29,33].

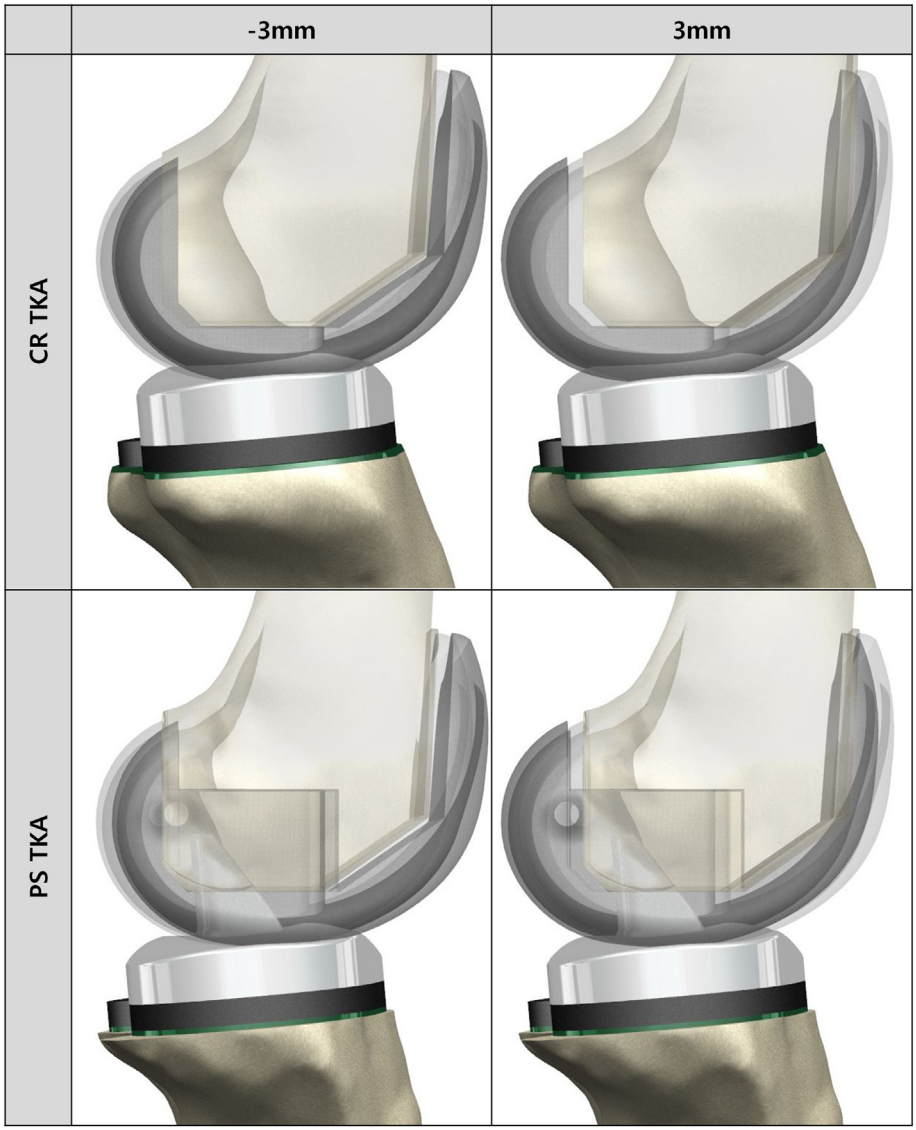

Figure 1. Schematic of the knee models with respect to change in posterior condylar offset in cruciate-retaining (CR) and posterior-stabilized (PS) total knee arthroplasty (TKA).

The PCO change model topologies provided six degrees of freedom to the TF and patellofemoral (PF) joints. The FE investigation included two types of loading conditions corresponding to the loads used in the experiments in the study for the TKA model validation and model predictions under deep knee bend loading conditions. The intact model was validated in a previous study [17–19], while the TKA model was validated through a comparison with the models used in a previous study [34]. A conservative ankle force of 50 N and a hamstring force of 10 N were continuously exerted with respect to a linearly increasing force and a maximum of approximately 600 N at a 90° flexion of the quadriceps actuators for the TKA model under the first loading conditions [34,35]. The second loading conditions corresponded to the deep knee bend loading applied to evaluate the effects of the increased PTS. A computational analysis was conducted with an AP force applied to the femur with respect to the compressive load applied to the hip [36–38]. A proportional–integral–derivative controller was incorporated into the computational model to control the quadriceps in a manner similar to that in a previous experiment [39]. A control system was used to calculate the instantaneous displacement of the quadriceps required to match the target flexion profile, which was the same as that in the experiment [39]. IE and varus–valgus torques were both applied to the tibia [36–38].

The FE model was analyzed using the ABAQUS software (Version 6.11; Simulia, Providence, RI, USA). The movement of the contact point and the kinematics in the TF joint, the forces on the collateral ligament and on the quadriceps and the PF contact stress were calculated throughout the deep knee bending task. The anterior tibial translation was calculated based on Grood and Suntay's definition of a joint coordinate system [40].

3. Results

3.1. TKA model validation

In the FE model for CR TKA, posterior tibial translations were 0.6, 3.2, 6.3, 5.1 and 4.1 mm, respectively, in 30°, 45°, 60°, 75° and 90° flexions (Figure 2 (a)), and in the FE model for PS TKA, the internal tibial rotations were 0.57°, −0.88°, −0.71°, −0.11° and 0.83°, respectively, in 20°, 40°, 60°, 80° and 100° flexions (Figure 2 (b)). The results of the simulation and a previous experiment showed good agreement within the range of values in both PS and CR TKA under the loading conditions applied to a prosthetic implant [34,35].

3.2. Tibiofemoral kinematics and contact point with respect to the PCO change in CR and PS TKA

Figure 3 shows the AP translation and the IE rotation for the TF joint with respect to the change in the PCO under the deep knee bend condition in both CR and PS TKA. Both CR and PS TKA posteriorly translated in the TF joint as the PCO translated in the posterior direction. The effect of the PCO change was greater in CR TKA than in PS TKA. The change of the TF joint translation was less in PS TKA because the PCO posteriorly translated. In addition, the amplitude of AP translation increased as the PCO translated in the posterior direction in both CR and PS TKA. Both CR and PS TKA externally rotated in the TF joint as the PCO translated in the anterior direction. A relatively smaller effect of the PCO change was found on the rotation compared to translation in the TF joint for both CR and PS TKA.

In contrast to AP translation, the change in IE rotation was greater in PS TKA than CR TKA. The distance traveled by the TF joint contact point translated in the posterior direction on both the medial and lateral sides with increases in the PCO for both CR and PS TKA (Figure 4). With respect to the neutral-position PCO reference, an increased PCO resulted in an increased excursion of the TF contact point that shifted to a more posterior position on both the lateral and medial sides in the extension. Figure 5 shows TF contact point displacement in deep knee bend simulation.

4. Discussion

The most important finding of this study was that the PCO change caused the kinematic changes in both CR and PS TKA. The CR and PS TKA movement in the TF joint increased as the PCO translated in the posterior direction.

A number of studies have compared the results of CR and PS TKA [11–15]. Hirsch et al. found that superior postoperative flexion was provided in PS TKA [13]. A potential disadvantage in CR TKA is a physiological function (e.g., pattern of change in tension through ROM) that cannot always be reproduced after TKA. Bellemans et al. found the mechanism of limited maximum knee flexion in vivo in CR TKA and reported that the maximum degree of active flexion was caused by a direct impingement of the posterior aspect of the PE insert against the shaft of the femur in 72% of the knees [5]. They further showed that a mechanical block caused by the impingement was related to a forward sliding of the femur during flexion, leading to the limitation of flexion in CR TKA with anteriorly translated PCO [5]. Arabori et al. reported that the magnitude of the PCO was correlated with a postoperative change for the flexion angle in CR TKA, while no such correlation was observed in PS TKA [11]. Moreover, the TF translation and rotation were important and led to a maximal flexion throughout the femoral rollback. Hence, flexion in the force application to the native knee flexor muscles may allow for a more physiologic method to assess the posterior TF translation and flexion [1,8,41].

To our knowledge, this study is the first to evaluate the translation and rotation in the TF joint with respect to the PCO change in both CR and PS TKA. We used the validated 3D FE model to investigate the change in the kinematic pattern with respect to the

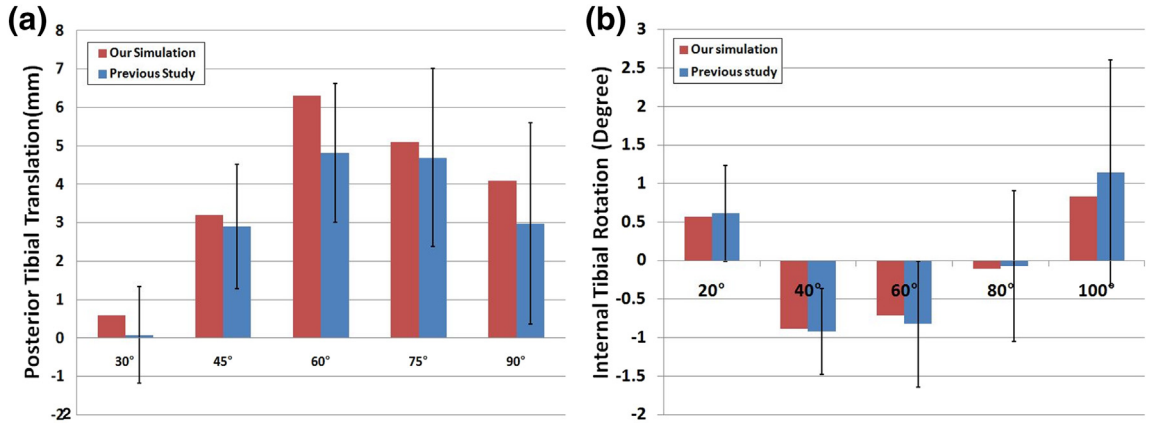

Figure 2. Comparison of (a) posterior tibial translation in cruciate-retaining total knee arthroplasty and (b) internal tibial rotation in posterior-stabilized total knee arthroplasty between finite element models and previous experimental data.

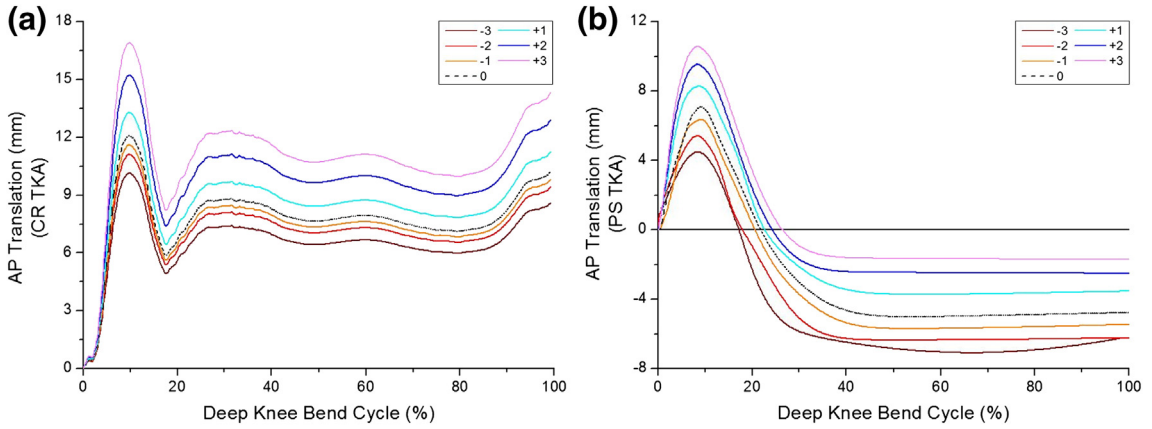

Figure 3. Change in anterior–posterior (AP) translation on tibiofemoral joint with respect to posterior condylar offset change in both (a) cruciate-retaining (CR) and (b) posterior-stabilized (PS) total knee arthroplasty (TKA).

PCO change. We found that the PCO change influenced the kinematics. AP translation change was more sensitive than IE rotation when PCO changed.

Posterior TF translation is important in TKA because it provides more flexion prior to TF impingement [1]. In addition, a more posterior TF contact point at full flexion improves the quadriceps moment arm and has been associated with improved International Knee Society Function scores in CR TKA. A properly balanced PCL is paramount in achieving maximal flexion in CR TKA [42,43]. Previous 3D fluoroscopic analysis of TKA found that PS TKA consistently provided posterior femoral rollback with flexion, while an anterior femoral translation with flexion was observed in CR TKA [44–46]. Therefore, in contrast to that in CR TKA, the post-cam mechanism in PS TKA can theoretically prevent an anterior femoral translation during flexion, causing posterior impingement even with the presence of the anteriorly translated PCO.

We investigated and proved that the TF joint translated in the posterior direction as the PCO increased in CR TKA. In other words, CR TKA with an increased PCO has a greater possibility of providing greater flexion. The TF joint also translated to the posterior direction as the PCO increased in PS TKA. Interestingly, the PCO change led to the translation of the TF joint in CR TKA, but relatively less in PS TKA, and it could be explained by the post-cam mechanism. Although the PCO changed, a limited ROM exists because of the post-cam mechanism in PS TKA.

Compared to CR TKA, PS TKA is characterized by different biomechanical mechanisms. Its post-cam mechanism can produce a femoral rollback similar to that of a normal knee during flexion [47]. Therefore, that PS TKA can prevent a posterior impingement is widely accepted, and the PCO is not related to ROM in PS TKA [11,48]. These results showed good agreement with those of the previous studies, in which the maximum flexion was improved by the translation of the TF joint in the posterior direction in CR TKA [1,5,11,49]. Such a trend was also found in previous studies on the posterior slope for in vitro and computational simulation [50–53]. Increasing the posterior tibial slope and the PCO induced a more posterior position of the femoral component. A more posterior contact position in the TF joint led to an increase in the quadriceps lever arm, showing an improvement in the movement efficiency that contributes to a reduced quadriceps muscle force [52,54,55]. Although the femoral component was in the posterior position, an advantage in the quadriceps muscle force was observed for CR TKA in a computational study [50,52].

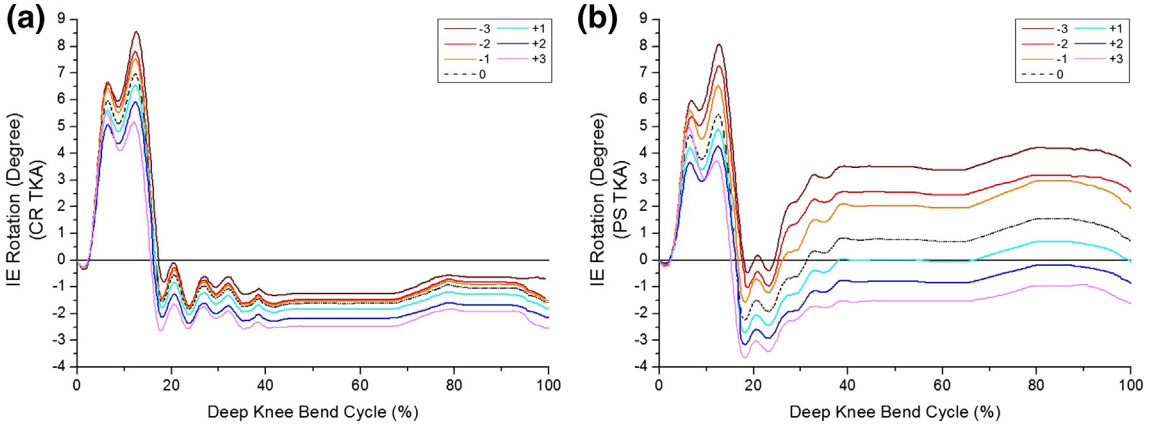

Figure 4. Change in internal–external (IE) rotation on tibiofemoral joint with respect to posterior condylar offset change in both (a) cruciate-retaining (CR) and (b) posterior-stabilized (PS) total knee arthroplasty (TKA).

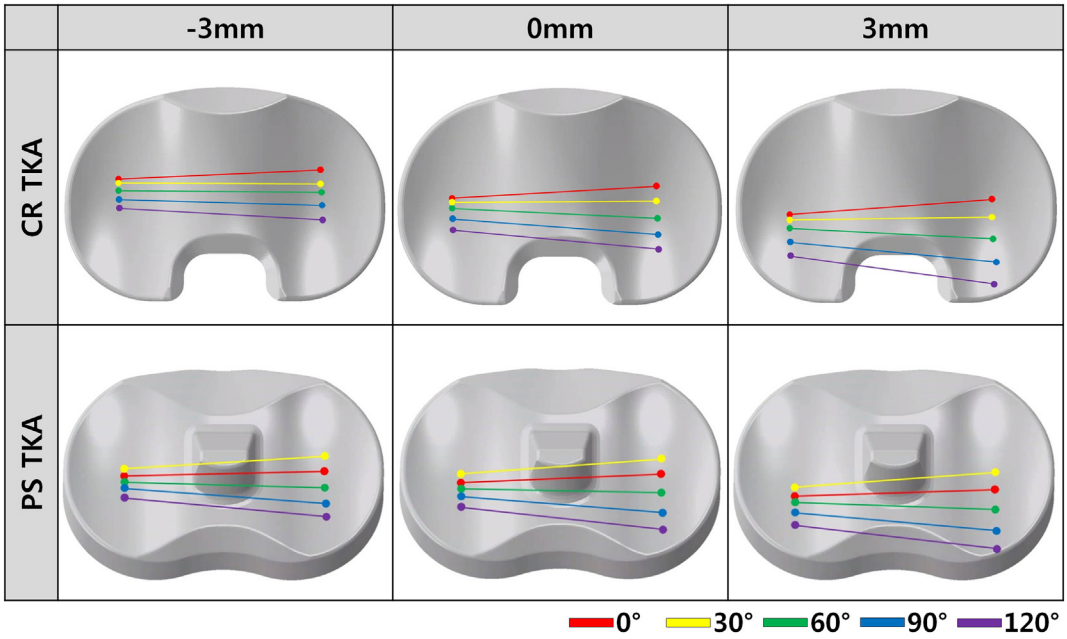

Figure 5. Tibiofemoral (TF) contact point displacement in deep knee bend simulation. CR, cruciate-retaining; PS, posterior-stabilized; TKA, total knee arthroplasty.

However, we found that the effect was smaller in PS TKA than CR TKA when the femoral component was in the posterior position but there was advantage in the quadriceps muscle force [54,55].

The flexion of a normal knee is accompanied by femoral rollback and tibial internal rotation. The asymmetric rollback of the femur relative to the tibia is a major factor for the ROM in the knee joint [56,57]. A decreased axial rotation in the TKA has been found in cadaveric studies as well as in active patients [58]. We found that the TF joint was less influenced by rotation compared to translation with the PCO change in both CR and PS TKA. The change in the sagittal curvature and the lever arm may influence the AP translation in the TF joint because of the femoral position with the PCO change. However, this change does not affect the coronal curvature, which is dominant in the IE rotation. In addition, the contact point has proven that the PCO change influences the position of the contact point and the AP translation of the TF joint, but not the IE rotation. Unlike AP translation, the total change in IE rotation in PS TKA was greater than CR TKA with respect to PCO change. It could also be explained by a post-cam mechanism. As TF joint increased flexion angle, IE rotation could increase due to post-cam.

Our results showed that the PCO change influenced the AP translation of the TF joint, but to a lesser extent in IE kinematics for both CR and PS TKA. The kinematic change was more sensitive in CR TKA than in PS TKA. Therefore, surgeons should be careful in preserving the PCO in CR TKA.

This study has several limitations. First, although a deep knee bending simulation was been performed, additional simulations related to more demanding activities are required in the future for a more reliable investigation. The simulation was performed under deep knee bending motions because such motions include both a wide range of flexion/extension and a significant muscular endeavor around the knee joint. Second, the computational model was developed using data from a single subject, but it does not represent an in vivo environment by considering anatomic variations and age-related changes in the ligament and the cartilage. Thus, the number of subjects in the future research must be expanded. This approach is widely used in orthopedic biomechanics [17–20,36,39,50,52]. Third, only one prosthesis was used for the simulation. Therefore, we should evaluate different types of implants in the future and compare the results to our present findings. TKA designs with different TF articular conformity, mobile-bearing designs, and designs with a medial or lateral pivot influence knee joint forces and kinematics, particularly AP translation, and cause different results for the medial and lateral condyles in the coronal plane. Future work should determine the sensitivity of our results to subject characteristics and TKA geometry. Finally, although the material properties and attachment points for the ligaments used in the model were assumed based on previously published studies, considerable variability exists. Our objective was not to determine the quantitative values for the muscle and ligament forces, but to determine the effects of variability in the PCO on our variables of interest.

In conclusion, the PCO change influenced a postoperative change in the kinematics for CR TKA. In contrast, a relatively smaller effect in kinematics was observed for PS TKA. In conclusion, the PCO is the important factor in TKA that may influence postoperative kinematics. Hence, surgeons should be careful in changing the PCO, especially in CR TKA.

Conflict of interest

The authors have no conflicts of interest to declare.

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