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Posterior tibial slope and anterior post-cam contact can change knee kinematics in extension in bi-cruciate stabilized total knee arthroplasty

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Aims

This study aims to investigate the effects of posterior tibial slope (PTS) on knee kinematics involved in the post-cam mechanism in bi-cruciate stabilized (BCS) total knee arthroplasty (TKA) using computer simulation.

Methods

In total, 11 different PTS (0° to 10°) values were simulated to evaluate the effect of PTS on anterior post-cam contact conditions and knee kinematics in BCS TKA during weight-bearing stair climbing (from 86° to 6° of knee flexion). Knee kinematics were expressed as the lowest points of the medial and lateral femoral condyles on the surface of the tibial insert, and the anteroposterior translation of the femoral component relative to the tibial insert.

Results

Anterior post-cam contact in BCS TKA was observed with the knee near full extension if PTS was 6° or more. BCS TKA showed a bicondylar roll forward movement from 86° to mid-flexion, and two different patterns from mid-flexion to knee extension: screw home movement without anterior post-cam contact and bicondylar roll forward movement after anterior post-cam contact. Knee kinematics in the simulation showed similar trends to the clinical in vivo data and were almost within the range of inter-specimen variability.

Conclusion

Postoperative knee kinematics in BCS TKA differed according to PTS and anterior post-cam contact; in particular, anterior post-cam contact changed knee kinematics, which may affect the patient's perception of the knee during activities.

Article focus

- This study investigated the effects of posterior tibial slope (PTS) on knee kinematics involved in the post-cam mechanism in bi-cruciate stabilized (BCS) total knee arthroplasty (TKA) using computer simulation.
- It was hypothesized that postoperative knee kinematics would vary with PTS, and the presence of anterior post-cam contact would affect knee kinematics.

Key messages

- Anterior post-cam contact occurred with the knee near extension when PTS was 6° or more.
- When PTS was less than 6°, screw home movement occurred without anterior post-cam contact.
- On the other hand, when PTS was 6° or more, knee kinematics with the knee extension showed bicondylar roll forward movement instead of screw home movement by anterior post-cam contact.

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Strengths and limitations

- Knee kinematics were analyzed with 11 different PTS angles using a computer model that was validated adequately with in vivo data.
- Only weight-bearing stair climbing was simulated in this study.

Introduction

Ideal postoperative knee kinematics after total knee arthroplasty (TKA) should reproduce normal knee kinematics as closely as possible. Bi-cruciate stabilized (BCS) TKA was designed to improve the disadvantages of conventional posterior-stabilized (PS) TKA, which showed several pivoting patterns.[1-3] The design concept behind BCS TKA is to promote normal knee kinematics by incorporating both anterior and posterior post-cam mechanisms to replicate the function of the anterior cruciate ligament (ACL) and the posterior cruciate ligament. In addition, the tibial articular geometry of BCS TKA is designed asymmetrically: it is medially concave and laterally convex in the sagittal alignment. These features can stabilize the knee in the sagittal alignment and guide screw home movement. Some studies reported that compared to conventional PS TKA, the in vivo kinematics of BCS TKA are closer to those of the normal knee.[2,4] However, the effects of postoperative alignment and implant design on knee kinematics were not reported in detail.

The post-cam mechanism in BCS TKA is expected to achieve greater knee stability and to induce constant femoral rollback, which increases the postoperative knee flexion angle and decreases the patellofemoral contact force.[5,6] However, none have investigated in detail the effects of the post-cam mechanism on postoperative knee kinematics in BCS TKA. The patient's perception of the knee during activities can be affected by the change of postoperative knee kinematics. In addition, it is unknown whether anterior post-cam contact always occurs near full knee extension in BCS TKA. Finally, the presence or absence of anterior post-cam contact may affect knee kinematics.

Posterior tibial slope (PTS) is also one of the factors that affects knee kinematics and function.[7,8] Increased PTS can improve knee flexion and reduce the amount of quadriceps force necessary for knee motion.[9,10] In contrast, Gromov et al[11] reported that implant survival requires a PTS within 0° to 7° because excessive PTS can lead to knee instability. It is difficult to determine the effect of PTS on knee kinematics, particularly knee conditions involved in post-cam mechanism by various factors. It would be useful to understand how the association between PTS and the post-cam mechanism influences knee kinematics under various postoperative conditions.

The purpose of this study was to use a computer simulation to investigate the effects of PTS on knee kinematics involved in the post-cam mechanism in BCS TKA. It was hypothesized that postoperative knee kinematics would vary with PTS, and the presence of anterior post-cam contact would affect knee kinematics.

Methods

Computer simulation. This study simulated BCS TKA (Journey 2 BCS; Smith & Nephew, Memphis, Tennessee, USA) implanted in a female patient with an osteoarthritic knee (a height of 162 cm and a weight of 58 kg), performing weight-bearing stair climbing. A 3-dimensional(3D) bone model was reconstructed from preoperative CT data using MIMICS (Materialise, Leuven, Belgium). All the components were implanted in an appropriate size for the patient's bone structure. Initial coordinates of implants were determined using a computer-assisted design software programme (Rhinoceros; Robert McNeel and Associates, Seattle, Washington, USA).[6,12] The origins of the initial coordinates for BCS TKA were the centre of the tibial insert, which is the intersection of the perpendicular bisector that creates rectangles in both the anteroposterior (AP) and mediolateral dimensions. Both femoral and tibial components were implanted perpendicular to the femoral and tibial mechanical axis in the coronal plane. For the sagittal alignment, the femoral component was aligned to the femoral mechanical axis. The neutral rotational alignments of the femoral and tibial components were aligned parallel to the femoral epicondylar axis and the tibial AP axis, respectively. The most distal condylar points of the femoral component were set on the surface of the tibial insert in the superoinferior dimension.

The bone and implant geometry were imported into a dynamic musculoskeletal modelling programme (LifeMOD/KneeSIM 2010; LifeModeler, San Clemente, California, USA; Figure 1). This model has been reported as a useful tool for kinematic evaluation.[6,13,14] KneeSIM employs rigid body dynamics to simulate weight-bearing stair climbing using an Oxford-type knee rig.[15] The masses of the limb segments and body weight generated a flexion moment on the knee, whereas the quadriceps muscle exerted an extension moment. This musculoskeletal model of the knee included the medial collateral and lateral collateral ligaments, the quadriceps muscle and tendon, the patellar tendon, and the hamstring muscles. The proximal attachment points of the medial collateral ligament and lateral collateral ligament were defined as the most prominent epicondyles of the femur. Collateral ligaments were modelled as nonlinear springs with material properties obtained from a published report.[16] Contact between the tibiofemoral and patellofemoral articular surfaces was simulated. The hip and ankle joints had all three rotational degrees of freedom. The ankle section had no translational degrees of freedom. The hip section was constrained in the mediolateral and AP directions but was free to translate vertically in the direction of gravity under axial forces that generated a flexion moment at the knee. We applied a constant vertical force of 3,000 N, which is equivalent to approximately five times body weight (58 kg) in this simulation. This load was applied at the hip and loaded onto the knee joint.[14,17]

Evaluation of knee kinematics and forces during computer simulation. Knee kinematics were calculated during
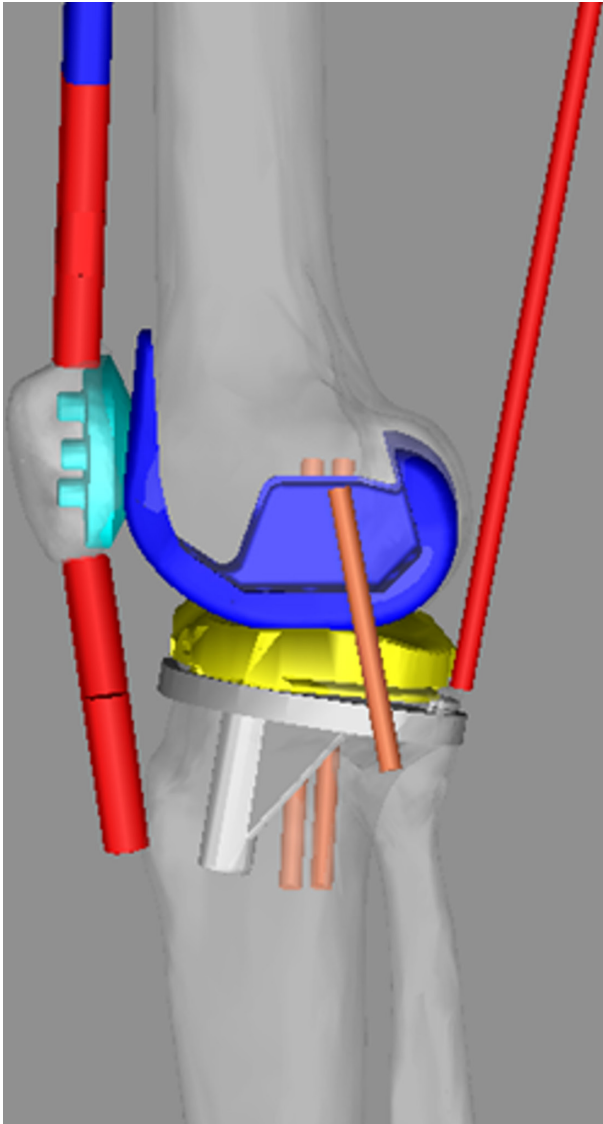
Fig. 1

Postoperative knee model imported into the LifeMOD/KneeSIM 2010 (lateral view).

simulated stair climbing (from 86° to 6° of knee flexion), and were expressed as the medial femoral condylar lowest point (CLP) and lateral femoral CLP on the surface of the tibial insert, and AP translation of the femoral component relative to the tibial insert. The AP translation of the femoral component and the medial and lateral femoral CLPs were defined as anterior (positive) or posterior (negative) relative to the midline of the tibial tray. The preoperative PTS of this simulation model was 8.4°. BCS TKA has a built-in anterior slope of 3° on the medial side and posterior slope of 1° on the lateral side. In total, 11 different PTS angles (0° to 10°) were simulated to evaluate the effect of PTS on knee kinematics; 0° of PTS was defined as perpendicular to the tibial mechanical axis, specified as the line connecting the centre of the insert to the centre of the ankle. We changed the PTS at 1° intervals, ranging

from 0° to 10°, based on the origin of the coordinates (the centre of the tibial insert) in the sagittal alignment.

Anterior/posterior post-cam contact was defined as contact between the anterior/posterior aspect of the tibial post and the femoral component in KneeSIM. Knee kinematics before and after anterior post-cam contact were evaluated using KneeSIM. In addition, the contact area on the anterior aspect of the tibial post was evaluated using a finite element (FE) model. FE simulations for BCS TKA were performed using FEMAP (Siemens PLM Software, Plano, Texas, USA). The femoral component, which is similar to the Co-Cr-Mo alloy femoral component, was modelled as a linear elastic body. The tibial insert consisting of ultra-high molecular weight polyethylene was modelled as a nonlinear elastoplastic body. The Young's modulus was set at 220 GPa for the femoral component and 0.9 GPa for the tibial insert, while Poisson's ratio was set at 0.31 and 0.45, respectively. The meshes of the femoral component and the tibial insert were generated based on tetrahedral elements at 0.5 mm. The generated mesh contained a total of 597,570, 637,093, and 493,919 nodes for the femoral component and 500,530, 523,973, and 600,790 nodes for the tibial insert. This was as a result of 405,722, 432,970, and 408,017 total elements for the femoral component and 346,627, 363,242, and 341,972 total elements for tibial insert, for simulations with PTS of 6°, 8°, and 10°, respectively. The maximum von Mises stress on the anterior aspect of the tibial post was analyzed.

Comparison of the simulation model and in vivo data. Clinical (in vivo) data were used to compare with the computational model. A total of 15 knees (three male and 12 female) received the Journey 2 BCS implant used in our computer simulation. This study was approved by the institutional review board of Kyushu University (No.28-366). Informed consent was obtained from all patients prior to study participation. Ten female knees were chosen to compare with the computer model after matching for sex and PTS (0° to 5°). The mean age was 71.3 years (SD 3.8), the mean PTS was 2.8° (SD 1.8°), and the mean postoperative follow-up was 13.0 months (SD 1.8). Pre- and postoperative patient-reported outcomes were assessed using the 2011 Knee Society Score (KSS 2011).[18] The subjective component of KSS 2011 evaluates the following: symptoms; patient satisfaction; and functional activities. Continuous sagittal radiological images were obtained in each patient during stair climbing using a flat-panel detector (Clavis; Hitachi, Tokyo, Japan), and analyzed using a 2D–3D image-matching technique.[19] Medial and lateral femoral CLPs were compared between the computer simulation and clinical data. The occurrence of contact between the anterior cam and the post was determined by the intersection of the femoral component and the tibial post, while assessing the configuration of the articular surfaces of the polyethylene insert.[19]

Results

Knee kinematics in the simulation. The femoral component of BCS translated anteriorly during stair climbing
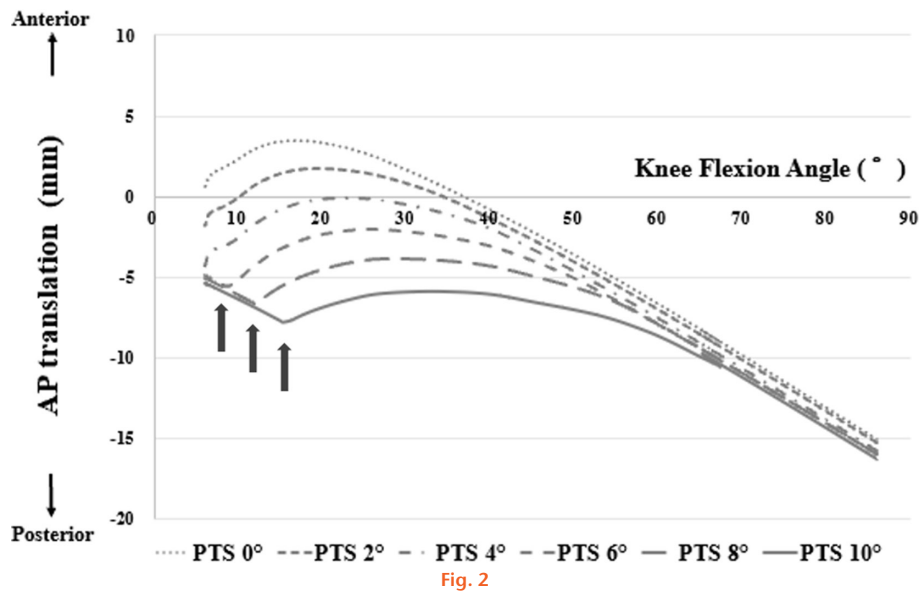
Fig. 2

Anteroposterior (AP) translation of the femoral component relative to the tibial insert during stair climbing using bi-cruciate stabilized (BCS) total knee arthroplasty (TKA). The arrows indicate points at which the femoral component has moved forward due to anterior post-cam contact (posterior tibial slope (PTS) of 6°, 8°, and 10°).
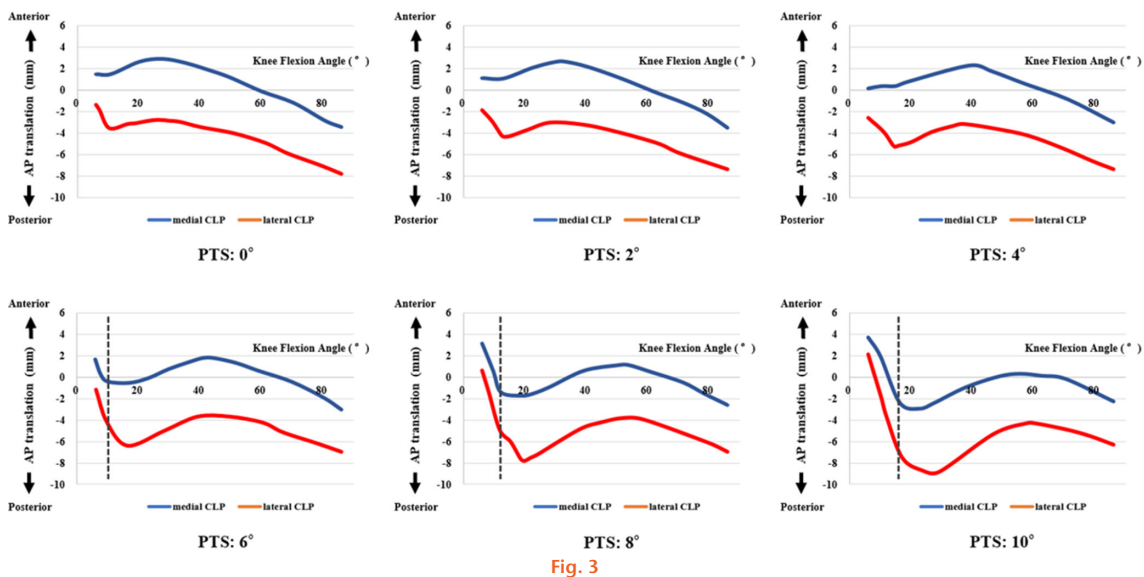

Fig. 3

The medial condylar lowest point (CLP) and lateral femoral CLP of the femoral component relative to the tibial insert in bi-cruciate stabilized (BCS) total knee arthroplasty (TKA). The dot lines indicate knee flexion angle at which the anterior post-cam contact occurred. AP, anteroposterior; PTS, posterior tibial slope.

from 86° to 6° of knee flexion (Figure 2). Increases in PTS resulted in a more posterior position of the femoral component relative to the tibial insert and reduced the amount of AP translation. All simulation models showed posterior post-cam contact from 86° to 65° of knee flexion, but posterior post-cam contact disengaged as the femoral component moved further forward.

When PTS was 6° or more, the femoral component moved forward due to anterior post-cam contact, which was observed with the knee near extension (Figure 2). Anterior post-cam contact in the simulation model with

PTS of 6°, 8°, and 10° occurred at knee flexion angles of 10.1°, 12.2°, and 16.3°, respectively. The existence of anterior post-cam contact depended on whether PTS was less than or more than 6°, and this boundary defined two patterns of knee kinematics from mid-flexion to knee extension. When PTS was less than 6°, medial femoral CLP stayed at almost the same location and lateral femoral CLP moved forward from mid-flexion to knee extension, indicating a screw home movement (Figure 3). On the other hand, for simulation models with a PTS of 6° or more, medial femoral CLP moved forward with lateral
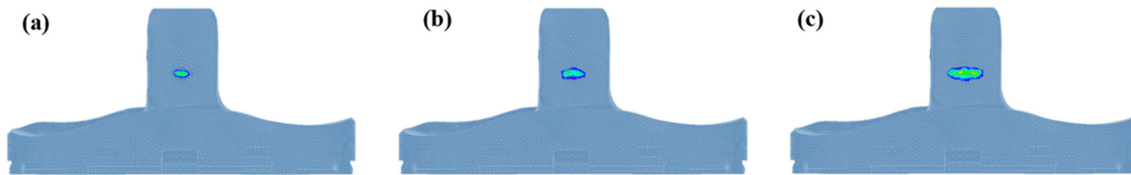
Fig. 4

Contact area of the anterior aspect of the tibial post using a finite element (FE) model (anterior view). a) Posterior tibial slope (PTS) of 6°, (b) PTS of 8°, (c) PTS of 10°.
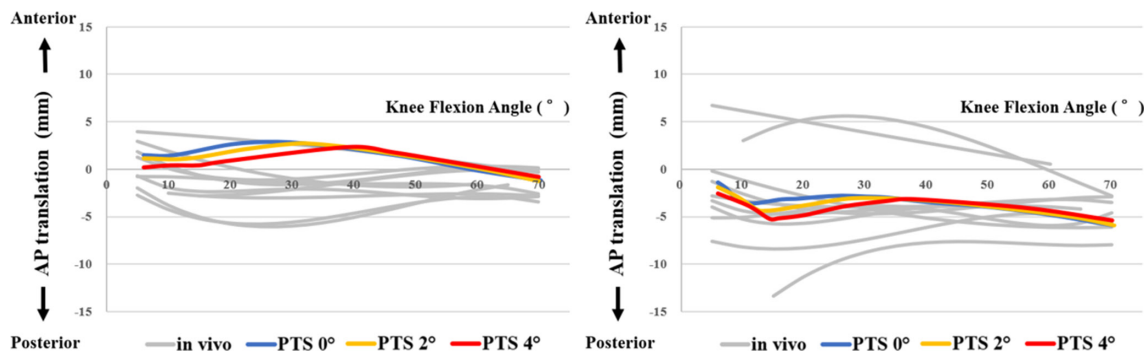

Fig. 5

Medial femoral condylar lowest point (CLP) (left) and lateral femoral CLP (right) of the femoral component relative to the tibial insert during stair climbing from 70° to 10° of knee flexion based on simulated and in vivo data in bi-cruciate stabilized (BCS) total knee arthroplasty (TKA). AP, anteroposterior; PTS, posterior tibial slope.

femoral CLP after anterior post-cam contact, indicating a bicondylar roll forward movement (Figure 3). The effects of PTS on knee kinematics differed because anterior post-cam contact changed the movement of the femoral component.

Anterior post-cam contact area and contact stress in the simulation. Figure 4 shows the anterior post-cam contact area between the anterior aspect of the tibial post and the femoral component with the knee near full extension in a FE model. Contact area constituted a horizontal band on the anterior aspect of the tibial post. Concentrated stress on the centre of the anterior aspect of the tibial post was observed when PTS was 6° or more. The maximum von Mises stress on the anterior aspect of the tibial post at 6°, 8°, and 10° of PTS were 26.7 MPa, 39.7 MPa, and 53.2 MPa, respectively. Maximum equivalent von Mises stress increased by increasing a PTS.

Comparison of knee kinematics compared to the simulation model. Mean preoperative KSS 2011 of ten knees were 9.3 (SD 4.5) for 'symptoms (25)', 14.0 (SD) 2.2 for 'patient satisfaction (40)', and 30.0 (SD 10.6) for 'functional activities (100)'. Mean postoperative KSS 2011 of the group with anterior post-cam contact (three knees) and without the anterior post-cam contact (seven knees) were 19.3 (SD 2.4) and 21.0 (SD 4.9) for 'symptoms', 26.7 (SD 4.7) and 30.9 (SD 10.0) for 'patient satisfaction', and 58.7 (SD 16.0) and 69.4 (SD 21.5) for 'functional activities' with no statistically significant difference. Like in the simulation model, the clinical data showed that the femoral components in BCS TKA translated anteriorly during stair climbing. Only three of ten knees exhibited anterior post-cam contact. Anterior post-cam contact was observed in three knees with PTS values of 1.1°, 3.7°, and 3.8°, respectively. Figure 5 shows that the medial and lateral femoral CLPs in BCS TKA were similar for the simulation model and clinical data. The medial femoral CLP was located almost in the centre of the tibial insert, while the lateral femoral CLP moved from a posterior position to the centre during knee extension. The predicted knee kinematics were almost within the range of inter-specimen variability.

Discussion

The most important finding in this study was that post-operative knee kinematics in BCS TKA differed according to PTS and anterior post-cam contact; in particular, anterior post-cam contact changed knee kinematics. PTS variations can have both positive and negative effects on knee function and kinematics, but there is little information concerning the effect of PTS on knee kinematics and the contact condition of the post-cam mechanism in BCS TKA.[6] After TKA, patients sometimes complain of feelings of discomfort and instability during activities such as gait, stair climbing, and standing up, all of which are affected by the knee condition in extension.[20] This study may be useful to surgeons since larger PTS values in BCS TKA could change knee kinematics and the anterior post-cam contact condition, affecting how the patient's knee feels.

The tibial articular geometry of BCS TKA enhances the constraint of the medial compartment compared to the lateral compartment due to an asymmetric design which

is medially concave and laterally convex in the sagittal alignment. This tibial articular geometry caused the lateral femoral CLP to move abruptly forward from mid-flexion to knee extension. When PTS was less than 6°, screw home movement from mid-flexion to knee extension is guided by the tibial articular geometry rather than the post-cam mechanism. By contrast, anterior post-cam contact induced a bicondylar roll forward movement when PTS was 6° or more. Grieco et al[21] used mobile fluoroscopy and 2D–3D registration to analyze the in vivo kinematics in BCS TKA during a deep knee bend. They reported that BCS TKA exhibited similar patterns of femoral rollback and axial rotation compared to the normal knee in early flexion; they did not provide details, but considered that the anterior post-cam mechanism may effectively substitute for the ACL with regard to AP motion but not axial rotation. Our study showed that anterior post-cam contact changed knee kinematics in knee extension, which means that axial rotational motion (screw home movement) may also depend on the presence of anterior post-cam contact.

Knee kinematics in the simulation showed similar trends to the clinical in vivo data and were almost within the range of inter-specimen variability. Anterior post-cam contact did not always occur, which is in contrast to the design concept of BCS TKA. The clinical data showed no anterior post-cam contact in most knees (seven of ten knees), but three knees occurred anterior post-cam contact despite a PTS of less than 6°. Anterior post-cam contact may have occurred with low PTS values due to the position of the femoral component in the sagittal plane and varus–valgus laxity in knee extension. Further research is needed to evaluate the intraoperative joint gap and postoperative component alignment using a 3D model.

The acceptable PTS range of TKA is still controversial. Okamoto et al[6] recommended PTS of less than 5° in conventional PS TKA to avoid anterior sliding of the tibial component during weight-bearing stair climbing. The optimal PTS range will differ among implant designs because the knee kinematics of BCS TKA and conventional PS TKA are different. Nishio et al[22] reported that patients with intraoperative medial pivot motion demonstrated significantly larger knee flexion angles and better subjective outcomes than patients with other types of pivot motion. Patients possibly feel near-normal knees, due to screw home movement occurring knee near full extension when PTS was less than 6°. Therefore, ideal knee kinematics of BCS TKA may be to achieve screw home movement without anterior post-cam contact. On the other hand, anterior post-cam contact induced a bicondylar roll forward movement when PTS was 6° or more. Anterior post-cam contact may change the patient's feeling by changing knee kinematics. In addition, repeated contacts may cause damage of the tibial post despite the fact that the post-cam shape of BCS TKA is different from conventional PS TKA.[23] However, anterior post-cam contact is useful to prevent excessive posterior translation of femoral component in case of large PTS.

There are several limitations to this study. First, only weight-bearing stair climbing was analyzed because we compared the computer simulation with available clinical data involving the same activity, using a 2D–3D image-matching technique. The contact condition of the post-cam mechanism may change according to activity. In addition, Kono et al[24] reported that knee kinematics were different in various activities, during squatting weight-bearing and active-assisted knee flexion non-weight-bearing. In future, it is necessary to simulate various motions such as squatting and walking. Second, only one bone model (small female knee) was simulated in order to match the in vivo data as closely as possible. Furthermore, the soft tissue material properties were based on data in the literature. However, knee kinematics in the simulation were almost within the range of inter-specimen variability. In future, both computer simulation and clinical data should be evaluated in males and in patients with knees of different sizes. Finally, since the postoperative courses of patients with in vivo data were as short as one year, it is necessary to examine the long-term results of many cases in the future regarding the effects of PTS on clinical outcomes. Despite these limitations, our study demonstrated the relationship between PTS and knee kinematics, including the conditions of post-cam contact, in BCS TKA.

In conclusion, postoperative knee kinematics in BCS TKA differed according to PTS and anterior post-cam contact. Anterior post-cam contact changed knee kinematics, which may affect the patient's perception of the knee during activities. Our study may assist surgeons in determining PTS of BCS TKA.

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- H. Higaki: Collected and analyzed the data.
- Y. Nakashima: Gave final approval to the manuscript.