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Original article

The effect of geometry of the tibial polyethylene insert on the tibiofemoral contact kinematics in Advance Medial Pivot total knee arthroplasty

Go Omori[1], Naoaki Onda[2], Masashi Shimura[3], Toyohiko Hayashi[3], Takashi Sato[4], and Yoshio Koga[4]

[1] Center for Transdisciplinary Research, Niigata University, 2-8050 Igarashi, Nishi-ku, Niigata 950-2181, Japan
[2] Division of Orthopedic Surgery, Department of Regenerative and Transplant Medicine, Niigata University Graduate School of Medical and Dental Science, Niigata, Japan
[3] Faculty of Engineering, Niigata University, Niigata, Japan
[4] Orthopedic Surgery, Niigata Kobari Hospital, Niigata, Japan

Abstract

Background. In modern total knee arthroplasty (TKA), it is important to reproduce both medial pivot motion and posterior femoral rollback to obtain greater postoperative knee flexion. Several studies have reported the factors affecting knee motion and range of motion after TKA. The purpose of this study was to evaluate the effect of the tibial insert geometry on the tibiofemoral contact kinematics, especially focusing on the medial pivot motion and posterior femoral rollback.

Methods. Seven cadaveric knees were replaced with the Advance Medial Pivot TKA, and two different geometries of polyethylene tibial insert, the standard medial pivot design (MP-design) and double high design (DH-design), were biomechanically compared. Four experimental configurations were evaluated in each specimen in this order: (1) the MP-design with posterior cruciate ligament (PCL) retaining, (2) the DH-design with PCL retaining, (3) the MP-design with PCL sacrificing, and (4) the DH-design with PCL sacrificing.

Results. Under the PCL-retaining condition, both designs showed no medial pivot but bicondylar femoral rollback more than 60° of knee flexion. In the MP-design, tibiofemoral contact point (estimated contact point, ECP) of the medial compartment was located on the posterior lip of the ball-in-socket structure while demonstrating greater than 120° of knee flexion. The posterior translation was also the same in both designs. On the other hand, ECP of the MP-design and the DH-design showed only medial pivot pattern under the PCL-sacrificing condition. In the DH-design, ECP of the lateral compartment showed paradoxical anterior translation from 0° to 60° of knee flexion. Total posterior translation was significantly greater in the lateral compartment than that in the medial compartment.

Conclusions. The results of this study suggest that in this type of TKA system the ball-in-socket geometry in the MP-design has an advantage for reproducing medial pivot motion in the PCL-sacrificing condition, and the flexion path structure in the DH-design is considered to be both effective and safe for femoral rollback in the PCL-retaining condition. However, neither design is sufficient to reproduce medial pivot motion and posterior femoral rollback. Therefore, a different design of tibial insert is needed for more physiological kinematics after TKA.

Introduction

An important aim of total knee arthroplasty (TKA) is to return the arthritic knee to as close to normal function as possible. The physiological motion of the knee joint has both medial pivot motion and femoral rollback.[1–3] This motion pattern is seen not only in the midflexion area but also in a deep flexion range of more than 100°.[4] Therefore, the combination of a medial pivot motion and femoral rollback is thought to be the key motion for high flexion of the knee joint. There are several factors that influence the three-dimensional knee motion after TKA: these include the geometry of the femoral and tibial component, the setting alignment of these implants to the bone, changes in the level of the joint line, soft tissue balance and tension, and retention or sacrifice of the posterior cruciate ligament (PCL).[5–8] Fluoroscopic studies of modern TKA have not yet demonstrated expected knee motion close to normal conditions but rather a nonphysiological motion such as paradoxical sliding forward or paradoxical rolling forward.[8–10] Furthermore, these studies have analyzed the knee motion during normal gait, up/down stairs, and rising from/sitting in a chair. In these activities, the maximum flexion of the knee joint is never greater than 90°; therefore, precisely how the knee joint moves after TKA thus remains unclear, especially in deep flexion.

Recently, an asymmetrical tibial polyethylene insert, a ball-in-socket on the medial side and an arcuate

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groove on the lateral side, was introduced to reproduce the medial pivot motion during knee extension-flexion.[11] In this type of TKA system, the typical medial pivot motion was observed by an in vivo kinematic study using fluoroscopy.[12] However, it is not clearly demonstrated whether we should preserve or sacrifice the PCL at surgery. Furthermore, it is unknown whether posterior femoral rollback is reproduced in this type of TKA system. The purpose of the current study was to evaluate the effect of polyethylene tibial insert geometry in the medial pivot TKA on the tibiofemoral contact kinematics in relationship to retaining or sacrificing PCL, especially focusing on the medial pivot motion and posterior femoral rollback in deep knee flexion.

Materials and methods

Seven fresh-frozen cadaveric knee joints were used in this study. Consent for the design of this study was obtained from the Institutinal Review Board and the ethical committee of our institute. X-ray examination was previously performed to select knee joints of almost the same size. None of the knees had any evidence of skeletal deformity, and it was confirmed that the PCL was in an intact condition.

After the skin and subcutaneous tissue were stripped, leaving the capsule, ligaments, and muscles intact, each knee was replaced with the Advance Medial Pivot Prosthesis (Wright Medical Technology, Arlington, TN, USA). The distal femur was cut in 5° of valgus and 3° of external rotation. The proximal tibia was cut at a right angle to the tibial axis in the coronal plane and 3° of posterior slope in the sagittal plane. The PCL was preserved, and the patella was not resurfaced. After bone cutting was completed, a size 2 femoral and tibial component with a 10-mm-thick polyethylene insert was placed. The metal rods were inserted into the intramedullary space of the femur and tibia, and the femoral rod was rigidly fixed to the motion frame. The tibial rod was fixed to the clamp that allows 6-degrees-of-freedom motion. The knee joint was moved from 0° to 150° of flexion by a load cell under the loading condition of 40 N on the quadriceps tendon and 20 N on each medial and lateral hamstring muscle through the semitendinosus and biceps femoris tendon. The load ratio of quadriceps and hamstring was according to previous reports; however, the actual amount of load was less than that of the physiological condition as a result of the strength of the motion frame and load cell.[13,14]

The tibiofemoral contact kinematics was then evaluated using the photostereometric knee motion analysis system (KKN/1B), which was basically developed at our institute (Faculty Engineering, Niigata University). This system consists of eight LEDs (BR 3371X; Stanley Denshi, Tokyo, Japan) with marker devices mounted onto the femoral and tibial bone, two sets of three linear high resolution CCD cameras (TCD141C; Toshiba, Tokyo, Japan) for tracking the LED position, and a PC for data analysis. The spatial resolution was designed to be 0.06 mm when the LEDs were located on the focal plane of the CCD cameras, and overall accuracy of the measuring system was within 0.52 and 0.11 mm at any point on the femoral component. Three-dimensional computer-aided design (CAD) solid models of the femoral component, tibial tray, and polyethylene insert were obtained, and the positional relationship between these models was also measured. Intersurface distance between the femoral component and polyethylene insert was quantitatively assessed, and the area where the value of the intersurface distance was less than or equal to 0.75 mm was defined as the estimated contact area. The center of the estimated contact area was finally defined as the estimated contact point (ECP), and the contact kinematics was evaluated by changing the ECP.[15–17]

In the current study, two different designs of the polyethylene tibial insert were compared: one was the standard medial pivot design (MP-design) and the other was the double high design (DH-design). In the MP-design, a medial socket exactly conformed to the sphere of the femoral component, thus providing the medial ball-in-socket kinematics, and the lateral part was an arcuate groove centered on the medial socket. The basic geometry of the DH design was the same as the MP-design: the main difference between the MP-design and the DH-design was the geometry of the posterior lip. In the MP-design, the geometry of the posterior lip was part of the ball-in-socket and arcuate groove design; on the other hand, the posterior lip of the DH-design was 3 mm lower than that of the MP-design, which resulted in a posterior slope (Fig. 1a–c). The concept of posterior slope was that this slope will act as a "flexion path" when femoral rollback occurs. The medial pivot femoral component was used for both the MP-design and the DH-design. Both medial and lateral condyles of the medial pivot femoral component had a sphere and C-curve design with a single radius in all three planes. Both types of polyethylene inserts were exchanged on the same metal tibial component, so that the difference of the design was directly comparable using the same cadaveric knee joint.

Four experimental configurations were evaluated in each specimen in this order: (1) the MP-design with PCL retaining, (2) the DH-design with PCL retaining, (3) the MP-design with PCL sacrificing, and (4) the DH-design with PCL sacrificing.

At the time of measurement under the PCL-sacrificing condition, the extension gap and the flexion gap were evaluated and a polyethylene insert 2 mm thicker was used.

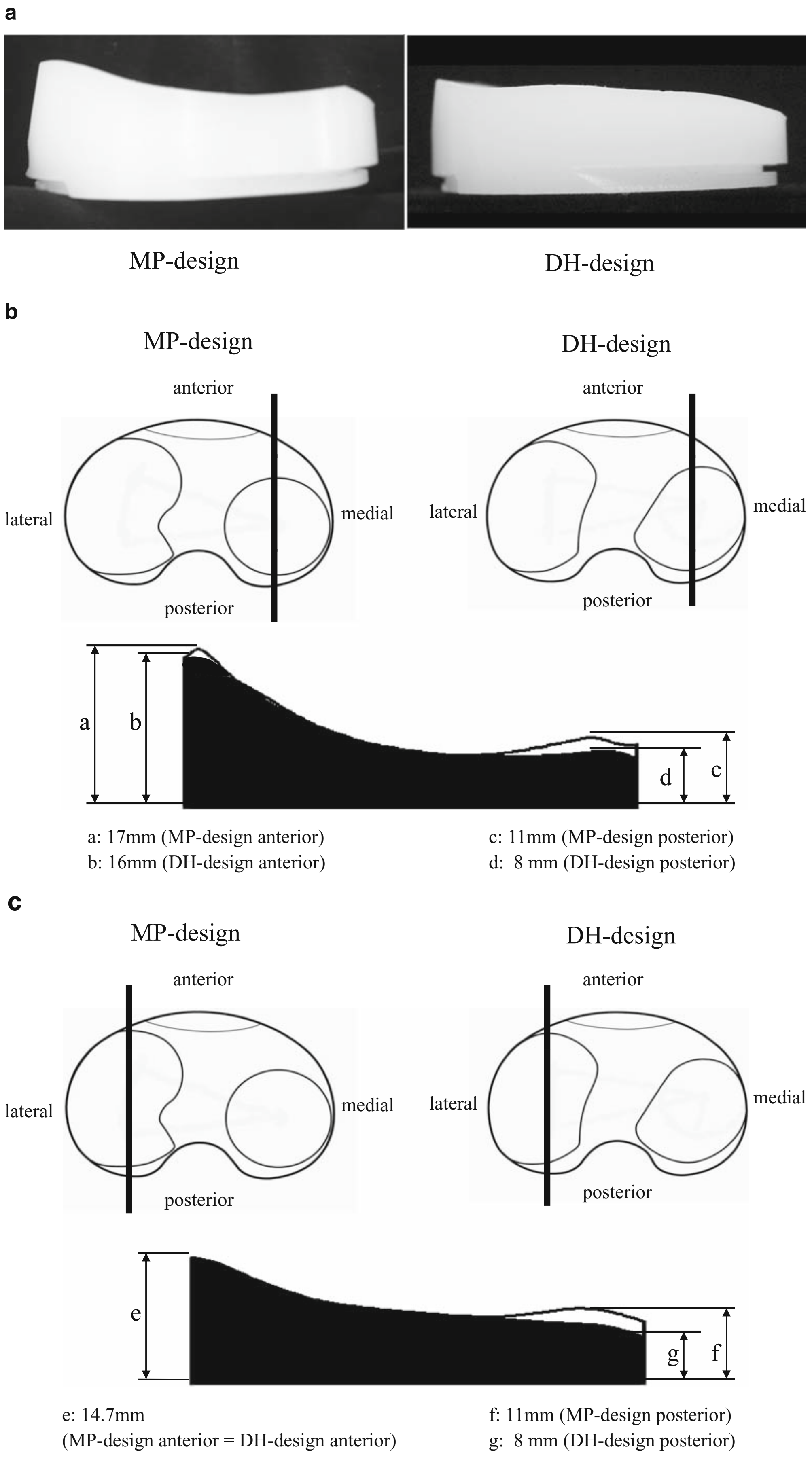

Fig. 1. Geometric characteristics of medial pivot design (DH-design) and double high design (DH-design). **a** Lateral view. **b** Cross-sectional geometry of the medial compartment. **c** Cross-sectional geometry of the lateral compartment

In this study, the anteroposterior motion of the ECP in the medial and lateral condyles was analyzed. Two-way analysis of variance (ANOVA) with within factors was used to analyze the effect of tibial insert geometry on the contact kinematics. The within factors were the aforementioned four different configurations. The significance level was set at a probability value less than 0.05.

Results

The MP-design showed bicondylar posterior translation under the PCL-retaining condition and medial pivot motion under the PCL-sacrificing condition. When the PCL was retained, the ECP of the medial compartment shifted posteriorly mainly more than 60° of knee flexion, and the ECP of the lateral compartment showed continuous posterior translation along knee flexion. The ECP of the medial compartment was located on the posterior lip of the ball-in-socket structure while demonstrating greater than 120° of knee flexion (Fig. 2a). The posterior translation of the ECP was 15.1 ± 3.1 mm (mean ± SD) in the lateral compartment and 11.6 ± 2.9 mm in the medial, and no statistical difference was seen between either compartment (Fig. 3). After the PCL was sacrificed, the MP-design showed a typical medial pivot motion. The ECP of the medial compartment was located at almost the same point from 0° to 90° of knee flexion followed by a slight posterior translation of greater than 100° of flexion. On the other hand, the ECP of the lateral compartment showed continuous posterior translation along knee flexion (Fig. 2a). The posterior translation of the ECP was significantly greater in the lateral compartment (11.1 ± 3.8 mm) than that in the medial compartment (3.3 ± 2.5 mm) (*P* = 0.022) (Fig. 3).

The DH-design had basically the similar tracking pattern of the ECP as the MP-design under PCL-retaining conditions, which included a posterior shift of the medial ECP of greater than 60° of knee flexion and a continuous posterior translation of the lateral ECP. Both medial and lateral ECP shifted posteriorly on the posterior slope of the flexion path more than 120° of knee flexion (Fig. 2b). The posterior translation of the ECP was 14.5 ± 4.2 mm in the lateral compartment and 10.7 ± 3.8 mm in the medial compartment, and no statistical difference was found according to these results

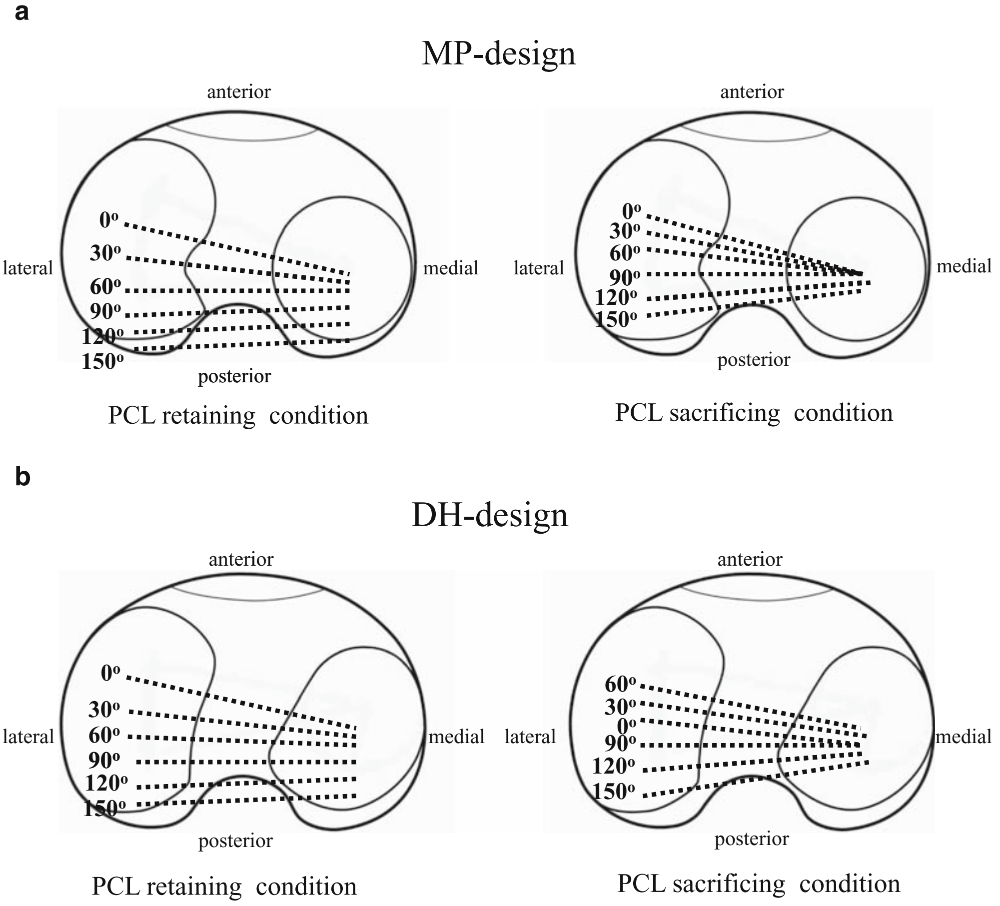

Fig. 2. Position movement of the estimated contact point (ECP). **a** MP-design. ECP of the medial compartment located the posterior lip of the ball-in-socket structure greater than 120° of knee flexion under posterior cruciate ligament (PCL)-retaining condition. **b** DH-design. ECP of the lateral compartment showed paradoxical anterior translation from 0° to 60° of knee flexion

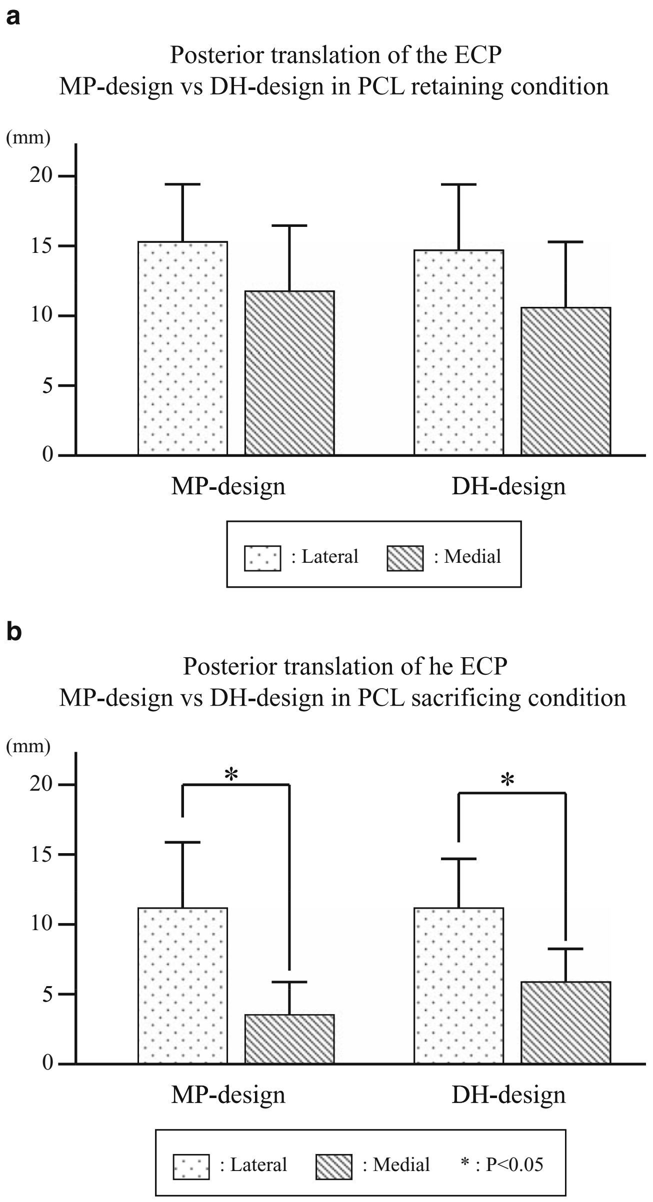

Fig. 3. Posterior translation of the ECP. **a** PCL-retaining condition. **b** PCL-sacrificing condition

(Fig. 3). The DH-design also showed a medial pivot motion after the PCL was sacrificed. The ECP of the medial compartment did not move from 0° to about 120° of knee flexion and then it slightly shifted to the posterior direction. In the lateral compartment, ECP showed paradoxical anterior translation from 0° to 60° of knee flexion followed by continuous posterior translation (Fig. 2b). The posterior translation of the ECP was 11.2 ± 3.6 mm in the lateral compartment and 5.5 ± 2.7 mm in the medial compartment, and then the posterior translation in the lateral ECP was significantly greater than that on the medial compartment ($P = 0.028$) (Fig. 3).

When comparing both designs, posterior translation of the ECP was not statistically different between the MP-design and DH-design under both PCL-retaining and PCL-sacrificing conditions.

Discussion

Currently, very few studies exist on the kinematic analysis of the medial pivot type TKA. Saari et al.[18] evaluated the Samuelson total knee prosthesis and described that the medial spherical condyle stabilized anteroposterior motion. Schmidt et al.[12] studied the Advance Medial Pivot prosthesis using fluoroscopy and showed medial pivot motion during the stance phase of the gait cycle. Moonot et al.[19] analyzed the Medial Rotation Knee with fluoroscopy and demonstrated medial pivot motion in a lunge motion.

In the present study, two different geometries of the polyethylene insert in the Advance Medial Pivot TKA were compared. The medial pivot geometry (MP-design) has a highly conformed "ball-in-socket" design to reproduce the medial pivot motion. On the other hand, the double high tibial insert (DH-design) is designed to achieve both medial pivot motion and posterior femoral rollback in deep knee flexion that will hopefully lead to more physiological kinematics and a better flexion angle. However, our data in the current study demonstrate that the contact kinematics by ECP did not substantially differ between the MP-design and the DH-design, especially in the deep flexion area greater than 120° of knee flexion. When the PCL was retained, both designs showed no medial pivot but did have bicondylar rollback, and, when the PCL was sacrificed, both designs showed no femoral rollback but typical medial pivot motion.

The first reason for this result is that medial ball-in-socket geometry is a highly conformed design and has an advantage in reproducing medial pivot motion, but it is insufficient for femoral rollback even if the posterior slope was made. The second reason is that femoral rollback is essentially controlled by the PCL, and this effect is stronger than that of the geometric conformity of the tibial insert as the MP-design and the DH-design under the PCL-retaining condition. Most et al.[20] analyzed femoral rollback after cruciate-retaining and stabilizing TKA and described that the cam-spine engagement structure played an important role in restoring posterior femoral rollback in the PCL-substituting TKA. However, the cam-post mechanism is not thought to reproduce medial pivot motion. Therefore, this study suggests that if we would reproduce both medial pivot motion and femoral rollback after TKA, a new concept and design of the tibial insert geometry will be needed.

In the MP-design, the ECP of the medial compartment located on the posterior edge of the ball-in-socket structure greater than 120° of flexion from bicondylar femoral rollback under the PCL-retained condition. Li et al.[21] evaluated the in vivo tibiofemoral contact kinematics of a cruciate-retaining TKA and showed that the current component design did not allow the femoral condyle to roll off the polyethylene edge at high degrees of flexion because of the geometry at the posterior lip. Abnormal contact conditions between the polyethylene insert and metal tray in the MP-design may present some risk of polyethylene wear or limitations of knee flexion. On the other hand, the lateral ECP of the DH-design showed paradoxical anterior translation from 0° to 60° knee flexion under the PCL-sacrificing condition, possibly because of the lesser conformity of the medial ball-in-socket structure by decreasing the height of the anterior and posterior lip. Recently, short- to mid-term clinical results of the Advance Medial Pivot prosthesis were reported. However, none of the authors clearly described the treatment for the PCL.[11,12,22] From the results of the present biomechanical study, it is recommended that the PCL should be sacrificed when the MP-design is used and retained when the DH-design is used.

There are several limitations because this is an in vitro cadaveric study. The first limitation is the number of specimens. Only seven cadaveric knees were evaluated in this study because it was difficult to obtain enough cadavers. Moreover, we selected knee joints of the same size for sequential evaluations, eliminating interspecimen variations. The second limitation is the loading condition. The load ratio of quadriceps and hamstring was close to physiological conditions; however, the actual amount of load was smaller than that of physiological condition as a result of the strength of the motion frame and load cell. In the near future, an in vivo kinematic study comparing the MP-design and the DH-design is needed.

The results of this study indicate that the ball-in-socket geometry in the MP-design has an advantage in reproducing medial pivot motion in the PCL-sacrificing condition and that the flexion path structure in the DH-design is effective for femoral rollback in the PCL-retaining condition. However, neither design is sufficient to reproduce medial pivot motion and posterior femoral rollback. Thus, a different design of tibial insert with a new concept is needed for more physiological kinematics after TKA.

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