The Cruciate Ligaments in Total Knee Arthroplasty

A Kinematic Analysis of 2 Total Knee Arthroplasties

James B. Stiehl, MD,* Richard D. Komistek, PhD,† Jean-Marie Cloutier, MD,‡ and Douglas A. Dennis, MD†

Abstract: In vivo weight-bearing fluoroscopic kinematic analysis using an interactive model fitting technique with 3-dimensional computer-aided design solid models was done using 16 anterior and posterior (bicruciate)-sparing and 6 posterior cruciate-sparing total knee arthroplasties (TKAs). All patients had a satisfactory clinical result with a minimum of 12 months' follow-up. The femorotibial contact position of TKAs started posterior to the midline in extension. Bicruciate TKAs revealed gradual posterior femoral rollback and limited anterior-posterior translation but remained posterior to the sagittal plane midline in all positions. Posterior cruciate-sparing TKAs began significantly posterior in extension, demonstrated progressive anterior translation with flexion, and had exaggerated medial condyle translation on deep knee bend. The posterior cruciate-retaining TKAs of this study had the most abnormal kinematic performance. Key words: total knee arthroplasty, kinematics, posterior cruciate, anterior cruciate.

Surgical technique in total knee arthroplasty (TKA) has evolved with treatment of the cruciate ligaments as an important theoretical consideration. Early implant designs employed a variety of options, including bicruciate (anterior and posterior) preservation, sacrifice of both cruciate ligaments, substitution of the posterior cruciate ligament (PCL), or sacrifice of the anterior cruciate ligament (ACL) with PCL retention. The advantage of bicruciate-retaining implants was improved functional performance, documented by early gait studies, improved range of motion and stability, and maintenance of joint kinematics to near-normal [1,2]. PCL retention was believed to improve prosthetic longevity by decreasing the forces on the tibial interface, improve range of motion by maintaining the normal joint line, and preserve posterior femoral rollback [3]. Andriacchi et al. [2] compared each of the cruciate techniques with gait studies, finding the best function with stair climbing in the bicruciate-retaining Cloutier TKA. PCL-retaining TKAs showed extensor moment weakness with forward leaning on stair climbing and decreased stance phase knee flexion. Extensor mechanism efficiency could be diminished in these cases resulting from joint line elevation or altered femorotibial kinematics.

Clinical results with various cruciate techniques have shown no clear advantage of 1 method [5–7]. Becker et al. [8] evaluated bilateral-paired PCL-retaining and PCL-sacrificing TKAs and found sim-
ilar motion with gait and passive motion. Dorr et al. [9] evaluated the functional outcome in bilateral PCL-retaining and PCL-sacrificing TKAs and found similar gait and passive flexion. Pritchett [10] compared bicruciate-retaining and PCL-retaining TKAs with bilateral replacements in the same patient, finding a substantial preference with stair climbing and step-up gait in patients in whom the ACL was spared. Similarly, Laurencin et al. [11] found a significant advantage of ACL-preserving unicompartmental arthroplasties when compared with PCL-retaining TKAs [11].

We have used weight-bearing in vivo fluoroscopic kinematic analysis to assess the function of TKA designs. We have refined our technique to use a 3-dimensional capture system that allows simultaneous portrayal of medial and lateral condyle femorotibial contact. The purpose of this study is to compare the in vivo kinematics of TKAs that preserve both cruciate ligaments or sacrifice the ACL.

Methods

Twenty-two subjects with the primary selection criterion as excellent clinical outcome were selected to participate in this study. Sixteen subjects had a TKA that preserved the ACL and the PCL (Ceraver Osteal, Paris, France) performed by one of the authors (J.M.C.). Six subjects had a TKA that sacrificed the ACL but preserved the PCL (Advantim, Wright Medical Technology, Arlington, TN) performed by another author (J.B.S.). These 2 prosthetic implants have a femoral geometry of the total condylar type with a relatively flat tibial polyethylene insert in the frontal and sagittal planes. Each subject was asked to sign an investigational research review board consent form for this study. All subjects included in this study were judged to be clinically successful and had a minimum follow-up of 12 months. Without exception, all patients were noted to have stable ligamentous balance with frontal plane femorotibial alignment of 5° to 7° valgus.

Patients in this study were asked to perform 3 weight-bearing deep knee bends from full extension to maximum flexion allowed while a technician carefully centered the knee on the video fluoroscopy screen. One investigator directly coached all patients in this study in a standardized fashion. The videos for each subject were downloaded to a workstation computer. Solid computer-aided design models for the femoral and the tibial components for each implant studied were entered into the model fitting scheme (Fig. 1). Four distinct fluoroscopic images for each patient were selected. Kinematic analysis was done at flexion angles of 0°, 30°, 60°, and 90°. Using an interactive model fitting algorithm, the 3-dimensional solid models of the femoral and tibial components were overlaid onto the 2-dimensional fluoroscopic images. The implants were grouped together and rotated to a pure sagittal view with respect to the tibia. The medial and lateral condyle contact positions with respect to the midline of the tibia in the sagittal plane were then measured. If the condyle contact position was anterior to the midline of the tibia in the sagittal plane, it was denoted as positive. If the condyle contact position was posterior to the midline, it was denoted as negative. Kinematic comparisons were made between the subjects within each group, and the average kinematics for each group were compared. Statistical analysis of patient groups was performed using a 2-tailed distribution, 2-sample unequal variance Student’s t-test.
Error Analysis

An error analysis was performed by obtaining fluoroscopic images of implant components mounted on a 6°-of-freedom apparatus. Accurate positioning of the components was achieved using rotational and translational stages with an accuracy of 15 arc-sec and 0.01 mm. The components were set in an initial position, then rotated and translated to known values. Fluoroscopic images of the components were created at each setting. The 3-dimensional model fitting process was performed for each setting of the rotational and translational stages to determine the relative pose of the components. A second dynamic test was performed to determine the effect of motion. The components were pulled through the fluoroscopic scene at a variable speed between 0.5 and 1.0 feet/s. The translational and rotational 3-dimensional model fitting technique was 0.5 mm and 0.5° [9]. A threshold of 0.75 mm and 0.75° (50% safety factor) was used to account for unknown variables.

Results

While performing a weight-bearing deep knee bend to maximum allowable flexion, the subjects with a PCL-retaining TKA experienced condylar contact positions in the extreme posterior position. At full extension, the average lateral condyle contact position was −12.1 mm (posterior to the sagittal plane midpoint of the proximal tibia), whereas the medial condyle contact position was −9.7 mm. At 90° of flexion, the lateral condyle contact position slid in the anterior direction to a final position of −9.6 mm, whereas the medial condyle contact position slid in the anterior direction to a condyle contact position of −3.3 mm (Figs. 2 and 3, Table 1).

The subjects with a bi cruciate-retaining TKA typically experienced posterior femoral rollback during a deep knee bend. At full extension, the average lateral condyle contact position was −3.3 mm, whereas the medial condyle contact position was −0.9 mm. At 90° of flexion, the average lateral condyle contact position rotated in the posterior direction to a position of −7.7 mm, whereas the medial condyle contact position rotated in the posterior direction to a final position of −4.3 mm. When fully extended, the bi cruciate-retaining TKAs experienced more anterior contact positions, with 1 patient as far anterior as +9 mm (Figs. 2 and 3). These results are similar to previous studies analyzing the femorotibial contact positions of the normal knee [12,13]. It also appeared that some of the subjects with the bi cruciate-retaining TKA had a dysfunctional ACL. These subjects experienced condyle contact positions at full extension in the range of −8 to −12 mm posterior. The femoral condyle contact positions for these subjects were similar to the kinematics of the subjects with a PCL-retaining knee design.

Comparing the bi cruciate-retaining TKAs and the PCL-retaining TKAs revealed that the medial and lateral condyle contact points of the bi cruciate-retaining TKAs were significantly anterior at 0° flexion (P < .01, medial; P < .001, lateral). At 60° flexion, the lateral condyle was more anterior for the bi cruciate-retaining TKAs (P < .05).

Discussion

Dynamic fluoroscopy is an important technique for investigating kinematic performance of TKA. In
could be related to a variety of technical problems. Abnormal posterior condylar wear may also be reflected in difficulties with the posterior contact positions in TKA. Several authors have identified abnormal wear patterns in certain implant retrievals of PCL-retaining TKAs. We are concerned that the exaggerated medial condyle anteroposterior translation noted by the Advantim TKA may be related to pattern wear identified by Blunn et al. [19] and Wasielwski et al. [20]. Blunn et al. [21] have shown that sliding of 2 contact points causes the most severe delamination wear, as opposed to rolling and gentle gliding that produce minimal wear. We have examined an 8-year Advantim tibial polyethylene insert with delamination wear that would correlate with the exaggerated medial condyle anteroposterior sliding with a relatively limited lateral condyle pivot. This situation is in contrast to the normal circumstance, in which limited translation occurs about a medial condyle pivot early in flexion, and greater translation of the lateral condyle is noted. From literature review, there is a significant correlation with abnormal medial condyle translation and ACL deficiency. Dejour and Bonnin [22]

<table>
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<tr>
<th>Condyle</th>
<th>0° Flexion</th>
<th>30° Flexion</th>
<th>60° Flexion</th>
<th>90° Flexion</th>
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<tr>
<td><strong>Advantim (average, mm)</strong></td>
<td>9.6</td>
<td>12.1</td>
<td>12.8</td>
<td>13.2</td>
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<tr>
<td><strong>Advantim (maximum, mm)</strong></td>
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<td>13.2</td>
<td>13.3</td>
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<tr>
<td><strong>Advantim (minimum, mm)</strong></td>
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<td>10.3</td>
<td>11.1</td>
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<td>Cloutier (average, mm)</td>
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<td>3.3</td>
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<tr>
<td>Cloutier (maximum, mm)</td>
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<td>12.8</td>
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<td>Cloutier (minimum, mm)</td>
<td>7.6</td>
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<td>11.3</td>
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**Statistical analysis**

P < .01 P < .001 P < .05

*Positive is anterior to the midsagittal plane of the tibia, and negative is posterior.*

1992, our initial experience with a computer vector analysis method allowed us to identify significant kinematic abnormalities with PCL-retaining designs. Those early studies evaluated femorotibial contact of the lateral condyle in the sagittal plane. Most significantly, femorotibial contact was always posterior in extension, reflecting the deficiency of the ACL. Posterior femoral rollback was absent or inconsistent in most cases, and there was net anterior translation with deep flexion [12].

More recently, we have used an interactive modeling system that allows us to manipulate the 3-dimensional computer-aided design model implant precisely onto the video. The fluoroscopic image can then be extracted leaving the computer-aided design image from which kinematic calculations are possible [13]. The advantage of our current method is that we can study movement of both condyles at each point in time and space. Using this technique, the results of PCL-retaining TKAs were similar to our previous findings with exaggerated anterior translation with increasing flexion. An unexpected finding, however, was the increased to-and-fro sliding motion involving the medial femoral condyle. This finding was enlightening because we originally studied only the lateral condyle, speculating from prior anatomic studies that greater sagittal plane translation was likely with the lateral femoral condyle [14]. Markovich et al. [15] used dynamic fluoroscopic video analysis with step-up gait, finding similar kinematics with translation to a more posterior position in extension and exaggerated movement of the medial condyle compared with the lateral.

Clinical and biomechanical studies have shown difficulties with the posterior contact positions in TKA. Swany and Scott [16] and Lewis et al. [17] identified abnormal posterior condylar wear if this occurs and cited PCL tightness in extension that could be related to a variety of technical problems. These problems may include malrotating or placing a semiconstrained tibial tray too far anteriorly and underresecting the posterior femoral condyles, causing flexion gap tightness. In knees with severe valgus or varus deformities, medial or lateral ligament release may require placing a thicker polyethylene insert, causing tightening of the PCL. Dennis et al. [13] found that certain patients with PCL-retaining TKAs maintain an abnormal posterior contact position throughout the range of motion. Gabriel et al. [18] used a finite element model to show 48% increased tensile strain on the anterior bone-metal tibial tray interface with posterior femoral contact. Optimally, femorotibial contact should load the tibial tray near the midline tibia throughout range of motion. From the results of our study, posterior condylar contact is less likely with the bicruciate-retaining TKA.
performed a radiologic Lachman test and 20° monopodal stance test, showing significantly higher anterior medial tibial condyle translation with ACL deficiency.

Preservation of the ACL in TKA remains an attractive objective for restoring improved clinical function. Andriacchi and Galante [4] showed a clear advantage on stair climbing with the bicruciate-preserving Cloutier TKA. Large series that have used the bicruciate-retaining TKAs have revealed excellent long-term clinical results [1,10,23]. The ACL is often absent or the clinical deformity too great to allow for a technique that retains the ACL. In the present study, each knee group (ie, bicruciate-retaining or PCL retaining) was analyzed at a different center, and this study was not a randomized clinical trial. We cannot state whether or not the preoperative condition of the knees was similar and cannot eliminate the possible bias of bicruciate TKA being performed in easier, less deformed knees.

To our knowledge, this article reports the first kinematic analysis of a bicruciate-retaining TKA. Posterior femoral rollback was present in early flexion and midflexion in all cases. The abnormal anteroposterior translation of the medial femoral condyle typical of PCL-retaining TKAs was not identified in any of the knees with a functioning ACL. The primary abnormality of this implant was the mildly posterior contact position in extension with anterior translation in deep flexion. The crossed pin distractor or tensor technique described by Cloutier [23] appears to be novel and required for making the appropriate bone cuts necessary in the bicruciate-retaining TKAs. Future improvements must advance this concept further.

**Conclusion**

This study compared the in vivo weight-bearing kinematics of the Ceraver Osteal bicruciate-retaining TKA and the Whiteside Advantim PCL-retaining TKA. Implant geometry plays an important role in determining kinematics, and our results may not be generalized to each implant class on the whole. The specific PCL-retaining design of this study revealed femorotibial contact patterns comparable to ACL-deficient knees with posterior contact in full extension with variable anterior translation in flexion. Sliding translation of the medial femoral condyle was exaggerated in some cases and believed to be a detrimental factor for wear performance. The bicruciate-retaining design started mildly posterior to the tibial midline but showed early posterior femoral rollback. This rollback could be attributed to preserved ACL in the bicruciate-retaining TKA. Although regarded as technically demanding and of limited value by most surgeons, bicruciate-retaining TKA holds promise for offering improved wear mechanics and functional outcome.

**References**