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Knee

In Vivo Adduction and Reverse Axial Rotation (External) of the Tibial Component Can Be Minimized

By Stephen M. Howell, MD; Esther E. Hodapp, MS; Kyle Kuznik, BS; Maury L. Hull, PhD

Abstract

Mechanical alignment with conventional total knee arthroplasty (TKA) instruments often requires collateral ligament releases, which result in a high prevalence of adduction and reverse axial rotation (external rotation) of the tibial component during knee flexion with a variety of component designs. We used a radiographic image-matching technique to determine the contact kinematics during standing and kneeling at 90° and maximum flexion in a series of 35 patients in which a new image-guided, custom cutting block system was used to kinematically align a cruciate-retaining prosthesis with the intent of restoring the 3 kinematic axes of the knee. The kinematically aligned prosthesis had a minimal prevalence of adduction (3%) and reverse axial rotation (8.5%). The anteroposterior contact positions of the lateral and medial femoral condyles did not edge load the tibial liner. The moderate association between abduction and internal rotation, the degree of knee flexion, and the contact position of the medial femoral condyle suggest that abduction was not a sign of lift-off of the medial femoral condyle, but the result of the medial femoral condyle moving up the anterior slope of the tibial liner. These more normal contact kinematics were achieved without release of the collateral ligaments or lateral retinaculum. In contrast to mechanical alignment with conventional surgical techniques, the use of kinematic alignment with custom-fit cutting guides and a cruciate-retaining, symmetric medial and lateral femoral–tibial bearing surface minimizes the undesirable consequences of adduction and reverse axial rotation (external rotation).

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Malpositioning of prosthetic components leads to biomechanical changes, often resulting in deteriorating functional outcome.[1] This justifies the need for evaluating new treatments for aligning the prostheses with early measurement of contact kinematics as a way to assess the potential for wear when longer-term clinical studies are not yet feasible.[2,3]

In mechanical alignment with conventional total knee arthroplasty (TKA), uneven medial and lateral loading of the tibial component is an undesirable, commonplace phenomenon treated by collateral ligament release.[4-6] Adduction or lift-off of the lateral femoral condyle is disconcerting because it further overloads the medial compartment.[5,6] In the mechanically aligned TKA, the pattern of axial rotation of the tibial component alternates between internal and external

tibial rotation as flexion increases, which does not occur in the normal knee.[2] Clinically, abnormal internal/external rotation alters the forces and tracking of the patellofemoral joint and flexion of the knee.[2,3] Therefore, a treatment that minimizes adduction and restores a consistent pattern of internal rotation may lessen biomechanical changes and improve the clinical outcome of TKA.

The present study describes the contact kinematics of a kinematic alignment technique in which symmetric, cruciate-retaining components were shape-matched to a 3D model of the femur with the intent of restoring the 3 kinematic axes of the knee. We measured adduction/abduction rotation, internal/external rotation, and the anteroposterior (AP) contact positions of the lateral and medial femoral condyles on the tibial component during standing and kneeling in 90° and maximum flexion to determine whether adduction and reverse axial rotation (external) of the tibial component are minimized. We also identified factors associated with adduction/abduction of the tibial component to assess whether lift-off of the lateral or medial femoral condyle occurred in any of these knee positions.

Materials and Methods

A database of 134 consecutive patients treated with a custom-fit total knee from September 2006 to June 2007 was retrospectively reviewed with institutional review board approval. The inclusion criteria were a preoperative diagnosis of end-stage osteoarthritis of the knee and completion of 3 lateral radiographs in full extension and kneeling in 90° and maximum flexion at least 3 months after knee replacement. Thirty-five knees in 35 patients were included. Patient demographics included a mean age 67±9.8 years (range, 53-92 years), 23 women and 11 men, and a body mass index of 31±6.5.

The preoperative varus/valgus deformity was measured with a long goniometer with the patient supine, hence the range of deformity was less than that with the patient standing. Nineteen patients had <6° of valgus, with a maximum varus deformity of 15° and a maximum valgus deformity of 16°. The maximum flexion contracture was 32° and the greatest limitation in flexion was 90°. Follow-up averaged 4±1.3 months (range, 3-10 months) from the time of replacement. Postoperatively, knee flexion was 116°±9.60°, Knee Society Score was 93 (range, 75-100), and Oxford Score was 37 (range, 22-48, with 48 being the best score and 0 the worst).

Kinematic alignment was performed preoperatively from a 3D model constructed from a magnetic resonance image (MRI) of the knee.[7-9] A sagittal MRI scan was obtained using a high field scanner with a dedicated knee coil. The general scanning parameters included a 16-cm field of view centered at the joint line of the knee, 256 matrix, 2-mm slice thickness, and alignment of the coronal and axial slice planes perpendicular to the cortical–cancellous junction of the distal and posterior femur, respectively. We used the following sequence on a 1.5 T scanner (General Electric, Milwaukee, Wisconsin): 2D FRFSE PD, 26 to 35 TE, 2400 to 3500 TR, 31.25 Hz bandwidth, and 2 excitations. From each sagittal slice, the femur, tibia, articular cartilage, and osteophytes were segmented, and a 3D arthritic model was generated using proprietary software (OtisMed Corp, Alameda, California). The arthritic knee model was transformed into a "naturally aligned" normal knee model by filling in articular defects by interpolating from neighboring areas of minimal wear or by morphing areas of severe wear with use of a normal knee as a standard, removing osteophytes, and approximating the joint surface. Surface models of the best-fitting femoral and tibial components were shape-matched to the articular surface of the normal knee model. The theory behind shape-matching is that the flexion–extension axis of the femoral component is aligned coincident with the flexion–extension of the femur, which is the sine qua non for restoring both the patellofemoral flexion–extension axis and the tibial–femoral flexion–extension axis (Figure 1).[10]

Shape-matching the posterior edge of the femoral component to the posterior edge of the normal knee model in the axial projection sets internal/external rotation, which is difficult with conventional and computer-assisted techniques (Figure 2).[11,12] Kinematic alignment of the femoral and tibial components to these 3 axes balances the collateral ligaments without the need for release as long as ligament length is restored by removal of marginal osteophytes.[7-10,13] A commercially available cruciate-retaining prosthesis (Vanguard; Biomet, Inc, Warsaw, Indiana) was used in all cases. The sagittal and coronal radii of the bearing surfaces of both components were symmetric and the tibial bearing was fixed.
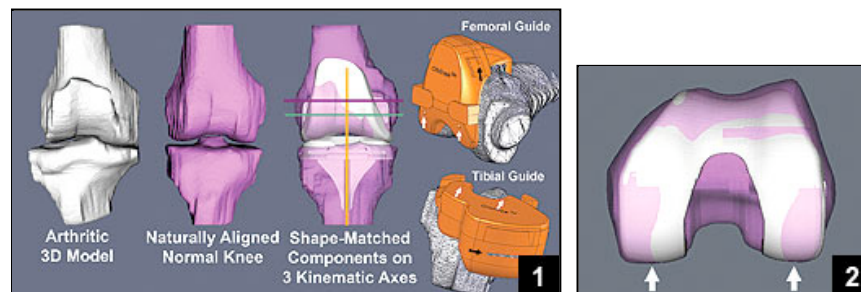

Figure 1: Composite showing the sequential steps of the naturally aligned TKA process progressing from left to right. A 3D arthritic model is made from an MRI of the patient's knee. The naturally aligned normal knee is created from the arthritic knee by filling in worn surfaces, removing osteophytes, and realigning the joint surface. The femoral and tibial components are shape-matched to the respective bones. Theoretically, the shape-match aligns the 3 kinematic axes of the TKA knee with those of the naturally aligned normal knee. The tibial–femoral flexion/extension axis (green line) is approximately parallel to the patellofemoral

flexion/extension axis (magenta line), and both of these axes are approximately perpendicular to the tibial–femoral internal/external rotational axis (orange line). Femoral and tibial cutting guides are made to custom fit the arthritic surface of the patient's knee and transfer the virtual cut planes to the operating room. The saw slots (black arrow) set flexion/extension, varus/valgus, and proximal/distal placement. The 2 pin holes (white arrows) set internal/external rotation, anterior/posterior, and medial/lateral placement by providing reference points for the conventional chamfer guide and tibial alignment guide. **Figure 2:** A schematic of the axial projection of the best-fitting femoral component (silver) superimposed and shape-matched to the distal and posterior articular surface of the 3D model of the normal femur. Aligning the posterior edge of the femoral component to that of the normal femur (white arrows) sets the internal/external rotation of the femoral component the same as the femur.

The cut planes corresponding to the position of the tibial and femoral components were transferred to the arthritic model to make cutting guides. Custom-made femoral and tibial cutting guides were machined using a biocompatible plastic (Delrin; DuPont, Wilmington, Delaware) to fit the arthritic knee. The saw slot in each guide set the proximal/distal translation and the flexion/extension and varus/valgus rotations of the femoral and tibial components. The 2 holes in the distal surface of the femoral guide and the proximal surface of the tibial guide were used to drill reference holes for seating the femoral chamfer guide and the tibial positioning guide, which set the anterior/posterior and medial/lateral translations and the internal/external rotation. Hence, each guide determined the size and position of the femoral and tibial components in all 6 degrees of freedom.

One surgeon (S.M.H.) performed the knee replacement on all patients in which all 3 components were affixed with cement.[7,8] The posterior cruciate ligament (PCL) was retained and the patella was resurfaced in all cases. The knee was exposed through a mid-vastus approach without patella eversion. The custom-fit femoral guide was seated on the anterior cortex, trochlear groove, and distal femur and secured with pins, and the distal cut was made setting proximal/distal translation, flexion/extension rotation, and varus/valgus rotation. The chamfer guide corresponding to the size of the femoral component was inserted in the distal pin holes, and the chamfer cuts were made setting anterior/posterior translation, medial/lateral translation, and internal/external rotation. An intramedullary femoral alignment rod was not used.

The tibia was dislocated anteriorly, preserving the insertion of the PCL. The custom-fit tibial guide was seated on the articular surface and the anteromedial cortex of the tibia and secured with pins, and the proximal cut was made setting proximal/distal translation, flexion/extension rotation (posterior slope), and varus/valgus rotation. The trial femoral component was centered on the femur and the lug holes were drilled. A trial reduction was performed. Any binding of the knee during passive motion was corrected by removing osteophytes, not by releasing soft tissues. The tibial positioning guide corresponding to the size of the tibial component was superimposed over the proximal pin holes, which set anterior/posterior translation, medial/lateral translation, and internal/external rotation. While maintaining the internal/external rotation of the tibial positioning guide with respect to the 2 holes, small 1- to 2-mm medial/lateral and anterior/posterior translations of the guide were made when necessary to center the tibial component on the tibia. A long alignment rod was not used to check the varus/valgus orientation of the tibial cut. The need for collateral ligament and lateral retinacular release to restore motion and balance the knee was recorded.

Contact kinematics were measured by 1 observer (E.E.H.) with a radiographic measurement technique that provides a detailed 3D kinematic assessment of the femoral and tibial components during standing in full extension and kneeling in 90° and maximum flexion.[14,15] Lateral radiographs were taken in 3 positions with the patient in single-leg stance and with the treated knee kneeling on a padded stool at 90° and maximum flexion (Figure 3). The knee was centered on the light projecting from the radiograph tube. The focal distance of the radiograph was documented.[16,17]
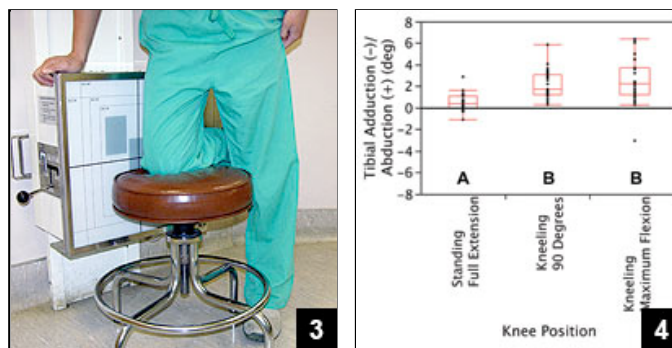

Figure 3: Patient kneeling on padded stool with knee in 907 of flexion for a lateral radiograph of the knee. The knee and radiographic film were centered on the crosshair of the beam of light projecting from the radiograph tube (right). The focal distance of the radiograph was documented. Projections were also taken with the knee in maximum flexion and with the patient standing with the knee in extension. **Figure 4:** Box plot of the adduction/abduction rotation of the tibial component on the femoral component. The thick transverse black line marks the neutral alignment of the tibial component. Due to the accuracy of the measurement technique, values from 1 to 1 were considered neutral. Only 1 radiograph (1%) showed the knee aligned in adduction. Abduction was significantly greater when kneeling in flexion (B) than when standing in extension (A; P.05).

The radiographs were digitized and analyzed according to published techniques.[14-17] The in vivo position and orientation of the prosthetic components from the digitized radiographs were determined from computer matching of the manufacturer-supplied computer-generated geometric models of the knee arthroplasty system. Four dependent variables were measured: adduction (–)/abduction (+) rotation, internal (–)/external (+) rotation, and anterior/posterior contact position of the medial and lateral femoral condyle. The anterior/posterior contact position was measured with respect to a line drawn medial to lateral, which bisected the medial and lateral condyles of the tibial baseplate into anterior and posterior halves. A positive value indicated a contact position in the anterior compartment and a negative value indicated a contact in the posterior compartment. The contact position is the closest point between each femoral condyle and the tibial baseplate. Rotations >1° were considered different from 0 because previous calibration studies demonstrated this technique of component matching to be accurate to approximately 1° for all rotations and 0.5 mm for translations.[18]

Descriptive statistics determined the prevalence of adduction and reverse axial rotation (external) of the tibial component. Box plots compared adduction (–)/abduction (+) rotation, internal (–)/external (+) rotation, and contact position of the medial and lateral femoral condyles with respect to the AP centerline of the tibial liner between each knee position. The height of the box is the interquartile range, which represents half of all values. Twenty-five percent of values are higher and 25% of values are lower than the box. The median is displayed as a horizontal line across each box. The whiskers extending from the ends of the box mark the outermost data point that falls within 1.5 times the interquartile range. Points outside the whiskers are possible outliers. A 1-way analysis of variance determined whether the position of the knee (standing, kneeling in 90°, and maximum flexion) affected abduction/adduction rotation, internal/external rotation, and AP contact position of the medial and lateral femoral condyle with Tukey's test used to detect significant differences between the dependent variables and the knee positions ($P<.05$). Simple linear regression analyses were used to determine whether there was an association between abduction/adduction rotation, internal/external rotation, and AP contact position of the medial and lateral femoral condyle. Statistical tests were performed with commercial software (JMP 7; SAS Institute Inc, Cary, North Carolina).

Results

The prevalence of adduction of the tibial component was 3% (1 of 35 patients) and was observed in 1 radiograph with the patient kneeling in maximum flexion. The tibial component was in abduction in 66% and neutral in 33% of the radiographs. The average abduction of the tibial component increased from standing (0.5±0.8°) to kneeling at 90° (2.5±2.0°) and from standing to maximum flexion (2.1±1.2°; $P<.05$; Figure 4).

The prevalence of reverse axial rotation (external) of the tibial component was 8.5% (3 of 35 patients) and was observed in 1 radiograph with the patient standing and in 2 with the patient kneeling in maximum flexion. The tibial component was in internal rotation in 92% and neutral rotation in 5% of the radiographs. Internal rotation of the tibial component increased from standing (5.5±4.6°) to kneeling at 90° (13.8±6.4°) and from standing to maximum flexion (15.2±7.5°; $P<.05$; Figure 5).

The contact position of the lateral femoral condyle did not change between standing and kneeling at 90° and between standing and maximum flexion ($P=.08$). The average contact position of the lateral femoral condyle was –7.4±4.3 mm posterior to the center line of the tibial liner when standing, –6.9±5.5 mm when kneeling in 90° of flexion, and –9.6±5.7 mm when kneeling in maximum flexion (Figure 6).

The contact position of the medial femoral condyle moved anterior to the center line of the tibial liner between standing and kneeling at 90° between standing and kneeling in maximum flexion ($P<.05$). The average contact position of the medial femoral condyle was –3.3±3.3 mm posterior to the center line when standing and moved to a position 3.8±3.3 mm anterior to the center line when kneeling at 90°, and 4.5±3.3 mm when kneeling in maximum flexion (Figure 7).
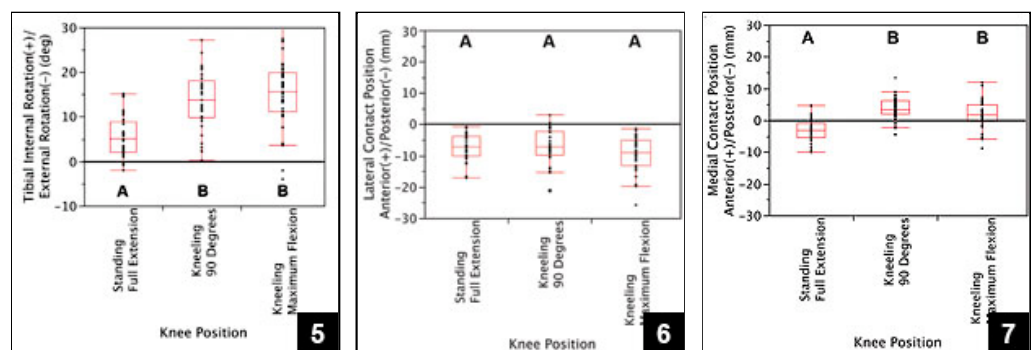

Figure 5: Box plot of the internal/external rotation of the tibial component on the femoral component. The thick transverse black line marks the neutral alignment of the tibial component. Only 3 radiographs (3%) showed the knee had reverse axial rotation (external). Internal rotation of the tibial component was significantly greater when kneeling in flexion (B) than when standing in extension (A; P.05). The top whisker of kneeling maximum flexion is cut off. **Figure 6:** Box plot of the contact position of the lateral femoral condyle on the tibial plateau with the patient standing and kneeling in 907 and maximum flexion. The thick transverse black line marks the AP center line of the tibial component. The spread of the lateral contact positions stayed between 2 mm anterior to 25 mm posterior for each of the 3 knee positions. The lateral contact position remained posterior and

unchanged when the patient was standing and kneeling in 907 and maximum flexion (A). **Figure 7:** Box plot of the contact position of the medial femoral condyle on the tibial plateau with the patient standing and kneeling in 907 and maximum flexion. The thick transverse black line marks the AP center line of the tibial component. The spread of the medial contact positions stayed between 13 mm anterior to 10 mm posterior of the center line for all 3 knee positions. The medial contact position was significantly more posterior when standing in extension (A) and more anterior to the center line when kneeling in 907 and maximum flexion (B; P.05).

There was a moderate association between abduction and internal rotation (r^2=0.39; P<.0001), between abduction and the degree of knee flexion (r^2=0.32; P<.0001), and between abduction and the contact position of the medial femoral condyle (r^2=0.31; P<.0001).

None of the knees required a release of a collateral ligament or the lateral retinculum to restore motion or improve stability.

Discussion

The purpose of the present study was to measure the contact kinematics of a kinematic alignment technique in which symmetric, cruciate-retaining components were shape-matched to a 3D model of the femur with the intent of restoring the 3 kinematic axes of the knee. The most important finding of the study was that both adduction and reverse axial rotation of the knee were minimized when the patient was standing or kneeling in 90° and maximum flexion.

Another important finding was that the prevalence of adduction of 3% with the treatment in the present study appears less than mechanical alignment with conventional TKA. The reported prevalence of adduction is 70% in cruciate-retaining and 80% in posterior cruciate-substituting conventional TKA with symmetric medial and lateral sagittal and coronal radii of the femoral–tibial bearing surfaces (Press-Fit Condylar System; Johnson & Johnson, Raynham, Massachusetts).[5] It is generally agreed that adduction or lift-off of the lateral femoral condyle should be avoided because there is a 3-fold greater distribution of force across the medial side of the knee during midstance.[6,19-21] The additional overload of the medial compartment caused by adduction may lead to eccentric loading, premature wear of polyethylene, excessive load on subchondral cancellous bone, and premature loosening or subsidence of the prosthesis.[5,22,23] Whether the treatment in the present study reduces wear and loosening by minimizing adduction and medial overload requires long-term clinical studies.

One possible explanation for the low prevalence of adduction in the present study is that shape-matching the tibial articulating portion of the femoral component to the 3D model of the restored normal femur sets the internal/external rotation of the femoral component accurately (Figure 2).[7-9] The use of mechanical alignment with conventional axes (ie, posterior condylar axis, Whiteside's line, transepicondylar axis, and individual surgeon's preferred method) by 11 surgeons skilled in the art of TKA resulted in femoral component alignment errors ranging 28°, from 13° of internal rotation to 16° of external rotation.[12] Accurate internal/external rotational alignment of the femoral component is essential because rotational malpositioning is the most common cause of adduction,[24] and malrotation often requires selective ligament releases to restore motion, which further imbalances the knee and generates large variations between the medial and lateral contact forces.[25] Theoretical studies have suggested that aligning the femoral component to reestablish the 3 kinematic axes should restore motion and stability (ie, avoiding adduction) without collateral ligament release,[10,13,26] which is an observation supported by the surgical experience, clinical findings, and minimization of adduction in the present study.

The mechanism responsible for the high prevalence of abduction (66%) and whether there was medial lift-off of the femoral component in the kinematic alignment technique deserves comment. We visually inspected the AP view and top (ie, proximal) view of the pose of the femoral and tibial components and compared the degree of internal rotation of the tibial component and anterior position of the medial femoral condyle in all 3 knee positions in each patient (Figure 8). Our visual observations prompted a regression analysis, which showed that abduction was greater when internal rotation of the tibial component, anterior translation of the contact position of the medial femoral condyle, and knee flexion were greater. These visual and computational observations, combined with the knowledge that the sagittal design of the tibial liner has an anterior upslope, suggest that abduction is not a sign of lift-off of the medial femoral condyle, but rather is caused by the medial femoral condyle moving up the anterior slope of the tibial liner (Figure 9). The effect of the sagittal contour of the tibial liner on adduction/abduction contact kinematics should be considered when designing components.
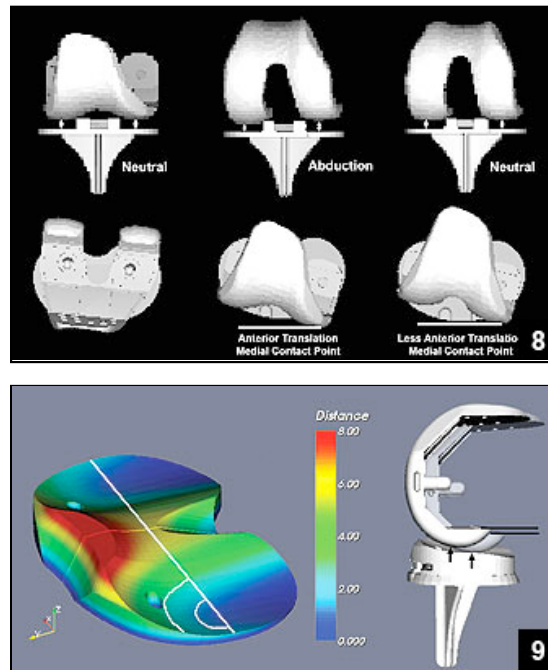
Figure 8: Composite showing the relationship between the femoral and tibial components of the right knee of a patient standing in extension (left), kneeling in 907 of flexion (middle), and kneeling in maximum flexion (right). Upper row shows the AP view and lower row shows the top view. Abduction occurred when the contact position of the medial femoral condyle moved anterior to the center line of the tibial liner (middle). Neutral coronal alignment occurred when the contact position of the medial femoral condyle was centered or posterior to the center line tibial liner (left and right). **Figure 9:** Contour plot of the height of the tibial liner (left). The white line is the AP center line of the tibial liner. Movement of the medial femoral condyle anterior to the AP center line within the 2.00-mm region (curved white lines) during flexion and internal rotation causes abduction of the femoral component. The abduction results from movement of the medial femoral condyle up the anterior slope of the tibial liner (right) and may not represent loss of contact or lift-off between the medial femoral condyle and tibial component.

Another important finding is that the prevalence of reverse axial rotation of 8.5% in the present study appears less than conventional TKA. The prevalence of reverse axial rotation was 41% during gait and 24% in 90° of flexion in conventional TKA, the majority of which had symmetric medial and lateral sagittal and coronal radii of the femoral–tibial bearing surfaces.[2] Restoring a normal pattern of internal rotation of the tibial component is essential for good patellar tracking, reduction of patellofemoral shear forces, and maximization of knee flexion.[2]

One possible explanation for the low prevalence of reversal of rotation in the present study is that shape-matching the tibial component to the 3D model of the restored normal tibia sets the internal/external rotation of the tibial component accurately.[7-9] The use of mechanical alignment with conventional axes (ie, axes between the PCL and the medial border or medial third of the tubercle, the line between the most medial and most lateral points of the plateau, the line between the medial third of the tubercle and the PCL attachment [medial third PCL], the line between the medial border of the tubercle and the PCL [medial border PCL], and the line between the projection of the anterior crest and the PCL) by 11 surgeons skilled in the art of TKA resulted in tibial component alignment errors ranging 90°, from 44° of internal rotation to 46° of external rotation.[27] Small amounts of combined femoral and tibial component internal rotation (1°-4°) have been associated with lateral tracking and tilting of the patella, whereas larger amounts of internal rotation (7°-17°) have been associated with patellar dislocation and patellar prosthesis failure.[28] Further study is required to determine whether kinematic alignment reduces patellofemoral complications.

We showed that the lateral AP contact position was closer to the normal knee than a review of a variety of different component designs implanted with conventional techniques.[3] In the present study, with the patient kneeling in 90° of flexion, the contact position of the lateral femoral condyle was 7 mm posterior to the center line, which is 4 mm more posterior than the reported 3 mm posterior contact position of conventional PCL-retaining arthroplasties,[3,4,29-31] but not as far posterior as the 18-mm posterior contact point in the normal knee.[32] When kneeling in maximum flexion, the contact position of the lateral femoral condyle moved to 10 mm posterior to the center line, which is consistent with the needed increase in posterior femoral rollback of the lateral femoral condyle required to restore deep flexion.[2] Although

normal flexion requires a posterior contact position of the lateral condyle similar to the normal knee, a too-posterior contact position edge loads the liner and accelerates wear and should be avoided, which was fortunately not observed in the present study.[33]

The medial AP contact position of the symmetric, cruciate-retaining component implanted with the kinematic alignment technique is different from that of a normal knee, but similar to that of a variety of conventional TKAs reviewed by Victor et al.[3] In the present study, the contact position of the medial femoral condyle moved from 3 mm posterior to the center line when standing to 4 mm anterior when kneeling at 90° of flexion. This 7-mm anterior movement of the contact point is opposite from the 7-mm posterior movement from 0° to 90° of flexion in the normal knee,[32] but similar to the anterior movement of the medial femoral condyle in PCL-retaining arthroplasties.[3,4,29,30] In the present study, the anterior movement of the medial femoral condyle from standing to kneeling at 90° of flexion may have been caused by a vertically directed upward ground reaction force acting on the tibial tuberosity and tibial component and a vertically directed downward force of half body weight acting on the femoral component from the hip joint.[17,33]

One challenge today is to design implants that will survive ≥30 years.[34] Perhaps another equally important challenge is to develop surgical techniques that position the components so that the kinematics avoid undesirable contact patterns such as adduction and reverse axial rotation. Although the importance of reproducing normal contact kinematics after implantation of a TKA has been questioned, other authors share our view that the reproduction of normal contact kinematic patterns is the best option for preserving stability and restoring movement.[2,3] The present study showed minimal adduction and reverse axial rotation with kinematic alignment of a cruciate-retaining prosthesis with a symmetric medial and lateral femoral–tibial bearing surface, a finding that has not been commonly reported in cruciate-retaining and cruciate-substituting components implanted with mechanical alignment with conventional TKA instrumentation.

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Authors

Drs Howell and Hull are from the Department of Mechanical Engineering, and Ms Hodapp is from the Department of Biomedical Engineering, University of California at Davis, and Mr Kuznik is from OtisMed, Alameda, California.

Dr Howell is an unpaid consultant and co-founder of OtisMed Corp. Mr Kuznik is an employee of OtisMed Corp. Ms Hodapp and Dr Hull have no relevant financial relationships to disclose.

Correspondence should be addressed to: Stephen M. Howell, MD, 8100 Timberlake, Ste F, Sacramento, CA 95823.

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