The Cruciate Ligaments in Total Knee Arthroplasty

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Abstract

The early knee replacements were hinge designs that ignored the ligaments of the knee and resurfaced the joint, allowing freedom of motion in a single plane. Advances in implant fixation paved the way for modern designs, including the posterior-stabilized (PS) total knee arthroplasty (TKA) that sacrifices both cruciate ligaments while substituting for the posterior cruciate ligament (PCL), and the cruciate-retaining (CR) TKA designs that sacrifice the anterior cruciate ligament but retain the PCL. The early bicruciate retaining (BCR) TKA designs suffered from loosening and early failures. Townley and Cartier designed BCR knees that had better clinical results but the surgical techniques were challenging.

Kinematic studies suggest that normal motion relies on preservation of both cruciate ligaments. Unicompartmental knee arthroplasty retains all knee ligaments and closely matches normal motion, while PS and CR TKA deviate further from normal. The 15% to 20% dissatisfaction rate with current TKA has renewed interest in the BCR design. Replication of normal knee kinematics and proprioception may address some of the dissatisfaction.

Hinge knee arthroplasty was introduced in the 1950s.[1] All 4 major ligaments were replaced by the hinge, which provided stabilization while allowing sagittal plane motion. Its goal was stability, not replication of normal kinematics. The addition of methyl methacrylate cement improved fixation and allowed surface design modifications that addressed normal articular motion. Implants such as the Gunston Polycentric,[2] the Duocondylar,[3] and the Geometric[4] resurfaced the medial and lateral compartments of the knee while preserving the cruciate ligaments. The implants were subject to greater translational forces without the hinge and loosening became a major problem despite the advances in cementing. It became evident in the 1970s that preservation of the cruciates complicated the procedure. Cruciate resection simplified the operation and allowed improved fixation. The ICLH prosthesis resected the cruciates and used the articular surface design to give stability to the knee.[5,6] The total condylar prosthesis had a "tibial" imminence that mimicked the shape of the tibial surface but also sacrificed both of the cruciate ligaments (**Figure 1**).

Designers recognized that the cruciate ligaments affected knee kinematics; however, they elected to sacrifice the anterior cruciate ligament (ACL) for surgical simplicity and implant longevi-

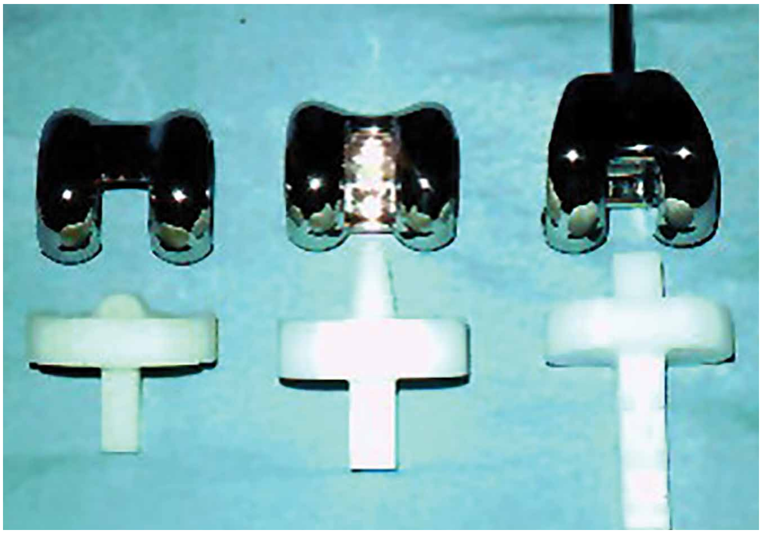

Figure 1. The total condylar knee prosthesis on the left with the total condylar prosthesis II and the total condylar prosthesis III.

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ty.[6] In the early 1980s, both the cruciate-retaining (CR) total knee arthroplasty (TKA) (**Figure 2**) and posterior-stabilized (PS) TKA (**Figure 3**) designs addressed the posterior cruciate ligament (PCL) function. The PCL was preserved in the "cruciate-retaining" TKA, substituted in the "posterior-stabilized" TKA using a cam-post mechanism. The CR TKA designers believed that PCL preservation produced a more balanced knee with a more anatomical result, a more normal joint line, and better function, especially on stair climbing. The PS TKA designers admitted the value of posterior stabilization but argued that it was too difficult to consistently save the PCL in all cases, and that the PS knee was easier for surgeons to implant with more reliable roll back.[7]

The Geometric knee was developed in the 1970s to retain both cruciate ligaments.[4] Unfortunately, it created a kinematic conflict by using a constrained articular surface design that prevented the motion required by the cruciate ligaments. This conflict resulted in tibial loosening and early failures. The compromised results decreased interest in the bicruciate-retaining (BCR) TKA designs, allowing the CR TKA and PS TKA designs to flourish for the next 20 years with little or no attempts to retain the ACL.

In the 1980s the BCR TKA design was pursued by Townley[8] and Cartier.[9] Townley[8] believed that cruciate resection was a concession to "improper joint synchronization"[8] and Cartier[9] thought that cruciate preservation permitted more normal proprioception.[9] Unlike prior BCR TKA designs, the mid-term clinical results were equal to or better than the standard CR TKA or PS TKA of the time, and 9- to 11-year follow-up demonstrated comparable outcomes.[8] While these results highlighted the possibility of a BCR TKA, the surgical technique and failures of the Geometric knee discouraged surgeons from pursuing the BCR TKA.

Figure 2. A typical cruciate-retaining total knee prosthesis.

Figure 3. A typical posterior-stabilized total knee prosthesis with the cam on the posterior aspect of the femoral component.

Interest in cruciate-preserving knee arthroplasty returned with partial knee replacements, with patients reporting more normal proprioception and motion.[10] The techniques became more popular with the introduction of the minimally invasive surgeries in the early 2000s and cruciate ligament preservation became a more interesting concept.[11,12] Some surgeons preserved the cruciates by using separate implants for the medial, lateral, and patellofemoral surfaces.[10] These results were acceptable for the time but required considerable surgical talent and did not report 20-year results similar to the CR and PS knees.

Most prosthetic designs attempt to copy the normal knee anatomy. Using fluoroscopic studies and computer analysis, designers began to investigate the motion (or kinematics) of the normal knee and realized that despite the fact the TKA looked like the human knee, the designs were not kinematically correct.[13]

Although TKA successfully treats pain secondary to degenerative joint disease, many patients are unable to return to their prior level of function, with up to 20% reporting dissatisfaction with their level of activity.[14] The observed differences in kinematics between a normal knee and a TKA may explain part of this discrepancy.

Normal Knee Motion

The tibiofemoral articulation in a normal knee follows a reproducible pattern of motion as the knee moves from extension to flexion. The lateral femoral condyle (LFC) translates posteriorly with a combination of rolling and sliding motion, while the medial femoral condyle (MFC) has minimal posterior translation and thus acts as a pivot for knee motion. The MFC is larger, less curved, and has a biphasic shape with 2 distinct radiuses of curvature that correspond to an "extension" and "flexion" facet. The transition between the MFC facets occurs at approximately 30° of flexion, whereby the contact point transfers posteriorly with little condylar translation.[15-17] In contrast, the LFC is smaller, has a single radius of curvature, and gradually translates posteriorly throughout flexion. Static magnetic resonance imaging of the knee from 0° to 120° shows an average of 19 mm posterior translation for the LFC and 2 mm for the MFC.[15-20]

In deep flexion, beyond 130°, posterior translation continues for both condyles. The LFC experiences enough excursion to cause loss of joint congruity and partial posterior subluxation.[19,20] The MFC shows little additional posterior translation, yet it too loses joint congruity through condylar lift-off. Contact between the posterior horn of the medial meniscus and the posterior femoral condyle limits further flexion.[16,21]

The difference in motion between the condyles leads to internal tibial rotation during flexion. The initial 10° of knee flexion produces 5° of internal rotation, and an additional 15° of internal tibial rotation occurs throughout the remainder of knee flexion.

Fluoroscopic imaging with computed tomography (CT)- or magnetic resonance (MR)-based modeling has shown the dynamic in vivo relationship of the tibiofemoral joint. Studies have confirmed significantly greater LFC posterior translation as compared to the MFC;[22] however, in vivo studies have also shown notable variability in articular rotation and translation based on activity. This highlights the role of ligamentous tension and muscle contraction in kinematics.[21-23]

The ACL in TKA

The majority of current TKA designs sacrifice the ACL without substituting for its function. The loss of the ACL has significant effects upon the kinematics of the knee.

The ACL is composed of 2 bundles, the anteromedial and posterolateral bundles, which originate on the LFC and insert broadly onto the tibial intercondylar eminence. Its primary role is to resist anterior tibial translation, particularly from 0° to 30° of flexion, which corresponds to the peak quadriceps force that pulls the tibia anteriorly.[24] ACL deficiency causes anterior tibial translation during early flexion and abnormal internal tibial rotation.[25-27] ACL deficient knees demonstrate a posterior femoral position in full extension, and increased MFC translation during knee flexion.[28-32]

The role of the ACL in knee arthroplasty has been evaluated by comparing unicompartmental knee arthroplasty (UKA) with TKA, as a reflection of ACL preserving vs sacrificing procedures.[33-35] Sagittal plane translation is similar between UKA and normal knees,[33,34] while the CR TKA and PS TKA designs show anterior tibia subluxation in full extension.[33-35] The difference between UKA and TKA is greatest in extension, corresponding to the ACL functional range. These findings highlight kinematic similarities between TKA designs and the ACL deficient knee.

The majority of UKAs demonstrate near-normal kinematics. A small percentage of the study group demonstrated aberrant anterior tibial motion, highlighting a concern over ACL attenuation with time. Additionally, studies that evaluate the ACL in osteoarthritic knees have questioned the baseline integrity of the ACL.[36] Yet the long-term outcomes in UKA design have shown preservation of kinematics due to intact cruciates.[37]

The PCL in TKA

Because the majority of TKA designs sacrifice the ACL, the classic debate has focused on the utility of the native PCL. Both the CR and PS TKA are designed to offer posterior stabilization; however, kinematic studies have demonstrated notable differences.[38,39]

The CR TKA design relies on the PCL to resist posterior sag and to prevent the hamstring musculature from pulling the tibia posteriorly during flexion. Studies have shown paradoxical anterior translation of both femoral condyles during flexion, particularly on the medial side of the knee.[40] There is also increased variability in femoral rollback. It is unclear whether the PCL can function normally in the absence of the ACL, which causes the PCL to adapt a less anatomic vertical position. The PCL may also be unable to function significantly without the ACL because of pre-existing degenerative histological changes.[41]

The PS TKA utilizes a cam-post mechanism for posterior stabilization. In contrast to normal knee kinematics, this mechanism creates equal MFC and LFC posterior translation, 8 mm on average at 90° flexion.[40] The equivalent translation in PS designs contributes to decreased internal tibial rotation and an increased polyethylene wear at the post.

Role of Surface Geometry

The articular geometry of the knee plays an important role in normal knee kinematics. Initial TKA designs used a femoral component with a single radius of curvature for both femoral condyles.[42] Current TKA designs that match the femoral component to the native femoral anatomy, by differing the medial and lateral condyle geometry, have demonstrated kinematics that better resemble a native knee.[43] Additional changes to the radius of curvature along the posterior facet of the femoral condyles may reduce impingement during deep flexion. These "high flex" designs have demonstrated equivalent range of motion in some studies[44] and improved weight-bearing motion in others.[45] Surface geometry is important but is not the entire answer to kinematics.

Advances in TKA Design

Knee motion is guided by multiple factors, including the tibiofemoral articular geometry, the surrounding soft tissue tension, and muscle tone. Bicruciate-substituting (BCS) TKA and BCR TKA are forms of evolution from the CR and PS TKA and attempt to respect the function of both cruciate ligaments and provide better kinematics.

The BCS TKA utilizes a modified cam-post articulation to provide both anterior and posterior stabilization (**Figure 4**).[46] The surgical approach remains the same and the implant geometry affects the motion. The BCS TKA design demonstrates femoral rollback at 90° with an average of 14 mm for the MFC and 23 mm for the LFC, and 10° internal tibial rotation.[46,47] Additionally, it provides increased sagittal stability during early flexion and an improved pivot shift (indicating improved anterior stabilization).

The BCR designs preserve both cruciates and provide anterior and posterior stabilization. Fluoroscopic imaging has demonstrated contact points in full extension, and posterior rollback at 90° flexion that more closely replicates the normal knee.[48]

Design and Surgical Techniques for Bicruciate Knee Replacements

If all of the ligaments are preserved, the TKA surfaces must allow motion to be driven by the ligaments in combination with the surfaces alone. The femur can be designed anatomically with asymmetric condyles. The femoral box must allow for preservation of the tibial bone island without impinging upon the cruciate ligaments. The tibial surface must be minimally constrained with concavity medially and convexity laterally.

The bone island preservation does not permit a single-piece tibial polyethylene insert. Therefore, the inserts will replicate the UKA designs (**Figure 5**). The knee should allow greater range of motion with the possibility of heel to buttocks contact. This increased motion will lead to greater roll back of the femur on the tibia and can lead to subluxation of the femoral runner off of the tibial surface on the lateral side, mimicking the normal knee. This subluxation is desirable but may lead to increased wear of the polyethylene on the lateral side of the knee.

The instruments should be specific for the design but must also be user-friendly. The 2 major issues with the surgery are balancing the knee in full extension and flexion, and preservation of the tibial bone island. The preexisting knee deformity should be <10° in all planes to limit the amount of collateral ligament releases. The collaterals must be balanced in a similar fashion to the standard TKA. Flexion contracture can be treated with posterior capsular release around the cruciates or with an increased distal femoral resection (2 mm at the maximum).

It is important to size the femur correctly because it will be difficult to adjust the flexion gap on the tibial side. A 9-mm posterior medial femoral condyle resection is a reasonable guide if the condyle is not atrophic. However, the exact resection thickness will be implant-specific and should be correlated with the dimensions of the prosthesis being implanted. The tibial bone island must be properly rotated with respect to the center line (Akagi's line)[49] and must not be undercut. The tibial instrument should include pins or blocks to prevent the sawblades from undercutting the island (**Figure 6**), as undermining leads to fracture in full extension. If undermining occurs, it may be possible to place a cancellous screw through the island and still preserve the ligaments. The integrity of the island is best tested by bringing the knee to full extension and

Figure 4. Sagittal cutaway view of a bicruciate-substituting knee (Journey Bi-Cruciate Stabilized Knee System, Smith & Nephew) showing anterior contact of the post with the box of the femoral component substituting for the anterior cruciate ligament.

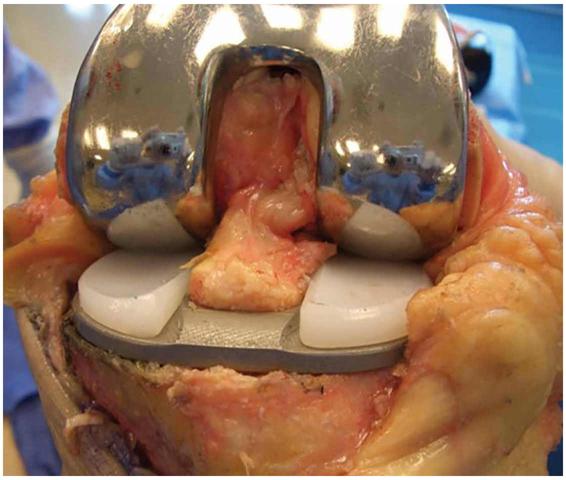

Figure 5. A bicruciate-retaining total knee arthroplasty knee prosthesis (Journey II XR, Smith & Nephew) showing preservation of the intercondylar notch and both cruciate ligaments.

checking for liftoff of the bone. If there is significant compromise of the island, the bone should be resected and either a CR or PS TKA can be implanted. Della Valle and colleagues[50] reported a 9.2% incidence (11 of 119 cases) of bone island fracture in their early experience with a BCR TKA and improved this to 1.9% (5/258 cases) after reassessing their technique.

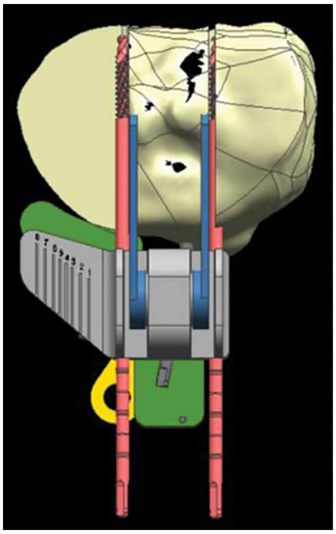

Figure 6. Schematic view of the top of the tibia with 2 anterior-to-posterior pins that protect the bone island during the plateau preparation (Journey XR Tibia, Smith & Nephew).

The gap tension should be evaluated either with traditional spacer blocks or with tensioning devices on the medial and lateral side of the knee after the tibial resections are completed. The polyethylene inserts are anatomically different. It may be possible to vary the thickness from medial to lateral, but not in excess of 2 mm.

As the BCR surgical techniques evolve, the balancing and tibial resection may be refined through specialized instrumentation. Such "smart instruments" that incorporate gyros may expedite tibial alignment, and sensor devices may assist with gap balancing. Haptic surgical robotic guides may assist in the tibial resection, facilitating bone island preservation by avoiding any possibility of undermining. At present these assistive aides are not necessary for the operation but may play a future role.

Clinical Results of Knee Arthroplasties

The results of knee replacements improved steadily from the 1970s through the 1990s. The scoring systems were somewhat limited and there was little data on the perception of the patients. The prosthetic designs stabilized at the end of the 1990s with only minor modifications since the year 2000. The 20-year results show similar findings for both the CR and the PS designs. There is little evidence to suggest a clinical correlation with the observed kinematic differences between CR and PS TKA designs.[40,51-58] Multiple studies have demonstrated equivalent range of motion[38,39,59] and subjective outcome measures (**Table 1**).[60] A randomized prospective trial that compared kinematics and functional scores between the 2 designs failed to observe significant differences in function despite differences in kinematics.[46] Equivalence in clinical outcome was further supported by a Cochrane Review meta-analysis that evaluated 1810 patients in 17 selected studies.[61] The Knee Society scores have all been in the 92% to 95% ratings with survivals between 90% and 95%.

However, only 80% to 90% of patients are fully satisfied with their implants. The reasons for the dissatisfaction include unexplained anterior knee pain, stiffness, unexplained swelling, loss of range of motion, changes in proprioception, and loss of preoperative functions.[14]

The mid-term results of the BCR knees that were performed in the 1980s showed similar

Table 1. **Randomized Control Trials Comparing Cruciate Retaining (CR) and Posterior Stabilized (PS) Total Knee Arthroplasty**

			Number of Knees		Range of Motion		Knee Society Score	
Study	**Implant**	**Follow-up (months)**	**CR**	**PS**	**CR**	**PS**	**CR**	**PS**
Catani, 2004[57]	Optetrak—Exactech	24	20	20	97	114	89	90
Tanzer, 2002[52]	Legacy, NexGen—Zimmer	24	20	20	112	111	90	93
Victor, 2005[66]	Genesis II—Smith & Nephew	60	22	22	114	117	82	77.9
Kim, 2009[60]	NexGen LPS-/CR-Flex—Zimmer	28	250	250	126	129	94	95
Harato, 2008[56]	Genesis II—Smith & Nephew	60	111	111	111	117	90.8	94.4
Maruyama, 2004[53]	PFC Sigma—DePuy	31	10	10	122	129	89.8	89.5

Abbreviation: LPS, legacy posterior stabilized.

Table 2. **Studies on Bicruciate Design**

Implant Design	Study	Implant Name	Number of Knees	Outcome Summary
Bicruciate-retaining	Townley, 1985[8]	Anatomic total knee	532	Average flex: 91% > 90°, 21% 110°–120°, 12% > 120°, 89% good-excellent results at 11 years
	Cloutier, 1999[9]	Hermes 2C	104	Average flex – 107°, Knee Society Score—91, 95% 10-year survival
	Sabouret, 2013[63]	Hermes 2C	32	Average flex – 103°, Knee Society Score—87, 82% 20-year survival
	Pritchett, 2011[62]	Biopro; Wright ACL + PCL	137	Average flex – 119°, Knee Society Score—92.6, 87% prefer to contralateral PS TKA, 79% prefer to CR TKA
Bicruciate substituting	Catani, 2009[47]	Journey Bi-Cruciate Stabilized Knee System, Smith & Nephew	16	Average flex – 118°, Knee Society Score—90.7

Abbreviations: ACL, anterior cruciate ligament; CR, cruciate-retaining; PCL, posterior cruciate ligament; PS, posterior-stabilized; TKA, total knee arthroplasty.

results to the CR and PS knees. Townley[8] reported excellent clinical results with only 2% loosening at 2 to 11 years after surgery. Cloutier and colleagues[9] reported 95% survival with improved proprioception at 9 to 11 years after surgery (**Table 2**).[62,63]

Studies comparing traditional TKA designs with cruciate preserving designs, both UKA and BCR, have found differences in subjective outcomes.[62,64] Comparison of UKA and TKA in the same patient demonstrated significant preference for UKA, particularly with stair-climbing.[65] Similarly, comparison between BCR and PS TKA or CR TKA demonstrated preference for BCR in 85% of patients.[62]

The new BCR knee designs have just started to come to the market.[50] The surgical techniques are much improved over the 1980s and cruciate preservation is certainly much easier now. The new designs can produce full range of motion with kinematics that are almost identical to the normal knee in the cadaver laboratory and in computer analyses. These designs certainly should have a similar 20-year survival to the original BCR knees. However, the critical evaluation will be the patient satisfaction scores. With greater motion, better kinematics, and more precise balancing the scores would improve with these designs.

Conclusion

The cruciate ligaments of the knee are central to control of the motion of the normal knee. TKA is a successful operation with at least a 40- to 50-year history. The techniques have continued to develop but 15% to 20% of patients are dissatisfied with the results.[14] Evaluations of the prostheses are more sophisticated and kinematics appears to have a central position in the evaluation. If the knee is to move more anatomically correctly, all of the ligaments must be preserved. Proprioception certainly plays a role in the patient's judgment of the result. History has shown that a BCR knee can be implanted with good mid-term results and it should certainly be possible to build on these results and design a knee that will incorporate all of the ligaments with full range of motion and increased levels of activity.

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This paper will be judged for the Resident Writer's Award.