Chapter 10

Implant Designs of Total Knee Arthroplasty

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Abstract

The continued development of implant geometries and materials used in total knee arthroplasty is motivated by the recognition of patient dissatisfaction, increased use in young and active patients, and concerns regarding metal hypersensitivity. Single-radius and multiradius femoral designs appear to be associated with equivalent clinical outcomes. Anatomic tibial trays can reduce the likelihood of internal rotation if tibial coverage is maximized to guide placement. Recent meta-analyses and registry studies suggest equivalent outcomes for all-polyethylene and metal-backed tibial components. Anatomic or biomimetic articular surfaces together with anterior cruciate ligament retention or substitution may be key to restoring normal kinematics following total knee arthroplasty. Restoration of the native joint line by using surgical technique or asymmetric thickness components may also play an important role in improving function following TKA. Several materials have shown promise as alternatives to cobalt-chromium-molybdenum alloys. Bulk ceramics and oxidized zirconia have shown particularly excellent mid- to long-term outcomes and may be viable options for patients with suspected metal hypersensitivity.

Keywords: anatomic articular surface; anterior cruciate ligament; ACL function; anatomic joint line; all-polyethylene tibial component; ceramics

Introduction

Total knee arthroplasty (TKA) implant designs continue to evolve, given that 20% to 30% of patients are dissatisfied with how their knee feels and functions after surgery; use of these procedures has increased in active patients younger than 65 years; and concerns exist regarding metal hypersensitivity in some patients. New implant technologies, together with improvements in technique and instrumentation, can hopefully result in a more normal-feeling knee postoperatively, with longevity extending to the second and third decade. It is important for the orthopaedic surgeon to be aware of the considerations and developments related to implant geometry and implant materials, with a focus on issues that continue to be debated and new technologies that are being explored.

Implant Geometry

The implant geometry directly influences joint biomechanics, including function of the native soft tissues, tibiofemoral kinematics, and patellar tracking. Previously, sex-specific implants were proposed to better fit male or female knee anatomy. Subsequent research has not supported the need for sex-specific designs, but instead has shown a need for size-specific aspect ratios and/or provisions for sufficient implant sizes. Similarly, although high-flexion designs reduce tibiofemoral contact stresses in deep flexion, they do not provide increased range of motion (ROM). In addition, these newer designs do not treat the underlying kinematic limitations of contemporary implants, which have been associated with functional limitations and patient dissatisfaction. One study reported that patients who underwent TKA have greater difficulty performing activities such as kneeling, carrying loads, playing tennis, dancing, and gardening compared with their age-matched peers; only 40% of the functional deficit seemed attributable to the normal effects of aging.¹ Research and development efforts are ongoing to
create implant designs that can provide more normal kinematics via modifications of the femoral and tibial articular surfaces, the provision of asymmetric components to reduce rotational malpositioning, and the restoration of anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) function via retention or substitution.

**Femoral Implant**

**Single-Radius Versus Multiradius Designs**

Both single-radius and multiradius femoral implant designs are commercially available (Figure 1). Multiradius designs use a changing radius of curvature with increased knee flexion that results in a center of rotation that shifts through the ROM. Single-radius designs have a consistent radius of curvature throughout the flexion-extension arc and a more posterior center of rotation, which theoretically creates more consistent soft-tissue/collateral ligament tension to minimize instability in mid flexion and increases quadriceps muscle strength. A 2015 study examined three cohorts of patients (16 patients after single-radius TKA, 16 patients after multiradius TKA, and 16 healthy control patients) in a gait analysis laboratory. Preoperatively, no

![Figure 1](image-url)

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significant differences in gait cycle parameters existed between patients in the single-radius and multiradius groups. Postoperatively, several significant differences were noted between the patients in the multiradius group and control patients in several gait parameters, including increased knee extension and decreased power absorption in the multiradius group. No significant differences between the single-radius group and control patients were detected. Despite these findings, no functional differences were observed in patient-reported outcome measures.

A lack of functional difference between single-radius and multiradius designs has been reported. A prospective cohort study with a standardized surgical and rehabilitation protocol reported on 250 patients who underwent single-radius TKA and 224 patients who underwent multiradius TKA with 5-year follow-up. No significant differences existed between the single-radius and multiradius groups at 1 and 5 years following surgery in Knee Society scores, Medical Outcomes Study 36-Item Short Form physical scores, postoperative ROM, or patient satisfaction. In addition, a recent meta-analysis of 15 studies compared single-radius and multiradius TKA designs and found no difference in Knee Society scores, knee flexion, complications, isometric peak torque of the knee, or survival rates. Thus, the theoretical advantages of a single-radius design are not supported by available clinical data. This finding may be because the actual geometric difference between single-radius and multiradius femoral designs for most of the active flexion range (10° to 110°) is small. Implant systems with single-radius versus multiradius designs also vary substantially in the geometry of other components, such as the tibial articular geometry. Therefore, it may be difficult to ascertain the effects of femoral design alone from clinical data.

**Restoration of the Anatomic Joint Line**

Historically, the two primary approaches to coronal plane positioning of the joint line were anatomic and functional alignment. Anatomic alignment, along with its modern iteration termed kinematic alignment, aims to restore the natural joint line orientation to promote natural knee mechanics. Functional alignment, also termed mechanical alignment, is the prevailing convention and aims to create a joint line perpendicular to the overall mechanical axis.
of the lower limb. This approach is thought to load each compartment equally, avoiding an overload of the tibial component medially.\(^{5}\)

Although mechanical alignment has produced excellent results in millions of patients, natural knee kinematics are not maintained when this method is used. This is, in part, because although the implants generally have equal medial and lateral condylar thicknesses, the corresponding bone cuts have asymmetric thicknesses. For example, in a typical varus knee, approximately 9 mm of bone is removed from the distal medial femoral condyle, which equals the implant thickness, and approximately 7 mm of bone is removed from the distal lateral femoral condyle, which is less than the thickness of the implant. In this situation, the medial joint line will remain anatomic but the lateral joint line will be displaced distally by approximately 2 mm with standard femoral implants (Figure 2). Joint line depression is not ideal because it is linked to patellofemoral pain, subluxation, and diminished functional gains at deviations as small as 3 mm of depression.\(^{6}\) Alternatively, if distal femoral resection increases by 2 mm, the lateral joint line will remain anatomic and the medial joint line will be elevated. Joint line elevation also is not ideal because it is linked to patellar impingement on the tibial component, midflexion instability, and patellofemoral pain at deviations as small as 5 mm of elevation.\(^{6}\) Furthermore, because mechanical alignment does not re-create natural knee kinematics, collateral ligament tension and strain are significantly altered during knee ROM.\(^{7}\)

One approach to restoration of the anatomic joint line is to use standard nonanatomic implants positioned parallel to the native joint line. However, placing nonanatomic implants in an anatomic coronal position can be problematic. Placing the tibial component in varus has been associated with high failure rates in many studies.\(^{8}\) In addition, placing the tibial component in varus necessitates internal rotation of the femoral component to create a symmetric flexion gap, which elevates the lateral anterior femoral flange and rotates the trochlear groove.
medially. Furthermore, by placing the femoral component in relative valgus, the proximal trochlear groove is shifted medially, which potentially predisposes the patella to tilt and maltracking.\(^9\) Despite these issues, proponents of kinematic alignment report reasonable short-term results.\(^10\) Long-term studies are necessary to clarify the role of this method in TKA.

Instead of placing components in anatomic position, another option is to restore the anatomic joint line using the implant design. This restoration is achieved in some designs by using the concept of anatomic contour matching to match the thickness of the bone removed to the thickness of the bone replaced. To restore an anatomic varus joint line orientation of 3°, the lateral side of the tibial insert is thicker than the medial side. Concomitantly, the distal medial side of the femoral component is thicker than the distal lateral side. Using asymmetric implant thicknesses allows these designs to more closely match the normal anatomy of the typical femur and tibia while using standard mechanical alignment bone cuts (Figure 3). Thus, an anatomic joint line can be achieved while maintaining a tibial cut perpendicular to the tibial mechanical axis, thereby minimizing shear forces and the potential for mechanical failure at the tibial interface. Restoration of the anatomic joint line in conjunction with other design features such as anatomic tibial articular geometry and bicruciate substitution, may contribute to the reproduction of near-normal knee kinematics.

**Tibial Tray**

**Symmetric/Asymmetric Versus Anatomic Design**

Tibial tray design has the potential to influence tibial coverage and rotational alignment. In practice, coverage and rotation may be conflicting, prompting reduction of the tibial component size and coverage to optimize rotational alignment. Increased recognition of population and ethnic differences in proximal tibial morphology has resulted in more tibial tray implant design options. Currently, symmetric, asymmetric, and anatomic designs are commercially available (Figure 4). A 2014 study compared proximal tibial morphology obtained from the CT scans of Caucasian cadavers and living Indian, Korean, Chinese, and Japanese subjects with six contemporary TKA designs.\(^11\) Compared with asymmetric and symmetric designs, the anatomic design demonstrated better conformity to tibial size/shape and tibial coverage (92% versus 85% to 87%, respectively), and a lower incidence of downsizing (3% versus 39% to 60%, respectively) to ensure rotational alignment. An MRI-based study of symmetric, asymmetric, and anatomic tibial trays from a single manufacturer showed significantly higher proximal tibial coverage with the anatomic design (80.8%) compared with the symmetric (76.3%) and asymmetric (75.8%) designs when rotational alignment was constrained to the anterior-posterior axis.\(^12\) In contrast, another 2014 study found similar tibial coverage for symmetric, asymmetric, and anatomic trays aligned to the tibial anterior-posterior axis,\(^13\) as well as similar variations in rotational position when maximizing tibial coverage. However, in that study, symmetric and asymmetric designs were biased toward internal rotation and the anatomic design was biased toward external rotation, which indicates that anatomic designs may provide only a slight advantage regarding tibial coverage. However, anatomic designs may reduce the incidence of internal tibial rotation if maximal tibial coverage is used to guide tray placement.

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**Figure 4** Illustration depicts anatomic, symmetric, and asymmetric tibial trays overlaid on a proximal tibial surface. The maximum tibial coverage and resulting rotation for each tray design are also indicated. (Reproduced with permission from Stulberg SD, Goyal N: Which tibial tray design achieves maximum coverage and ideal rotation: Anatomic, symmetric, or asymmetric? An MRI-based study. *J Arthroplasty* 2015;30[10]:1839-1841.)
All-Polyethylene Versus Modular Tibial Components

All-polyethylene tibial components have been used since the earliest tibial component designs were developed. However, most knee implants currently use modular metal-backed tibial components because of advantages such as intraoperative flexibility, the potential for isolated bearing exchange, and the availability of a press-fit fixation option. Modular metal-backed tibial components also are proposed to diminish stress and strain at the implant-cement interface.

Initial poor results and early failures for all-polyethylene tibial components were attributed to surgical technique and implant design problems, specifically, the lack of articular congruity of the tibial component. However, recent meta-analyses and registry-level studies suggest that clinical outcomes of all-polyethylene tibial components are equivalent to those of metal-backed components. A systematic review and meta-analysis of 1,798 TKA implants in 12 studies published from 1990 to 2011 identified all-polyethylene tibial components as one of the treatment arms.15 Although no findings were significant, respective risk reductions of 29% and 14% were identified at 10 and 15 years after the index procedure for revision for all-polyethylene components compared with metal-backed components. Furthermore, no significant difference was found in functional outcome or adverse events between the all-polyethylene and metal-backed groups. Additional meta-analyses of previously published studies also demonstrated no significant differences in functional outcomes and complications between all-polyethylene and metal-backed tibial components.15

A 2013 study published data from a large community-based total joint registry of 27,657 patients who underwent TKA with the same implant (91.7% in the metal-backed group and 8.3% in the all-polyethylene group).16 The surface geometry of the tibial implant was the same for both the metal-backed and all-polyethylene tibial components. The revision rate was lower for all etiologies in the all-polyethylene group than in the metal-backed group (1.95% versus 2.17%, P < 0.001). After adjusting for age and sex, the risk of revision for all etiologies of an all-polyethylene tibial component was 0.51 times higher than the risk of revision for a metal-backed component (95% confidence interval: 0.33-0.78). A 2014 study published the comparative revision rates of cruciate-retaining all-polyethylene and metal-backed tibial components performed with the same implant with identical surface geometry in 27,733 patients from the Swedish Knee Arthroplasty Register (median follow-up, 4.5 years; 57.7% metal-backed components, 42.3% all-polyethylene components).17 Unadjusted 10-year survival was 96.6% for the metal-backed tibial component and 97.2% for the all-polyethylene tibial component (P = 0.002). Cox multiple regression analysis demonstrated that all-polyethylene tibial components had a lower risk of revision for any reason, with an adjusted relative risk of 0.75 (95% confidence interval: 0.64-0.89), compared with metal-backed tibial components.

In addition, all-polyethylene tibial components may provide the added benefit of reduced costs. One study showed a 20% to 30% reduction in cost when using all-polyethylene components compared with metal-backed components; another study calculated $95,000 in savings on implant costs for every 100 patients who received an all-polyethylene component instead of a metal-backed component.18,19

PCL Function: Retention, Substitution, or Sacrifice

The debate regarding the merits of PCL retention in cruciate-retaining designs versus PCL substitution in posterior-stabilized designs has been long-standing. However, no clinically relevant differences have been found in ROM, pain, clinical, or radiologic outcomes for cruciate-retaining versus posterior-stabilized designs.20 In a cruciate-substituting or ultracongruent design, the PCL is sacrificed, with no cam-post mechanism (unlike posterior-stabilized designs) to substitute its function. One potential advantage of ultracongruent designs over posterior-stabilized designs is greater bone preservation resulting from the absence of a femoral box cut. Potential disadvantages of ultracongruent designs include increased wear resulting from greater contact area and reduced ROM because of reduced rollback or greater paradoxical anterior sliding. These designs generally share the same tibial articular geometries as their cruciate-retaining counterparts, except for a higher anterior lip (and often a higher posterior lip), which is designed to minimize anterior femoral sliding in flexion. However, some studies show greater anterior femoral translation in flexion for ultracongruent designs compared with posterior-stabilized and cruciate-retaining designs, indicating that the anterior lip may not fully compensate for the stability provided by the PCL or the post-cam mechanism. No significant differences in clinical outcomes, including ROM, function scores, and radiographic evaluation, have been noted for ultracongruent versus cruciate-retaining or posterior-stabilized designs.22-24 Similarly, a multicenter study found no difference in 10-year survivorship for ultracongruent, cruciate-retaining, or posterior-stabilized TKA designs.25

The similar outcomes among ultracongruent, cruciate-retaining, and posterior-stabilized designs may partly be explained by their relatively similar kinematics,
compared with their kinematic differences from the preoperative or normal condition. Two separate studies both found paradoxical anterior translation approximately 2 mm greater for ultracongruent designs than for posterior-stabilized and cruciate-retaining designs. In contrast, another study measured the intraoperative kinematics of patients receiving ultracongruent implants and reported 8 mm of anterior translation of the medial condyle and 20 mm of anterior translation of the lateral condyle relative to the preoperative condition.

**Tibial Articular Surface**

One important factor responsible for kinematic limitations of contemporary implants is the nonanatomic tibial articular geometry. In the native knee, the medial tibial plateau has a shallow dish profile, and the lateral plateau is convex. This geometry, coupled with the differential stability of the medial versus lateral menisci, results in differential anterior-posterior excursion of the medial and lateral femoral condyles during flexion. However, the ball-in-socket analogy commonly used to describe the medial condyle is only partially true because its motion is not completely restricted. During activities of limited flexion such as walking or stair climbing, the anterior-posterior motion of the medial and lateral condyles can be similar, resulting in lateral or variable pivot patterns. Nevertheless, for its full ROM and during high-flexion activities, the knee shows an overall medial pivot with greater rollback of the lateral femoral condyle.

In contrast to asymmetric native tibial anatomy, most contemporary implants (for example, cruciate-retaining and posterior-stabilized implants) have identical medial and lateral articular geometries. A notable exception is the ball-in-socket medial pivot concept that was first introduced in the mid 1990s. Several newer versions of these designs that maintain this original philosophy have been introduced in recent years. In vivo and in vitro studies show that the design objectives of minimizing medial condyle motion and paradoxical anterior sliding are achieved via these ball-in-socket implants. However, the extent of medial pivot rotation and lateral condyle rollback are smaller in magnitude compared with normal knees. This feature may be a result of the prominent posterior lip or the absence of normal lateral convexity, which limits lateral condyle rollback. Other concerns with the strict ball-in-socket concept are the inability to accommodate normal pivot center variations during low-flexion activities and conflicts with the PCL if used in the cruciate-retaining setting. The conflict with native PCL may explain why ball-in-socket implants are generally indicated for use with a PCL-sacrificing technique. Thus, development
continues of advanced articular surfaces that allow restoration of activity-dependent kinematics of the knee.

In 2015, a new biomimetic technique was described to create articular surfaces directly from the in vivo kinematics of healthy knees, which was achieved by moving the femoral component in virtual space along the in vivo kinematics to carve a compatible biomimetic tibial articular surface. Theoretically, this method accounts for normal anatomy and kinematics, allows hand-in-hand design of femoral and tibial articular surfaces, and incorporates the effect of surgical placement. The resulting biomimetic surface has an anatomic profile, including a shallow medial surface similar to some conventional implants, and a convex lateral plateau with a relatively low anterior and minimal posterior lip. Progressive deviations from the biomimetic geometry resulted in increasingly abnormal kinematics during a simulated knee bend. In another study, a biomimetic cruciate-retaining implant was found to more closely mimic normal kinematic patterns than contemporary cruciate-retaining implants during various simulated activities (Figure 5). The biomimetic cruciate-retaining implant particularly showed medial pivot motion during the deep knee bend and chair sit while accommodating pivot center variations during stair ascent. This concept has not been evaluated in vivo.

In contrast, an ACL-/PCL-substituting (bicruciate-substituting) implant with anatomic tibial articular surfaces has been available since 2005, and a cruciate-retaining version of the same design was recently introduced (Figure 6). Positive results regarding the restoration of normal kinematic patterns have been reported for the bicruciate-substituting design. One study reported profiles of the patellar tendon angle and patellar flexion for the bicruciate-substituting knee to be more normal than other TKA designs. During a deep knee bend activity, another study measured medial and lateral condyle rollback of 14 and 23 mm, respectively, in bicruciate-substituting knees. Average axial rotation...
patterns were similar but lower in magnitude than in normal knees (Figure 6).

**ACL Function**

Currently, three strategies are being explored to incorporate ACL function in TKA: native ACL and PCL retention, ACL substitution and native PCL retention, and ACL and PCL substitution.

**ACL and PCL Retention**

Retention of the ACL and PCL during TKA is a concept that was introduced in the 1970s (for example, the Geomedic knee and the anatomic knee). However, ACL and PCL retention did not attain widespread acceptance because of perceived difficulties in balancing both the ACL and PCL, concerns regarding the viability of the ACL in the arthritic knee, fracture of the tibial bony eminence, polyethylene wear, and the strength of the tibial baseplate. Many of these challenges were specific to a few designs as well as older-generation polyethylene, which was susceptible to oxidative degradation. Avoiding keels in the tibial baseplate that can weaken the tibial bone island, minimizing the removal of cortical bone anterior to the tibial eminence, and avoiding eminence undercutting can help reduce the risk of bone island failure. Despite the aforementioned challenges, some clinical series have shown excellent long-term outcomes. The clinical aspects of ACL retention are beyond the scope of this chapter.

Patients with bicruciate-retaining implants generally have been reported to exhibit more normal kinematics than patients with ACL-sacrificing implants. However, a 2015 study noted that the analysis of available kinematic data shows that contemporary bicruciate-retaining implants do not fully restore normal kinematics. Abnormal early posterior femoral shift and subsequent paradoxical anterior sliding, which are observed with ACL-sacrificing implants, are generally not observed with contemporary bicruciate-retaining implants. The 2015 study used dynamic computer simulations to compare the kinematics of a biomimetic bicruciate-retaining design with an anatomic tibial articular surface with that of contemporary bicruciate-retaining and cruciate-retaining implants (Figure 7). The biomimetic bicruciate-retaining implant exhibited kinematics most similar to healthy knees. Another study compared biomimetic bicruciate-retaining and biomimetic
cruciate-retaining implants and reported that the absence of the ACL in the cruciate-retaining design resulted in a more posterior location of the femur and reduced femoral rollback. However, restoration of the native articular geometry in the biomimetic cruciate-retaining implant preserved medial rotation features, which may indicate that restoration of the native anatomy together with ACL preservation is required to achieve kinematics close to those of the native knee.

**ACL Substitution**

**ACL Substitution and PCL Retention**
An alternative to native ACL retention is to substitute its function to avoid the potential challenges discussed previously and to provide an option for patients with an absent or nonfunctional ACL at surgery (approximately 14% to 75% of patients). The concept of an ACL-substituting and PCL-retaining implant (ASCR) has been proposed recently as an evolution of the cruciate-retaining implant in which the ACL is sacrificed with no mechanism to substitute for its function. In the ASCR implant, the anterior surface of a post on the tibia engages with the femoral intercondylar notch in low flexion to substitute for the absent ACL (Figure 8). The tibial post also is designed to accommodate the native PCL. A 2016 study used dynamic simulations to compare the kinematics of the ASCR design with ACL-retaining and ACL-sacrificing (that is, cruciate-retaining) implants during deep knee bend, chair sit, stair ascent, and walking. As with ACL-retaining implants, the ASCR design provides kinematic improvements over contemporary ACL-sacrificing implants by reducing abnormal early posterior femoral shift and avoiding paradoxical anterior sliding. However, this concept has not been evaluated clinically.

**ACL and PCL Substitution**
In a bicruciate-substituting design, ACL and PCL function are substituted using anterior and posterior cam-post interaction, respectively. The bicruciate-substituting concept can be considered as an extension of the posterior-stabilized philosophy that substitutes not only for the missing PCL but also for the ACL. First-generation bicruciate-substituting designs were introduced in 2005 and showed promising kinematic results. Several in vivo studies showed more normal kinematics than contemporary TKA, including the magnitude of internal tibial rotation and posterior femoral rollback as well as the absence of paradoxical anterior sliding (Figure 6). Reported rates of clinical complications were higher than expected, including dislocation and...
iliotibial band syndrome. These complications seem to be related to insufficient jump height, excessively forced rollback by posterior cam, and a prominent anterior femoral flange. However, no complications were reported regarding fracture of the bicruciate-substituting tibial post or wear of the anatomic tibial articular surface. Second-generation bicruciate-substituting designs have been introduced to address these design issues. Additional studies are needed to assess the clinical significance of these design improvements.

**Implant Materials**

The most commonly used materials in TKA implants are cobalt-chromium-molybdenum (CoCrMo) alloy for the femoral component, conventional (minimally cross-linked or non–cross-linked) ultra-high–molecular-weight polyethylene (UHMWPE) for the tibial insert, and titanium alloy for the tibial baseplate. However, the pursuit of improved implant survivorship via the reduction of polyethylene damage and concerns regarding metal hypersensitivity have motivated the exploration of alternative materials. Clinical and registry studies continue to monitor the long-term performance of highly cross-linked UHMWPE, which was introduced in the early 2000s, and newer antioxidant-stabilized polyethylene, which was introduced in 2008.

**Bulk Ceramics**

Ceramics have several advantages, including reduced coefficient of friction, increased lubricity due to reduced wetting angle, high hardness and abrasion resistance, and excellent biocompatibility. In the past 5 years, mid- to long-term clinical data have been published for several ceramic TKA implants. One study reported 5-year survivorship of 98.6% with no revisions for aseptic loosening, osteolysis, or ceramic fractures for an alumina metallic-pivot TKA. Another study published 10-year clinical results for an alumina ceramic implant that has been used in Japan since 1992. At a mean follow-up of 11.7 years, the mean Knee Society score was 93.3, survivorship with any reoperation or radiographic failure as an end point was 95.9%, and no fractures of the ceramic femoral component occurred. Another study reported on the clinical outcomes of a ceramic TKA with an alumina matrix composite femoral component that was strengthened with yttria-stabilized tetragonal zirconia particles. At 5-year follow-up, implant survivorship was 96.0%, with no implant migration or loosening. In one case, a midline longitudinal crack was noted on the ceramic femoral component following a traumatic event, and two fractures of the femoral component that occurred during intraoperative impaction were reported. Subsequent analysis showed hard impaction at high velocity and the femoral resection angle to be likely causes of failure.

**Ceramicized Metals**

TKA implants with various ceramic coatings are currently in clinical use, including titanium nitride (TiN) on Ti6Al4V (a grade 5 titanium alloy), TiN on cobalt-chromium (CoCr), zirconium nitride (ZrN)–coated CoCr, and titanium niobium nitride (TiNbN)–coated CoCr. Although many preclinical studies indicate favorable tribologic properties (for example, high scratch resistance, low coefficient of friction, less UHMWPE wear) of these ceramic coatings, other studies have not replicated these findings and concerns have been noted regarding loss of coating and increased wear. However, the coating process may have a substantial effect on coating performance. One particular ZrN coating technology uses a top coat of ZrN, five layers of chromium nitride–chromium carbonitride (CrN-CrCN), and a thin chromium bond coat on top of a standard CoCr alloy (overall thickness, 3.5 to 5.0 μm). The multilayer coating provides a gradient between the hard coating and the relatively soft substrate to improve the mechanical integrity of the coating. A 2011 study reported no scratches, pitting, or coating damage during a 3-million-cycle knee simulator study of a mobile-bearing implant with ZrN-coated metallic components created with this coating technology. A few recent studies have published clinical performance data for such ceramic-coated knee implants. A 2015 retrospective study compared short-term (mean follow-up, 2 years) clinical results for a TiNbN-coated implant with CoCr implants of the same design. This study found no differences in clinical, radiographic, or patient-reported outcomes, and no patients underwent revision in either group. A 2014 retrospective study of 305 TiN-coated mobile-bearing implants reported 10-year survivorship of 95.1% with revision for any reason as the end point and 99.1% with revision for aseptic loosening as the end point.

Oxidized zirconium (OxZr) knee implants were introduced in 1997. Unlike the ceramic coating applied to a metal substrate, OxZr is created via thermal diffusion, which transforms the surface of wrought zirconium-niobium (2.5% niobium) alloy to a ZrO2 (monoclinic) layer approximately 5 μm thick. Although numerous laboratory wear studies have demonstrated a reduction in polyethylene wear with OxZr versus CoCr femoral components (range, 42% to 85%), until recently, in vivo data have been lacking. That recent retrieval study found significantly lower femoral component roughness as well as lower damage scores for
both femoral components and polyethylene inlays with OxZr compared with matched paired CoCr TKAs. A 2011 study published results of a randomized controlled trial with patients with bilateral TKA who received a CoCr femoral implant in one knee and an OxZr implant in the contralateral knee. At 5-year follow-up, no significant differences were reported between the two groups regarding mean Knee Injury and Osteoarthritis Outcome Scores or radiologic evaluation findings. In a retrospective review of 109 OxZr TKAs performed in 82 patients with a mean follow-up of 5.9 years, no revisions were performed for wear, loosening, osteolysis, or infection. The mean Knee Society score was 92 points (range, 49 to 100 points) and the mean function score was 81 points (range, 30 to 100 points). A 2014 study reported 10-year results of a prospective study for 84 patients at final follow-up. Overall survivorship was 97.8%; two knees needed revision for femoral component loosening. The mean knee score was 84 points (range, 64 to 100 points) and the mean function score was 83 points (range, 55 to 100 points).

**Summary**

Implant design has a major influence on both short- and long-term outcomes following TKA. Important issues pertaining to implant geometry and materials are currently being debated, and new technologies are under investigation.

Available evidence does not indicate superiority of single-radius or multiradius femoral designs in relation to clinical outcomes. Anatomic tibial trays may offer only a slight advantage for increased tibial coverage; however, they could reduce the probability of internal rotation if attainment of maximal tibial coverage is used to guide tray placement. Cost advantages coupled with equivalent outcomes to metal-backed components could increase the use of all-polyethylene tibial components. PCL-retaining (cruciate-retaining), PCL-substituting (posterior-stabilized), and PCL-sacrificing (ultracongruent) designs seem to have similar clinical outcomes and long-term survivorship. However, the high anterior tibial lips in ultracongruent designs may not fully compensate for PCL function, resulting in increased anterior femoral sliding.

Contemporary implants show significant kinematic alterations relative to the preoperative and normal knee, which may partly explain the similar patient outcomes observed with cruciate-retaining, posterior-stabilized, and ultracongruent designs. Provision of anatomic or biomimetic articular surfaces together with ACL retention or substitution may be key to restoring normal kinematics following TKA. However, such new implant designs do not preclude the importance of surgical technique. Techniques designed to facilitate more normal collateral ligament function via anatomic joint line restoration may play a crucial role in achieving normal knee function following TKA.

Several materials continue to be evaluated as an alternative to CoCrMo alloy. Bulk ceramics and oxidized zirconia have demonstrated excellent mid- to long-term outcomes and may be viable options for patients with suspected metal hypersensitivity. Early clinical results of ceramic-coated metal seem to be positive, but more clinical data are needed to determine whether ceramic-coated metals are a cost-effective alternative.

**Key Study Points**

- Both anatomic articular geometry and ACL function (via retention or substitution) may be required to restore normal knee kinematics following TKA.
- Anatomic joint line restoration via the appropriate positioning of standard implants or implants with asymmetric thicknesses may facilitate more normal soft-tissue function.
- All-polyethylene tibial components have been shown to have long-term clinical outcomes equivalent to those of metal-backed components.
- OxZr and bulk ceramics are alternatives to CoCr that have excellent mid- to long-term survivorship and favorable clinical outcomes.

**Annotated References**


This study compared gait analysis, electromyography, and patient-reported outcome measures in patients who underwent single-radius and multiradius TKA with those of healthy control patients. Decreased power absorption and increased knee extension were noted in the multiradius group, but no functional differences were detected in outcome measures. Level of evidence: II.

This prospective study demonstrates no significant differences between single-radius and multiradius TKA groups at 1- or 3-year follow-up for Knee Society scores (knee, function, or total), Medical Outcomes Study 36-Item Short Form physical scores, postoperative ROM, or patient satisfaction. Level of evidence: II.


This meta-analysis incorporated data from 15 studies comparing single-radius and multidiameter TKA designs. No differences were found between the groups in Knee Society scores, complications, knee flexion, isometric peak torque, and survivorship; however, decreased ROM was noted for single-radius knees. Level of evidence: II.


This review provides an overview of alignment strategies in TKA and discusses the implications for outcome. Level of evidence: V.


This randomized controlled trial compared joint line maintenance and outcomes between patients undergoing computer-assisted and conventional TKA. No significant difference in joint line maintenance was found between the techniques. However, TKAs with a depressed joint improved the least in functional scores. Level of evidence: I.


This study compared medial collateral ligament and lateral collateral ligament strains in six cadaver knees before and after posterior-stabilized TKA. Strain was significantly different before and after TKA at some but not all points measured throughout the flexion arc. Level of evidence: V.


An overview of alignment strategies in TKA is provided and implications on outcome are discussed. Level of evidence: III.


This randomized controlled trial compared the results of mechanically aligned versus kinematically aligned TKAs in 88 patients. Function, ROM, and pain improvement scores were superior among patients with kinematically aligned TKAs 2 years postoperatively. Level of evidence: I.


This study examined 479 healthy tibiae in Asian and Caucasian patients. Compared with asymmetric and symmetric designs, the anatomic tibial tray design demonstrated better conformity and tibial coverage, and less downsizing to ensure rotational alignment. Level of evidence: III.


This MRI-based study of 100 knees evaluated three different tibial tray designs: anatomic, symmetric, and asymmetric. Equivalent coverage was observed across the three tibial tray designs; however, the anatomic tibial tray required less malrotation to maximize coverage. Level of evidence: III.


Tibial anthropometric measurements for 14,791 patients who underwent TKA were compared across four commercial tibial tray designs. All designs provided similar bone coverage. Rotating the tibial tray to maximize coverage did not significantly increase coverage but induced variability in tray alignment. Level of evidence: III.


This systematic review and meta-analysis of 1,798 patients who underwent TKA from 12 studies reported no significant differences in revision or radiographic failure.
between all-polyethylene and metal-backed components at 2-, 10-, or 15-year follow-up. No functional difference was identified. Level of evidence: I.


This meta-analysis included 26 articles with more than 12,500 patients who underwent TKA and reported no differences in revision rates, functional outcomes, ROM, or alignment between the all-polyethylene and metal-back components, except for higher component migration in the metal-backed group. Level of evidence: I.


This study examined a large community-based total joint registry of 27,657 patients undergoing TKA with the same implant (91.7% were metal-backed; 8.3% were all-polyethylene). The revision rate for all etiologies was lower for the all-polyethylene group than for the metal-backed group (1.95% versus 2.17%; P < 0.001). Level of evidence: III.


This study examined patients who underwent TKA with metal-backed (57.7%) or all-polyethylene (42.3%) tibial components at a median follow-up of 4.5 years. All-polyethylene tibial components had superior 10-year survival, reduced risk of revision for any reason, and reduced risk of revision because of infection. Level of evidence: III.


This study used systematic review and meta-analysis of randomized and quasirandomized controlled trials to compare PCL retention and sacrifice in TKA. No clinically relevant differences in ROM, pain, clinical, or radiologic outcomes were noted between PCL retention and sacrifice. Level of evidence: II.


The in vivo kinematics of Triathlon cruciate-retaining implants (10 knees) and cruciate-stabilizing insert implants (10 knees) were evaluated during deep knee bending. Cruciate-stabilizing knees showed significantly greater medial anterior translation, indicating that the increased anterior lip could not fully control anterior sliding. Level of evidence: III.


In this randomized controlled study, the intraoperative kinematics and clinical outcomes (3-year follow-up) were compared for mobile ultracongruent and mobile posterior-stabilized TKAs. Ultracongruent knees showed greater paradoxical anterior translation, but no difference in clinical outcomes was detected between groups. Level of evidence: II.


Intraoperative stability and ROM were compared before and after TKA with cruciate-retaining or ultracongruent inserts. Stability and ROM were similar between the two insert types, and both showed significant increases in postoperative anterior–posterior translation in flexion. Level of evidence: II.


This study tested the intraoperative kinematics of 10 knees replaced with hypercongruent inserts. Significant changes in kinematics relative to the nonsurgical condition were detected, including abnormal posterior location at full extension, reduced rollback, and persistent forward rolling on the medial side. Level of evidence: II.

This retrospective study assessed 826 TKA patients. Most TKAs sacrificed the PCL (65% posterior-stabilized versus 35% ultracongruent); 10-year TKA survivorship was 92% independent of the design and level of mechanical stress. Revision was mainly performed for infection or loosening. Level of evidence: IV.


This report described a novel design process to create biomimetic tibial articular surfaces directly from the in vivo kinematics of normal knees. Geometric comparisons and kinematic simulations are used to demonstrate the role of articular geometry in the restoration of normal kinematics. Level of evidence: V.


The in vivo kinematics of 21 healthy subjects were evaluated using biplanar fluoroscopy during step-up activity. Medial-pivot motion was not observed during this activity. Mean (±SD) medial and lateral tibiofemoral contact points moved almost equally with knee extension (13.5 ± 3.2 and 10.7 ± 5.0 mm, respectively). Level of evidence: IV.


In vivo kinematics during pivoting, kneeling, lunge, and step-up/-down activities were studied using fluoroscopy in 14 patients who underwent TKA. Observed kinematics were similar in pattern but smaller in magnitude compared to normal knees. No paradoxical anterior motion was observed for any activity. Level of evidence: IV.


Computer simulations were used to compare the kinematics of a bicruciate-retaining TKA with an anatomic (biomimetic) articular surface with that of contemporary cruciate-retaining implants. The biomimetic implant more closely mimicked normal kinematic patterns than contemporary cruciate-retaining implants across different simulated activities. Level of evidence: V.


Knee extension kinematics of medial-pivot TKAs were evaluated in cadaver knees. Tibiofemoral rotation and translation were similar in direction but reduced in magnitude for prosthetic knees compared with intact knees. Quadriceps force was not statistically different between prosthetic and intact knees. Level of evidence: V.


In this study, simulated kinematics of a cruciate-retaining implant with an anatomic (biomimetic) articular surface were compared with those of contemporary cruciate-retaining implants. The biomimetic implant more closely mimicked normal kinematic patterns than contemporary cruciate-retaining implants across different simulated activities. Level of evidence: V.


The in vivo kinematics of 10 Journey bicruciate-substituting knees were compared with that of 20 normal knees. The Journey knees showed no paradoxical anterior movement, and the patellar tendon angle and patellar flexion profiles were more normal than other TKA designs. Level of evidence: III.


In this study, ACL integrity was evaluated using the Lachman test in 200 patients who underwent TKA and in 100 patients using MRI. The ACL was intact in 78% of knees. The Lachman test alone had poor sensitivity; when combined with MRI, sensitivity of 93.3% and specificity of 99% were attained. Level of evidence: IV.

This study compared the simulated kinematics of an ASCR design with an ACL-sacrificing cruciate-retaining implant and ACL-retaining bicruciate-retaining implant. The results showed that the ACL substitution mechanism could successfully replicate the kinematic function of the ACL across different activities. Level of evidence: V.


Complication and revision rates in 226 journey bicruciate-substituting TKA patients were studied (average implantation time, 3.5 years): 33 complications in 25 patients (14.6%) required minor or major revision. Caution was advised for less-experienced surgeons using this implant. Level of evidence: IV.


In this study, four cases of posterior dislocation were described for patients with Journey bicruciate-substituting TKAs. The authors concluded that specific design features contributed to higher-than-expected dislocation rates. Level of evidence: IV.


Ligament length changes and tibiofemoral kinematics were evaluated in cadaver knees with three TKAs: Journey bicruciate-substituting, Journey II bicruciate-substituting, and Genesis II posterior-stabilized implants. The results supported the hypothesis that increased internal rotation and rollback in the original Journey bicruciate-substituting system caused excessive soft-tissue tightening. Level of evidence: V.


The clinical results of 107 alumina medial-pivot TKAs were evaluated at a mean follow-up of 5 years. Significant improvements in Knee Society scores and postoperative ROM were noted. No knees exhibited aseptic loosening, osteolysis, or ceramic fractures. Survivorship was 98.6%. Level of evidence: IV.


Clinical and radiologic assessments were performed for 107 TKA patients with MultiGen-Plus ceramic knees. Nonprogressive radiolucent lines were observed around the femoral component in four cases. Neither implant migration nor loosening was registered. Kaplan-Meier survivorship was 96.0% at 60 months. Level of evidence: IV.


This study used finite-element analysis to evaluate the influence of distal femur preparation on stresses within a ceramic femoral component. A deviation of 3° from the intended resection angle was shown to cause critical stresses, thus underscoring the importance of precise femoral resection. Level of evidence: V.


This review discussed preclinical studies and clinical outcomes of TiN-coated implants. Although TiN coating was reported to have positive effects on biocompatibility and tribology, several cases of third-body wear were reported as a result of delamination and cohesive failure of the TiN coating. Level of evidence: V.


Knee simulator wear tests were conducted for a multilayer ZrN-coated mobile-bearing unicompartmental prosthesis. No loss of coating was observed following 3 million test cycles. Both new and tested components showed macro pores and micropores, which were likely created by the coating process. Level of evidence: V.


This retrospective study compared 40 TiNbN-coated TKAs with 80 conventional CoCr implants at a mean follow-up of 2 years. No differences in clinical, radiologic, or patient-reported outcomes were observed. No

This retrospective study examined the outcomes of 305 TiN-coated mobile-bearing TKAs. The 10-year survival with revision for any reason as the end point was 95.1%, and with revision for aseptic loosening as the end point was 99.1%. Level of evidence: IV.


This review of both in vitro and in vivo studies evaluated the performance of oxidized zirconium TKAs and the results from retrieval analyses. Level of evidence: V.


This study reported on 40 consecutive patients who underwent bilateral cruciate-retaining TKA with an OxZr femoral component in one knee and CoCr component in the contralateral knee. No significant differences were reported in clinical, subjective, or radiographic outcomes at 5-year follow-up. Level of evidence: I.


This study retrospectively reviewed 109 TKAs in 82 patients at minimum follow-up of 5 years. Survivorship free of bearing-related complications was 100%. No revisions were reported for loosening, osteolysis, implant failure, or deep infection. Level of evidence: IV.


This prospective study reported 10-year outcomes for 94 patients with oxidized zirconium TKA. Survivorship was 97.8% at 10 years. Two knees were revised for aseptic loosening of the femoral component. No other major complications were observed clinically or radiologically. Level of evidence: IV.