Current Reviews in Musculoskeletal Medicine (2022) 15:194–204
https://doi.org/10.1007/s12178-022-09755-6

REVERSE SHOULDER ARTHROPLASTY (B FEELEY, SECTION EDITOR)

Biomechanics and Outcomes of Modern Tibial Polyethylene Inserts

Darshan Shah[1] · Taylor Bates[1] · Craig Kampfer[1] · Donald Hope[1]

Accepted: 3 March 2022 / Published online: 6 April 2022

Abstract

Purpose of Review There have been many attempts to use variations in tibial polyethylene design to better recreate normal knee kinematics in the total knee arthroplasty. The goal of this review is to provide an overview of the various types of tibial inserts that exist and review the theoretical mechanics versus what was demonstrated in vivo.

Recent Findings Many polyethylene inserts have been attempted to re-create normal knee kinematics, but none have been able to successfully do so. Previously the only two types of inserts were posterior stabilized (PS) and cruciate retaining (CR) polyethylene inserts. Both of these have shown excellent long-term survival but neither has demonstrated native kinematics. Initially, it was thought that retention of the posterior cruciate ligament (PCL) would allow for more native kinematics, but fluoroscopic evidence has shown that the PCL alone cannot accomplish this. Newer inserts try to restore femoral roll back and the screw home mechanism. The bicruciate retaining total knee inserts are having the most "normal" kinematics, suggesting the importance of both the ACL and PCL in knee biomechanics.

Summary Modern polyethylene inserts show favorable short-term data with bicruciate retaining inserts having the best kinematics; however, long-term studies are still needed to determine if survivorship and patient outcomes remain favorable.

Keywords Biomechancis · Arthroplasty · PCL · Polyethylene

Introduction

The gold standard in the treatment of knee osteoarthritis remains the total knee arthroplasty. Each year over 750,000 total knee arthroplasties are performed in the USA alone [1]. Unfortunately, patient satisfaction has varied between 82% in younger patients and 91% in older patients [2••, 3]. Stiffness and poor range of motion are key driving forces behind poor satisfaction rates [3]. As a result, several types of tibial polyethylene inserts have been developed with an emphasis on recreating native knee biomechanics [4, 5•, 6, 7••, 8, 9]. The goal of this review is to summarize the studies that have been done on the biomechanics of the classic posterior stabilized and cruciate retaining inserts as well as the more modern inserts. A brief review of outcomes will also be discussed.

This article is part of the Topical Collection on *Reverse Shoulder Arthroplasty*

Darshan Shah
Dshah1225@gmail.com

1 Department of Orthopaedics, Brooke Army Medical Center, 3551 Roger Brooke Dr., San Antonio, TX 78234, USA

Biomechanics of the Native Knee

The knee is a modified hinge joint which has six total degrees of freedom, three translational and three rotational. Translational degrees of freedom are; anterior-posterior, medial-lateral, and inferior-superior [5, 10]. Rotational degrees of freedom are; flexion-extension, internal-external rotation, and adduction-abduction [11•].

Through range of motion of the knee, the medial and lateral condyles experience different amounts of translation in various activities. Fluoroscopic studies have shown the medial femoral condyle moves −4.7 mm while the lateral condyle moves −11.8 mm during normal gait [12••]. However, during deep bending, the medial condyle moves −4.5 mm while the lateral condyle moves −16.3 mm [12••]. This results in internal rotation of the tibia relative to the distal femur as well as posterior translation of the femur relative to the tibia. The knee typically has the ability to achieve 140–160° of flexion [13] (Table 2). The difference in movement of the lateral condyle versus the medial condyle while the knee is bending is termed "femoral roll-back." During the first 15 to 20°, we see primarily rotation, while beyond 20°, we get primarily posterior translation of the femur. The opposite of this is termed the "screw home mechanism," where the tibia externally rotates and the femur translates anteriorly [11].

Debate remains on whether or not to sacrifice the posterior cruciate ligament (PCL) in total knee arthroplasty (TKA) [4, 5, 14, 15•, 16]. The primary role of the PCL in the knee is to prevent excessive posterior translation of the tibia [17•, 18]. Another function of the PCL is to prevent excessive tibial internal rotation between 90° and 120° of flexion [19]. Through a cadaveric analysis, it was found that an intact and functional PCL allows for appropriate levels of femoral roll-back and prevents excessive posterior translation of the tibia relative to the femur [17]. This supports the belief that retention of the PCL allows for more physiologic knee kinematics after TKA specifically allowing the screw home mechanism to occur in the final 20 degrees of extension [20].

Posterior Stabilized Implant Biomechanics

Posterior stabilized (PS) TKA implants utilize a tibial post to function as the PCL, which is sacrificed during joint preparation (Table 1). Compared with the native knee, conventional PS-TKA demonstrates less overall motion in both normal gait and with deep flexion. However, the most notable difference is that, on average, the posterior stabilized cam-post design demonstrates paradoxical anterior translation of the lateral condyle relative to the tibia during normal gait. This is opposite that of the native knee which demonstrates posterior translation of the lateral condyle with femoral rollback during gait [13, 21•].

However, during deep flexion, PS-TKA demonstrated normal axial rotation of 10.4° with the tibia rotating internally with progressive knee flexion and posterior femoral rollback of −7.1 mm [21•] (Table 2).

Within the PS umbrella, there are a multitude of customized cam-post designs which are all aimed at best re-creating normal knee kinematics [22••]. All conventional and customized cam-post designs demonstrate less rollback and internal rotation when compared to a native knee [22••].

The rationale for the paradoxical movement in normal gait with return of normal rollback during deep flexion is that the post does not engage the cam during normal gait. However, during deep flexion, the post uses the cam as a lever to induce the normal femoral rollback seen in the native knee [21•].

One variation of the PS design seeks to replace both the ACL and PCL with posts, bicruciate stabilized (BCS) TKA designs utilize an anterior cam-post to substitute for the ACL, similar to the mechanism used for replication of the PCL. These implants theoretically provide the technical implantation ease of traditional CR components with increased stability and more natural biomechanics provided by the anterior post. However, the ability of the anterior post-cam design to mimic the biomechanics of a native knee may be limited. Grieco et al. [12••] used fluoroscopy to compare in vivo kinematics of BCS-TKA and the normal knee. They conclude that the dual cam-post mechanism does not adequately substitute the cruciate ligaments in mid-flexion, a point at which ACL tension is decreasing and PCL tension is increasing.

Cruciate Retaining Biomechanics

The theoretical benefit of maintaining the PCL in a total knee arthroplasty is the maintenance of normal knee kinematics (Table 2). This is accomplished by decreasing sheer stress over the femoro-tibial interface by decreasing posterior translation [17•]. Cruciate retaining total knee arthroplasties (CR-TKA) were designed as an improvement over PS-TKA to improve kinematics and function. However, in a biomechanical study of CR-TKAs, Dennis et al. [21•] demonstrated paradoxical anterior translation of the femur relative to the tibia during regular gait [13, 21•].

In the cruciate retaining knee during normal gait, the medial femoral condyle moves anteriorly 0.9 mm and the lateral condyle moves anteriorly 0.1 mm which results in a paradoxical external rotation of the tibia in addition to paradoxical anterior translation [21•] (Table 1).

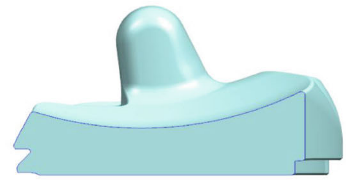
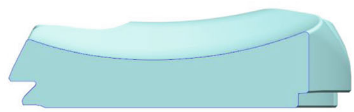
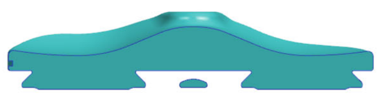
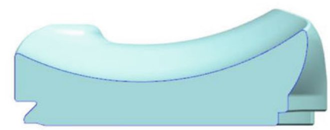
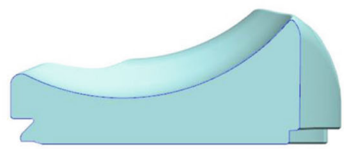
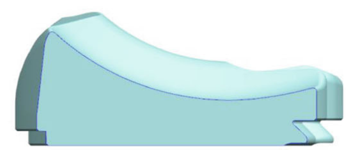
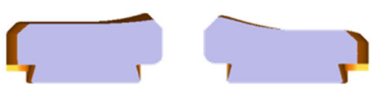
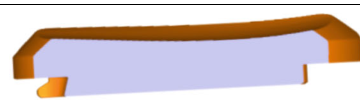
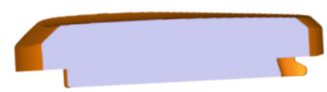
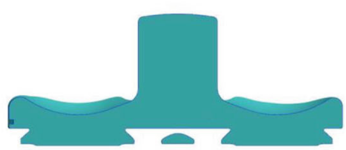
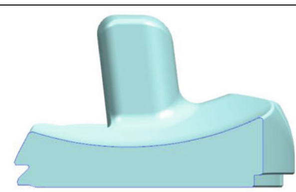
During deep bends, there was noted to be −1.7 mm of medial condyle motion and −0.7 mm of lateral condyle motion [21•]. Though there was no paradoxical anterior motion as seen in normal gait, the tibia continues to paradoxically rotate externally during deep flexion in the CR-TKA design. This shows that, though the PCL is retained in an effort to improve kinematics, femoral rollback was not restored in these designs and paradoxical anterior translation is seen during normal gait [13, 21•] (Table 1).

One possible explanation for the paradoxical motion has been the amount of slope built into the tibial component. Several studies have shown that in CR-TKA when the posterior tibial slope is greater than 3°, the femoral condyles demonstrate normal femoral rollback from 20 to 90°. However, when this slope is decreased to less than 3°, the motion becomes paradoxical [23–25].

Outcomes and Shortcomings

The overall goal in developing the various designs of TKA is to improve outcomes and survivorship in an effort to improve patient care. Though PS-TKA total knees have demonstrated improved motion in kinematic studies, survivorship has been better

Table 1 Summary of polyethylene inserts

Type	Coronal Mid Section	Sagittal Midsection of Medial Plateau	Sagittal Midsection of Lateral Plateau
Posterior stabilized			
Cruciate Retaining			
Congruent Articular Surface			
Medial Pivot			
Bi-cruciate Retaining			
Varus-Valgus Constrained			

with CR-TKA designs. Fifteen year outcome data puts survivorship of CR-TKA around 90% and 77% for PS-TKA [4]. This trend holds true across multiple long-term studies [5, 15•, 16].

CR-TKA and PS-TKA are also not without fault. Though CR-TKA has been shown to have improved survivorship in patients with fixed varus deformities, overall outcomes have been mixed with numerous studies showing no difference at short, middle, and long-term follow-up, while patients with rheumatoid are predisposed to late PCL rupture in CR-TKA [5, 26, 27, 28••, 29••, 30, 31].

Eliminating the PCL during surgery raises a separate set of concerns. The polyethylene post has been reported to fracture and the post can be jumped by the femoral component in an unstable knee [32, 33, 34••]. Additionally, the removal of bone from the inter-condylar notch during surgery possesses a greater risk for possible condyle fracture in PS-TKA when compared to CR-TKA [35, 36].

With both designs showing significant shortcoming and overall range of motion being lower for CR-TKA at long-term follow-up, room for improved designs remains [5•, 10, 37].

"Congruent Articular Surface"

With the long-standing debate over the merits of cruciate retaining versus posterior stabilized designs, most authors agree if the PCL is sacrificed, then it should be substituted. One alternative to the PS design is the congruent articular surface (CAS) tibial insert in which there is no cam-post mechanism and the PCL can be substituted with a higher anterior and posterior lip (Table 1).

This design has the theoretical benefits of bone preservation as no box cut is required, and it distributes the loads over a

Table 2 Summary of amount of medial and lateral condylar movement for normal gait (heel strike to toe off 0–30° of knee flexion) and deep bending of the knee (0–90°)

Implant	Normal gait		Deep bend		Total flexion
	Medial condyle movement	Lateral condyle movement	Medial condyle movement	Lateral condyle movement	
Native knee [12,13]	−4.7 mm	−11.8 mm	−4.5 mm	−16.3 mm	140–160
Posterior stabilized [21,34]	−0.2 mm	0.6 mm	0.9 mm	−7.1 mm	119 ± 7.5
Cruciate retaining [21,34]	0.9 mm	0.1 mm	−1.7 mm	−0.7 mm	113.8 ± 8.7
Congruent articular surface [36,91]	3 ± 4 mm	−2 ± 6 mm	−5 ± 2 mm	−22 ± 8 mm	113.5 ± 14°
Medial pivot [41–43]	−0.5 mm	−1.1 mm	−3 ± 1 mm	−7 ± 4 mm	102–125°
Bicruciate retaining [64,93]	−4.6 mm	−10.7 mm	−5.1 mm	−11.0 mm	128°

Data represented in Table 2 was derived from fluoroscopic analysis of knee motion during gait deep bending

larger surface area disturbing the forces more evenly at the bone-implant interface [38•]. This design also avoids the risks of the cam-post mechanism such as fracture, post wear, and jumping the post.

A potential drawback of the CAS insert is having increased contact surface area potentially leading to increased wear characteristics; however, the radiographic data has not been shown to have increased rates of osteolysis [38•]. Another potential drawback is decreased ROM on deep knee flexion due to the posterior lip preventing effective femoral rollback. In vivo fluoroscopic studies have shown that congruent designs have less AP-translation when compared to flat, or mobile bearing, polyethylene cruciate-retaining designs but had non-physiologic rollback when compared to the native knee [39, 40•] (Table 2). With regards to AP stability and ROM, the CAS insert has been shown to be similar when compared to CR inserts [41].

In a retrospective study with short-term results, the ultra-congruent, or anterior stabilized, polyethylene inserts have demonstrated no difference in Knee Society Scores and rates of complications when compared to cruciate-retaining designs, and they demonstrated a lower rate of revision surgery (1.5% vs 4.6%) [42].

Medial Pivot

Normal knee kinematics based upon multiple in vivo fluoroscopic studies have demonstrated that during flexion, the medial femoral condyle pivots while there is a posterior translation or "rollback" of the lateral femoral condyle [43••].

To address the paradoxical movement of the femoral condyles of traditional knee arthroplasty designs, the medially congruent or medial pivot (MP) design was developed (Table 2). This unique design involves a concave shape medially with an anterior lip, or "ball and socket articulation" and a less congruent shape to the lateral compartment which allows anterior to posterior translation meant to replicate normal knee kinematics [39] (Table 1, Fig. 1).

Fluoroscopic kinematic studies have demonstrated that MP designs produce similar motion to the native knee with posterior translation of the lateral femoral condyle without the paradoxical anterior motion during weight bearing activities including deep knee bending [44•, 45, 46••] (Table 2).

KSS and OKS scores have been shown to be similar comparing MP and PS fixed bearing designs in patients, and have been shown to have better FJS-12 scores, especially with deep knee flexion and stability, at 1 year [46••, 47••]. Patients reportedly were less aware that they had an artificial joint when they had an MP design compared to PS cam post designs [47••]. 15-year outcome data reported by Karachalios et al. in a retrospective study showed that the MP knee design has a 96.4% survivability rate for any cause, and significant improvement in knee outcome scores [48]. Similar rates of survivability and improvements were found in the study performed by Macheras et al., and they noticed no difference in functional outcome scores between patients in which the PCL was retained versus resected at 15 years [49].

Lateral and Dual Pivot

Despite the development of medial and lateral pivot designs, various kinematic studies have demonstrated a complex pattern of pivot motions at various degrees of flexion [50–55]. Early flexion angles, such as those that occur with activities such as walking and running, are characterized by a lateral pivot movement. In contrast, deep flexion angles are characterized by a medial pivot pattern. Lateral pivot implants have been developed to improve patient outcomes by providing more natural kinematics during activities such as walking.

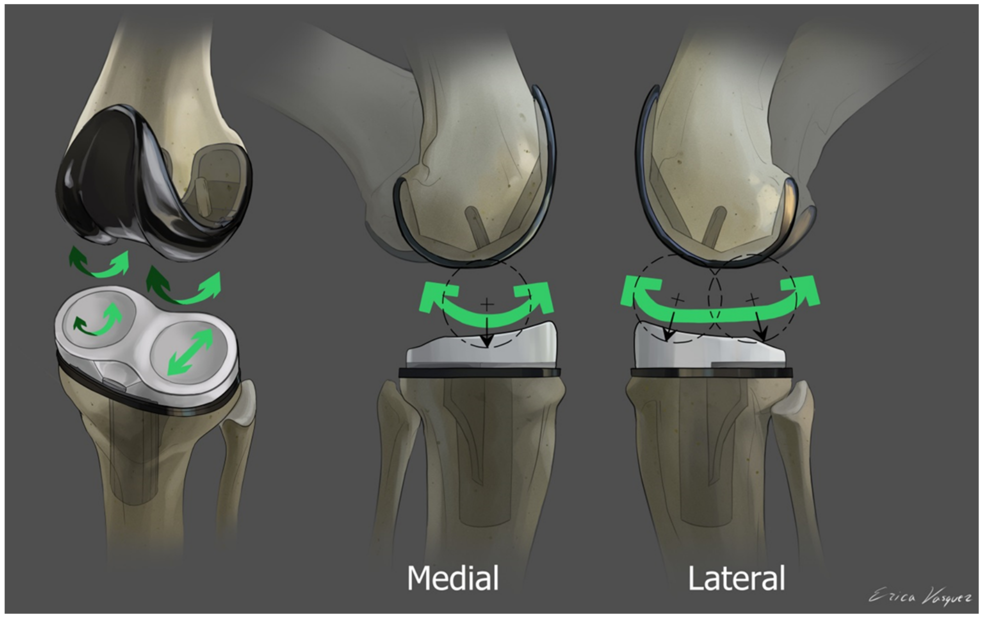


Fig 1 Schematic diagram of the medial pivot polyethylene biomechanics. As the knee goes into flexion, the medial compartment's rotation moment is converted to translation moment in the lateral plateau allowing for femoral rollback

However, lateral pivot designs are far less common than medial pivoting implants.

Dual-pivot implants are designed to better mimic natural knee kinematics by providing a lateral and medial pivot point at lower and higher flexion angles, respectively. Meneghini et al. [50] used sensor trials to record intra-operative knee kinematics in one hundred twenty TKAs. The authors report higher Knee Society Function Scores, greater one-year functional scores, more normal feelings knees, and higher overall satisfaction in patients with early lateral/later medial pivot kinematics. The authors conclude that replicating the dual-pivot kinematic pattern may improve function and satisfaction after TKA.

Sandberg et al. [56••] compared outcomes of two similar cohorts who underwent TKA with either traditional (n = 183) or dual-pivot (n = 183) TKA designs and minimum 1-year follow-up. Patients with a dual-pivot TKA reported less walking pain ($p = 0.022$), greater participation in very active activities or impact sports ($p = 0.067$), and were more likely to report that their knee feels normal ($p = 0.091$). Importantly, 89% of patients in both groups reported that they were satisfied or very satisfied with their outcome. The authors conclude that the dual-pivot design may provide potential benefit, but not similar overall satisfaction between the two groups.

Bicruciate Retaining

Bicruciate retaining (BCR) or bi-unicompartmental surgeries are desirable given the retention of native knee kinematics and proprioception through the preservation of the native ACL and PCL (Table 1). Preservation of both cruciate ligaments is supported by studies demonstrating improved patient satisfaction in BCR TKA designs. Patients surveyed after TKA have reported abnormal feeling knees after replacement, which is possibly explained by a failure or inability to recreate normal kinematics and loss of intra-ligamentous sensory function [57, 58]. Implants that preserve or substitute the anatomy of both cruciate ligaments provide the theoretical benefit of closely mimicking the natural biomechanics of the native knee and preserving proprioceptive feedback. The contribution of the ACL to the "screw-home" mechanism and the PCL's function to control femoral rollback both play a major role in knee stability [59–62, 63•]. Furthermore, various studies have demonstrated more native-like kinematics when the ACL is preserved during TKA [63•, 64, 65, 66•, 67, 68•]. Despite potential benefits of preserving the ACL, it is commonly sacrificed. Reasons for ACL sacrifice include technical difficulties, implant availability, and absence of a properly functioning ACL [63•]. In addition, BCR-TKA has been shown not to restore native tibiofemoral articular contact kinematics [69].

Tibial baseplate design and insertion have played a significant role in the creation of bicruciate retaining implants. With sacrifice of the ACL, the joint space can be opened widely and the tibia can be subluxated anteriorly, allowing for insertion of a stemmed tibial baseplate. Two approaches to baseplate design have predominated to allow ACL preservation. The first is similar to a standard PCL-retaining baseplate and polyethylene; however, the recess is extended anteriorly to accommodate the ACL. One drawback to this design is the narrow connecting bridge, which can fail secondary to torsional loading [70]. The second approach to ACL preserving implants is the use of two separate baseplates, one for each tibial condyle [70, 71]. The main challenge to this approach is component malalignment both intraoperatively and throughout the implants lifespan. Intraoperative error or different patterns of subsidence between the two over time can lead to accelerated wear and need for early revision [70]. Nowakowski et al. [70, 72] have designed the transversal support tibial plateau (TSTP) concept to address subsidence rates between the medial and lateral baseplate [68•, 70]. Their design incorporates a transverse post, which connects the two baseplates beneath the joint line; however, long-term clinical data is not yet available.

In addition to baseplate design, the quality of the intact ACL, its attachments, and the effects of ligament balancing play important roles in the outcome and implant survival. Despite an intact ACL, the ligament may be attenuated from prior trauma or chronic wear. Furthermore, balancing during TKA has potential to increase tension on the ACL and tibial bone cuts, which spare the ACL, leave a bone island that can fracture [9, 63•, 73, 74]. Therefore, BCR-TKA is technically challenging and typically longer to perform, which may help explain poor acceptance among orthopedic surgeons.

Despite potential advantages of BCR-TKA, it may carry a higher reoperation rate compared to other implant designs. Christensen et al. [75•] evaluated revision rates in 475 primary TKAs, which included 78 BCR-TKAs and 294 CR-TKAs. They demonstrate a higher all-cause revision rate in the BCR group (5%) compared to other groups (1.3%). In addition, the BCR group had a higher frequency of irrigation and debridement with component retention. They conclude that BCR implants may have inferior survivorship compared with conventional CR implants. In contrast, Pritchett [9] has reported an 89% survivorship at 23 years with a 5.6% revision rate. Revisions were most commonly performed for polyethylene wear.

Varus-Valgus Constrained

Varus-Valgus Constrained Total Knee Arthroplasty (VV-TKA) uses a polyethylene with a taller and wider post that is more constrained by the femoral box to prevent coronal instability (Table 1). The wider post, through contact with the intercondylar notch, restricts varus-valgus and rotation motion more than a traditional PS [76] (Fig. 2).

This is in addition to the primary function of the post, which is to resist posterior translation and serve as a lever for the CAM mechanism. Additional constraint without the need for extra bone cuts or component revision is useful when coronal balancing cannot be achieved through soft tissue techniques alone. Another advantage of VV-TKA includes less resection of bone than a Rotating Hinge [77]. Indications for a VV-TKA include a severe valgus deformity, incompetent medial collateral ligament (MCL), or severe flexion contracture in which the knee cannot be balanced [78, 79].

One drawback to increasing the constraint of the implant is that this leads to additional stress on the femoral, tibial, and polyethylene components. The increased constraint provided by the VV-TKA is a risk factor for accelerated wear rates of the polyethylene and component loosening [80]. In addition, knee biomechanics are altered and the polyethylene post may undergo permanent deformation due to bending loads and torques applied by the femoral box [81]. Excessive forces have caused post breakage and failure of the locking mechanism that can secure the polyethylene into the tibial base-plate [82–85]. Pitta et al. [86••] found that VV-TKA implants had a higher rate of failure and were twice as likely to undergo revision compared to PS implants in a prospective study of 18,065 modern total knee arthroplasties; however, early outcomes of VV-TKA are similar to standard PS designs at 2 years [81, 86,•• 87••].

Studies are conflicting on the actual impact of higher constraint on implant survivability [80–82, 87••]. This may be due to several factors, including the need for more constraint with severe deformities and when soft tissues laxity requires the implant to bear large biomechanical stresses. Cholewinski et al. [88] reported on long-term outcomes of primary VV-TKA. Their retrospective study comprised 43 knees in 41 patients with a mean age of 66 years and minimum 10-year follow-up. Complications other than venous thrombosis occurred in 16% of patients, which included 2 cases of septic loosening and 1 case of major instability in a patient with an ipsilateral hip arthrodesis. No cases of osteolysis or constraint-mechanism failure were identified. The 11-year prosthesis survival rate was 88.5% after excluding cases of infection. They conclude that long-term functional gains were similar to PS-TKA with a higher complication rate and decreased survival. However, they note that pre-operative deformities were severe and two-thirds of knees had one or more prior surgical procedures.

Siqueira et al. [89] also reported on survivorship and modes of failure in 685 cases: primary (n = 247), aseptic (n = 315), and septic (n = 123) revision TKAs with constrained implants. The authors report 10-year survival as 89%, 75%, and 55%, respectively. The most common mode of failure was infection. Mechanical failure was typically due to peri-prosthetic fracture (45%) and soft tissue instability (19%).

Despite the known complications that arise from increased constraint, several studies support its use when appropriately indicated. Rai et al. [90••] found 95% prostheses survival at an average of 6.5 years in a retrospective review of 38 primary VV-TKAs. Patients had improved Knee Society Scores (KSS) scores, improved Hospital for Special Surgery (HSS) scores, and improved Range of Motion (ROM). Radiolucency was noted in 13 knees, primarily affecting the tibial implant. Sabatini et al. show improved functional KSS, no evidence of loosening, or peri-prosthetic fractures, and full recovery of extension in a series of 28 primary VV-TKAs with an average of 31 (6–48) months of follow-up. They conclude that the implants are safe and practical for primary TKA in cases of

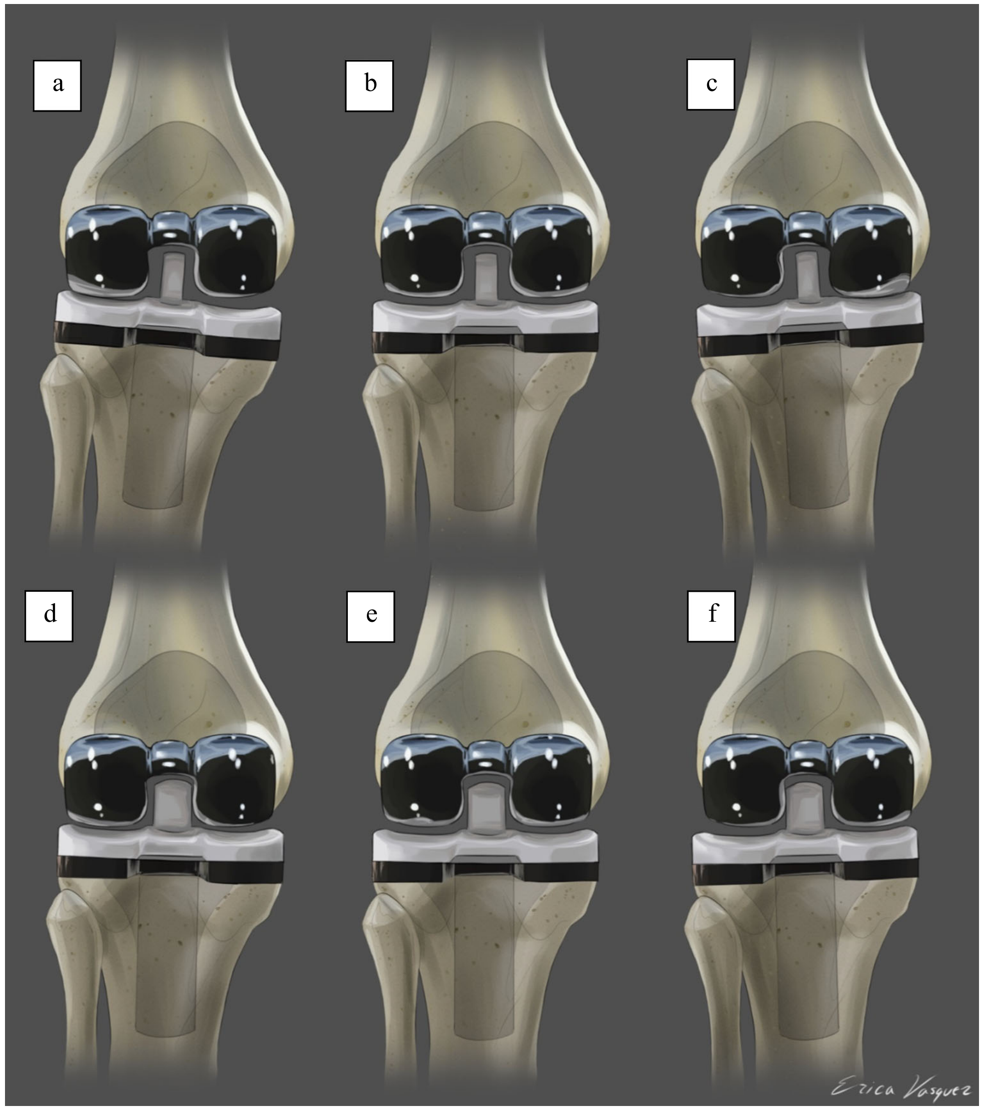


Fig 2 **a**–**c** Standard PS insert demonstrating that with even significant amounts of varus or valgus displacement, the post does not engage the condyles thereby relying on the collateral ligaments and bony anatomy for stability. Post's main function is to provide anterior-posterior stability. **d**–**f** Varus-Valgus constrained total knee polyethylene insert demonstrating how it engages the medial/lateral condyle earlier compared to the standard PS insert thereby allowing for increased varus-valgus stability

severe deformity that cannot be managed with soft tissue releases alone.

Some authors recommend using stemmed tibial and femoral component to address increased stresses of constrained implants [91, 92]. Moussa et al. [92] report a significantly higher revision rate (2.20% vs 0.98%) for constrained prostheses (n = 817) compared to PS knees (n = 817) due to mechanical failure. In contrast, Anderson et al. [93] demonstrated a 2.5% failure rate in 192 knees after VV-TKA without stem extensions at a mean of 47 months. Failures were comprised of 2 infections, 1 aseptic loosening, 1 supracondylar femoral fracture, and 1 tibial post fracture. They concluded the use of a non-modular constrained condylar knee for difficult primary TKA demonstrated reliable short- to mid-term results and question the use of routine use of intramedullary stem extensions.

Conclusion

Overall outcomes comparing the various types of modern polyethylene inserts have all yielded results suggesting that though there are benefits to certain inserts, there is no one insert that is superior to the others.

Congruent articular surface inserts provide a true cruciate retaining type implant which preserves femoral bone stock. Additionally, its highly congruent articular surface allows a more even distribution of forces [38•]. However, due to the increased congruence and lipped design, deep flexion is limited and greater amounts of polyethylene wear is possible with the increased congruence [38•, 39, 94].

Similar to the congruent articular surface design, medial pivot inserts have a highly congruent concave medial side which prevents deep flexion, but this design was able to solve the conundrum of paradoxical anterior translation that is seen with the other traditional CR designs [13, 39, 41, 44•, 45, 94]. In spite of the improved kinematics, there is still no significant difference in outcomes at 15 years when compared to posterior stabilized total knees [46••, 47••, 48, 49].

Dual pivot inserts seem to have improved patient-reported outcomes with their more natural feeling knee that has both a medial and lateral pivot. Though overall outcome medium and long-term data are still needed, early data suggests that patients may notice improved outcomes with this design [50, 56]. Additionally, while patients are reporting a more natural feeling knee, we are also lacking kinematic studies showing how close to a native knee the articulation truly is.

Bicruciate retaining total knees have demonstrated the best kinematics and range of motion, but the technically challenging procedure and high revision rate seem to be the limiting factor for this design [63•, 64, 65, 66•, 67, 68, 75•].

Though the VV-TKA serves a different purpose than the other CR inserts discussed in this paper, it allows the surgeon the ability to increase stability without modifying the femoral cut [76, 77]. Though short-term/smaller studies have demonstrated no significant increase in revision rate, larger studies with longer follow-up have shown a significant increase in the need for revision in VV-TKA [86••, 88, 89, 90••].

The optimal polyethylene inserts still remain to be determined. Long-term studies on newer designs need to be completed and older designs such as the CR and PS may have a good track record of survivorship lack the ability to truly recreate the biomechanics of the native knee [4, 5•, 15•, 16, 21•, 37]. Ultimately, we are not able to recommend for or against any one design. The optimal insert is one the surgeon feels most comfortable using and the one that serves that specific patient's needs.

Acknowledgements We would like to acknowledge Erica Vasquez, Brooke Army Medical Center Graphic Designer and Illustrator. We would like to also acknowledge Zimmer (Warsaw, IN) and Smith and Nephew (London, United Kingdom) for allowing us to use their polyethylene insert images.

Author Contribution All authors contributed to the conceptualization of the review. Darshan Shah, Craig Kampfer, and Taylor Bates were equally responsible for literature review, analysis, writing, editing. Donald Hope provided supervision and critically reviewed and revised the draft.

Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Surgeries in Hospital-Based Ambulatory Surgery and Hospital Inpatient Settings, 2014 #223 [Internet]. [cited 2019 Oct 29]. Available from: https://hcup-us.ahrq.gov/reports/statbriefs/sb223-Ambulatory-Inpatient-Surgeries-2014.jsp
2••. Lange JK, Lee Y-Y, Spiro SK, Haas SB. Satisfaction rates and quality of life changes following total knee arthroplasty in age-differentiated cohorts. J Arthroplasty. 2018;33:1373–8. **Retrospective analysis of 529 younger patients and 2001 older patients that demonstrated satisfaction rates greater than 85% in young patients and over 91% in older patients. Young was defined as patients under 55 years of age**.
3. Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KDJ. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? Clin Orthop. 2010;468:57–63.
4. Abdel MP, Morrey ME, Jensen MR, Morrey BF. Increased long-term survival of posterior cruciate-retaining versus posterior cruciate-stabilizing total knee replacements. J Bone Joint Surg Am. 2011;93:2072–8.
5•. Verra WC, van den Boom LGH, Jacobs W, Clement DJ, Wymenga AAB, Nelissen RGHH. Retention versus sacrifice of the posterior cruciate ligament in total knee arthroplasty for treating osteoarthritis. Cochrane Database Syst Rev. 2013;CD004803. **Systematic review that included 18 articles for a total of 2206 knees that showed overall minimal difference in CR vs PS total knees. Overall range of motion was 2.4 degrees better in CR knees**.
6. Chinzei N, Ishida K, Tsumura N, Matsumoto T, Kitagawa A, Iguchi T, Nishida K, Akisue T, Kuroda R, Kurosaka M. Satisfactory results at 8 years mean follow-up after ADVANCE® medial-pivot total knee arthroplasty. The Knee. 2014;21:387–90.
7••. Dehl M, Bulaïd Y, Chelli M, Belhaouane R, Gabrion A, Havet E, et al. Total knee arthroplasty with the Medial-Pivot knee system: clinical and radiological outcomes at 9.5 years' mean follow-up. Orthop Traumatol Surg Res. 2018;104:185–91. **74 patient retrospective analysis of consecutive knees that received medial pivot knees. Average range of motion was 110 degrees and survival was 93% and 95.9% when excluding trauma or infection**.
8. Mazzucchelli L, Deledda D, Rosso F, Ratto N, Bruzzone M, Bonasia DE, et al. Cruciate retaining and cruciate substituting ultra-congruent insert. Ann Transl Med [Internet]. 2016 [cited 2019 Jul 21];4. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4716943/
9. Pritchett JW. Bicruciate-retaining total knee replacement provides satisfactory function and implant survivorship at 23 years. Clin Orthop. 2015;473:2327–33.
10. Chaudhary R, Beaupré L, Johnston D. Knee range of motion during the first two years after use of posterior cruciate-stabilizing or posterior cruciate-retaining total knee prostheses: a randomized clinical trial. J Bone Jt Surg-Am Vol. 2008;90:2579–86.
11•. Vaienti E, Scita G, Ceccarelli F, Pogliacomi F. Understanding the human knee and its relationship to total knee replacement. Acta Bio-Medica Atenei Parm. 2017;88:6–16. **Provides basic anatomy and kinematic background to the total knee and native human knee**
12••. Grieco TF, Sharma A, Dessinger GM, Cates HE, Komistek RD. In vivo kinematic comparison of a bicruciate stabilized total knee arthroplasty and the normal knee using fluoroscopy. J

Arthroplasty. 2018;33:565–71 In vivo analysis using fluoroscopic radiography to analyze kinematics of bicruciate retaining total knee versus the total knee.

13. Komistek RD, Dennis DA, Mahfouz M. In vivo fluoroscopic analysis of the normal human knee. Clin Orthop. 2003;410:69–81.
14. Stronach BM, Adams JC, Jones LC, Farrell SM, Hydrick JM. The effect of sacrificing the posterior cruciate ligament in total knee arthroplasties that use a highly congruent polyethylene component. J Arthroplasty. 2019;34:286–9.
15•. Vertullo CJ, Lewis PL, Lorimer M, Graves SE. The effect on long-term survivorship of surgeon preference for posterior-stabilized or minimally stabilized total knee replacement: an analysis of 63,416 prostheses from the Australian Orthopaedic Association National Joint Replacement Registry. J Bone Joint Surg Am. 2017;99:1129–39.
16••. Spekenbrink-Spooren A, Van Steenbergen LN, Denissen GAW, Swierstra BA, Poolman RW, Nelissen RGHH. Higher mid-term revision rates of posterior stabilized compared with cruciate retaining total knee arthroplasties: 133,841 cemented arthroplasties for osteoarthritis in the Netherlands in 2007-2016. Acta Orthop. 2018;89:640–5. **Registry analysis of 133,841 total knees done in the Netherlands. Shows higher mid-term revision rates for posterior stabilized implants compared to cruciate retaining implants**.
17•. Sorger JI, Federle D, Kirk PG, Grood E, Cochran J, Levy M. The posterior cruciate ligament in total knee arthroplasty. J Arthroplasty. 1997;12:869–79. Kinematic analysis of the knee using a cadaveric model. Femoral rollback was determined 5 different settings. (1) intact knee , (2)ACL deficient knee, (3) PCL retaining total knee, (4) PCL retaining total knee without PCL, (5) PCL substituting knee. **Study demonstrated that the PCL when intact was able to preserve roll back.**
18. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL-Y. Quantitative analysis of human cruciate ligament insertions. Arthroscopy. 1999;15:741–9.
19. LaPrade CM, Civitarese DM, Rasmussen MT, LaPrade RF. Emerging updates on the posterior cruciate ligament: a review of the current literature. Am J Sports Med. 2015;43:3077–92.
20. Goodfellow J, O'Connor J. The mechanics of the knee and prosthesis design. J Bone Joint Surg Br. 1978;60-B:358–69.
21•. Dennis DA, Komistek RD, Mahfouz MR. In vivo fluoroscopic analysis of fixed-bearing total knee replacements: Clin Orthop. 2003;410:114–30. In vivo kinematic study using fluoroscopy to determine kinematics of PS vs CR total knees. Study demonstrated that patients with PS total knees had better weight bearing range of motion and more physiologic femoral rollback compared to patients with CR total knees. **Additionally, patients with CR total knees had paradoxical anterior sliding during deep knee bending. Paradoxical rollback was seen in normal gait in both PS and CR designs**.
22••. Koh Y-G, Son J, Kwon O-R, Kwon SK, Kang K-T. Effect of post-cam design for normal knee joint kinematic, ligament, and quadriceps force in patient-specific posterior-stabilized total knee arthroplasty by using finite element analysis. BioMed Res Int [Internet]. 2018 [cited 2019 Jul 21];2018. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6169244/. **Computation analysis of various cam-post designs to determine how cam-post variations affect tibio-femoral kinematics**.
23. Pan X, Peng A, Wang F, Li F, Nie X, Yang X, Ji G, Wang XM. Effect of tibial slope changes on femorotibial contact kinematics after cruciate-retaining total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2017;25:3549–55.
24. Fujimoto E, Sasashige Y, Tomita T, Iwamoto K, Masuda Y, Hisatome T. Significant effect of the posterior tibial slope on the weight-bearing, midflexion in vivo kinematics after cruciate-retaining total knee arthroplasty. J Arthroplasty. 2014;29:2324–30.
25. Tomita T, Yamazaki T, Oda K, Yoshikawa H, Sugamoto K. Influence of posterior tibial slope on kinematics after cruciate-retaining total knee arthroplasty. J Arthroplasty. 2018;33:3778-3782.e1.
26. Li N, Tan Y, Deng Y, Chen L. Posterior cruciate-retaining versus posterior stabilized total knee arthroplasty: a meta-analysis of randomized controlled trials. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2014;22:556–64.
27. Jiang C, Liu Z, Wang Y, Bian Y, Feng B, Weng X. Posterior cruciate ligament retention versus posterior stabilization for total knee arthroplasty: a meta-analysis. PloS One. 2016;11:e0147865.
28••. Migliorini F, Eschweiler J, Tingart M, Rath B. Posterior-stabilized versus cruciate-retained implants for total knee arthroplasty: a meta-analysis of clinical trials. Eur J Orthop Surg Traumatol Orthop Traumatol. 2019;29:937–46. **Meta-analysis completed in 2018 of 36 studies which demonstrated no significant differences between PS and CR knees at mid-range follow-up**.
29••. Longo UG, Ciuffreda M, Mannering N, D'Andrea V, Locher J, Salvatore G, et al. Outcomes of posterior-stabilized compared with cruciate-retaining total knee arthroplasty. J Knee Surg. 2018;31:321–40. **Systematic review of 5,407 knees that demonstrated no significant difference in clinical outcome of PS vs CR knees**.
30. Laskin RS. The Insall Award. Total knee replacement with posterior cruciate ligament retention in patients with a fixed varus deformity. Clin Orthop. 1996;1:29–34.
31. Laskin RS, O'Flynn HM. The Insall Award. Total knee replacement with posterior cruciate ligament retention in rheumatoid arthritis. Problems and complications. Clin Orthop. 1997;1:24–8.
32. Shimizu N, Tomita T, Yamazaki T, Yoshikawa H, Sugamoto K. The effect of weight-bearing condition on kinematics of a high-flexion, posterior-stabilized knee prosthesis. J Arthroplasty. 2011;26:1031–7.
33. Kumar N, Yadav C, Raj R, Yadav S. Fracture of the polyethylene tibial post in a posterior stabilized knee prosthesis: a case report and review of literature. J Orthop. 2015;12:160–3.
34••. Diamond OJ, Howard L, Masri B. Five cases of tibial post fracture in posterior stabilized total knee arthroplasty using prolong highly cross-linked polyethylene. The Knee. 2018;25:657–62. **Case series that reports on one of the major risks of PS total knees, post fracture**.
35. Pun AHF, Pun W-K, Storey P. Intra-operative fracture in posterior-stabilised total knee arthroplasty. J Orthop Surg Hong Kong. 2015;23:205–8.
36. Alden KJ, Duncan WH, Trousdale RT, Pagnano MW, Haidukewych GJ. Intraoperative fracture during primary total knee arthroplasty. Clin Orthop. 2010;468:90–5.
37. Öztürk A, Akalın Y, Çevik N, Otuzbir A, Özkan Y, Dostabakan Y. Posterior cruciate-substituting total knee replacement recovers the flexion arc faster in the early postoperative period in knees with high varus deformity: a prospective randomized study. Arch Orthop Trauma Surg. 2016;136:999–1006.
38•. Hofmann AA, Tkach TK, Evanich CJ, Camargo MP. Posterior stabilization in total knee arthroplasty with use of an ultracongruent polyethylene insert. J Arthroplasty. 2000;15:576–83. Retrospective review of 100 total knees (53 primary and 47 revision) that outlined the enhanced geometry of the ultra-congruent polyethylene. There is a 12.5 mm anterior build up and overall enhanced congruence. **Study demonstrated no revision due to instability.**
39. Daniilidis K, Skwara A, Vieth V, Fuchs-Winkelmann S, Heindel W, Stückmann V, Tibesku CO. Highly conforming polyethylene inlays reduce the in vivo variability of knee joint kinematics after total knee arthroplasty. The Knee. 2012;19:260–5.

40•. Massin P, Boyer P, Sabourin M. Less femorotibial rotation and AP translation in deep-dished total knee arthroplasty. An intraoperative kinematic study using navigation. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2012;20:1714–9. Intraoperative study using navigation to determine stability and kinematics. **Ultra-congruent tibial polyethylene showed reduced posterior displacement without reductions in range of motion**.
41. Lützner J, Firmbach F-P, Lützner C, Dexel J, Kirschner S. Similar stability and range of motion between cruciate-retaining and cruciate-substituting ultracongruent insert total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2015;23:1638–43.
42. Peters CL, Mulkey P, Erickson J, Anderson MB, Pelt CE. Comparison of total knee arthroplasty with highly congruent anterior-stabilized bearings versus a cruciate-retaining design. Clin Orthop. 2014;472:175–80.
43••. Sabatini L, Risitano S, Parisi G, Tosto F, Indelli PF, Atzori F, et al. Medial pivot in total knee arthroplasty: literature review and our first experience. Clin Med Insights Arthritis Musculoskelet Disord [Internet]. 2018 [cited 2019 Apr 14];11. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5758963/. Short term (1 year) data on medial congruent tibial inserts.
44•. Shimmin A, Martinez-Martos S, Owens J, Iorgulescu AD, Banks S. Fluoroscopic motion study confirming the stability of a medial pivot design total knee arthroplasty. The Knee. 2015;22:522–6. Fluoroscopic analysis of medial pivot total knee inserts that demonstrates normal, non-paradoxical femoral rollback during knee flexion. **Though the direction of rollback is appropriate the magnitude is less than that of native knees**.
45. Moonot P, Mu S, Railton GT, Field RE, Banks SA. Tibiofemoral kinematic analysis of knee flexion for a medial pivot knee. Knee Surg Sports Traumatol Arthrosc. 2009;17:927–34.
46••. Samy DA, Wolfstadt JI, Vaidee I, Backstein DJ. A retrospective comparison of a medial pivot and posterior-stabilized total knee arthroplasty with respect to patient-reported and radiographic outcomes. J Arthroplasty. 2018;33:1379–83. Retrospective review of 88 patients with PS and 76 patients with medial pivot total knee arthroplasties. **Overall patients with medial pivot total knees showed improved forgotten joint scores and deep knee motion.**, 2018
47••. Benjamin B, Pietrzak JRT, Tahmassebi J, Haddad FS. A functional comparison of medial pivot and condylar knee designs based on patient outcomes and parameters of gait. Bone Jt J. 2018;100-B:76–82. Outcome and gait analysis of 45 patients who were randomized prospective study between medial congruent and signle radius design. **Overall there were no differences in the two types of implants in KSS, OKS, cadence, walking speed, or gait parameters**.
48•. Karachalios T, Varitimidis S, Bargiotas K, Hantes M, Roidis N, Malizos KN. An 11- to 15-year clinical outcome study of the Advance Medial Pivot total knee arthroplasty: pivot knee arthroplasty. Bone Jt J. 2016;98-B:1050–5. **10-15 year data on medial pivot total knees showing 97.3% overall survival and 98.8% survival when looking only at instability as the endpoint**.
49. Macheras GA, Galanakos SP, Lepetsos P, Anastasopoulos PP, Papadakis SA. A long term clinical outcome of the Medial Pivot Knee Arthroplasty System. The Knee. 2017;24:447–53.
50. Meneghini RM, Deckard ER, Ishmael MK, Ziemba-Davis M. A Dual-pivot pattern simulating native knee kinematics optimizes functional outcomes after total knee arthroplasty. J Arthroplasty. 2017;32:3009–15.
51. Isberg J, Faxén E, Laxdal G, Eriksson BI, Kärrholm J, Karlsson J. Will early reconstruction prevent abnormal kinematics after ACL injury? Two-year follow-up using dynamic radiostereometry in 14 patients operated with hamstring autografts. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2011;19:1634–42.
52. Koo S, Andriacchi TP. The knee joint center of rotation is predominantly on the lateral side during normal walking. J Biomech. 2008;41:1269–73.
53. Kozanek M, Hosseini A, Liu F, Van de Velde SK, Gill TJ, Rubash HE, et al. Tibiofemoral kinematics and condylar motion during the stance phase of gait. J Biomech. 2009;42:1877–84.
54. Yamaguchi S, Gamada K, Sasho T, Kato H, Sonoda M, Banks SA. In vivo kinematics of anterior cruciate ligament deficient knees during pivot and squat activities. Clin Biomech Bristol Avon. 2009;24:71–6.
55. Hoshino Y, Tashman S. Internal tibial rotation during in vivo, dynamic activity induces greater sliding of tibio-femoral joint contact on the medial compartment. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2012;20:1268–75.
56••. Sandberg R, Deckard ER, Ziemba-Davis M, Banks SA, Meneghini RM. Dual-pivot bearings improve ambulation and promote increased activity levels in total knee arthroplasty: a match-controlled retrospective study. The Knee. 2019;26:1243–9. **Retrospective case-control study of 183 traditional non-conforming TKAs and 183 dual pivot TKAs that demonstrated less walking pain the BCR group but no differences in overall satisfaction**.
57. de Beer J, Petruccelli D, Adili A, Piccirillo L, Wismer D, Winemaker M. Patient perspective survey of total hip vs total knee arthroplasty surgery. J Arthroplasty. 2012;27:865-869.e1-5.
58. Noble PC, Gordon MJ, Weiss JM, Reddix RN, Conditt MA, Mathis KB. Does total knee replacement restore normal knee function? Clin Orthop. 2005;431:157–65.
59. Amis AA, Bull AMJ, Gupte CM, Hijazi I, Race A, Robinson JR. Biomechanics of the PCL and related structures: posterolateral, posteromedial and meniscofemoral ligaments. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2003;11:271–81.
60. Conditt MA, Noble PC, Bertolusso R, Woody J, Parsley BS. The PCL significantly affects the functional outcome of total knee arthroplasty. J Arthroplasty. 2004;19:107–12.
61. Rong GW, Wang YC. The role of cruciate ligaments in maintaining knee joint stability. Clin Orthop. 1987;215:65–71.
62. Shelburne KB, Pandy MG, Anderson FC, Torry MR. Pattern of anterior cruciate ligament force in normal walking. J Biomech. 2004;37:797–805.
63•. Zumbrunn T, Duffy MP, Rubash HE, Malchau H, Muratoglu OK, Varadarajan KM. ACL substitution may improve kinematics of PCL-retaining total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2018;26:1445–54. **Simulation of BCR total knees which demonstrated similar kinematics of the BCR implant to the native knee**., 2018
64. Lo J, Müller O, Dilger T, Wülker N, Wünschel M. Translational and rotational knee joint stability in anterior and posterior cruciate-retaining knee arthroplasty. The Knee. 2011;18:491–5.
65. Dennis DA, Komistek RD, Mahfouz MR, Walker SA, Tucker A. A multicenter analysis of axial femorotibial rotation after total knee arthroplasty. Clin Orthop. 2004;428:180–9.
66.• Moro-oka T, Muenchinger M, Canciani J-P, Banks S, Banks SA. Comparing in vivo kinematics of anterior cruciate-retaining and posterior cruciate-retaining total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2007;15:93–9. **Comparison study of 5 PCL retaining total knees and 9 BCR knees where gait kinematics where observed using lateral fluoroscopy. Femoral rollback was improved in the BCR group during walking, stairs and deep flexion**.
67. Stiehl JB, Komistek RD, Cloutier JM, Dennis DA. The cruciate ligaments in total knee arthroplasty: a kinematic analysis of 2 total knee arthroplasties. J Arthroplasty. 2000;15:545–50.
68•. Heyse T, Slane J, Peersman G, Dirckx M, Vyver A, Dworschak P, et al. Kinematics of a bicruciate-retaining total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2017;25:1784–91. **In vivo**

infrared camera analysis of BCR total knees compared to native knees. With no weight bearing the kinematics between the BCR knee and native knee were very similar, however with weight bearing there increased paradoxical medial femoral condylar motion.
69••. Tsai T-Y, Liow MHL, Li G, Arauz P, Peng Y, Klemt C, et al. Bicruciate retaining total knee arthroplasty does not restore native tibiofemoral articular contact kinematics during gait. J Orthop Res Off Publ Orthop Res Soc. 2019;37:1929–37. Kinematic study using dual fluoroscopic imaging to track knee motion in BCR total knees. **Results from this study affirm earlier studies that demonstrate paradoxical motion in the medial compartment and overall less range of motion compared to the native knee**.
70. Nowakowski AM, Stangel M, Grupp TM, Valderrabano V. Comparison of the primary stability of different tibial baseplate concepts to retain both cruciate ligaments during total knee arthroplasty. Clin Biomech [Internet]. 2013 [cited 2019 Dec 2];28:910–5. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0268003313001939
71. Goodfellow JW, O'Connor J. Clinical results of the Oxford knee. Surface arthroplasty of the tibiofemoral joint with a meniscal bearing prosthesis. Clin Orthop. 1986;205:21–42.
72. Nowakowski AM, Stangel M, Grupp TM, Valderrabano V. Investigating the primary stability of the transversal support tibial plateau concept to retain both cruciate ligaments during total knee arthroplasty. J Appl Biomater Funct Mater. 2012;10:127–35.
73. Barrett TJ, Shi L, Parsley BS. Bicruciate-retaining total knee arthroplasty, a promising technology, that's not quite there. Ann Transl Med [Internet]. 2017 [cited 2019 Jul 27];5. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5440298/
74. Halewood C, Traynor A, Bellemans J, Victor J, Amis AA. Anteroposterior laxity after bicruciate-retaining total knee arthroplasty is closer to the native knee than ACL-resecting TKA: a biomechanical cadaver study. J Arthroplasty. 2015;30:2315–9.
75•. Christensen JC, Brothers J, Stoddard GJ, Anderson MB, Pelt CE, Gililland JM, et al. Higher frequency of reoperation with a new bicruciate-retaining total knee arthroplasty. Clin Orthop. 2017;475:62–9. Retrospective analysis of 294 CR knees and 78 BCR knees performed by 2 surgeons between January of 2013 and May 2014. At average 12 month follow up, the BCR group had higher all cause revision at 5% compared to 1.3% for the CR group. **There were no differences in measured outcome measures.** 2017.
76. Donaldson WF, Sculco TP, Insall JN, Ranawat CS. Total condylar III knee prosthesis. Long-term follow-up study. Clin Orthop. 1988:21–8.
77. Walker PS, Manktelow AR. Comparison between a constrained condylar and a rotating hinge in revision knee surgery. The Knee. 2001;8:269–79.
78. Lachiewicz PF, Soileau ES. Ten-year survival and clinical results of constrained components in primary total knee arthroplasty. J Arthroplasty. 2006;21:803–8.
79. Easley ME, Insall JN, Scuderi GR, Bullek DD. Primary constrained condylar knee arthroplasty for the arthritic valgus knee. Clin Orthop. 2000;380:58–64.
80. Li Z, Esposito CI, Koch CN, Lee Y-Y, Padgett DE, Wright TM. Polyethylene damage increases with varus implant alignment in posterior-stabilized and constrained condylar knee arthroplasty. Clin Orthop. 2017;475:2981–91.
81. Padgett DE, Cottrell J, Kelly N, Gelber J, Farrell C, Wright TM. Retrieval analysis of nonmodular constrained tibial inserts after primary total knee replacement. Orthop Clin North Am. 2012;43:e39–43.
82. Rapuri VR, Clarke HD, Spangehl MJ, Beauchamp CP. Five cases of failure of the tibial polyethylene insert locking mechanism in one design of constrained knee arthroplasty. J Arthroplasty. 2011;26:976.e21-24.
83. Shah SN, Schurman DJ, Goodman SB. Screw migration from total knee prostheses requiring subsequent surgery. J Arthroplasty. 2002;17:951–4.
84. Nadkarni JB, Carden DG. Acute locking in revision total knee arthroplasty due to disengagement of the locking screw. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2005;13:190–2.
85. Westrich GH, Hidaka C, Windsor RE. Disengagement of a locking screw from a modular stem in revision total knee arthroplasty. A report of three cases. J Bone Joint Surg Am. 1997;79:254–8.
86••. Pitta M, Esposito CI, Li Z, Lee Y, Wright TM, Padgett DE. Failure after modern total knee arthroplasty: a prospective study of 18,065 knees. J Arthroplasty. 2018;33:407–14. Retrospective institutional analysis of 18,065 total knees which demonstrated the most common reasons for failure within 2 years being infection and stiffness. **Risk factors for early failure included drug abuse, deformity/mechanical diagnosis preoperatively, post trauma diagnosis, and younger age**.
87••. Puah KL, Chong HC, Foo LSS, Lo N-N, Yeo S-J. Clinical and functional outcomes: primary constrained condylar knee arthroplasty compared with posterior stabilized knee arthroplasty. J Am Acad Orthop Surg Glob Res Rev. 2018;2:e084. **Case control study of 76 patients who underwent PS (38 knees) and Varus-Valgus constrained (38) total knees. No significant differences were noted at 2 years in terms of clinical or functional outcome**.
88. Cholewinski P, Putman S, Vasseur L, Migaud H, Duhamel A, Behal H, Pasquier G. Long-term outcomes of primary constrained condylar knee arthroplasty. Orthop Traumatol Surg Res OTSR. 2015;101:449–54.
89. Siqueira MBP, Jacob P, McLaughlin J, Klika AK, Molloy R, Higuera CA, Barsoum W. The Varus-Valgus constrained knee implant: survivorship and outcomes. J Knee Surg. 2017;30:484–92.
90••. Rai S, Liu X, Feng X, Rai B, Tamang N, Wang J, et al. Primary total knee arthroplasty using constrained condylar knee design for severe deformity and stiffness of knee secondary to post-traumatic arthritis. J Orthop Surg. 2018;13:67. **Single center retrospective analysis of 38 consecutive patients with minimum 3 year follow up that demonstrated 94.7% survival of varus-valgus constrained implants with improvements in KSS and HSS scores compared to preop**.
91. Ruel A, Ortiz P, Westrich G. Five year survivorship of primary nonmodular stemless constrained knee arthroplasty. The Knee. 2016;23:716–8.
92. Moussa ME, Lee Y-Y, Westrich GH, Mehta N, Lyman S, Marx RG. Comparison of revision rates of non-modular constrained versus posterior stabilized total knee arthroplasty: a propensity score matched cohort study. HSS J Musculoskelet J Hosp Spec Surg. 2017;13:61–5.
93. Anderson JA, Baldini A, MacDonald JH, Tomek I, Pellicci PM, Sculco TP. Constrained condylar knee without stem extensions for difficult primary total knee arthroplasty. J Knee Surg. 2007;20:195–8.
94. Massin P, Boyer P, Sabourin M. Less femorotibial rotation and AP translation in deep-dished total knee arthroplasty. An intraoperative kinematic study using navigation. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2012;20:1714–9.