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31 Year Evolution of the Rotating-Platform Total Knee Replacment: Coping With "Spinout" and Wear

ABSTRACT: Low-contact-stress rotating-platform knee replacements were the original mobile-bearing knees developed by the senior authors in 1978 to improve fixation and minimize wear, however, 1-2 % experienced "spin-out" and wear resulting in the development of a third generation rotating platform (Buechel-Pappas, or B-P) in 1991. The purpose of this study is to evaluate design modifications incorporated into the B-P device based upon clinical outcomes. Clinical results of the initial 310 cementless B-P rotating platform total knee replacements in 257 patients were analyzed using a strict knee scoring scale. Of that group, 259 total knees in 206 patients were followed for 2–18 years (mean: 7.6 years). The titanium alloy metallic implants had a 10 μm thick titanium nitride (TiN) coating on all bearing and fixation surfaces and sintered-bead porous-coating, pore size of 350 microns, on all fixation surfaces. The rotating-platform bearing allowed 45° of internal and external rotation with further rotation limited by a stop pin on the tibial component to block complete rotary subluxation/dislocation of the bearing in the event of significant flexion instability or rotational trauma. The study showed 86.4 % excellent, 12.3 % good, 0.3 % fair, and 1.0 % poor results using a strict knee scoring scale. Complications requiring revision included tibial component loosening in 2 super-obese (BMI >50), osteoarthritic patients (0.6%) and 1 late deep infection (0.3%) in a rheumatoid patient after 3.3 years. There were no cases of bearing wear, subluxation, or dislocation seen. Radiographic analysis, using >2 mm lucency in any implant zone, demonstrated 0 % of radiolucencies around femoral components, 2.6 % around tibial components, and 0 % around patella components. Survivorship, using an end point of revision for wear or component loosening was 99.4 % at the 18-year interval.

KEYWORDS: total knee replacement (TKR), rotating-platform, mobile-bearing, spin-out, bearing wear

Introduction

Wear and loosening problems associated with knee joint replacements have been the major mechanical causes of failure since their early use in the 1970s [1–7]. The development of mobile-bearings reduced the risk associated with these problems by allowing needed mobility to minimize loosening torques on fixation while providing an increased surface contact area on the bearings to reduce wear [8–17].

Various types of mobile-bearing low-contact-stress (LCS) total knee replacements were developed to satisfy the requirements posed by existing pathologies and deformities. The bicruciate-retaining meniscal bearing total knee replacement was displaced by the posterior cruciate-retaining meniscal-bearing knee mainly because of tibial component loosening problems and surgical difficulty in retaining an intact anterior cruciate ligament, [9,18] even though good results were reported [19]. Wear problems of the meniscal-bearings negatively affected their long-term survivorship, [8,9] which in turn, led to the development of the A-P Glide type meniscal-bearing knee replacement that functioned extremely well in comparison to a rotating-platform type, [20] especially when the fat pad was resected during the surgical procedure [21]. However, when the patellar fat pad was retained, the bulky A-P Glide bearing would often translate anteriorly in flexion to make painful contact with this richly innervated tissue, causing severe anterior knee pain [21]. Because of this technical drawback, use of the A-P Glide type meniscal-bearing

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knee remains limited and has even been rejected by one group in favor of the rotating platform after a comparative analysis [22].

The rotating-platform type mobile-bearing was developed by the two senior authors (F.F.B., Sr. and M.J.P.) and initially used in 1978 as a revision prosthesis to salvage failed bicompartmental fixed-bearing knee replacements [23]. This versatile implant quickly became useful in primary and revision knee replacements, including pathological conditions with fixed-varus, fixed-valgus, and significant flexion deformities [8,9,24–30]. Wear problems were encountered in 1-2 % of cases after long term use [8] as a result of increased loading activities and gamma-in-air sterilized shelf-aged polyethylene, [31–33] which has also been incriminated in rapid fixed-bearing wear [2,31,34].

Subluxation or rotatory dislocation, sometimes referred to as "spin-out," of rotating platform bearings have been observed in 1-2 % of cases by various authors [35,36]. The cause for this "spin-out" appears to be flexion instability at the time of surgery [8,37,38].

Revision surgery can result in significantly higher dislocation rates of rotating platforms due to challenging flexion-extension gap-balance problems [37] and rates of 5.8 % dislocation have been reported [25]. Despite these wear and dislocation problems, the rotating-platform type mobile-bearing knee replacement has demonstrated superior long-term survivorship in both cemented [26] and cementless [8,20,24,28,29,39,40] embodiments.

However, when an irreducible dislocation occurs, it usually requires revision surgery to implant a thicker bearing to control the flexion gap. Occasionally, even a thicker "deep-dish" bearing fails to solve the problem and recurrent dislocation can occur, requiring in some cases, revision to a more constrained-type of knee replacement or a custom rotating-platform with a rotational stop pin to limit excessive axial rotation [41].

Such rotating-platforms with rotational stop-pin bearings have been developed for use in primary and revision total knee replacement to eliminate or at least minimize the risk of "spin-out." This investigation examines the use of these advanced rotating-platform bearings in primary and multiply-operated knee replacements over an 18-year interval to evaluate potential improvements in wear and dislocation resistance.

Design Modifications

While the third generation B-P knee retains commonalities with specific variants of the LCS, key design features were added to the B-P, which is the subject of this clinical study, to address issues of wear and spin-out. The B-P knee design uses a generating curve around a series of parallel axes (Fig. 1) producing two spherical regions in the principal load bearing segment, which provides for 162° of flexion. The dimensions of the articulating surfaces of the B-P knee are such that fully congruent contact exists to about 50° of flexion, providing a greater degree of congruity in the most highly loaded phases of walking and stair climbing, and significantly reduces contact stresses compared to earlier generation LCS designs that provide quasi-congruent or area contact to about 35° flexion (Fig. 2). Full line contact occurs with the B-P knee at greater flexion angles while the LCS has quasi-line contact at these flexion angles.

The primary load bearing segment arc of the B-P femoral component is greater by 19°, thereby increasing the degree of congruent contact during flexion. A comparison of testing demonstrates that stresses in the B-P are substantially lower than the LCS knee at all flexion angles (Fig. 3).

The distal and posterior condylar thicknesses are the same so that the prosthetic gaps can be precisely reproduced. The fixation side of the sulcus is flat, providing contact with bone, and the medial anterior flange side wall angle is greater, eliminating overhang. The hard biocompatible TiN ceramic coating on the titanium substrate provides a less abrasive surface and reduces the potential for wear of the bearing surface [42].

The B-P tibial platform is anatomically shaped and contains a stop pin to limit bearing rotation and reduce the potential for spin-out. The stop pin on the superior surface of the tibial platform engages a slot in the inferior surface off of the bearing (Fig. 4) and provides ±45° axial rotation. The limits of the rotation are not encountered during any activity but are reached only in the event of subluxation of the bearing from the femoral component. This stop pin reduces the potential for spin-out as seen in the LCS where the combined effects of an A-P shearing load, distraction of one of the condylar compartments, and a lax collateral ligament associated with the distracted compartment, demonstrate that the rotating bearing can be forced to rotate to a dislocated position. With the LCS, only ligament tension sufficient to prevent the femoral condyle on the distracted side from climbing over the lip of the bearing can prevent such a dislocation.

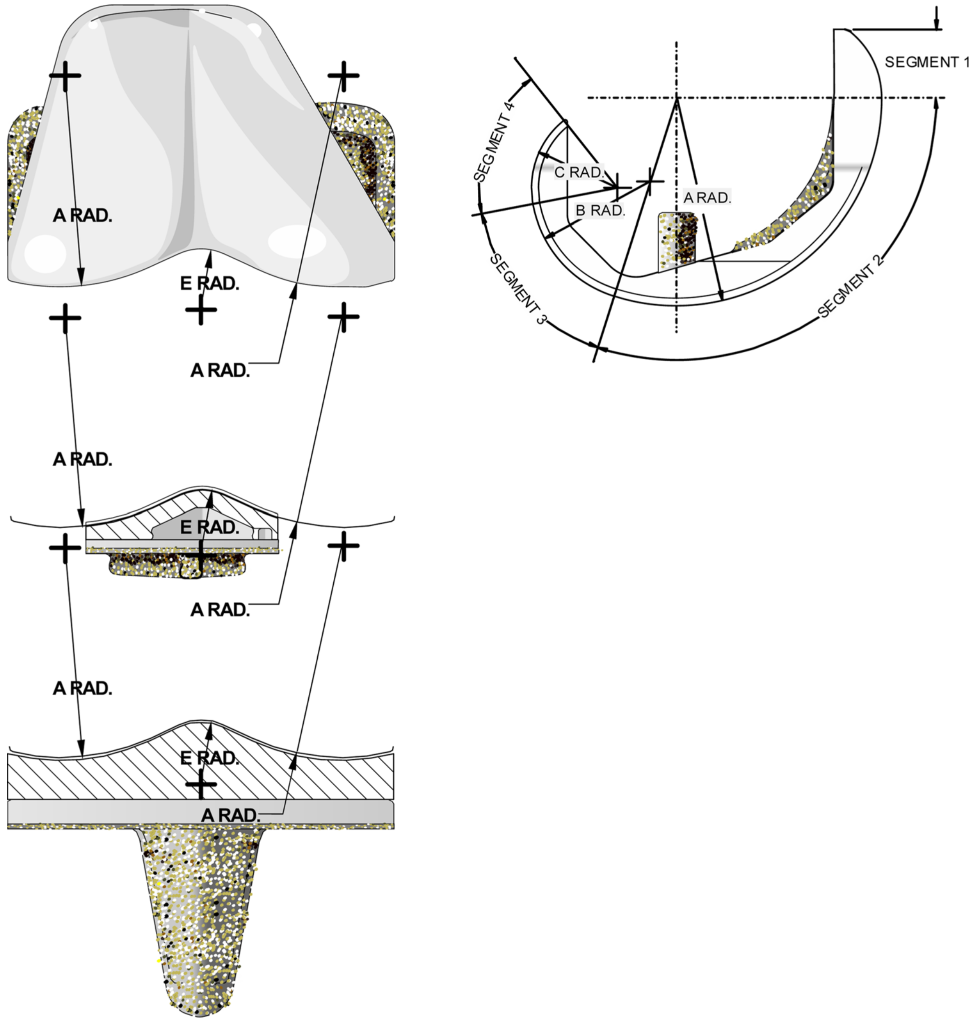


FIG. 1—*Use of common generating curve.*

The generating curve is designed to provide congruent medial-lateral stability since the bony structures naturally providing this stability are resected (Fig. 5). As an LCS based knee, the B-P uses a natural femoral component sulcus cross sectional shape with a normal sulcus angle and a conforming patella with an anatomic articulating surface. The spherical shape of the femoral condyles along with the lateral and middle patellar facets provide for patellar tilt without loss of congruency. The patella articulates over the primary load bearing segment for all of the range of motion (ROM) where there is significant compressive load and provides quasi-congruent contact on the lateral side where loads are heaviest throughout the patellofemoral motion range except near full extension. The femoral components use a common radius of curvature for most of the patellar articulation and part of the tibial articulation. A rotating patella bearing is used to accommodate the normal axial patellar rotation to the extent that it actually occurs. The femoral component, however, is designed to allow retention of the natural patella in many cases [43–46], based upon surgeon evaluation. The medial-lateral width of the femoral component has been developed for standard and narrow width patients regardless of gender [47–49].

Materials and Methods

Primary and multiply-operated Cementless B-P Rotating Platform Total Knee Replacements with Rotational Stop Pin (Endotec, Inc., Orlando, FL) were sequentially implanted from October 1991 to October 2009 and were prospectively evaluated, clinically and radiographically, in a cohort series [50] of 310 knees in 257 patients.

In the minimum 2-year interval (average follow-up 7.6 years: min 1.01 years; max 18.02 years), there were a total of 259 knees in 206 patients (53 patients had bilateral replacements). Knee system components used the same articulating geometry during the entire study period and included ultra-high molecular weight

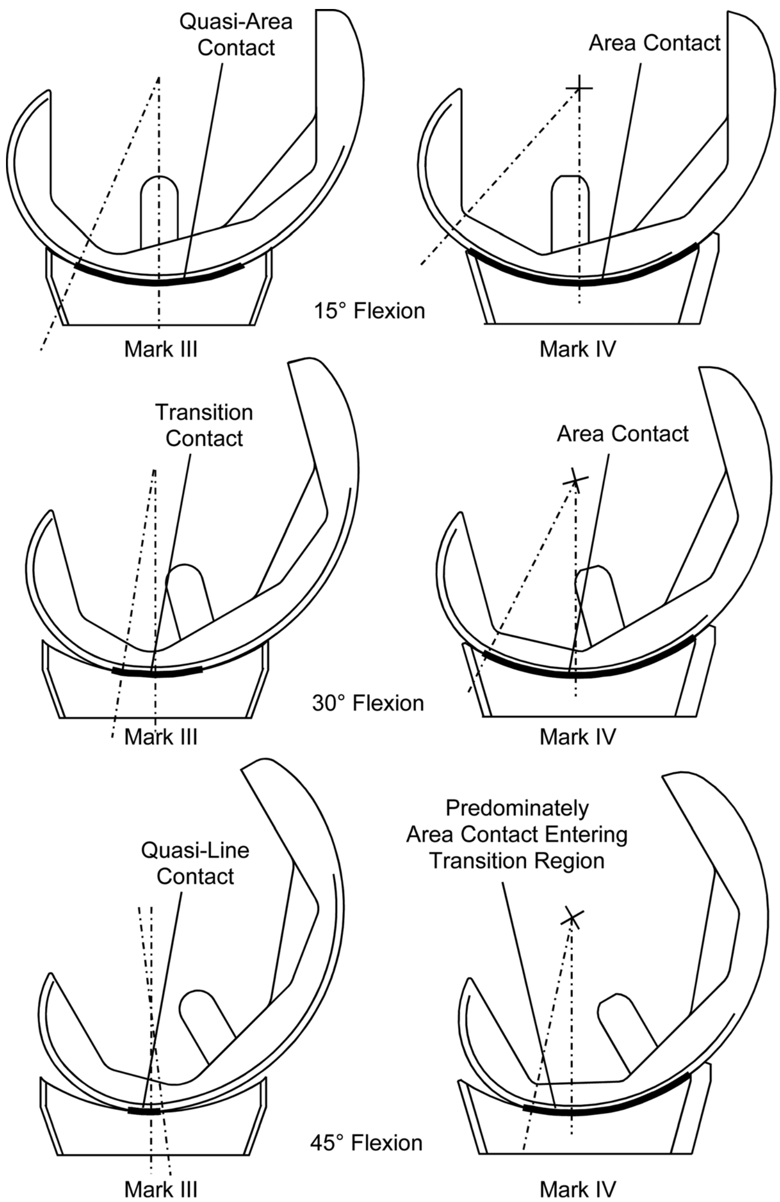


FIG. 2—*Contact in the first and third generation articulations.*

polyethylene cruciate-sacrificing rotating platform bearings mated with TiN femoral and tibial components. The metallic implants were made of a titanium alloy with a 10 μm thick titanium nitride (TiN) ceramic coating [51] on all bearing and porous coated fixation surfaces. All polyethylene bearings were sterilized by ethylene oxide. A rotating bearing patella component was used for tricompartmental replacement in 127 knees (49.0 %). The patella was rim-cauterized, debrided, and retained in 132 knees (51.0 %).

In this minimum 2-year interval there were 86 males and 173 females ranging in age from 34 to 91 years (mean: 67 years). Diagnoses were osteoarthritis in 233, post-traumatic arthritis in 4 patients and rheumatoid arthritis in 22 patients. Their height ranged from 53 to 75 in. (135 to 190 cm) (mean: 66 in. (168 cm)), and their weight ranged from 93 to 410 pounds (42 to 185 kg) (mean 197 pounds (89 kg)).

Clinical evaluations using the validated New Jersey Orthopaedic Hospital Knee Scoring Scale [52] (100 points) were performed after knee replacement surgery along with radiographs at 3, 6, and 12 months and biannually thereafter, for as long as the patient lived.

Radiographic analysis using $\geq$2 mm lucency in any zone around the femoral, tibial, or patellar components was identified for all available x-rays.

Kaplan-Meier Survivorship Analysis [53] was used to document comparative knee system component results using the following three end points: (1) revision for any reason in primary TKRs; (2) revision for any mechanical reason, including component loosening, bearing wear, or bearing dislocation; and (3) a poor clinical knee score.

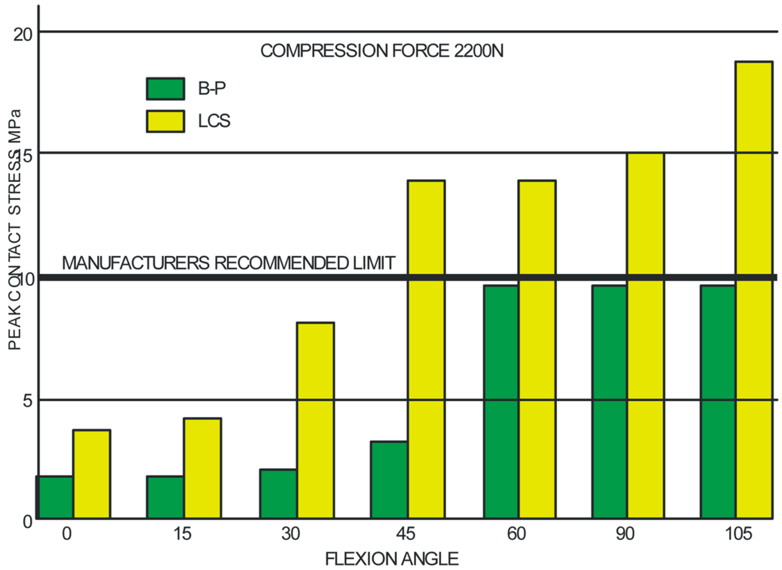


FIG. 3—*Contact stress comparison of B-P and LCS rotating platform knee replacements at a load of 2200 N using equations from Refs. [11] (B-P) and [16] (LCS).*

Exhaustive efforts were made to locate patients, in order to minimize patients that were lost-to-follow-up. These included Internet yellow page searches, social security death index searches, last known phone number/relative contacts, referring or covering physician contacts, and hospital/clinic contacts.

Results

The New Jersey Orthopaedic Hospital Knee Scoring Scale [52] ranged from 36 to 68 points out of a possible 100 points (mean: 52 points) pre-operatively, and 55 to 100 points (mean: 90 points) post-operatively. The pe-operative range of motion averaged a total arc of 100° (range 30° to 135°) and post-operatively increased to 116° (range 30° to 142°).

There were 37 deaths (42 knees) and 26 patients (31 knees) lost-to-follow-up (LTF). At the time of death, those patients had an average knee score of 86.4 points (excellent) (range: 71 to 96), while those patients LTF had an average of 87.9 points (excellent) (range: 70 to 96) at their last follow-up visit.

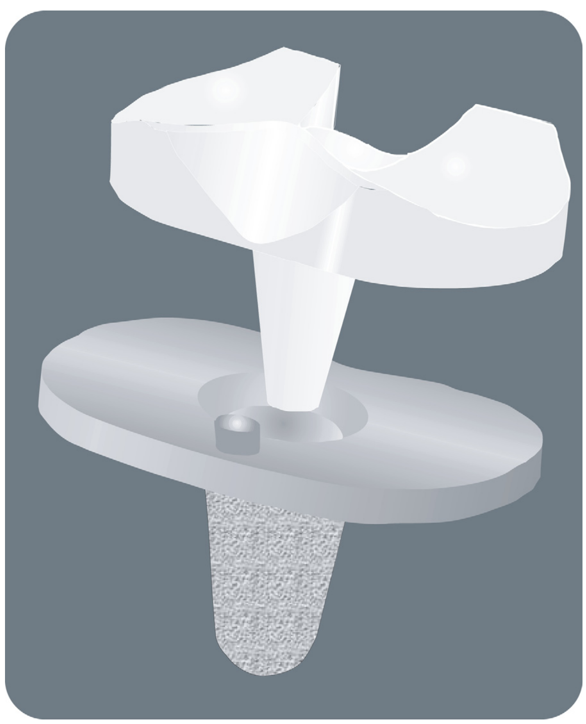


FIG. 4—*B-P tibial platform.*

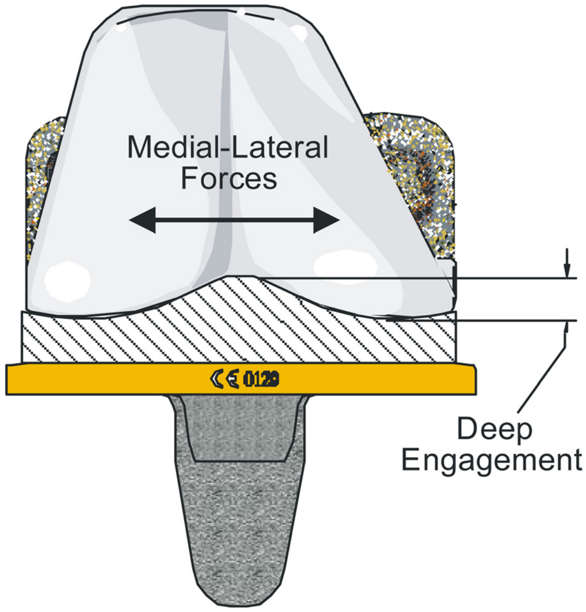


FIG. 5—*M-L stability provided by the articular surfaces.*

The study showed 86.4 % excellent, 12.3 % good, 0.3 % fair, and 1.0 % poor results. Radiographic zonal analysis for lucencies ≥2mm around the femoral, tibial, and patellar components are shown in Table 1, which demonstrates 0 % of radiolucencies around femoral components, 2.6 % around tibial components, and 0 % around patella components.

Kaplan-Meier survivorship analysis of cementless total knee replacement components using an end point of revision for any reason in patients without previous knee surgery (PRIMARY) was 100 % at 18 years (95 % confidence interval [54] of 0.61 to 1.19).

Survivorship in all cementless B-P total knee replacements, including those with previous knee surgery using an end point of revision for any mechanical reason (including component loosening, bearing wear and bearing dislocation), was 99.4 % at 18 years (95 % confidence interval of 0.64 to 1.16). Survivorship for a poor knee score (including persistent pain, loosening, instability, and infection) was 97.6 % at 18 years (95 % confidence interval of 0.64 to 1.16).

Complications

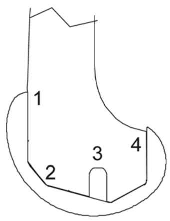
Complications requiring implant revision or fracture management in 310 B-P cementless rotating platform total knee replacements in 257 patients are shown in Table 2.

Two tibial components subsided in two multiply-operated, super obese (BMI >50) (318 lb. and 300 lb.) osteoarthritic male patients; one into valgus and the other into varus after 18 months and 11 months, respectively. In both cases, the tibial component settled into the previous fixed-valgus and fixed-varus

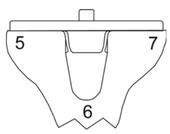
TABLE 1—*Complications requiring surgical management in 310 B-P total knee replacements in 257 patients.*

Complication	Number of Occurrences	Time of Occurrence, Years	Management
Supracondylar femur fracture	1	0.1	Fracture bracing
Femoral component loosening	0	…	…
Tibial component loosening	2	0.9, 1.5	Cemented revision with long-stem tibial component
Patellar component loosening	0	…	…
Bearing dislocation	0	…	…
Bearing wear	0	…	…
Patellar bearing wear	0	…	…
Ligamentous instability	2	1.0, 1.1	Thicker bearing and/or MCL repair
Deep infection	1	3.3	Exchange revision
Poor wound healing	4	0.1, 0.1, 0.1, 0.1	Wound revision and primary closure
Quadriceps rupture	2	0.1, 0.2	Quadriceps repair

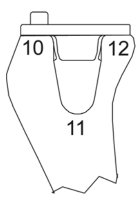
TABLE 2—*Radiographic zonal analysis results of patients with rotating platforms (RP) showing lucencies greater than or equal to 2 mm in B-P compared to LCS [8]knee replacements.*



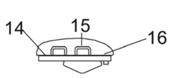
Zone	% Radiolucencies (> 2 mm) Cementless Rotating Platform (259 knees) B-P	(40 knees) LCS
1	0	0
2	0	0
3	0	0
4	0	0



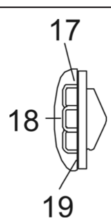
Zone	% Radiolucencies (> 2 mm) Cementless Rotating Platform (259 knees) B-P	(40 knees) LCS
5	2.6	7.5
6	1.3	2.5
7	2.6	5.0



Zone	% Radiolucencies (> 2 mm) Cementless rotating platform (259 knees) B-P	(40 knees) LCS
10	2.6	5.0
11	2.6	5.0
12	1.3	2.5



Zone	% Radiolucencies (> 2 mm) Cementless Rotating Platform (259 knees) B-P	(40 knees) LCS
14	0	0
15	0	0
16	0	0



Zone	% Radiolucencies (> 2 mm) Cementless Rotating Platform (259 knees) B-P	(40 knees) LCS
17	0	0
18	0	0
19	0	0

deformities, while cystic degeneration and evidence of avascular necrosis of the tibial plateau was noted under the tibial loading plates. Long-stemmed, modular revision tibial components, with screw-reinforced antibiotic cement were used to correct the deformities without removing the well-fixed femoral components.

Two total knees in two obese multiply-operated patients developed traumatic medial collateral ligament (MCL) instability after they both fell, one year from their initial total knee surgery. In both cases, knee braces failed to satisfactorily control the instability after a trial of 6 months. Surgical exploration revealed an intact, healed, but attenuated, MCL in one knee, while the other knee demonstrated a complete disruption of the MCL with resorption from the femoral attachment, requiring repair and augmentation through femoral drill holes. Excellent stability was achieved in both knees by using a 5 mm thicker rotating- platform bearing without disrupting the well-fixed metallic components.

One late (3.3 years) deep infection (staph aureus) developed in a 48-year-old rheumatoid woman, which was managed by primary bearing exchange, 6 weeks of intravenous antibiotics and 6 months of oral antibiotics with retention of her well-fixed, cementless, metallic components. After initially doing well, she developed leg ulcers, an open ankle infection, and a secondary knee infection with *Pseudomonas* 2 years later that required significant medical and surgical management prior to her death from rheumatoid pulmonary problems.

Wound revisions were successfully performed in 4 patients with poor initial wound healing. The wounds were elliptically excised and primarily closed. One patient had a subcutaneous abcess (MRSA) that was drained in conjunction with wound revision and debridement. The deep cultures were negative and the patient's wound responded to Vancomycin and Bactrim management without opening the knee joint.

Two elderly female patients developed traumatic quadriceps ruptures in the early post-operative period; one from a fall and the other from over-manipulation in physical therapy. Both patients underwent successful quadriceps repairs and regained terminal extension.

One supracondylar femur fracture in an osteoporotic woman, sustained during a rehabilitation session 2 weeks post-surgery, was successfully treated by closed reduction, cast immobilization, and fracture bracing over a 3 month interval.

Non-fatal pulmonary embolism was seen in 5 patients despite routine post-operative anti-coagulation. All patients responded to routine prolonged anti-coagulation and medical management without further complications.

No femoral component or patella component loosening was seen. Additionally, no rotating-platform bearing wear, osteolysis, or dislocation was seen in this study.

Case Reports

The following case reports provide clinical radiographic documentation of typical osteoarthritic and rheumatoid arthritic patients in this study.

Case #1—This 43 year old, 180 cm (71 in.) tall, 108 kg (240 lb.), osteoarthritic male patient underwent right cementless B-P TKR in 1993 for a 15° fixed varus deformity. He recovered uneventfully with a ROM of 0-125° and a knee score of 100 points (excellent) at 16 years post-op. Pre-operative and post-operative x-rays are shown in Fig. 6.

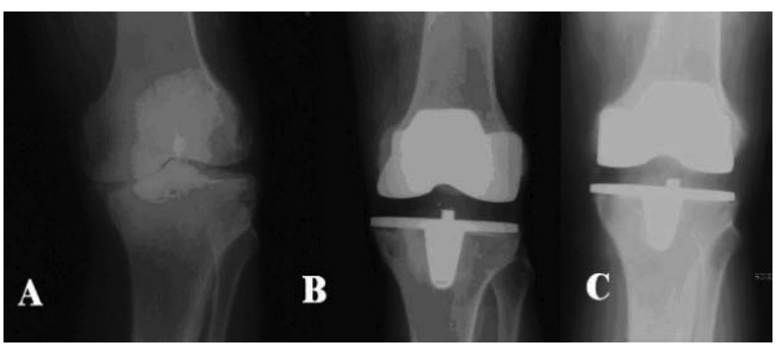


FIG. 6—*Anteroposterior radiographs shows: (A) pre-op; (B) 3 years post-op; and (C) 16 years post-op of the patient described in Case #1.*

Case #2—This 64 year old, 168 cm (66 in.) tall, 81 (180 lb.) kg, rheumatoid arthritic female patient underwent left cementless B-P TKR in 1995, and a right B-P TKR in 1996. She recovered uneventfully with a ROM of 110° in her right knee and 118° in her left knee, and bilateral knee scores of 84 points (good) at 13 and 14 years post-op for her right and left knees, respectively. Pre-operative and post-operative x-rays are shown in Fig. 7.

Discussion

The long term clinical success of total knee replacement has been documented for both fix-bearing [55–57] and mobile-bearing [3,8–10,15,24–26,29,58–61] designs, making knee replacement an extremely worthwhile and dependable treatment for end-stage arthritis. Cemented all-polyethylene components for elderly patients (≥75 years) have shown superior survivorship and appear to be more cost effective than metal-backed modular components [62]. Some modular fixed-bearing components have produced inferior survivorship to their cemented all-polyethylene counterparts, [63] even though they were designed to improve performance and longevity.

The explanation of the poor performance has been placed on the sterilization methodology and locking mechanisms in the case of fixed-bearing designs [64] and rotational instability in the case of mobile bearing designs [41,65]. Gamma-radiation-in-air and shelf aging with accelerated wear in polyethylene bearings [31,33,34,48] has been documented, however, surface congruity seems to play an even larger role in the evolution of bearing wear [16,32,66].

Collier and associates have evaluated fixed and mobile bearings after mid term and long term use with similar sterilization methodology and consistently found dramatic improvements in wear resistance in more-congruent mobile bearings over less congruent fixed-bearings [32,33,67]. These findings have been confirmed in simulator studies that demonstrate a four-fold improvement in the wear resistance of a rotating-platform type bearing over a less congruent fixed-bearing of the same implant system [12].

As patients become more active and undergo joint replacement at an earlier age, this wear difference between bearing types becomes an important issue. Maximizing contact areas to reduce contact stress during major load-bearing phases of motion while restoring normal flexion of the knee remains an important goal for implants to meet. Additionally, modularity which can provide for ease of removal and replacement of worn bearings without disturbing well-fixed components, remains another essential goal.

The LCS rotating platform set the standard for modular metal-backed components. Long term cemented [26] and cementless [8,24,28,40] studies have documented durability, while the ease of revise-ability in the event of wear-related failures has been demonstrated [68]. The major down-side of rotating platforms has been the occasional "spin-out" (1-2%) complication [8,35] that does not respond to a simple, increase-in-thickness, deep-dish bearing exchange. The B-P implant, which is the subject of this clinical report, was undertaken for design improvements (i.e., spin-out, contact stress and improved wear) in joint replacement systems [69].

The B-P rotating-platform system has incorporated an emergency stop-pin enhancement and contact stresses have been lowered in certain key load bearing regions without dramatically altering the "tried-and-true" LCS design concepts. No intercondylar posts have been added that would increase contact stresses; [70,71] condylar lift-off [72] is expected to be essentially unaffected in varus or valgus and may be improved compared to some recent designs [73,74] (i.e., increased spherical congruity and without the intercondylar post inhibition) [71,75]. Most importantly, wear-related and "spin-out" failures, although unusual (1-2 %) in the LCS [8,35,36] have been essentially eliminated in the current improved design.

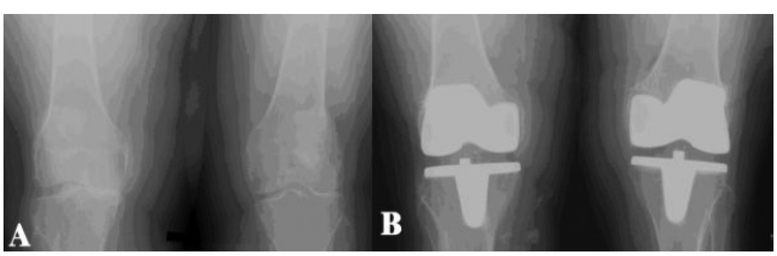


FIG. 7—*Anteroposterior radiographs shows: (A) pre-op; (B) bilaterally at 14 years and 13 years post-op of the patient described in Case #2.*

A TiN ceramic coating has been applied to reduce the allergy potential to Co-Cr metals, while maintaining excellent wear resistance, comparable to simulator evaluation [51] and long-term clinical studies of cementless hip [76] and ankle replacements [77] using the same material.

The current literature which reflects the discussion on resurfacing or not resurfacing the patella has been studied in multiple designs [78–81]. It appears that anatomically shaped or "patella friendly" trochlear designs allow for smooth articulation of the unresurfaced patella with few complications or the need for revisions. The LCS type femoral flange has been in use for over 30 years and has been viewed as "patella friendly" by multiple authors [28,43,44]. In fact, because of long-term rotating patella component failures [82], although generally less than 1 %, some surgeons have exclusively unresurfaced the patella with equally good results in the long term [44,81] .

The current study reflects a common-ground with both schools of thought. There were 132 (51.0 %) unresurfaced patellae and 127 (49.0 %) resurfaced patellae using the rotating-patellar component followed for 2–18 years (mean: 7.6 years). No failures or complaints of severe anterior knee pain were seen in either group; thus demonstrating no patient preference of patella resurfacing or unresurfacing in this series of knee replacements.

The rate of device-related complications in this clinical series is low. One infection occurred late (3.3 years) in an immuno-compromised rheumatoid patient and the other major complications included tibial component loosening, ligamentous instability, and quadriceps rupture in the early post-operative period (0.1 to 1.5 years). No other late failures were encountered.

A potential drawback in this study is the relatively small number of knee replacements followed for more than 15 years (32 of 310 patients), although 102 knee replacements were followed for 10 years or more. This drawback is overshadowed by the relatively minor design changes incorporated into the B-P device design from the LCS design, which do not allow contact with mechanical stops (except in an emergency or traumatic rotary subluxation of the tibia) or introduce intercondylar posts, which necessitate increasing contact stresses and surface incongruity [70,71,73,83]. It is envisioned that these subtle design changes may increase bearing longevity beyond 30 years, while eliminating or, at least, substantially reducing rotating-platform "spin-outs."

In summary, the current study of cementless B-P rotating-platform knee replacements has identified and apparently reduced or solved two of the long-term problems of the clinically successful LCS rotating platform; namely, wear and tibial bearing "spin-out.. Although these two problems represent only a 1-2 % complication rate [8,35], it is certainly worthwhile to address the design features that appear to be responsible for them. The improvement in bearing surface congruity, sterilization by ethylene oxide, and the addition of an emergency stop-pin to prevent rotary subluxation of the tibial bearing appear to have eliminated these problems without adding additional complexity or degrading the bearing surfaces. The 18 year survivorship of the cementless B-P knee replacement of 99.4 % compares most favorably to the 98.3 % 18 year survivorship of the cementless LCS device [8] while apparently reducing or solving two of its small but formidable problems. Future studies of extremely high-activity-level patients in an evidence-based approach [84] may be needed to discover the full potential of these design improvements.

Acknowledgments

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References

[1] Ducheyne, P., Kagan, A., and Lacey, J. A., "Failure of Total Knee Arthroplasty Due to Loosening and Deformation of the Tibial Component," *J. Bone Joint Surg. Am.*, Vol. 60, 1978, pp. 384–391.

[2] Engh, G. A., "Failure of the Polyethylene Bearing Surface of a Total Knee Replacement Within Four Years: A Case Report," *J. Bone Joint Surg. Am.*, Vol. 70, 1988, pp. 1093–1096.

[3] Goodfellow, J. W., O'Connor, J., and Murray, D.W., "The Oxford Meniscal Unicompartmental Knee," *J. Knee Surg.*, Vol. 15, 2002, p. 240.

[4] Gunston, F. H. and MacKenzie, R. I., "Complications of Polycentric Knee Arthroplasty," *Clin. Orthop. Relat. Res.*, Vol. 120, 1976, pp. 7–11.

[5] Riley, D. and Woodyard, J. E., "Long-Term Results of Geomedic Total Knee Replacement," *J. Bone Joint Surg. Br.*, Vol. 67, 1985, pp. 548–550.

[6] Robinson, R. P., "The Early Innovators of Today's Resurfacing Condylar Knees," *J. Arthroplasty*, Vol. 20(1), 2005, pp. 2–26.

[7] Shetty, A. A., Tindall, A., Ting, P., and Heaty, F. W., "The Evolution of Total Knee Arthroplasty. Part II: The Hinged Knee Replacement and the Semi-Constrained Knee Replacement," *Curr. Pract. Orthop. Surg.*, Vol. 17, 2003, pp. 403–407.

[8] Buechel, F. F., Sr., Buechel, F. F., Jr., Pappas, M. J., and D'Alessio, J., "Twenty-Year Evaluation of Meniscal Bearing and Rotating Platform Knee Replacements," *Clin. Orthop. Relat. Res.*, Vol. 388, 2001, pp. 41–50.

[9] Buechel, F. F. and Pappas, M. J., "New Jersey Low Contact Stress Knee Replacement System: Ten-Year Evaluation of Meniscal Bearings," *Orthop. Clin. North Am.*, Vol. 20, 1989, p. 147.

[10] Cohen, M., Buechel, F. F., and Pappas, M. J., "Meniscal-Bearing Unicompartmental Knee Arthroplasty: An 11-Year Clinical Study," *Orthop. Rev.*, Vol. 20, 1991, p. 443.

[11] Deutschman, A.D., Michels, W.J., and Wilson, C.E., *Machine Design: Theory and Practice*, Macmillan, New York, 1975, pp. 236–247.

[12] Fisher, J., McEwen, H., Tipper, J., Jennings, L., Farrar, R., Stone, M., and Ingham, E., "Wear-simulation Analysis of Rotating-Platform Mobile-Bearing Knees," *Orthopedics*, Vol. 29(9), 2006, pp. 36–41.

[13] Goodfellow, J. W. and O'Connor, J. J., "The Oxford Knee: A Clinical Trial," *J. Bone Joint Surg. Br.*, Vol. 64, 1982, pp. 620.

[14] Insall, J. N., "Adventures in Mobile-Bearing Knee Design: A Mid-Life Crisis," *Orthopedics*, Vol. 21, 1998, pp. 1021–1023.

[15] Keblish, P. A. and Briard, J. L., "Mobile-Bearing Unicompartmental Knee Arthroplasty: A 2-Center Study With an 11-Year (Mean) Follow-Up," *J. Arthroplasty*, Vol. 19(2), 2004, pp. 87–94.

[16] Pappas, M. J., Makris, G., and Buechel, F. F., "Biomaterials for Hard Tissue Applications," *Biomaterials and Clinical Applications: Evaluation of Contact Stresses in Metal-Plastic Total Knee Replacements*, P. G. Pizzoferrato, A. Marchetti, A. Ravaglioli, and A. J. C. Lee, Eds., Elsevier, Amsterdam, 1987, pp. 259–264.

[17] Hamelynck, K. J., "The History of Mobile-Bearing Total Knee Replacement Systems," *Orthopedics*, Vol. 29(9), 2006, pp. S7–S12.

[18] Hamelynck, K. J., "The Total Knee Prosthesis: Indications and Complications," *Ned Tijdschr Geneeskd*, Vol. 142, 1989, pp. 2030–2034.

[19] Hamelynck, K. J., "Bi-Cruciate Ligament Retention," *LCS Mobile Bearing Knee Arthroplasty: 25 Years of Worldwide Experience*, K. J. Hamelynck and J. B. Stiehl, Eds., Springer, New York, 2002, pp. 96–100.

[20] Kim, Y.-H. and Kim, J.-S., "Comparison of Anterior-Posterior-Glide and Rotating Platform LCS Mobile Bearing TKA's," *J. Bone Joint Surg. Am.*, Vol. 86, 2004, pp. 1239–1247.

[21] Miehlke, W., Drobney, T., and Munzinger, U., "Fat-Pad Impingement After Total Knee Arthroplasty With the LCS A/P-Glide System," *J. Bone Joint Surg. Br.*, Vol. 86, 2004, pp. 396.

[22] Kim, Y.-H., Kim, J.-S., and Choi, Y., "Osteolysis After Unidirectional and Multidirectional Mobile-Bearing Total Knee Arthroplasty in Young Patients," *J. Arthroplasty*, Vol. 24, 2009, pp. 586–593.

[23] Buechel, F. F., "The LCS Story," *LCS Mobile Bearing Knee Arthroplasty: 25 Years of Worldwide Experience*, K. J. Hamelynck and J. B. Stiehl, Eds., Springer, New York, 2002, p. 19–25.

[24] Ali, M. S. and Mangaleshkar, S. R., "Uncemented Rotating-Platform Total Knee Arthroplasty: A 4-Yearr to 12-Year Follow-Up," *J. Arthroplasty*, Vol. 21, 2006, pp. 80–84.

[25] Buechel, F. F., "Cemented and Cementless Revision Arthroplasty Using Rotating Platform Total Knee Implants: A 12-Year Experience," *Orthop. Rev.*, *Suppl*, 1990, pp. 71–75.

[26] Callaghan, J. J., Wells, C. W., Liu, S. S., Goetz, D. D., and Johnston R. C., "Cemented Rotating Platform Total Knee Replacement: A Concise Follow-Up, at a Minimum of Twenty Years, of a Previous Report," *J. Bone Joint Surg. Am.*, Vol. 92A, 2010, pp. 1635–1639.

[27] Hamelynck, K. J., Stiehl, J. B., and Woorhorst, P. E., "LCS Worldwide Multicenter Outcome Study," *LCS Mobile Bearing Knee Arthroplasty: 25 Years Of Worldwide Experience*, K. J., Hamelynck and J. B. Stiehl, Eds., Springer, New York, 2002, pp. 212–224.

[28] Sorrells, R. B., "Primary Knee Arthroplasty Long-Term Outcomes: The Rotating Platform Mobile Bearing TKA," *Orthopedics*, Vol. 19, 1996, pp. 793–796.

[29] Sorrells, R. B., Murphy, J. A., Sheridan, K. C., and Wasielewski, R. C., "The Effect of Varus and Valgus Deformity on Results of Cementless Mobile Bearing TKA," *The Knee*, Vol. 14, 2007, pp. 284–288.

[30] Sorrells, R. B., Stiehl, J. B., and Voorhorst, P. E., "Midterm Results of Mobile-Bearing Total Knee Arthroplasty in Patients Younger Than 65 Years," *Clin. Orthop. Relat. Res.*, Vol. 390, 2001, pp. 182–189.

[31] Collier, J. P., Sperling, D. K., Curier, J. H., Sutula, L. C., Saum, K. A., and Mayor, M. B. "Impact of Gamma Sterilization on Clinical Performance of Polyethylene in the Knee," *J. Arthroplasty*, Vol. 11, 1996, pp. 377–389.

[32] Collier, J. P., Williams, I. R., and Mayor, M. B., "Retrieval Analysis of Mobile Bearing Prosthetic Knee Devices," *LCS Mobile Bearing Knee Arthroplasty: 25 Years of Worldwide Experience*, K. J. Hamelynck and J. B. Stiehl, Eds., Springer, New York, 2002, pp. 74-20.

[33] Williams, I. R., Mayor, M. B., and Collier, J. P., "Impact of Sterilization Method on Wear in Knee Arthroplasty," *Clin. Orthop. Relat. Res.*, Vol. 358, 1998, pp. 170–180.

[34] Ries, M. D., Weaver, K., Rose, R. M., Gunther, J., Sauer, W., and Beals, N., "Fatigue Strength of Polyethylene After Sterilization by Gamma Irradiation or Ethylene Oxide," *Clin. Orthop. Relat. Res.*, Vol. 333, 1993, pp. 87–95.

[35] Buechel, F. F., Sorrells, B., and Pappas, M. J., "New Jersey Rotating Platform Total Knee Replacement: Clinical, Radiographic, Statistical, and Survivorship Analyses of 346 Cases Performed by 16 Surgeons," Food and Drug Administration Panel Presentation, Nov. 22, 1991, Gaithersburg, MD.

[36] Chiavetta, M. D., Fehring, T. K., Odum, S., Griffin, W., and Mason, J. B. "Importance of a Balanced-Gap Technique in Rotating Platform Knees," *Orthopedics*, Vol. 29(9), 2006, pp. 45–48.

[37] Fehring, T. K., "Ligamentous Balancing in Rotating-Platform Knees." *Orthopedics*, Vol. 29(9), 2006, pp. S56–S59.

[38] Ridgeway, S. and Moskal, J. T. "Early Instability With Mobile-Bearing Total Knee Arthroplasty: A Series of 25 Cases," *J. Arthroplasty*, Vol. 19, 2004, pp. 686–693.

[39] Buechel, F. F., Rosa, R. A., and Pappas, M. J., "A Metal-Backed, Rotating-Bearing Patellar Prosthesis to Lower Contact Stress: An 11-Year Clinical Study," *Clin. Orthop. Relat. Res.*, Vol. 248, 1989, pp. 34–49.

[40] Sorrells, R. B., Voorhorst, P. E., Murphy, J. A., Bauschka, M. P. and Greenwald, A. S., "Uncemented Rotating-Platform Total Knee Replacement: A Five to Twelve-Year Follow-Up Study," *J. Bone Jt. Surg., Am. Vol.*, Vol. 86A, No. 10, 2004, 2156–2162.

[41] Buechel, F. F., "Recurrent LCS Rotating Platform Dislocation in Revision Total Knee Replacement: Mechanism, Management, and Report of Two Cases," *Orthopedics*, Vol. 26, 2003, pp. 647–649.

[42] McEwen, H. M. J., McNulty, D. E., Auger, D., Farbar, R., Liao, Y. S., Stone, M. H., and Fisher, J., "Wear-Analysis of Mobile Bearing Knee," *LCS Mobile Bearing Knee Arthroplasty*, K. J. Hamelynck and J. B. Stiehl, Eds, Springer, New York, 2002, Chapter 8, pp. 67–73.

[43] Keblish, P. A. and Greenwald, A. S., "Patellar Resurfacing or Retention in Total Knee Arthroplasty: A Prospective Study of Patients with Bilateral Replacements," *J. Bone Joint Surg. Br.*, Vol. 76, 1994, pp. 930–937.

[44] Mockford, B. J. and Beverland, D. E., "Secondary Resurfacing of the Patella in Mobile Bearing Total Knee Arthroplasty," *J. Arthroplasty*, Vol. 20, 2005, pp. 898–902.

[45] Pappas, M. J. and Buechel, F. F., "On the Use of a Constant Radius Femoral Component in Meniscal Bearing Knee Replacement," *J. Orthop. Rheumatol.*, Vol. 7, 1994, pp. 27–29.

[46] Greenwald, A. S., "Stability Characteristics of the Tibial-Femoral and Patellar-Femoral Articulations," *LCS Mobile Bearing Knee Arthroplasty: 25 Years of Worldwide Experience*, K. J. Hamelynck and J. B. Stiehl, Eds., Springer, New York, 2002, pp. 53–56.

[47] Chin, K. R., Dalury, D. F., Zurakowski, D., and Scott, R. D., "Intraoperative Measurements of Male and Female Distal Femurs During Primary Total Knee Arthroplasty," *J. Knee Surg.*, Vol. 15, 2002, pp. 213–217.

[48] Csintalan, R. P., Schulz, M. M., Woo, J., McMahon, P. J., and Lee, T. Q., "Gender Differences in Patellofemoral Joint Biomechanics," *Clin. Orthop. Relat. Res.*, Vol. 402, 2002, pp. 260–269.

[49] Wei-Hsiu, H., Fisk, J. A., Yamamoto, Y., Debski, R. E., and Woo, S. L.-Y. "Differences in Torsional Joint Stiffness of the Knee Between Genders," *Am. J. Sports Med.*, Vol. 34, 2002, pp. 765–770.

[50] Bryant, D. M., Willits, K., and Hanson, B. P., "Principles of Designing a Cohort Study in Orthopaedics," *J. Bone Joint Surg. Am.*, Vol. 91(3), 2009, pp. 10–14.

[51] Pappas, M. J., Makris, G., and Buechel, F. F., "Titanium Nitride Ceramic Film Against Polyethylene: A 48 Million Cycle Test," *Clin. Orthop. Relat. Res.*, Vol. 317, 1995, p. 64.
[52] Buechel, F. F., "A Simplified Evaluation System for Rating of Knee Function," *Orthop. Rev.*, Vol. 11, 1982, pp. 97–101.
[53] Kaplan, E. and Meier, P., "Non-Parametric Estimation from Incomplete Observations," *J. Am. Stat. Assoc.*, Vol. 53, 1958, pp. 457–481.
[54] Dorey, F., Nasser, S., and Amstutz, H., "Current Concepts Review: The Need for Confidence Intervals in the Presentation of Orthopaedic Data," *J. Bone Joint Surg. Am.*, Vol. 75, 1993, pp. 1844–1852.
[55] Faris, P. M., Keating, E. M., Farris, A., Meding, J. B., and Ritter, M. A., "Hybrid Total Knee Arthroplasty: 13-Year Survivorship of AGC Total Knee Systems With Average 7 Years Follow-Up," *Clin. Orthop. Relat. Res.*, Vol. 466, 2008, pp. 1204–1209.
[56] Ranawat, C. S., Flynn, W. F., Sadder, S., Hansraj, K. K., and Maynard, M. J., "Long Term Results of the Total Condylar Knee Arthroplasty: A Fifteen Year Survivorship Study," *Clin. Orthop. Relat. Res.*, Vol. 286, 1993, p. 94.
[57] Ritter, M. A., Campbell, E., Faris, P. M., and Keating, E. M., "Long-Term Survival Analysis of a Posterior Cruciate Retaining Total Condylar Total Knee Arthroplasty," *J. Arthroplasty*, Vol. 4, 1998, p. 293.
[58] Buechel, F. F., Sr., "Long-Term Follow-Up After Mobile Bearing Total Knee Replacement," *Clin. Orthop. Relat. Res.*, Vol. 404, 2002, pp. 40–50.
[59] Buechel, F. F., Sr., Buechel, F. F., Jr., Pappas, M. J., and D'Alessio, J. "Twenty-Year Evaluation of the New Jersey LCS Rotating Platform Knee Replacement," *J. Knee Surg.*, Vol. 15, 2002, pp. 84–89.
[60] Dennis, D. A., Carothers, J., and Kim, R. H., "Primary and Total Knee Arthroplasty: The Impact of Technique—What is the Evidence for Mobile-Bearing Total Knee Arthroplasty?" *J. Bone Joint Surg. Am.*, Vol. 91(5), 2009, p. 61.
[61] Huang, C. H., Ma, H. M., Lee, Y. M., and Ho, F. Y., "Long-Term Results of Low Contact Stress Mobile-Bearing Total Knee Replacements," *Clin. Orthop. Relat. Res.*, Vol. 416, 2003, pp. 265–270.
[62] Gioe, T. J., Sinner, P., Mehle, S., Ma, W., and Killeen, K. K., "Excellent Survival of All- Polyethylene Tibial Components in a Community Joint Registry," *Clin. Orthop. Rel. Res.*, Vol. 464, 2007, pp. 88–92.
[63] Gioe, T. J., Stroemer, E. S., and Santos, E. R., "All-Polyethylene and Metal-Backed Tibias Have Similar Outcomes at 10 Years: A Randomized Level II Evidence Study," *Clin. Orthop. Relat. Res.*, Vol. 455, 2007, pp. 212–218.
[64] Engh, G. A., Lounici, S., Rao, A. R., and Collier, M. B., "in vivo Deterioration of Tibial Baseplate Locking Mechanisms in Contemporary Modular Total Knee Components," *J. Bone Joint Surg. Am.*, Vol. 83, 2001, pp. 1660–1665.
[65] Bert, J. M., "Dislocation/Subluxation of Meniscal Bearing Elements After New Jersey Low Contact Stress Total Knee Arthroplasty," *Clin. Orthop. Relat. Res.*, Vol. 254, 1990, pp. 211–215.
[66] Buechel, F. F., Pappas, M. J., and Makris, G., "Evaluation of Contact Stress in Metal-Backed Patellar Replacements: A Predictor of Survivorship," *Clin. Orthop. Relat. Res.*, Vol. 273, 1991, pp. 190–197.
[67] Atwood, S. A., Currier, J. H., Mayor, M. B., Collier, J. P., Van Citters, D. W., and Kennedy, F. E., "Clinical Wear Measurements on Low Conteact Stress Rotating Platform Knee Bearings," *J. Arthroplasty*, Vol. 23, 2008, pp. 431–440.
[68] Buechel, F. F., "Mobile Bearing Exchange in Revision TKA". Video Vignette," *18th Annual Current Concepts in Joint Replacement*, A. Seth Greenwald, D. Phil (Oxon), Director, Eds., Orlando, FL, Dec 14, 2001, Current Concepts in Joint Replacement, Cleveland, OH.
[69] Buechel, F. F., Pappas, M. J., and Greenwald, E. S., "Use of Survivorship and Contact Stress Analyses to Predict the Long Term Efficacy of New Generation Joint Replacement Designs: A Model for FDA Device Evaluation," *Orthop Rev.*, Vol. 20, 1991, pp. 50–55.
[70] Morra, E. A. and Greenwald, A. S., "Polymer Insert Stress in Total Knee Replacement Designs During High-Flexion Activities: A Finite Element Study," *J. Bone Joint Surg. Am.*, Vol. 87-A(2), 2005, pp. 120–124.
[71] Pappas, M. J. and Briard, J. L., "Evaluation of Posterior Stabilized Knee Replacement Systems," Biomedical Engineering Technical Report, 2006, Biomedical Engineering Corp., South Orange, NJ.

[72] Dennis, D. A., "Trends in Total Knee Arthroplasty," *Orthopedics*, Vol. 29(9), 2006, pp. S13–S15.
[73] Chiu, Y.-S., Chen, W.-M., Huang, C.-K., Chiang, C.-C., and Chen, T.-H., "Fracture of the Polyethylene Tibial Post in a NexGen Posterior-Stabilized Knee Prosthesis," *J. Arthroplasty*, Vol. 19, 2004, pp. 1045–1049.
[74] Gupta, S. K., Ranawat, A. S., Shah, V., Zikria, B. A., Zikria, J. F., and Ranawat, C. S., "The PFC Sigma RP-F TKA Designed for Improved Performance: A Matched-Pair Study," *Orthopedics*, Vol. 29(9), 2006, pp. S49–S52.
[75] Brockenbrough, G., "Surgeons at Odds Over the Benefits, Necessity of High-Flexion Knees," *Orthop. Today*, Vol. 27, 2007, p. 20.
[76] Buechel, F. F., Sr., Buechel, F. F., Jr., Helbig, T. E., D'Alessio, J., and Pappas, M. J., "Two to 12 Year Evaluation of Cementless Buechel-Pappas Total Hip Arthroplasty," *J. Arthroplasty*, Vol. 19, 2004, pp. 1017–1027.
[77] Buechel, F. F., Sr., Buechel, F. F., Jr., and Pappas, M. J., "Twenty-Year Evaluation of Cementless Mobile-Bearing Total Ankle Replacements," *Clin. Orthop. Relat. Res.*, Vol. 424, 2004, pp. 19–26.
[78] Barrack, R. L., Bertot, A. J., Wolfe, M. W., Waldman, D. A., Milicic, M., and Myers, L., "Patellar Resurfacing in Total Knee Arthroplasty: A Prospective, Randomized, Double-Blind Study With 5 to 7 Years of Follow-Up," *J. Bone Joint Surg. Am.*, Vol. 83, 2001, pp. 1376–1381.
[79] Barrack, R. L. and Wolfe, M. W., "Patellar Resurfacing in Total Knee Arthroplasty," *Am. Acad. Orthop. Surg.*, Vol. 8, 2000, pp. 75–82.
[80] Ewald, F. C., Wright, R. J., Poss, P., Thomas, W. H., Mason, M. D., and Sledge, C. B., "Kinematic Total Knee Arthroplasty: A 10 to 14 Year Prospective Follow-Up Review," *J. Arthroplasty*, Vol. 14, 1999, pp. 473–480.
[81] Whiteside, L. A., "Patella Resurfacing No Longer Considered Routine in TKA," *Orthopedics*, Vol. 29, 2006. pp. 833–834.
[82] Huang, C.-H., Liau, J.-J., Ho, F.-Y., Lin, C.-Y., Young, T.-H., and Cheng, C.-K., "Polyethylene Failure of the Patellar Component in NJ Low Contact Stress Total Knee Arthroplasty," *J. Arthroplasty*, Vol. 20, 2005, pp. 202–208.
[83] Maniar, R., "Rationale for the Posterior-Stabilized Rotating-Platform Knee," *Orthopedics*, Vol. 29(9), 2006, pp. S23–S27.
[84] Ahn, H., Bhandari, M., and Schemitsch, E. H., "An Evidence-Based Approach to the Adoption of New Technology," *J. Bone Joint Surg. Am.*, Vol. 91(3), 2009, pp. 95–98.