

SECTION VI - SUMMARY OF TESTING

This section includes a review of published reports of testing done on various types of mobile bearing knees (mbks). A literature search revealed 47 articles. This group can be subdivided into subject-matter categories that include "kinematics", "wear testing", and "biomechanics". Note that there are no biocompatibility or toxicity issues that are specific to mbks. The same orthopedic materials used for fixed bearing knees are used for mbks, and these materials (primarily titanium alloys, cobalt-chromium alloys, and polyethylene) have a long history of safe and effective use in knee arthroplasty. Therefore, no discussion of material biocompatibility or toxicity will be presented here.

A summary of published test findings and an abstract of each article are presented in this section. A comprehensive bibliography may be found in Appendix 6, and copies of each referenced article are included in Appendix 7.

Summary of Published Test Findings:

Kinematics

A large amount of data has been published that characterizes the kinematics of mbks and compares them to either normal (unimplanted) knees or to fixed bearing knees. Several key facts have emerged:

- The mobile bearing continues to retain mobility for a considerable time post-implantation. This has been demonstrated for the Oxford Unicompartmental knee¹⁴ (Biomet, Bridgend, UK), the G2S knee³³ (F.I.I., Saint-Etienne, France), the LCS (J&J DePuy, Warsaw, IN)⁴², and several other mbks⁶⁷. There are reports that bearings sometimes lose their mobility after implantation¹⁶⁴. Nevertheless, a compelling case has been made that mbks satisfy the requirements for movement within the joint at least as well as fixed bearing knees.
- Intact ligaments, and proper tensioning of soft tissues is critical to stability, particularly with the Oxford Unicompartmental knee⁵⁶.
- In many respects, the kinematics of most mbks are similar to those of fixed bearing knees^{41,42}. This includes some features in which kinematics diverge from those seen in the normal knee.
 - Numerous reports document that A/P motion of mbks does not replicate that of the normal knee, and generally is similar to that of fixed bearing knees. Although some testing (LCS) revealed that the A/P motion was not much different from the normal knee^{43,124}, other research reveals an anterior position of the tibia relative to normal, reduced or no femoral rollback, and paradoxical anterior sliding at approximately 60 degrees flexion^{14,67,124,151,164,165,166,171,181}. This was observed in a number of knees including the Oxford Unicompartmental, the LCS, Interax ISA (Stryker Howmedica Osteonics, Allendale, NJ), and the MBK (Zimmer, Warsaw,

- IN). In general, the phenomena are observed in posterior cruciate retaining (PCR) or in posterior cruciate sacrificing (PCS) designs, although posterior stabilized devices may provide more normal mobility. These deviations from normal kinematics are also common in fixed bearing knees, and are generally ascribed to the loss or lack of function of the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) function.
- Weight-bearing range of motion which is lower than the normal knee, but similar to fixed bearing has been reported (LCS^{164,165}). This was true with both posterior cruciate retention (PCR) or posterior cruciate sacrifice (PCS), and seems to be related to the loss of normal rollback.
 - Reports of rotation in mbks are variable. Investigators have reported that the TRAC PS⁴⁸ (Biomet, Warsaw, IN), the Oxford Unicompartmental⁵⁶, and the Minns¹¹⁴ (Corin, Gloucestershire, UK) knee have rotation similar to normal knees. However, other reports claim that none of the mbks tested replicated normal internal-external rotation, with screw-home movement rarely normal (LCS^{41,163,181}).
 - Mobile bearing knees have been reported to have normal varus-valgus angulation and stability (TRAC PS⁴³ and Oxford Unicompartmental⁵⁶).
 - Overall patellofemoral kinematics are similar to normal knees (Oxford Unicompartmental¹³⁴ and LCS¹⁶⁷).
 - Medial and lateral condylar lift-off, similar to fixed bearing knees, has been observed (LCS¹⁶³). However, posterior stabilized LCS knees had less condylar lift-off and medial translation than the PCS group¹⁶⁸.

Wear

Published data on wear rates in various mbks reveal that, as expected, increasing the contact area between the femoral and polyethylene component generally results in improved wear performance.

- Studies of mean penetration rate produced values for mbks that were only slightly greater than for Charnley hips, and a mere 1 to 2 percent of that seen in a fixed bearing knee (Oxford Unicompartmental^{3,5,149}, Accord⁶⁴ and Rotaglide¹⁷⁷ knees).
- Laboratory testing to demonstrate mean wear rate found greatly reduced wear compared to fixed bearing knees or hips, despite wear at two bearing surfaces (Oxford Unicompartmental knee³, Minns knee¹³⁶, Rotaglide knee, Corin, Gloucestershire, UK¹⁴⁹, LCS rotating platform knee¹⁰⁸). Pin-on-plate testing also demonstrated that a greater surface area reduces wear rate, with no disadvantage related to particle size or type¹⁴⁹.

- Unidirectional mbk designs (tracks or rotating only) produce less wear than multidirectional designs⁷⁷.
- Retrieved polyethylene components from failed uncemented mbks may show high rates of wear and scratching of the tibial plate due to metal beads or other particulate matter embedded in the inferior aspect of the polyethylene (LCS knee^{70,78}).

Biomechanics

- Frictional torque, measured or modeled by finite element analysis, is sufficiently high to explain the lack of bearing mobility at the tibial plate/polyethylene interface (LCS)^{1,2,128}.
- In general, mbks with closely conforming surfaces have lower contact stress, which could result in reduced wear^{40,111,174}. Mean and peak contact stress is lower despite varus tilt (LCS)¹⁰⁶. The effect of malrotation on contact stress is mitigated in mbk designs^{40,105,116}.
- Knee stability is better in mbks with varying types of mobility. The mobile bearing preserved rotational stability and varus-valgus stability, relative to the normal knee¹⁰⁷.

Abstracts of Included Articles:

Kinematics

A radiographic study of the kinematics of implanted Oxford Unicompartmental knees (Biomet, Bridgend, UK) was conducted by Bradley, et al.¹⁴ in 16 patients (20 knees) that had been implanted for an average of 18 months. Most replacements were of the medial compartment, but no significant differences were seen in the few lateral-compartment replacements. Backwards movement of the bearings on the tibia were significantly less than previously observed in cadaver specimens (average 4.4 mm in the medial compartment, 6.0 in the lateral compartment from full extension to 90 degrees flexion). Absence of the ACL in patients with medial compartment arthroplasty seemed to allow anomalous forward motion of the bearing on the tibial during flexion. Overall, the authors concluded that movement of the bearing continues for up to five years after surgery, both at the meniscotibial and meniscofemoral articulation, and that the movements are in the same direction as those observed in cadaveric knees and at the time of implantation. During flexion-extension and during rotation, the movements take place within the central half of the tibial component.

Castel, et al.³³ evaluated the kinematics of 15 patients implanted for one year or more with a “G2S” mobile bearing knee (F.I.I., Saint-Etienne, France). The bearing was a platform type that allowed movement in translation and rotation. Weight bearing A/P and lateral radiographs were taken in extension and flexion, with femoral internal and external rotation. In addition, lateral radiographs were taken in neutral rotation and in

A/P displacement with a 25 kg strength Telos, and A/P radiographs were taken in varus and valgus with Telos. The study confirmed that mobility of TKA tibial implants persists after implantation in all movements tested.

D’Lima, et al.⁴¹ measured knee kinematics during closed chain knee extension in a controlled cadaver model. They compared the natural knee versus (1) a PCR fixed bearing (2) PCR rotating bearing (3) PCS fixed bearing (4) PCS rotating-bearing (all designs of J&J DePuy, Warsaw, IN). All of the replacement knees significantly changed the kinematic patterns of the unimplanted normal knee. The normal knee rotates internally, and then reverses to external rotation at approximately 30 degrees when extending from 90 degrees flexion. None of the implanted knees retained the normal pattern, although the PCS rotating bearing came closest. Overall, rotating bearing knees did not significantly change knee kinematics when compared with fixed bearings. PCL treatment did produce significant differences. During rollback, cruciate retaining designs stayed more anterior and had more rollback than the substituting designs. They also exhibited greater tibiofemoral valgus angulation with flexion than cruciate substituting designs.

DeLima, et al.⁴² analyzed knee kinematics of mobile bearing designs in a closed chain dynamic knee extension model in PCR designs with high and low tibiofemoral conformity, and in PCS designs with and without rotational constraint (all knees by J&J DePuy, Warsaw, IN). Measurement of tibiofemoral axial rotation and the relative rotation between the insert and tibial platform in these rotating platform mobile bearing designs was conducted. The results indicate that mobile bearing inserts rotate with the femur. There were no significant differences in femoral rollback, tibiofemoral axial rotation, and tibiofemoral varus-valgus angulation between the standard and high-conforming or rotationally constrained designs, suggesting that increased tibiofemoral conformity does not affect overall kinematics of the knee in these designs, in this *in vitro* test system.

Draganich and Pottenger⁴³ performed three-dimensional laxity testing in 17 patients that had been implanted with the TRAC PS knee (Biomet, Warsaw, IN). The average postoperative time to testing was 17 months. Eighteen healthy control patients were tested. The Genucom three dimensional knee laxity testing system was used. In general, A/P translation, internal-external rotation, and varus-valgus rotation were similar for the implanted and the control knees. The A/P translational laxity of the TRAC PS patients was less than the controls at 30 degrees of flexion, which was expected because of the enhanced anterior and posterior stabilization built into the TRAC PS. The authors concluded that normal ligament balancing and normal internal-external rotational laxity were achieved with the prosthesis.

Goodfellow and O’Connor⁵⁴ present a description of the anatomical mechanisms controlling and limiting movement and serving to transmit load between the femur and the tibia. They deduce several principles that might guide the design of knee prostheses, and note that several contemporary designs (as of 1978) may neglect some of these principles. The principles are: the prosthetic components should be shaped to allow

distracting, sliding, and rolling movements between the bones; the components should apply only compressive stress to the juxta-articular bone; all surviving soft tissues should be kept and restored to their natural tensions; contact areas between prosthetic surfaces should be large enough to maintain the pressure under load at a level which the prosthetic materials can withstand. They propose an experimental prosthesis in which the menisci are replaced by washers, spherically concave adjacent to a spherical femoral surface, and flat adjacent to the flat tibial component. The “meniscus” is unconstrained, and free to move on the tibial surface. They demonstrate compliance with each of the defined principles with this model, and thus define the basis for the meniscal bearing knee.

Goodfellow and O'Connor⁵⁶ describe early kinematic testing and clinical results of their meniscal bearing knee. The kinematic testing was performed in cadaveric knees mounted in a specially designed rig. They compared pre- and post implant cadaveric mobility. They were able to reproduce the cadaveric range of tibial rotation after implantation of the meniscal prosthesis, showing that the range of rotation increased with increasing flexion angle up to 90 degrees of flexion; maximum range of rotation increased with increased applied torque and diminished as the external load balanced by the quadriceps increased. Varus-valgus stability was studied, and similar results obtained. The authors believe that stability depends less on the reproduction of the precise shapes of natural articular surfaces than upon the accurate tensioning of the soft tissues. A/P translation was reproduced by the meniscal prosthesis. Active rotation, induced by applying force to the tibia, caused the bearings to slide reciprocally, one forward and one backward. The proportion of their respective movements varied from position to position, demonstrating that there is no fixed axis of rotation. Measurement of quadriceps tension through the range of motion showed comparable results for cadaveric and implanted knees, suggesting that a prosthesis which allows the retention of all the natural ligaments and allows unconstrained movement of the articular surfaces will reproduce the natural leverage of the muscles and therefore natural muscle power. Biomechanical measurements demonstrated the advantages of using rigid components to distribute the applied compressive load equally over the bone-implant surface. They believe the separated components avoid the development of tensile stresses under one side of the joint when forces are transmitted through the other side (the see-saw effect of varus or valgus load).

Hartford, et al.⁶⁷ evaluated the movement of the meniscal bearings and femoral rollback in 81 Low Contact Stress meniscal bearing knees (LCS, J&J DePuy, Warsaw, IN). Average time post-surgery was six years. The prostheses were assessed on fluoroscopically centered lateral radiographs with the unloaded knee in full extension and full flexion. In some cases, medial and lateral bearings moved synchronously in the same direction. In some cases one bearing was stationary (11 percent), and in others the bearings moved reciprocally (12 percent). When both bearings moved synchronously, 39 (48 percent) knees moved anteriorly as they progressed from terminal extension to terminal flexion. Sixty-three (78 percent) knees demonstrated no femoral rollback as they were flexed. Knees with anterior sliding had a significantly lower average range of flexion and a lower average Knee Society score than did knees demonstrating femoral

rollback. The authors believe that lack of rollback indicates a functional insufficiency of the PCL.

Heim, et al.⁶⁹ applied biaxial loading to nine mobile-bearing designs to assess the intrinsic performance characteristics. Anterior, posterior, medial, lateral and rotational constraints were determined for each total knee design and evaluated to classify the prostheses into three distinct groups. All devices tested showed unconstrained motion in the rotational direction through a total of 15 degrees of internal/external rotation, which satisfies the requirements of normal gait. The devices demonstrated semi-constrained or constrained mobility in the medio-lateral direction, which is a characteristic of both mobile and fixed bearing designs and does not adversely affect clinical performance. Analysis of A/P mobility showed a wide range of constraint, with unconstrained designs prevailing. The authors caution that the lower levels of constraint require careful soft tissue balancing to achieve stability.

Lewandowski, et al.⁹⁹ evaluated the Low Contact Stress (LCS) PCL-retaining meniscal bearing knee and the LCS PCL-sacrificing rotating platform design (J&J DePuy, Warsaw, IN), and measured knee kinematics before and after implantation in cadavers. For the PCL-retaining meniscal bearing, they found: anterior translations were significantly greater, the extension gap was 2 mm greater, and quadriceps force needed to achieve full extension was 30 percent greater than in the intact knee. For the PCL-sacrificing rotating platform knee they found: anterior translation was constrained such that nearly normal anterior knee stability was retained, the extension gap was increased by 4 mm and the quadriceps force needed to achieve full extension was 50 percent greater than in the intact knee. Increasing the thickness of tibial components widens the flexion/extension gap but compromises quadriceps efficiency, particularly in the absence of PCL function.

Minns¹¹⁴ analyzed both axial rotation of the femoral component and torsional forces at different angles of knee flexion for the Minns meniscal knee (Corin, Gloucestershire, UK). The separate meniscal bearings had much lower axial torque against axial rotation characteristics through the flexion range of 0 - 90 degree than a total condylar design. The Minns knee could be rotated up to 59 degree in both internal and external rotation before dislocating. Torsional strain was measured on cemented and uncemented preparations and little differences between the two was observed.

Nilsson, et al.¹²⁴ analyzed the *in vivo* kinematics of two types of unconstrained, PCL-retaining knee prostheses. Ten Miller-Galante (Zimmer, Warsaw, IN) and five New Jersey LCS prostheses (J&J DePuy, Warsaw, IN) were analyzed one year postoperatively using roentgen stereophotogrammetric analysis (RSA). In both types of prostheses, there was decreased medial and increased proximal and posterior displacement. No femoral rollback was observed. The authors suggest that the abnormal kinematics may be due to the design of the articular surface, absence of the anterior cruciate ligament, and the dysfunction of the posterior cruciate ligament.

Price, et al.¹³⁴ used sagittal plane video fluoroscopy to compare the *in vivo* kinematics of normal knees (n=2), AGC (PCL-retaining) TKRs (n=2), and Oxford UKAs (n=3). The patellar tendon angle (PTA) and flexion angle were measured. The relation between the PTA and the flexion angle were similar in UKA and normal knees. In the TKRs, the PTA remained unaltered throughout the range of motion. The authors believe the more physiological movement of the UKA is due to retention of the ACL. They also believe this may explain, in part, the better patient function and fewer patellofemoral problems after UKA.

Schlepckow¹⁵¹ collected data relating to three-dimensional kinematics and stability patterns in 40 fresh, complete knee joint, amputated specimens. The femur was flexed on a fixed transverse axis while a freely mobile tibial assembly allowed measurement of all passive translational and rotational movements (anterior translation, internal rotation and valgus rotation) after implantation of either a mobile bearing knee (LCS) or a semi-constrained knee (Tricon M). The LCS knee design showed a full range of movement that did not differ substantially from an intact, natural knee joint. In contrast, the Tricon M shows no rotation in extension and only low rotation in flexion and the total scope of movement was significantly reduced. There was a high degree of congruence between the components for both knee types. The paper concluded that the LCS knee showed the better kinematic behavior compared to the natural knee.

In this review article, Schroeder-Boersch¹⁵² cites new observations that indicate knee flexion is not linked to femoral rollback, but to rotational movement between tibia and femur. The axis of rotation is normally situated in the medial compartment, but shifts to the lateral compartment if there is ACL insufficiency. He notes the form of the femoral condyle is round. He concludes that knee design should include an asymmetric surface of the polyethylene insert to accommodate the different movements in medial versus lateral compartments. He also recommends that the posterior femoral condyle should feature a single radius to allow high congruency with the articulating polyethylene. He notes that some newer designs of both fixed and mobile bearing knees have incorporated some of these features.

Stiehl, et al.¹⁶³ used 2-dimensional videofluoroscopy and an interactive model-fitting CAD tool to analyze the kinematics of the LCS knee (J&J DePuy, Warsaw, IN). Dynamic fluoroscopy under weight-bearing conditions was used on 20 patients with this cemented PCS mobile bearing knee (rotating platform). Ninety percent of the patients demonstrated significant condylar lift-off during the stance phase of gait, in both the medial and lateral condyles. There was considerable variability in screw-home rotation. Overall, little internal rotation was observed (mean, 0.5 degrees) during flexion. Only two patients had normal screw-home with lateral femoral tibial contact moving more posterior than medial contact on flexion. The authors conclude that significant variability in condylar lift-off and screw home can exist in successful total knee arthroplasties, but that such kinematic abnormalities, when exaggerated, can cause problems such as peripheral pattern and posterior-medial condylar wear. The data suggest that designs such as the LCS mobile-bearing platform, which accommodate significant rotation and

lift-off while maintaining high articular surface congruity, may diminish contact surface stresses. This may present an optimal solution to unresolved kinematic derangements.

Stiehl, et al.¹⁶⁴ compared kinematics in 10 normal patients versus 10 patients with a PCL-retaining meniscal bearing total knee replacement (Low Contact Stress [LCS], DePuy, Inc., Warsaw, IN). Patients were observed via sagittal plane fluoroscopy with CAD image matching, while performing three successive deep knee bends. Initial contact position (full extension) for the mobile bearing knee was posterior to the normal. The mobile bearing knee exhibited greater rollback at 60 degrees flexion, but from 60 to 90 degrees, slid anteriorly. Five of 10 mobile bearing knees had some movement of the bearings while the others remained fixed. Patellar kinematics were similar to normal but reflected tibiofemoral abnormalities. This study confirms that a meniscal bearing total knee replacement with posterior cruciate retention behaves, kinematically, similarly to other fixed bearing designs. This includes: posterior contact in extension, anterior sliding beyond 60 degrees flexion, erratic and less reproducible kinematic patterns beyond 60 degrees, and lower weight-bearing range of motion.

Stiehl, et al.¹⁶⁵ used video fluoroscopy and computer photogrammetry to evaluate 20 PCL-retaining (meniscal bearing) total knee arthroplasties and 19 PCL-sacrificing (rotating platform) total knee arthroplasties and compared them with 10 normal patients. Femorotibial contact position in extension was more posterior for both mobile bearing knees than for normal knees, probably due to the absence of the ACL. The high congruity of the mobile bearing implants from 0-40 degrees caused a constrained posterior femoral rollback in most bearings, but there was a trend for anterior translation after 60 degrees flexion. The PCL-sacrificing rotating platform knee was closer to the mid-plane tibia throughout the range of motion and demonstrated less A/P translation than the meniscal bearing implant. Patellofemoral kinematics of both mobile bearing implants revealed patterns similar to normal, but tended to be more inferior with higher degrees of flexion. Weight bearing range of motion in both mobile bearing knees was significantly less than in normal knees, perhaps due to loss of normal rollback. Kinematics and weight-bearing range of motion were similar for PCL retention or sacrifice.

Stiehl, et al.¹⁶⁶ described their experience with *in vivo* dynamic fluoroscopic kinematic analysis. Mobile bearing LCS total knees that retain the PCL (meniscal bearing) have consistently shown posterior contact in extension and anterior translation with flexion. PCL-stabilized LCS implants (rotating platform) with high conformity have a posterior femoral rollback more consistent with normal knees.

Stiehl, et al.¹⁶⁷ determined the sagittal plane patellofemoral kinematics for 81 subjects while performing a weight-bearing deep knee bend under fluoroscopic analysis. Fourteen were normal knees, 12 were ACL-deficient and 55 total knee arthroplasties (TKA). Of the TKA group, 39 used a dome-shaped patella, 8 used an anatomic mobile bearing patella and 8 were unresurfaced. J&J Press Fit Condylar PCR (posterior cruciate-retaining), PS (posterior cruciate-substituting) and DePuy LCS mobile designs were used for the study. The TKA patellae showed more superior patellofemoral contact than the

normal and ACL-deficient knees. Patellofemoral separation at 5 degree extension was noted in 86 percent of the posterior cruciate-retaining and 44 percent of the posterior cruciate-stabilized TKAs and 8 percent ACL-deficient knees but not in the normal knees or mobile bearing TKAs. The patellar kinematic patterns for TKA subjects were more variable than normal or ACL-deficient knees. The authors concluded that kinematic abnormalities of the prosthetic patellofemoral joint may reduce the effective extensor moment after TKA.

Stiehl, et al.¹⁶⁸ investigated frontal plane kinematics in ten TKA patients (LCS mobile bearing rotating platform). Five received the standard cruciate-sacrificing rotating platform device and five had the posterior-stabilized version. The posterior-stabilized group had significantly less condylar lift-off and medial translation than the cruciate-sacrificing group. This was attributed to the constraint of the posterior stabilizer mechanism in the frontal plane.

Stukenborg-Colsman, et al.¹⁷¹ measured the mechanical efficiency of quadriceps muscles, both before and after total knee arthroplasty. This was determined from the tibiofemoral pressure on fixed and mobile inserts, as well as the movement of the mobile inserts. The Interax TKA system was implanted in eight fresh, frozen knee cadavers and then mounted onto a knee simulator. Isokinetic extension motion was simulated by extending the knee specimens under a constant extension torque of 31Nm. The quadriceps muscle force required for this motion did not increase after prosthesis implantation. Pressure on the mobile bearing inserts was 60 percent lower than the fixed inserts. A 4 mm posterior migration of the mobile insert on the tibial baseplate was observed, with no movement of the femoral component. In contrast, the femoral component migrated posteriorly on the fixed insert. Thus, instead of moving posteriorly, the mobile insert femoral component contact area remained at the center during the entire extension motion.

Stukenborg-Colsman, et al.¹⁷² measured the *in vitro* range of motion of an Interax ISA mobile knee prosthesis (Stryker Howmedica Osteonics) under dynamic isokinetic loading conditions. They also determined the effect of rotational malalignment of the tibial baseplate on the range of motion. The Interax prosthesis was implanted in seven fresh, frozen cadaver knees where the ACL was sacrificed but the PCL was preserved. This knee prosthesis allows A/P sliding as well as rotation of the insert on the tibial baseplate. Movement is guided by two metal tibial baseplate pins that match corresponding grooves in the underside of the insert. Once implanted, the devices were mounted into a special knee simulator which simulates isokinetic flexion-extension movements but does not restrict any other movement. Relative movements of the insert and the tibial baseplate from 0 to 120 degrees of flexion was measured using ultrasonic markers. Experiments were performed with the tibial baseplate aligned normally, internally rotated and externally rotated at 5, 10 and 15 degrees to investigate the effect of tibial baseplate malalignment. For normal and internally rotated tibial baseplates, the insert displacement did not significantly change. However, when externally rotated greater than 10 degrees, the insert displaced 3.5 mm posteriorly during extension. The authors concluded that, for this mobile bearing prosthesis, at up to 10 degrees of rotational malalignment, the primary motion pattern was maintained. However, beyond 10 degrees, unintended

motion may occur. These results correlate to referenced radiographic measurements of mobile bearing inserts that also show movement differences between natural knees and mobile prostheses.

Walker, et al.¹⁸¹ measured the *in vivo* kinematics of an MBK mobile bearing knee (Zimmer) for ascending and descending a step, deep-knee bend, normal walking and twisting using fluoroscopy to determine if this knee displays motion paths similar to normal knees. This design of knee allows ± 20 degrees of rotation and 4.5 mm of A/P translation. The 4.5 mm A/P motion allowed the knee to adjust the center of axial rotation during use. The rotations and displacements during the measured activities were similar to those of moderate-to-highly constrained fixed bearing knees. The motion patterns of the MBK knee were variable (translation and internal-external rotation between subjects) and, in general, did not reproduce normal knee motion, however, because of the freedom of movement in the design, each knee could determine its own neutral position and its own axis of internal-external rotation, reducing constraint at the bearing surfaces and shear forces at the fixation surfaces.

Wear

Argenson³ studied the wear of 23 Oxford Unicompartmental inserts after a mean implant time of 38 months. The mean penetration rate of the polyethylene was 0.026 mm per year and was statistically correlated with implant time. The large areas of contact were able to reduce polyethylene wear to levels smaller than those reported for hips. Bearing movement was also studied on six cadaver specimens implanted with the Oxford knee. Movements within both compartments of the implanted knees were in the same direction as for normal menisci during flexion-extension and rotation.

Argenson and O'Connor⁵ estimated polyethylene wear by measuring the penetration rate of the metal components into the meniscal bearings of retrieved bicompartmental Oxford knee prostheses. Twenty-three meniscal bearings were recovered from 16 patients in which knees had failed 1-9 years after implant. Failures were attributed to metal component loosening, bearing subluxation, or both. The mean penetration rate, calculated by two methods was either 0.043 or 0.026 mm per annum. This compares with 0.19 mm per annum reported for the Charnly hip. The rates reported here suggest that the beneficial effects of reduction in contact stress outweigh any potential adverse effect of increased contact area.

Hailey, et al.⁶⁴ conducted a tribological study of 27 retrieved Accord “meniscal bearing” (rotating platform) knees. Sixteen knees were excluded because their mode of failure generated large amounts of metal debris that would have confounded analysis of polyethylene wear. For the remaining 11 knees, the average duration of implantation was 33.4 months. Measurement of surface roughness (R_a) of the femoral and polyethylene surface revealed that the femoral components generally had R_a values similar to the unworn control. R_a for the polyethylene component generally decreased due to polishing and smoothing, although generalized degeneration of the surface was observed in a few cases. Penetration depth into the menisci was highly variable, and did not correlate with

wear life, patient weight, or patient activity. Overall, the pattern of surface wear was similar to that seen in hips with comparable penetration rates for the two types of joints.

Hirakawa et al.⁷⁰ evaluated wear debris from 47 failed implants, six of which were mobile bearing knees. Particulate debris was extracted from the soft tissue surrounding the implant. For the six samples from LCS mobile bearing knees, they observed a higher rate of particle production (particles per month) than was observed for either PCL-retaining or PCL-sacrificing or substituting fixed bearing knees (particles smaller than 10µm. Metal beads were identified embedded in the inferior aspect of the mobile polyethylene bearings, suggesting that third-body-wear at the interface between the polyethylene and the metal tray may have been a source of debris particles in this group of uncemented tibial components. The authors state that perhaps there would be less third-body wear observed for cemented implants, but they have too few retrieved mobile bearing implants available for a comparative analysis.

Jones, et al.⁷⁶ evaluated the performance of UHMWPE sliding against a cast cobalt chrome (CoCr) plate that was either untreated or coated with Amorphous Diamond Like Carbon (ADLC). ADLC represents a harder, more scratch-resistant surface than the standard CoCr metallic articulating counterfaces. This surface could potentially limit the effects of slight changes in roughness or damage from third-body particles that can produce increased UHMWPE wear rate. Testing utilized a multidirectional pin-on-plate reciprocating machine, using a model representative of *in vivo* motion at the tibial counterfaces of unconstrained mobile bearing knees. Although previous studies had shown ADLC coatings to give unidirectional total knee replacements improved resistance to third body damage, the present study in a mobile bearing model revealed poorer frictional and wear performance. These findings negate any potential benefits of improved resistance to third body damage.

Jones, et al.⁷⁷ compared wear rates of unidirectional (linear tracks or rotating-only platform) versus multidirectional (allowing A/P and M/L movement) designs of mobile bearing knees. They used a scale model, pin-on-flat testing apparatus. They found that multidirectional motion designs can generate significantly higher volumes of polyethylene wear debris compared to the rotating platform linear designs. They concluded that design and kinematics are critical determinants of polyethylene wear at the tibial counterface in mobile bearing knee prostheses.

Jones, et al.⁷⁸ analyzed wear on the tibial trays and polyethylene components of 14 pairs of explanted LCS knees. Six sets were rotating platform (RP), six sets were meniscal bearing (MN), and two sets were anterior-posterior glide designs (A/P). The explanted metal trays exhibited significantly greater surface roughness than unimplanted controls. Most showed scratches, which were parallel to the unidirectional counterface motion in the RP and MN explants. In the A/P explants, with multidirectional motion, there were two distinct scratching patterns corresponding to translation in the A/P direction and rotation about the central axis. The counterface of the polyethylene components showed two types of wear: highly polished areas due to burnishing and pitting, and deep scratching in cases where embedded debris had been present. Embedded particles were

present in seven of the explants and evidence of third body scratching or pitting was observed in all 14. The authors note that other testing has shown increased polyethylene wear in the presence of counterface scratches when the scratches are perpendicular to the direction of motion. They recommend development of designs that utilize different counterface materials or coatings designed to minimize wear.

McEwen, et al.¹⁰⁸ compared six PFC Sigma fixed bearing and six LCS rotating platform mobile bearing knees (both J&J DePuy, Warsaw, IN) using a physiological knee simulator with high rotation kinematic inputs. The rotating platform polyethylene inserts exhibited a mean wear rate which was one-third of the fixed bearing knee inserts despite having increased femoral contact areas and additional tibial wear surfaces. Other potential influences for this result were low contact stress, low rotational constraint forces, smaller anteroposterior displacement, different UHMWPe resin and an alternate method of sterilization for the mobile bearing inserts.

Minns¹¹³ described wear and contact area studies of a Minns meniscal knee prosthesis (Corin, Gloucestershire, UK). Wear studies were conducted using a knee simulator at 4x body weight, at 37 degrees C, and between 10 and 30 degrees flexion to 1 million cycles. Contact area studies were performed using contact films between the femoral and polyethylene inserts at 0, 20 and 90 degrees flexion. Average contact stresses were estimated every 100,000 cycles for 1 million total cycles. Initial stresses on the polyethylene inserts are high but drop to a fifth after 1 million cycles due to plastic flow and creep. Minimal wear was observed.

Psychoyios, et al.¹³⁶ examined 16 failed, explanted Oxford meniscal bearing unicompartmental knee (Biomet, Bridgend, UK) polyethylene inserts for wear. The thickness of each specimen was measured, compared to unused inserts and the data corrected for implantation time. The mean rate of penetration was 0.036 mm per year (both upper and lower surfaces). The initial thickness of the insert had no correlation with wear rate; however, 10 with evidence of impingement had greater wear than those inserts with no impingement.

Sathasivam, et al.¹⁴⁹ investigated the hypothesis that knee wear rates are reduced as the contact area is increased. The experimental model was a series of flat-ended UHMWPe pins (8-23 mm) that were reciprocated and rotated on polished metal plates under constant load. Pin diameters of 8-12 mm had a mean wear rate range of $5.0-16.0 \cdot 10^{-10}$ g/cycle while pin diameters of 17 and 23 mm had a mean wear rate of $1.0 \cdot 10^{-10}$ g/cycle. This data and the results of scanning electron microscopy of the pin surfaces supported the hypothesis that larger contact areas produce lower wear rates and suggested that there was no disadvantage regarding particle type or size associated with the larger areas of contact.

Tsakonas, et al.¹⁷⁷ assessed polyethylene wear in the Rotaglide congruent meniscal bearing knee (Corin, Gloucestershire, UK) and a partially congruent fixed bearing design under a load of 2960 N/mm^2 and an extension-flexion movement from 0-70 degrees. The results showed a lack of measurable wear on the Rotaglide device up to 3.5 million

cycles, while the fixed bearing device began to show wear from the first million cycles and progressed to 0.38 mm at about 3.5 million cycles. At 11 million cycles, the Rotaglide showed penetration wear of 0.35 mm as compared to 2.1 mm for the fixed bearing.

Biomechanics

Studies by the Orthopaedic Biomechanics Laboratory¹ investigated the possibility that bearing motion actually may not occur in a substantial number of individuals with implanted mobile bearing knees. The DePuy LCS Standard rotating platform total knee replacement (J&J DePuy, Warsaw, IN) was studied. Torque resisting insert rotation with respect to the tibial tray was measured for various levels of axial load, condylar load allocation and knee flexion. At peak physiologic joint load (2750 N), static frictional torques measured extend well into the peak range of endo/exorotation torques reported for level walking for knee arthroplasty patients. This tends to support fluoroscopic observations of patients in which bearing non-motion was observed in approximately half of the patients studied.

The Orthopaedics Biomechanics Laboratory developed a three-dimensional finite element model of the DePuy LCS Standard rotating platform total knee² (J&J DePuy, Warsaw, IN). Analyses of various parameters such as the amount of torque-resisting endo/exorotation are being performed at physiologically relevant axial loads, condylar load allocations, and flexion angles. These models confirm complementary experimental measurements of resisting torque. The data suggest that peak torques reached during normal walking may be sufficient to restrict bearing motion during functional loading.

D'Lima, et al.⁴⁰ evaluated the effect of knee alignment and articular conformity on contact stresses, using a finite element model. The authors modeled the polyethylene insert and femoral components in high and low conformity conditions, applying a load at different knee positions. They found that malalignment in rotation created high contact stresses, especially in highly conforming knees. They concluded that mobile bearing designs with increased articular congruity may result in lower contact stresses, especially the rotating bearing designs that theoretically minimize rotational malalignment.

Matsuda, et al.¹⁰⁵ measured tibiofemoral contact stress in a fixed bearing system (Tricon II, Smith & Nephew, Memphis, TN) and in three specially designed mobile bearing systems having either A/P sliding, rotational sliding, or a combination of A/P and rotational sliding. Contact stresses were measured under compressive loads in cadaver knees from 0 to 90 degrees flexion and when the tibial component was normally aligned or when it was malrotated at 15 degrees internal and external rotation. Undersurface stress of the rotationally sliding component was also measured with a 30 and 45 degree malrotated tibial tray. With 15 degree malrotated tibial components, surface stresses increased to twice the yield stress of the polyethylene in the fixed bearing surface, while all mobile bearing surfaces mitigated the effect. However, when severely malrotated (45 degrees) systems were tested, rotationally unconstrained mobile bearings demonstrated edge contact that drastically increased undersurface stress, which could lead to deformity

and subluxation. Results indicated that mobile meniscal bearing surfaces offer an advantage over a standard fixed bearing component when moderate rotational malalignment of the tibial component occurs.

Matsuda, et al.¹⁰⁶ investigated the effect of varus tilt on contact stress in five knees, including one meniscal bearing knee (LPS, DePuy, Warsaw, Indiana). Interface contact area and surface stress measurements were made with the components seated normally and at 5 degrees varus tilt, using a specially constructed fixture in an Instron servohydraulic testing device. The LCS had the lowest mean and peak contact stress at both 0 and 5 degrees tilt. The authors conclude that the femoral component surface should have a radius of curvature that matches that of the tibial articular surface in the coronal plane throughout the range of motion. If, in addition, the design uses nonconforming radii in the sagittal plane, more optimal rollback and additional flexion can be achieved, and lower shear stresses would be transmitted to the bone-implant interface.

Matsuda et al.¹⁰⁷ evaluated knee stability, comparing fixed bearing (Tricon II, Smith & Nephew, Memphis, TN) versus specially designed A/P, rotational and combined A/P and rotational mobile bearings, in seven cadaver knees, first with intact ACL, then without. The A/P and combined A/P and rotationally sliding component significantly increased A/P laxity above the normal knee. Rotationally movable bearings preserved the rotational stability of the normal knee. Movability of the bearing surface did not change varus-valgus stability significantly as compared to the normal knee. The results of this study suggest that the rotating, highly conforming meniscal bearing offers the best compromise to achieve near-normal kinematics, acceptable range of motion, and low contact stress.

Menchetti, et al.¹¹¹ evaluated the contact pressure distribution across the upper and lower bearing surfaces of closely conforming mobile bearing knees to determine the effects of small differences in the radii of curvature. The results confirm that between closely conforming surfaces, the pressure distribution is uniform. Small differences (> 0.2 mm) in the relative radii of curvature significantly affect the pressure distribution. However, for completely conforming surfaces to avoid bending of the polyethylene insert if there was overhang, the authors recommended a small clearance of 0.1 to 0.2 mm between the femoral and insert radii.

Minns, et al.¹¹⁶ used a pendulum testing machine on a 3-component sliding meniscus knee to evaluate the direct loads and the anteroposterior and mediolateral bending moments during the loading phase. The bending moments changed with variation of the component positions. Tilting the tibial plateau produced the greatest change in lateral bending moment, but alteration in plateau rotation or femoral tilting produced little change in bending moment. With this prosthesis design, it is necessary to ensure that the tibial component is positioned horizontally on the tibial plateau, but it is not necessary to be concerned about the angle of the femoral component to the vertical or the rotational misalignment of the tibial component.

Otto, et al.¹²⁸ used testing and finite element analysis (FEA) to assess the mobility and contact mechanics of an LCS rotating platform mobile bearing knee. The torque required to initiate rotation (static torque; 9.47 ± 0.61 Nm) was greater than that to sustain rotation (dynamic torque; 5.51 ± 0.38 Nm). These high frictional torques observed at the mobile interface may explain why a percentage of these devices fail to rotate under routine functional load.

Statler, et al.¹⁶⁰ determined the articular surface contact areas for seven total knee replacements, including three mobile bearing knees (the LCS, DePuy, PFC, J&J, and Kinemax, Howmedica). The knees were tested at 1, 20 and 45 degrees flexion and at four load levels (400, 800, 1200 and 1600 N). The AMK (DePuy) and the Kinemax had the lowest contact areas at 0 degrees flexion (and therefore potentially the highest contact stresses). The PFC and LCS had larger contact areas. The authors state that it appears that the LCS femoral and meniscal bearings are not appropriately matched. The femoral components radii of curvature in the coronal plane is greater than that of the corresponding meniscal curvature at all angles of flexion. It is also greater in the sagittal plane at 0 degrees of flexion. This explains why the contact observed experimentally was on the outside edges of the bearings.

Szivek, et al.¹⁷⁴ tested seven total knee arthroplasty systems for contact area and stress patterns. They included one mobile bearing knee system, the LCS (DePuy, Warsaw, IN). The knees were loaded to 2000 N at 15, 60, 90 and 135 degrees of flexion at 24 and 37 degrees C. Results at 37 degrees C and 15 and 60 degrees flexion indicated that the LCS meniscal bearing mobile knee, the AMK knee with a constrained insert, and the PFC (J&J) knee with a posterior-lipped insert had the lowest average contact stresses (near or below 10 MPa). All of the knees tested had some areas of contact with maximum stresses in excess of 15 MPa. Some systems had contact stresses above (30 MPa) the approximate yield strength of UHMWPe. Although the peak contact stresses measured from the LCS knee system were in excess of 30 MPa in some areas at low flexion, the design has large areas of contact and may wear less than other designs.