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Knee joint kinematics, fixation and function related to joint area design in total knee arthroplasty

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THESIS

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III. Flat vs. concave tibial joint surface in total knee arthroplasty. Randomized evaluation of 39 cases using radiostereometry.
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Definitions and abreviations

ACL Anterior cruciate ligament.

AMK Total knee replacement, manufactured by DePuy, Johnson & Johnson.

AP Anterior-posterior.

C Concave, a relatively conformed (constrained) tibial insert.

F Flat, a relatively nonconformed tibial insert.

FAP Prosthesis-femur angle on the anteroposterior view. Varus = <90°.

HKA Hip-knee-ankle angle.
Varus = <180°, valgus = >180°.

HSS score The Hospital for Special Surgery knee score.

Inducible displacement Continous change of the position of the prosthesis during active movement.

Migration Difference of the prosthesis position occuring between two RSA examinations.

MTPM Maximal total point motion.

OA Osteoarthrosis

PCL Posterior cruciate ligament.

PS Posterior-stabilized tibial insert with a central tower.

PT Position of the tibial component on the anteroposterior view. Varus = <90°.

PTS Prosthesis-tibia angle on the lateral view. Posterior tilt = <90°.

RLL Radiolucent line.

RSA Radiostereometry.

TKA Total knee arthroplasty.

TKR Total knee replacement.

UmRSA Software for radiostereometric examination, developed by RSA Biomedical examinations

Abstract

The aim was to study the influence of different designs of the joint area on tibial component fixation, kinematics and clinical outcome after a cemented total knee arthroplasty (TKA). The HSS score and a special questionnaire were used at the clinical examination. Conventional radiography was done to record the positioning of the implants and development of radiolucencies. The migration and inducible displacement were evaluated using radiostereometry (RSA). The kinematics of the knee during active extension was studied using dynamic RSA.

In randomised and prospective studies 87 knees in 83 patients (28 male, 55 female, age 69, range 50–83) received an AMK (DePuy, Johnson & Johnson) TKA. The patients were divided into two groups. In group 1 the patients had varus/valgus deformities of ≤ 5° and the PCL was retained. The PCL was resected in group 2 where the patients had deformities exceeding 5° and/or fixed flexion deformities of more than 10°. In group 1 a flat (F, n=20) or a concave (C, n=20) design was implanted (study 3). In group 2 (study 4) the patients received a concave (n=25) or a posterior-stabilised (PS, n=22) tibial plateau. The migration of the tibial component, positioning of the prosthesis, development of radiolucencies and the clinical outcome was evaluated after 1 and 2 years. Twenty-two patients (11 F, 11 C) in group 1 (study 1) and 22 knees in 20 patients in group 2 (study 2, 11 C, 11 PS) were examined 1 year postoperatively to evaluate the kinematics of the knee. Eleven normals served as controls. During active extension of the knee the inducible displacements of the tibial component were recorded in 16 knees (15 patients). Based on successful RSA examinations 5 knees (4 F, 1 C) from group 1 and 11 knees (5 C, 6 PS) from group 2 were selected (study 5).

Abnormal kinematics and especially increased AP translations compared to normals ($p < 0.0005$) were recorded in all designs. The concave design showed the widest AP-translations in both studies. The clinical outcome in terms of HSS score did not differ between the flat versus the concave designs in study 1 and between the concave versus the PS implants in study 2.

Up to two years the migration of the tibial component and the development of radiolucent lines were of the same magnitude for the flat versus the concave inserts in study 3 and the concave versus the PS design in study 4. Also did the positioning of the implant and the fulfilment of the patients expectations on the surgery preoperatively not differ. The AMK prosthesis migrated at about the same amount as have been reported for similar designs.

In study 5 all implants showed a correlation between some of the inducible displacements (anterior-posterior tilting and maximum total point motion) and the corresponding migration 0–2 years. The more the anterior tilt the more the migration in the same direction. If the PCL was sacrificed during the knee replacement the change into increased anterior tilt occurred earlier (i.e. at more degree of flexion) if a concave insert was used compared to the PS design. When the active extension reached 25° there were more anterior tilt of the tibial component in the concave design ($p=0.001$) and if the tibial plateau centre had a medial position ($p<0.0005$).

Compared with normal knees all prosthetic designs showed abnormal pattern of motion. The extent of this abnormality was influenced by the design of the joint area. A corresponding influence on the fixation of the tibial component could not be verified. The choice of joint area and recorded kinematics had no or small influence on the clinical results. Feelings of instability could to some extent be related to the kinematics of the knee joint.

Key words: Total knee arthroplasty, polyethylene insert, kinematics, migration, clinical outcome, inducible displacement of the tibial component, radiostereometry.

Introduction and background

Attempts to replace the knee joint with an arthroplasty have been made for at least 140 years (Habermann et al. 1973). A breakthrough appeared about 50 years ago when Börje Walldius (Walldius 1957, reprint 1996) introduced the hinged knee replacement followed by numerous designs. Important factors to speed up this development were the concomitant introduction of polyethylene and bone cement originally employed in arthroplasties of the hip. In 1973 Insall introduced the Total Condylar Prosthesis. The design was based on research made by Walker and others and influence from the ICLH (Freeman and Swanson) prosthesis (Freeman et al. 1973). The Total Condylar implant aimed to mirror the kinematics of the normal knee (Ranawat et al. 1993) and this design is still considered the gold standard among total knee arthroplasties. Today, total knee replacement (TKR) is a successful surgical procedure (Robertsson et al. 2000). The older patients can expect that the implant will last for the rest of their lives (Regnér 1998). However, both in vitro and in vivo studies have shown that knees with implanted prostheses have an abnormal kinematic behaviour. Theoretically there are different ways to alter the kinematics of artificial knees by changing the configuration of the surfaces of the joint, the addition of stabilising devices such as a central spine or by resection of the PCL or not. These modifications of a TKR can also have other effects. The wear of the polyethylene might change due to changes in the pattern of motion and load (Soudry et al. 1986). The forces transmitted to the implant/bone or cement/bone interfaces can be expected to mirror the inherent stability of the design and will thus have an influence on the fixation of the components. Finally, but not least, the design of the joint will most probably also influence the clinical function and the subjective opinion of the patient about the outcome of the operation (Andriacchi et al. 1986).

The true effects of variations of the design are, however, not completely known. There are only few randomised clinical trials in this field and most of them did not try to isolate single factors, but rather compared two completely different designs. Some kinematic studies had limited resolution or were based on static measurements making definite conclusions unattainable (Nilsson et al. 1991, Kärrholm et al. 1994).

Consequently, the development of the form of the tibial joint surface has been based on different theories and practical experiences. The detailed influence of the design of the tibial plateau on the kinematics, fixation and clinical function remains partly unclear. Therefore, this study was initiated to improve our understanding in this field of joint arthroplasty.

History

Early trials

In 1860 Verneuil suggested “the interposition of tissues between resected bone to prevent fusion”. One year later Ferguson presented a well functioning knee joint resection performed 5 years earlier.

Jules Emelie Péan, one of the leading surgeons in Paris, described in 1894 the first attempt with an articular prosthesis of metal in a severely ill patient suffering from tuberculosis of the humerus. The patient refused disarticulation and therefore a prosthesis made of hardened rubber and platinum was inserted. According to the surgeon the procedure was successful. Pean reported that Gluck and others earlier had tried ivory and animal bone, but with failure mainly due to quick resorption.

Attempts to replace the knee with homografts were undertaken as early as 1908 (Young 1963). In 1938 Venable and Struck presented a classic work when they significantly improved the quality of vitallium and certain steel alloys. This raised the success rate for all metal implants and meant a significant step forward in the development of implant surgery.

In the 1920s and 1930s other materials such as free fascial grafts were tried by Campbell to salvage ankylosed knees. The operation was claimed to have some success. During the early 1940s moulded hemiarthroplasties were tried by Campbell and Boyd (Campbell 1940) and Smith-Petersen (Mahalingam and Reidy 1996), but the pain relief was not satisfactory according to Guyton (1998).

Hinged prostheses

The era of modern knee arthroplasty started with Börje Walldius, who in 1951 began the development of the hinged knee prosthesis. This implant was made of acrylic resin and consisted of a femoral and tibial part, joined by a stainless steel rod to form a hinged joint (Walldius 1957, reprint 1996), which was originally fixed without cement. The early results were encouraging, especially against the background of previous trials and inclusion of patients with severe deformities (Walldius 1957, 1960, reprint 1996). The majority of the patients had severe rheumatoid arthritis affecting both knees, which made them almost complete invalids. Walldius reported that 75 percent of the patients were free from pain with an average active mobility of 84° (observation period 7 months – 4 years 10 months). The acrylic proved not to be strong enough. So the design was changed to stainless steel and later to cobalt chromium alloy (Jones 1973). In 1972 Wilson presented the results of the Walldius knee replacement in patients with severe rheumatoid arthritis. The total range of motion was not improved but the pain was eliminated or reduced. Habermann et al. (1973) reported the outcome after implantation of the Walldius prosthesis made of vitallium. In the same year the results for the cemented Walldius total knee arthroplasty (TKA) was presented (Bain 1973). The author reported that the operation produced significant functional improvement. However, at the 3-year follow-up in 100 knees seven deep infections, five prosthetic loosenings and one fracture were reported.

Shiers and several others presented modified designs (Shiers 1954, 1960, 1965, Phillips 1973, Watson et al. 1976, MacAusland 1957, Von Hellens 1961, Young 1963, 1971). The “LL prosthesis” (Letournel and Lagrange 1973, Lagrange and Letournel 1975) was made of chrome cobalt alloy and plastic and was implanted with cement. The axis of rotation moved between two halves of a high density polyethylene (HDPE) block. The Stanmore prosthesis (Lettin et al. 1978, 1984), manufactured of titanium with cobalt chrome alloy bearings or entirely from cobalt chrome was also used with cement and showed a cumulative success rate of 80 percent at seven years (Grimer et al. 1984). In the GUEPAR prosthesis, the axis of rotation was placed more posteriorly but with consequent high frequencies of loosening, penetration of the femoral cortex and infection (Mazas 1973, Deburge 1976, Jones et al. 1979, LeNobel and Patterson 1981, Gross et al. 1982). These different types of hinged knee replacements were considered to be suitable for severely damaged knees. More modern versions of the hinged knee such as the Spherocentric and the Kinematic Rotation Hinge have not shown better results than the GUEPAR prosthesis (Rand 1993). Gschwend presented the GSB knee prosthesis, a nonconstrained hinged joint, which, according to the authors, combined the advantages of the Condylar prosthesis with the constrained hinged knee replacements (Gschwend 1978, Gschwend and Loehr 1981, Gschwend and Ivosevic-Radovanovic 1988). The Link (Waldemar Link GmbH & Co, Hamburg) hinged prosthesis is still in use, but primarily for patients with severe deformities or in cases of revision.

Condylar prostheses

Gunston (1971) presented one of the first modern condylar prosthesis. Its design was based on the theories of the centres of instant motion of the knee (Reuleaux 1876) and also on ideas from the low friction arthroplasty of the hip by Sir John Charnley. The Gunston prosthesis relied on the cruciate and collateral ligaments for stability. It was fixed with polymetylmethacrylate (PMMA), but failed mainly due to loosening. Gunston also described femoral rollback and pointed out that the knee does not function like a hinge with a single axis of rotation. Instead the femoral condyles were claimed to roll and glide posteriorly on the tibia with increasing flexion.

The designers of another geometric non-hinged TKA (Coventry et al. 1972), also inserted with retention of the cruciate ligaments did, however, not seem to pay any attention to these kinematic principles.

The prosthesis developed by Freeman and Swanson (Freeman and Swanson 1972, Freeman et al. 1977, Freeman 1977) was, like the Gunston knee replacement, a reduced design of the hinged TKA. It depended on stability from the collateral ligaments. In the beginning of the 1970s this implant was recommended for knees with limited deformity. It was expected to be associated with less complications than the hinged designs (Arden 1973). At that time some authors (Jackson and Elson 1973) were of the opinion that only severely crippled patients should have a knee arthroplasty. Patients with less destructive arthrosis were better off with a high tibial osteotomy.

In 1973 Freeman and Swanson presented the results of their first 69 arthroplasties. They were of the opinion that the procedure could "relieve pain, improve function, increase the range of movement, correct deformity and control instability". The Imperial College London Hospital (ICLH) prosthesis had a "roller-in-trough" design, with a concave tibial component, no tibal stem and both cruciate ligaments resected. Later on, loosening of the tibial component and patella dislocation were reported to be a problem.

In the Modular knee (Smith and Nephew, Memphis, TN; Marmor 1973, 1977, 1988) and in the Oxford knee (Biomet, Warzaw, IN; Goodfellow and O'Connor 1986) one or both compartments could be replaced. The same philosophy was used by Walker et al. (Ranawat and Shine 1973) when they developed the Duo-Condylar knee from the original Gunston design. Poor fixation was frequently observed and also deformation of the tibial component. In consequence these designs were modified, abandoned or were restricted to cases with less destructive arthrosis, where only the medial compartment needed replacement.

Beuchel created a Low Contact Stress (LCS; DePuy, Johnson & Johnson, Warsaw, IN) knee replacement, which could be used with one moveable polyethylene platform or two separate menisci (Beuchel and Pappas 1989). It had some similarity to the Oxford design, but the meniscus/ menisci were supported by a central stud or separate grooves on the tibial component to reduce the risk for dislocation.

Insall and associates developed the Total Condylar prosthesis (Howmedica, Rutherford, NJ) at the Hospital for Special Surgery. The design was influenced by the ICLH prosthesis, with the intention to create a knee replacement with kinematic characteristics as similar as possible to the normal knee. It was introduced in 1973 and has set a standard for knee replacements with 94% survival at 15 years (Ranawat et al. 1993).

In 1978 the Insall-Burstein posterior-stabilized (Zimmer, Warzaw, IN) design was presented as a modification of the Total Condylar design. This model had a central tower on the tibial component and a corresponding "box" or indentation on the femoral component. The idea with this mechanism was to simulate the function of the posterior cruciate ligament (PCL) and facilitate femoral rollback. This would increase flexion and decrease the risk of dislocation.

The Insall-Burstein Constrained Condylar knee (Zimmer, Warzaw, IN) with a larger central tower was developed to control varus-valgus instability. It was intended to replace the hinged knee; especially in revision situations. The increased stability of this design did, however raise concerns with progressive bone-cement radiolucencies and loosening; important reasons for abandoning the hinged prosthesis (Rosenberg et al. 1991).

The geometry of the optimal configuration of the polyethylene surface has been much debated. According to Insall (1993), inserts with shallow condylar surfaces, aimed for retention of the PCL, could result in higher contact stresses than those with deeper hollows. He also claimed that such more constrained and stable designs would be subjected to increased risk of tibial component loosening.

The concept of the Total Condylar Knee, with a stem on the tibial component to prevent tilting, has been used in many designs of knee arthroplasties. Originally the tibial component was all polyethylene but later on metal backing was added to facilitate stress transfer to larger areas and also to prevent deformation of the polyethylene (Bartel et al. 1982).

The biomechanics of the knee joint

Evaluation of knee function and biomechanics after TKA should be viewed against the background of the situation in the normal and the arthrotic knee. Due to the difficulties of examining function in vivo, many studies were made using biomechanical models (Shaw and Murray 1973, Andriacchi et al. 1983, Blankevoort et al. 1988, Lloyd and Buchanan 1996, Riener et al. 1996, Zavatsky 1997, Arnold et al. 2000) or measurements on cadavers. In vivo measurements have mainly been based on photogrammetric recordings of markers placed on the skin and external force measurements with force plates. Kinematic and anatomic studies of knee joint motion using magnetic resonance imaging (MRI) and radiostereometry (RSA) have recently provided more detailed information, but not so far combined with force measurements. Kinematic data describe the motion in a joint. Kinetic results will help us to analyze the forces acting on a joint (Nordin and Frankel 1980).

There are three contact areas in the knee: the patellofemoral joint and the medial and lateral aspects of the joint. The medial and lateral parts of the tibiofemoral joint can be considered as working separately but co-ordinated with one another. Rotations in the sagittal plane predominate, but there are also rotations in the horizontal and frontal planes. Even under normal conditions the joint is not totally stable in itself, but depends on muscular function for stability.

The knee is considered to be the most exposed joint in the body (Kim et al. 1993). It is subjected to heavy loading in most activities. In the western world knee flexion over 90 degrees is not necessary in most situations, with the exception of sports requiring squatting. In Asian cultures deep knee flexion is more important and a prerequisite for many social activities. Kettlekamp (1973) found that normal gait required 67 degrees of flexion during swing phase, 83 degrees for stair climbing, 90 degrees for descending stairs and 93 degrees to rise from a chair. One problem is that the muscles acting around the knee are comparatively inefficient due to the short effective moment arms of the tendons involved, especially when compared with the external forces acting on the knee. To counteract the external moments the muscles need to work at high intensity. In the normal knee the contact areas in the joint are large, which will reduce the pressures. However, under abnormal conditions, for example after removal of the medial meniscus or tear of the anterior cruciate ligament, the contact area will decrease or the relative tibiofemoral positions will change (Brandsson 2000), which can be expected to increase cartilage load, eventually resulting in degenerative changes.

When more demanding physical activity is performed, such as running or jumping, the knee is vital as a shock wave absorber to protect the hip and spine. A complex system including the muscles, ligaments, joint capsule, menisci and cartilage will reduce the transmission of forces proximally. The reduction of forces is greatest for the flexed knee.

Studies of the load axis in the knee have not reached consensus, probably due to different measuring methods. In TKA the biomechanical axis is considered to be most important and the purpose of surgery is to restore normal alignment. The mechanical axis of the femur is defined by a line from the centre of the femoral head (H) to the centre of the knee (K) and the corresponding mechanical axis of the tibia from the centre of the knee to the centre of the ankle (A).

During daily activities such as walking on level ground and up stairs, or rising from a chair, the compressive forces in the knee reach three to seven times bodyweight (Kaufmann 1991). The posterior shear forces are estimated at 0.4 to 1.7 times bodyweight and the corresponding anterior forces 0.04 to 0.1 times the bodyweight. Wear of the polyethylene in TKA is thought to be mainly an effect of shear forces (Kim et al. 1993).

Gunston (1971) studied gait in a normal population and found differences in the amount of knee flexion at heel strike between men and women. He also found that gait differed between patients older or younger than 55 years.

Schneider et al. (1983) examined the effect of walking speed on hip, knee and ankle motion. They found that the ankle and knee contributed more to the motion at lower speed; with increasing speed the influence of hip motion increased.

Stauffer et al. (1977) noted a positive correlation between increased knee flexion when standing and pain, functional disability and instability of the knee joint in patients with gonarthrosis and rheumatoid arthritis. These patients also tried to reduce the compressive force on the joint by reduced knee flexion when walking. They also walked with a wider gait pattern (“waddling”) in order to improve stability.

Kinematics and gait analysis

Kinematic studies of different designs of total knee arthroplasties have shown diverging results. There seems, however, to be consensus on one point. All TKR show abnormal kinematics. The clinical significance of this finding is still unclear. A knee replacement need not necessarily have the same kinematics as the normal knee. Kim et al. (1993) concluded that “today’s TKR provides acceptable kinematics in the range of 0–90 degrees of flexion”. Pronounced deviations from normal can, however, be expected to result in unfavourable and even disastrous effects. The moment arms and function might deteriorate, the ligament stresses will increase, the stability of the joint might be jeopardised, the risk of polyethylene wear might increase and the joint might even dislocate.

Cadavers and radiography

Walker et al. (1985) used the lateral view of sequential radiographs to study the geometry and the kinematics of the normal knee. In this study and earlier (Walker et al. 1972) they noted that the shape of the posterior parts of the femoral condyles were spherical. Interestingly, this had been reported by German anatomists much earlier (Weber and Weber 1836, Strasser 1917). Internal tibial rotation with flexion of the knee was the most striking observation but also varus rotation and posterior translation were seen. These observations were used in the design of the Total Condylar knee replacement. In a cadaver study of 36 right femoral condylar specimens, Röstlund et al. (1989) observed a more spiralized shape of the sagittal curvature of the medial compared to the lateral femoral condyle; which was more rounded. This could (according to the authors) speak for using separate and different designs of the medial and lateral condyles in a bicondylar knee prosthesis.

Incavo et al. (1997) studied the kinematics before and after TKA in cadaver knees using different designs of tibial inserts (standard, flat and dished) with retention of the PCL and also with a posterior-stabilised plateau. None of the designs studied could restore the kinematic pattern of the normal knee. At 90 degrees of flexion all designs had a more posterior position of the tibia than in the normal knee. In full extension they positioned the tibia posteriorly and proximally compared to normals.

Goodfellow and O’Connor (1978) investigated the kinematics of the knee and the influence of prosthesis design in human cadaver joints and in living patients. They reported the presence of femoral rollback during flexion, which was supposed to be induced by the presence of the PCL. Andriacchi and Galante (1988) and Sorger et al. (1997) also held this opinion.

Soudry et al. (1986) performed in vitro studies on cadavers when prosthetic components were implanted and tested in a loading rig. They found that retention of the PCL resulted in contact areas closer to the centre of the component at low shear forces. At higher shear forces rocking movements occurred, thought to be more damaging to the polyethylene. If the cruciate ligament was resected without substitution with posterior stabilised (PS) design, the contact point moved anteriorly on the tibial component. This finding caused concerns about fixation problems and spoke against the existence of femoral rollback with these designs of TKRs.

Kim et al. (1997) tried to find out if femoral rollback occurs in PCL retaining TKR. They recorded almost no change of the contact point from full extension to 90 degrees of flexion, and concluded that no demonstrable rollback was present.

Freeman and Railton (1988) concluded that resection of the anterior cruciate ligament (ACL) with retention of the PCL will destroy the normal mechanism of femoral rollback and rollforward in the knee.

Gait analysis

In 1981 Rittman et al. compared the gait of healthy volunteers with patients operated with different designs of TKRs. They found no implant specific pattern of walking, but considerable variation of motions in the transverse and coronal planes in both normal and operated knees. Kramers-de Quervain et al. (1997) studied gait in patients with different designs of TKR in the left and right knee. Clinically good results were reported, but gait analysis reported reduced walking speed. There was also a modulation of the vertical forces and sagittal plane knee motions. The two sides showed marked asymmetry of maximum knee flexion (up to 15 degrees) without any relation to design. Slow and irregular loading with prolonged muscle activity was also found. The authors could not find any reasonable explanation for their results.

Andriacchi et al. (1982) investigated the influence of implant design on walking and stair-climbing in five different designs of knee replacements; 1) the Geometric prosthesis with congruous articular surfaces (and resection of the ACL), 2) the Polycentric design with two separate semicircular runners that articulated with two independent tibial components (and retention of the ACL and PCL), 3) the Total Condylar Knee replacement (with resection of both cruciate ligaments), 4) the Duo patellar design (with retention of the PCL) and 5) the Cloutier TKA (with retention of both ligaments). Most patients (75%) had abnormal patterns of flexion-extension moments during stance phase (especially in the middle). Patients operated with the Total Condylar prosthesis descended stairs more slowly than did patients with the four other designs and when compared with normals. The patients with the Cloutier prosthesis were the only ones that had normal ROM while ascending and descending stairs. These design variations were smaller when walking on level ground. All groups operated with knee arthroplasty had abnormal gait; short stride length, reduced midstance knee flexion and abnormal patterns of external flexion-extension moment despite good clinical result. The authors concluded that patients with less constrained tibial inserts and cruciate-retaining designs had more normal gait during stair climbing than patients with more constrained, cruciate-sacrificing designs. Four and six years later some of these authors (Andriacchi et al. 1986, Andriacchi and Galante 1988) reported that retention of the PCL improved knee motion, stair climbing and muscular function. This design was also believed to reduce the stresses at the interfaces without jeopardising the integrity of the polyethylene by excessive wear. These opinions were supported by Leffers et al. (1983). They found that patients with a posterior-cruciate retaining design had greater increase in middle stance knee flexion, but also reported abnormal gait in the same patient population.

Wilson et al. (1996) compared a posterior-stabilised design (Insall-Burstein PS II, Zimmer, Warsaw, IN) with age-matched controls. During stair ascent no significant difference in range of knee motion was recorded, but when walking on level ground or descending stairs the range of motion was significantly decreased in the knees implanted with a posterior-stabilised prosthesis. In the authors view the posterior-stabilised prostheses and posterior-cruciate retaining designs were comparable with respect to gait. These two designs did result in a more normal pattern of motion than cruciate-sacrificing prostheses without a central cam.

Bolanos et al. (1998) studied gait and muscle function in patients with posterior-stabilised knee replacement in one knee and a posterior cruciate-retaining design in the contralateral knee. Both designs were regarded to have good and equal results. There were no differences in the function of the hamstrings and quadriceps muscles, gait pattern or range of motion in the knee when walking on level ground or on stairs. However, in this study only patients with good or excellent results were included, which could have influenced the results.

Andriacchi et al. (1999) used a point cluster method to enhance the resolution of gait analysis. They tested the hypothesis that femoral rollback occurs during stair climbing and that presence of the PCL is necessary for the occurrence of this phenomenon. Patients with cruciate retaining or posterior stabilised TKA and age matched normals were studied. All patients had HSS scores better than 85 (so-called excellent results). The authors found that femoral roll back was dependent on the phase of stair climbing. In the early phase anterior femoral translation was seen. At 45 degrees of flexion the femur started to move posteriorly, explained by increasing tension of the PCL. The patients operated with the PS design had the largest anterior displacement of the femur. The authors explained this observation by absent function of the stabilising cam before 70 degrees of flexion, which was regarded to be too late in the swing phase to copy the normal function of the PCL.

Fluoroscopy

Stiehl et al. (1995) studied the kinematics of the knee during single-leg deep-knee bends with fluoroscopy in normal knees and in patients operated with posterior-cruciate-retaining knee arthroplasty. During weight bearing, the operated patients had maximum flexion to 98 degrees, but some patients to no more than 70 degrees. The replaced knees had a starting contact point posterior to the tibial midline (10 ± 5 mm). This contact point translated to a contact point 5 ± 3 mm anterior to the midsagittal point with increasing flexion. This pattern could not, however, be consistently reproduced in individual patients. In normals at full extension the femur contacted the tibia 6 ± 1 mm anterior to the midline and translated 2 ± 1 mm posterior during flexion.

In 1997 the same group (Stiehl et al. 1997) used the same method to study patients with posterior cruciate retaining mobile bearing total knee replacements and normals. Rollback was noted in both groups. At 60 degrees of flexion the normal knees had rolled back to -5.8 mm (range -2.5 to -13.2 mm) and -7.8 mm (range -5.8 to -13.8 mm) at 90 degrees. The mobile bearing TKR showed still more posterior translation of the contact point at 60 degrees (-9.2 mm, range -4 to -17 mm). In flexion (between 60 to 90 degrees) the mobile bearing knees moved anteriorly to -5 mm (range 2 to -12 mm). The authors concluded that the mobile bearings had to some extent a roll back. In one further study of mobile bearing knee replacements (LCS with cruciate resection) Stiehl et al. (1999) observed both medial (up to 2.1 mm) and lateral (up to 3.5 mm) lift off during the stance phase of gait in 90 percent of the patients. The mean internal/external rotation from flexion to extension was 0.5 degrees, with a range between a maximum negative or reversed screw-home of 6.2 degrees to a maximum positive screw-home of 9.6 degrees. The authors stated that condylar lift-off and screw-home motion commonly occurred in the rotationally unconstrained LCS design.

Dennis et al. (1996) used fluoroscopy to study the kinematics during deep knee bends in patients operated with different TKRs, in normal and anterior-cruciate deficient knees. The tibiofemoral contact was studied in the sagittal plane. In normals and patients with posterior-stabilised designs the mean contact point at full extension was positioned anterior to the tibial midpoint; in normal knees 6.5 mm, and in the PS implants 0.3 mm. In the posterior cruciate retaining designs and anterior cruciate ligament deficient knees the initial contact position was positioned posteriorly at full extension (PCL retaining design: -5.1 mm /ACL deficient knees: -5.5 mm). In the two former groups the contact point translated posteriorly during flexion. In the latter two groups the contact point moved anteriorly in several of the patients during flexion. Abnormal change of contact points (or areas) was believed to be one reason for premature polyethylene wear seen in retrieval studies in the cruciate retaining designs of TKA.

Two years later Dennis et al. (1998) examined tibiofemoral contact at 0, 30, 60 and 90 degrees of flexion in patients operated with different kinds of TKA. The patients with retained posterior cruciate ligaments received a flat or curved tibial insert. When the PCL was resected it was substituted with a PS design. As noted in the previous study the femoral component in the posterior cruciate retaining designs had a posterior tibial contact at full extension. The contact point usually translated anteriorly with increasing flexion. In all patients with a PS implant there was a posterior femoral rollback laterally from full extension to 90 degrees of flexion. This only occurred in about half of the patients with a flat design and two thirds of the knees with a curved insert and the PCL retained. The authors concluded that the results were remarkably similar to their previous studies. None of the PCL retaining designs displayed posterior femoral rollback, but instead the reverse motion. In the posterior cruciate substituting knee replacements posterior femoral rollback occurred, but less than normal. This was explained by contact between the tibial cam and edge of the “box” in the femoral component. Also in this study the authors expressed their concerns about premature polyethylene wear in the posterior-cruciate retaining designs.

Banks et al. (1997) studied step-up activity with fluoroscopy in three groups of patients with excellent clinical results and no differences regarding range of motion. Group 1 received a comparatively flat insert with retention of the PCL and group 2 had the same insert and resection of the PCL. In group 3 the PCL was resected but was substituted using PS design. Abnormal kinematics was observed in all three groups. The axial rotations and condylar translations were, however, similar to those reported for normal and ACL deficient knees in group one. If the PCL was resected or substituted less axial rotations and translations was seen and especially in the latter group. The authors concluded that both component selection and surgical technique influence the kinematics during functional activity.

Radiostereometry (RSA)

Despite that radiostereometry as a method dates back to the late 19th century (Davidson 1898), it did not reach general acceptance as a scientific method until the last decades of the previous century. The scientific approach and methodology presented by Göran Selvik (1974, reprint 1989) and the ensuing development of his system both technically (Söderkvist and Wedin 1993, Nyström et al. 1994, Östgaard et al. 1997, Vrooman et al. 1998, Yuan 1999, Börlin 2000) and in clinical praxis (Kärrholm 1989, Kärrholm et al. 1997) contributed to this increased interest. RSA can be used for studies of migration, inducible displacements of prosthetic components and kinematics of the knee.

The first dynamic study of the knee using the RSA technique was performed using film-exchangers. With this equipment active knee motion could be recorded at a speed of four exposures per second. The set-up did, however only allow studies with the patient in the supine or prone position. Later, studies were undertaken during weight bearing, but these were pursued statically by repeated exposures from 70–80 degrees of flexion to full extension. Studies of the normal side in patients with a unilateral tear of the ACL revealed increasing internal tibial rotation and minimum varus angulation up to 40–45 degrees of flexion. There was individual variation and some of the knees displayed a slight external rotation and valgus angulation with increasing flexion (Kärrholm et al. 1988, Jonsson et al. 1989, Jonsson and Kärrholm 1994).

Later, these studies were repeated using a new set-up, which allowed examinations in the weight-bearing position. Kärrholm et al. (2000) have performed radiostereometric studies of normal knees during active extension when the patients ascended a platform. The tibia rotated about 5° externally from 50° of flexion to full extension. During extension the medial femoral condyle displaced posteriorly contrary to the lateral condyle, which translated anteriorly between 40° and up to full extension. The authors also found that the relative motions of the femoral condyles could change if the foot was placed in external rotation. Pinskerova et al. (1999) and Iwaki et al. (1999) who had pursued MRI studies of the unloaded cadaver knee, had earlier predicted these observations. Hill et al. (1999) had reported similar results when they performed MRI examinations of unloaded and living knees.

Nilsson et al. (1990) used film-exchangers to study the kinematics of the Tricon-M (Smith and Nephew, Memphis, TN) knee prosthesis, which is a relatively constrained prosthesis with two deep concave excavations for the femoral condyles. In the prone position this prosthesis showed only small rotations in the horizontal and frontal planes up to 25 degrees of flexion. This was explained by the conformity of the joint area. Beyond 25 degrees the initially small internal tibial rotation tended to increase and there was a more pronounced valgus angulation. The anterior-posterior (AP) translations were twice of those observed in normal knees. These findings indicated that the stability decreased with increasing flexion because of decreasing contact area and a tendency of the femoral component to dislocate out from of tibial trough. The authors hypothesised that absence of the cruciate ligaments was one important reason for this observation.

Later the same group (Nilsson et al. 1991) investigated the Miller-Galante I (Zimmer, Warsaw, IN) with shallow tibial surface and the LCS (DePuy, Johnson & Johnson,Warsaw, IN) knee replacements with the same set-up. Despite retention of the PCL the posterior tibial translation was as pronounced as in their previous study. The Tricon-M and Miller-Galante knee replacements were also studied using static exposures and weight-bearing (Kärrholm et al. 1994). At the observed ranges of flexion/extension the findings were fundamentally the same. Compared to normal both designs showed decreased internal rotation and increased posterior translations of the tibial plateau during flexion of the knee. The authors believed that the PCL had lost its normal function after the TKR.

The posterior cruciate ligament, retain or sacrifice?

Arguments for retention

Many authors have discussed the role of the PCL in knee replacements; if it should be retained, resected or substituted with a posterior-stabilised design. Despite this, and as far as I know, no study evaluated this question in a prospective and randomised way. In clinical practice three factors with a more or less pronounced interference influence the surgeons choice between these alternatives. Those are 1) preferences of the individual surgeon, which are influenced by clinical and scientific experience and other unknown reasons, 2) degree of knee deformity, and 3) type of implant chosen, which partly can be related to points one and two.

As have been discussed earlier, many authors (Andriacchi et al. 1982, Andriacchi and Galante 1988, Andriacchi and Hurwitz 1997) prefer retention of the PCL because they found that less constrained cruciate retaining TKAs were associated with more normal gait, increased range of motion and better quadriceps efficiency. Authors in favour of retention (Goodfellow and O'Connor 1978, Sorger et al. 1997, Andriacchi et al. 1999) also claim that the PCL will facilitate femoral rollback. Li et al. (1995) concluded that the PCL not only improved range of motion and stability but also proprioception, which was also pointed out by Skinner et al. (1984). Another argument to retain the ligament has been that resection is not compatible with the use of a non-conforming design, which is believed to subject the interface to lower stresses (Hungerford and Krackow 1985, Landon et al. 1986, Thatcher et al. 1987). Dorr et al. (1988) questioned resection of the PCL as this procedure resulted in increased medial loading and higher joint reaction forces, which could affect the durability of the prosthesis.

Retention equal to resection

Several studies have not been able to find any substantial differences between cruciate retaining and sacrificing designs. Becker et al. (1991) compared bilateral-paired cruciate-retaining and cruciate-substituting total knees. No clinical advantage of one TKA over the other was observed, but the authors recommended resection to avoid problems with ligament tension. In this study the choice of prosthetic design was, however, not randomised as the more deformed knees usually received the cruciate-substituting prosthesis. Also Shoji et al. (1994) studied patients with bilateral TKR where the PCL was retained in one knee and resected in the other. Patients who ascended and descended stairs with one leg at a time seemed to prefer the side with the ligament left in place, whereas patients who could use their legs in sequence had no preference for any of their knees.

Hirsch et al. (1994) evaluated three groups of patients with total knee arthroplasties with preserved, resected or substituted ligament. They found no difference except a significantly increased range of motion in the PCL substituting prosthesis and suggested that the retained PCL did not necessarily improve the function of the TKR. Maloney and Shurman (1992) compared patients operated with the total condylar prosthesis or the posterior stabilised design. Contrary to the previous authors they did not find any differences in range of motion or functional result. The authors had the opinion that, whatever design used in a knee replacement, the improvement regarding the range of motion decreased with increasing range of preoperative motion. Huang et al. 1998 could not find that presence of the ligament had any influence on the strength of the hamstring muscles after a knee replacement. Neither could Lattanzio et al. (1998) demonstrate any improvement of knee-joint proprioception and suggested that retention of the PCL did not improve the function after TKA.

Arguments for resection

In knees with severe deformities several authors have recommended resection of the PCL to facilitate the surgical procedure (Freeman and Railton 1988, Worland et al. 1997, Pereira et al. 1998). Stein et al. (1988) pointed out that not only prosthetic design but also surgical technique used to obtain ligamentous balancing might influence the final result. Many studies (Insall 1988, Aglietti and Buzzi 1988, Groh et al. 1991) have reported excellent results after substitution of the PCL with a posterior-stabilised design. Matsuda et al. (1997) concluded that resection improved extension strength and range of motion, but increased the risk of dislocation (Galinat et al. 1988, Lombardi et al. 1993).

In conclusion, there is no consensus whether the PCL should be retained or sacrificed. The final decision will often depend on the preoperative status of knee, the choice of implant, previous experience of the surgeon or the surgical team at the local hospital. There is, however, no doubt that the surgical procedure will be facilitated if the PCL is resected in cases with severe deformities (Freeman et al. 1978).

Wear

The bearing surface in knee replacements is made of ultra-high molecular weight polyethylene. The weakness of this material to resist shear stresses is today considered to be the major limitation for the longevity of total knee arthroplasty. Inflammatory reaction due to wear particles, delaminating and exposure of the tibial metalbacking to the femoral component can result in rapid and massive destruction of the underlying bone.

The true wear is more difficult to measure on radiographs of total knee prostheses than with hip replacements (Colizza et al. 1995). The amount of wear depends on the degree of conformity (Wright and Bartel 1986, Argenson and O'Connor 1992, Plante-Bordeneuve and Freeman 1993), operative technique including mechanical alignment and fixation of the components (Plante-Bordeneuve and Freeman 1993, Cameron 1994, Wasilewski et al. 1994). Other factors of importance are the presence of third bodies (Hood et al. 1983, Landy and Walker 1988) and the thickness and the quality of the polyethylene (Bartel et al. 1986, Wright and Bartel 1986, Wright et al. 1988, Engh et al. 1992, Li and Burstein 1994).

Compared to total hip replacements, the wear particles from the polyethylene in a knee prosthesis are larger and often flake-shaped (Landy and Walker 1988, Wright et al. 1988, Collier et al. 1991). According to Blunn et al. (1997) the most dangerous and destructive wear is delamination of the polyethylene.

Schmalzried and Callaghan (1999) divided wear into four types. Mode-1 is necessary for the function, whereas modes-2 to 4 are unintended. Thus, mode-1 wear is an effect of the intended motion between 2 surfaces (known as primary surfaces), e.g. the femoral component that moves against the polyethylene in a knee replacement. Mode-2 wear is non-intended and occurs when one primary surface moves against an "unintended" surface e.g. if the femoral component moves against the metal backing of the tibial component due to severe polyethylene damage. Mode-3 corresponds to third body wear. Mode-4 wear occurs when two surfaces, meant to be fixed move against each other (e.g. a modular stem or peg that moves at its fixation to the tibial tray).

Reduction of wear particles has been regarded to be of vital importance to reduce the risk of osteolysis (Kadoya et al. 1998). Osteolysis is not as common in knee replacements as in hip replacements, probably because the wear particles have a different size distribution. According to Colizza et al. (1995) it is more frequent when flat components are used, at least in cemented implants.

Oxidation of the polyethylene will facilitate its degradation. This process is accelerated by free radicals caused by gamma irradiation in air for sterilising purposes. Delamination of the plastic might be initiated in oxidised areas located one to two millimetres under the articulating surface (McKellop et al. 1999).

In modular knee implants the polyethylene insert may also wear at its backside (that is against the metal backing). Engh et al. (2000) demonstrated that such wear could be an effect of inefficient locking mechanism.

As early as 1986 Bartel et al. recommended that the thickness of the polyethylene in knee replacements should be at least eight to ten millimetres. Later, Wright et al. 1992 raised concerns about the use of thin polyethylene in non-conforming design and especially if they were used in young and active patients. Findings of high wear in non-conforming TKR also became a common observation (Engh 1988, Mintz et al. 1991, Engh et al. 1992, Jones et al. 1992, Tsao et al. 1993, Bosco et al. 1994, Toksvig-Larsen et al. 1996, Kadoya et al. 1998, Wimmer et al. 1998). According to Blunn et al. (1997) increased knee joint laxity, which may occur more easily with the use of flat inserts, will result in edge loading. Consequently, very high contact forces resulting in delamination towards the edges of the tibial component will occur. There have also been concerns that the abnormal anterior femoral translations in the posterior cruciate retaining knee replacements could be a factor in premature polyethylene wear (Dennis et al. 1996, 1998).

The more conforming tibial inserts have larger contact areas and consequently lower contact stresses. This will result in better wear characteristics (Insall et al. 1983, Colizza et al. 1995, Szivek et al. 1996).

Thatcher et al. (1987) investigated the laxity of knee replacements. They pointed out that conformity not only influences the degree of laxity but also the stresses in the plastic and thereby long-term wear. As in a number of previous and later studies they also raised concerns that conforming prostheses would create greater implant-bone interface stresses. However, this has not been found to result in greater migration for constrained prostheses evaluated with RSA (Regnér et al. 2000). Moreover, in posterior-stabilised designs repeated contact between the central polyethylene cam and the corresponding femoral box may increase the total burden of wear particles produced.

Fixation—migration

RSA studies of the fixation of the tibial component in TKA have mainly focused on the use of cement or not. In uncemented knee replacements most of the migration will occur in the first three months and then stabilise. The migration of the cemented prosthesis will initially be small but continues over time. According to Ryd et al. (1995) the migration of the tibial component during the second postoperative year can be used to predict future clinical loosening. In that study 155 patients were followed over a period of 13 years. In the patients who were not revised the mean migration of the tibial component was about 1 mm at one year and at ten years 1.5 mm. The migration recorded was significantly higher at one year in patients revised due to loosening of the tibial component. Fukuoka et al. (2000) reported a similar correlation between early stability and later migration.

Pioneer studies of cemented and non-cemented tibial components reported mean migration values of one and two mm (maximum total point motion, MTPM) after two years follow up (Ryd 1986). Albrektsson et al. (1990) found that a tibial stem significantly improved the stability in cementless fixation. In later studies the migration values have tended to decrease to about 0.5 mm (Regnér et al. 1997, 1998). Improvements in cementing technique, prosthetic design and the introduction of hydroxyapatite (HA) coating are probably the reasons for this improvement.

Cemented versus uncemented fixation

Nilsson et al. (1991) randomly compared porous coated Tricon-M (Smith and Nephew, Memphis, TN) prostheses with and without cement in patients with arthrosis and rheumatoid arthritis. They found no differences between these groups. When the same implant was used with a stem in rheumatoid patients superior fixation was observed, but only in the cemented group (Nilsson et al. 1993). The same group also compared porous coated Miller-Galante I (Zimmer, Warsaw, IN) prostheses fixed with or without cement. After two years the tibial component displayed more medial/lateral tilt in the uncemented group, whereas the fixation turned out to be equal on the femoral side (Nilsson et al. 1995).

Albrektsson et al. (1992) studied the effect of cementing the tibial component of the Freeman-Samuelson (Protek AG, Berne, Switzerland) prosthesis. The cemented implants had significantly less migration one year postoperatively, with mean values of 0.5 and compared with 1.5 mm in the cementless group. Toksvig-Larsen et al. (1998) found less subsidence of cemented porous coated anatomic (PCA; Howmedica, Rutherford, NJ) prostheses compared to uncemented components of the same design after two years.

Regnér et al. (1998) studied the uncemented Miller-Galante II (Zimmer, Warsaw, IN) prosthesis with or without hydroxyapatite/tricalcium phosphate (HA/TCP) coating. At two years the HA/TCP tibial components had smaller anterior-posterior tilt and less subsidence. Toksvig-Larsen et al. (2000) studied four different uncemented knee arthroplasties and could confirm that HA coating improved the fixation. Önsten et al. (1998) compared the migration in hydroxyapatite-augmented porous coating, porous coating, and cemented fixation of the tibial component in the Press-Fit Condylar (PFC; DePuy, Johnson & Johnson, Warsaw, IN) design. The authors found that the porous group had significantly larger MTPM differences at two years than the HA and the cemented knees. It was concluded that HA-coated prostheses had a clinical advantage over porous coating but were not better than cemented implants. Nilsson et al. (1999) found that the HA-coated Tricon II (Smith and Nephew, Memphis, TN) total knee arthroplasties displayed most of the migration in the first three months after surgery and then stabilized. The cemented knees showed initially lower migration that increased over time. No differences in the fixation were detected between the two types of implants after five years. In summary, comparisons between cemented and uncemented fixation using press-fit or porous coatings have shown that cemented fixation is either superior or that there is no difference. Two studies have shown that HA improves the fixation of uncemented implants, but none that it is superior to cemented fixation. It should, however, be noted that the follow up periods in these studies do not exceed five years.

Other factors which influence fixation

Other issues that have been studied in a randomised way are the use of a stem/metal backing or not (Albrektsson et al. 1990, Hilding et al. 1995, Adalberth et al. 2000), cooled saw blade vs. conventional (Toksvig-Larsen et al. 1994) and bone cements (Nilsson and Dalén 1998, Adalberth et al. 2000). The influence of the design of the tibial insert on the migration has not apparently, been studied exclusively.

Fixation—inducible displacements

Inducible displacement is defined as "instant micromotions occurring in response to external forces" (Ryd et al. 1986) or as "reversible motion of the prosthesis relative to the bone induced by external force" (Toksvig-Larsen et al. 1998). Ryd et al. (1986, 1989) were of the opinion that these motions mirrored the quality of the prosthetic-bone or cement-bone interface.

Toksvig-Larsen et al. (1998) found a weak correlation between inducible displacement at one year and migration up to one year in tibial components inserted with or without cement. A similar correlation had previously been demonstrated by Hilding et al. (1995). Regnér et al. (2000) examined uncemented tibial components and found an association between the inducible displacement at one and the migration at five years. It can be concluded that inducible displacement of the tibial component can, to some extent at least, predict implant migration.

Radiographic evaluation of knee replacements

Despite the development of more sophisticated methods, conventional radiography and especially weight-bearing examinations, remain as cornerstones to establish the presence and severity of arthrosis (Boegård and Jonsson 1999). The scoring system (grade 1 to 5) introduced in 1968 by Ahlbäck is still widely used to determine the degree of OA.

Hagstedt and Tjörnstrand introduced the hip-knee-ankle angle (HKA) in the beginning of the 1980s to better determine the preoperative deformity before performing a high tibial osteotomy (Hagstedt et al. 1980, Tjörnstrand et al. 1981). The HKA angle is determined on long-leg radiographs. Positions less than 180 degrees are in varus. Weidenhielm (1992) and Hilding et al. (1995) found correlations between the knee joint moments in the frontal plane and the Hip-Knee-Ankle (HKA) angle before and after TKA, which confirms that this angle reflects the loading conditions during gait.

As early as 1977 Lotke and Ecker discussed the importance of correct positioning of the prosthesis to avoid failure. Measurements of implant positioning are therefore an important part of the clinical evaluation. In 1989 the Knee Society introduced the Total Knee Arthoplasty Roentgenographic Evaluation and Scoring System (Ewald 1989). They also introduced the FAP-angle corresponding to the alignment of the femoral component on the AP-view. If this angle is less than 90 degrees the component is placed in varus.

Albrektsson and Herberts (1988) presented a method to measure the position of the tibial component on the AP-view (PT-angle) and on the lateral radiographs (PTS-angle). A PT angle less than 90 degrees was defined as varus and a PTS angle less than 90 degrees as posterior tilt. According to several authors (Blaha et al. 1982, Albrektsson and Herberts 1988) angular tilt less than three degrees is not possible to detect on standard radiographs.

The information from different studies has raised questions regarding the ideal positioning of the components in TKA (Kim et al. 1993). There seems, however, to be agreement that increased risk of failure will occur if the tibial component is positioned in more than five degrees of varus, due to subsidence into more varus (Tew and Waugh 1985, Jeffery et al. 1991).

Nilsson et al. (1991) introduced a way to determine the AP position of the tibia in relation to the femur on lateral radiographs of the extended knee. A reconstructed centreline of the femoral diaphysis divides the tibia into two parts, one anterior (a) and one posterior (b). The ratio 100 x a/(a + b) is calculated. A value less than 50 means that the tibial centre is positioned anterior to the femoral centre line.

Measurements of the width and length of the radiolucent lines (RLL's) under the tibial tray and around the stem are widely used to estimate the fixation of tibial component. A simplified way to report these measurements is the Knee Society X-ray score (Ewald 1989). For a tibial component of seven regions (like the AMK-prosthesis with stem) the RLL's are rated into three groups: 1) total sum of RLL's up to 4 mm (i.e. probably non-progressive, probably not significant), 2) 5–9 mm (should be followed for progression), and 3) 10 mm or more (possible or impending failure, regardless if symptoms or not). Smith et al. (1999) evaluated "the natural history" of the radiolucent lines in cemented tibial components. The authors concluded that in low-wear prostheses the RLLs were caused by failure to inject cement into sclerotic bone. These lines were nonprogressive and did not affect the fixation of the tibial component. However, in the case of severe wear these lines could represent a portal for entry of debris into the interface and thereby cause progression and lysis. Other authors have regarded progression of the radiolucent lines to be a sign of instability (Ritter et al. 1994, Nilsson et al. 1995, 1999).

Clinical evaluation of outcome

Since the early reports of Walldius it became more and more evident that introduction of total knee replacement could improve the quality of life by elimination or reduction of pain and improved function. The extent of these beneficial effects needs objective documentation. Today, there are an increasing number of scores to assess results after this surgical procedure. These scores can be divided into three different types; general, disease-specific and patient-specific questionnaires.

1) A *general* (generic) scoring system mirrors the general health of the patient (health-related quality of life evaluation, HRQL). It enables comparison of treatments for different diseases also outside the orthopaedic fields of medicine (Bombardier et al. 1995). A disadvantage is that this type has shown low responsiveness. The Medical Outcomes Study 36-item Short-Form Health Survey (SF-36) and the Nottingham Health Profile (NHP) are examples of self-administered general questionnaires with high validity (i.e. it measures what it is supposed to measure) and reliability (i.e. reproducible over time). The NHP was created in the 1980s in Europe and consists of 45 questions (Yes or No) and originates from the Sickness Impact Profile (SIP) with more than 100 questions. It has been criticised for difficulty to

make statistical evaluations (nominal data). An earlier version of SF-36 is the Medical Outcome Study (MOS), which also has more than 100 questions (compared with 36 questions for SF-36). The SF-36 was originally developed in Northern America in the beginning of the 1990s for use in psychometric theory. It was used to test health-related quality of life and was also compared to NHP (Ware and Sherbourne 1992, Brazier et al. 1992). The SF-36 has the advantage of quantitative responses, which facilitates statistical interpretations. However, older people or the untalented might have difficulties in understanding the questions. Depending on the complexity of the SF-36 efforts have been made to create simpler tests such as the SF-12 and EuroQol (also known as EQ or EQ-5D). This latter test consists of five questions, which can be answered in three different ways. The disadvantage with the EuroQol is that it is considered to be less responsive than the SF-36, but does have acceptable validity and reliability although lower than SF-36 or NHP (Söderman and Malchau 2000).

2) A *disease-specific* scoring system provides questions about the disease under study (e.g. knee arthrosis) and should not be influenced by other illnesses. This type will give higher responsiveness than general (generic) questionnaires/scoring systems. By its nature it cannot be used to compare e.g. the degree of success of a total hip replacement with coronary by-pass surgery. Another disadvantage is the risk of bias if a staff-administrated questionnaire is used (e.g. for Harris Hip Score or the HSS score) (Harris 1969, Ranawat and Shine 1973). The Western Ontario and McMaster University Osteoarthritis Index (WOMAC; Bellamy et al. 1988, Sun et al. 1997) is an example of a modern self-administered questionnaire with both high validity and high reliability and also with high responsiveness. WOMAC has been tested in more than 20 different countries with good results. Söderman and Malchau (2000) recommended it after total hip arthroplasty.

3) *Patient-specific* evaluations such as the McMaster Toronto Arthritis Patient Preference Disability Questionnaire (MACTAR; Tugwell et al. 1987) focus on the patients' physical and social function. Before treatment the patient ranks his or her disabilities. At the follow-up after the treatment, changes in the ability of each activity are recorded. Disadvantages with the MACTAR questionnaires are difficulty in testing validity and reliability.

The most used outcome measure of knee replacements is the HSS score developed at the Hospital for Special Surgery (Ranawat and Shine 1973) and the Knee Society Scoring System (Ewald 1989). It is a staff-administered questionnaire with a maximum score of 100 points. Pain at rest and when weight bearing has a high impact (30 percent of the total score). Function (walking distance, if aid is necessary when walking, ability in stair climbing and rising from a chair) gives maximum 22 points and range of motion 18 points. Finally a maximum of 30 points are used to evaluate extension defects (active and passive), instability and muscular strength. A HSS score between 85 and 100 points is regarded as excellent. Disadvantages include risk of bias and difficulties to compare patient groups e.g. with single, bilateral or multiple joint disease (Albrektsson 1991).

In conclusion, reliable outcome measures to give an indication of results after TKA are important, but all systems seem to suffer from more or less pronounced limitations. The advantage with the HSS score is that it is widely used and therefore comparison with earlier results can be made. Generic tests enable comparison of the outcome after TKR with other treatments not only within orthopaedics. Patient specific questionnaires are interesting tools to collect information about the expectations of the patient and to what extent these expectations have been fulfilled by the treatment given.

Aims of the study

The overall aim was to study the influence of designs of the joint area on the knee joint kinematics, tibial component fixation, and clinical outcome after a cemented AMK total knee arthroplasty (Depuy, Johnson & Johnson, Warsaw, IN) with the PCL retained or resected. The work was performed in a series of randomised clinical trials.

The kinematics of the knee during active extension were studied using dynamic radiostereometry. Migration and inducible displacements of the tibial component were evaluated using RSA. Conventional radiography was used to evaluate the positioning of the implant and development of radiolucencies. The HSS score and a questionnaire about the patient's expectations and the fulfilment of these expectations one and two years postoperatively were used at the clinical evaluation.

The specific aims were:

Study 1: In vivo kinematics of total knee arthroplasty. Flat versus concave tibial joint surface

To study the influence of the configuration of the joint area on the kinematics of the knee in patients with deformities not exceeding five degrees in varus/valgus and fixed flexion deformities less than ten degrees. The patients randomly received a non-conformed (flat) or a more concave (constrained) tibial polyethylene insert (Figure 1). The PCL was retained. Our hypothesis was that use of a concave joint area would result in smaller rotations and translations during active motions. Presence of any relation between the kinematics and component positioning or the clinical result one year after the operation was evaluated. These patients also participated in study 3.

Study 2: In vivo kinematics of total knee arthroplasty. Concave versus posterior-stabilised tibial joint surface

To evaluate the influence of the configuration of the joint area on the kinematics of the knee in patients with deformities exceeding five degrees in varus/valgus and/or fixed flexion deformities of more than ten degrees. The patients randomly received a concave (constrained) insert or a posterior stabilised (Figure 2) prosthesis. The PCL was resected. Our hypothesis was that use of the posterior stabilised design results in less translation and rotation. Correlations between the kinematics and component positioning or the clinical result one year after the operation were studied. These patients also participated in study 4.

Study 3: Flat versus concave tibial joint surface in total knee arthroplasty. Randomised evaluation of 39 cases using radiostereometry

To evaluate if the choice of a non-conformed or a more concave polyethylene insert had any influence on tibial component migration, development

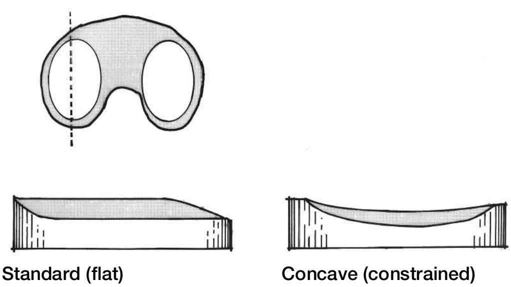

Figure 1. Diagram showing (top) a sagittal section through the central part of the condyle in the flat (standard-left) and concave (constrained-right) designs.

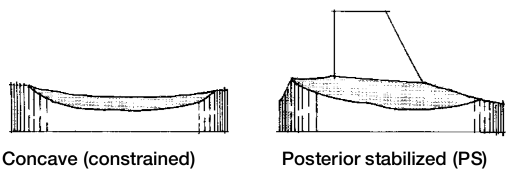

Figure 2. Diagram showing (top) a sagittal section of the condylar area of the two components and the concave (left) and posterior-stabilised (right) inserts of the AMK knee replacement.

of radiolucent lines or the clinical results two years after the operation. All patients who entered the study had the same type of deformities as presented in study 1 and the PCL was retained in all cases. Our hypothesis was that use of a comparatively non-conformed design would result in smaller micromovements of the tibial component.

Study 4: Concave versus posterior-stabilized tibial joint surface in total knee arthroplasty. Randomized evaluation of 47 knees

To evaluate if the choice of a concave polyethylene insert or a posterior stabilised design had any influence on tibial component migration, development of radiolucent lines or the clinical results two years after the operation. Patients who entered the study had the same type of deformities as presented in study 2. The PCL was resected in all cases. Our hypothesis was that use of a concave design would result in smaller micromovements of the tibial component. We also hypothesised that the PS design would result in improved feeling of stability.

Study 5: Inducible displacements of cemented tibial components. Observations during dynamic radiostereometry related to joint positions and 2 years history of migration in 16 TKR

To study the inducible displacements of the tibial component during active extension of the knee in patients, who had received an AMK knee replacement with different designs of the joint area. Our hypothesis was that variations of the inducible displacements were dependent on the degree of flexion and that motions of the knee induce rocking and translatory motions of the tibial tray. The number of knees available was limited due to difficulties in visualising prosthetic markers during dynamic examination. In groups with sufficient observations we also tried to evaluate whether the inducible displacements were related to the design of the joint area. These patients were recruited from study 1 and 2.

Patients, methods and study design

Patients

Study 1: The kinematics of the knee were studied in 22 patients after a TKA with the PCL retained. They all had deformity of the knee not more than than five degrees of varus/valgus (Table 1).

Study 2: The kinematics were studied in 20 patients (22 knees) after a knee replacement with the PCL resected. All knees had deformity exceeding five degrees of varus/valgus and/or a fixed flexion deformity of more than ten degrees. Two patients (males) underwent surgery on both sides but not with the same implant (Table 2).

Study 3: Migration of the tibial component and clinical outcome were studied in 40 patients after a TKA with the PCL retained. The deformities were of the same type as in study 1 (Table 3). One patient (female, concave insert) died of causes not related to the knee replacement. In one patient poor tantalum marking made RSA evaluation impossible and in one patient sufficient markers were not visualised at the postoperative examination but at the following evaluations (i.e. 3 months – 2 years). Thus, 37 patients (20 flat, 17 concave) were examined with RSA up to two years.

Study 4: Migration of the tibial component and clinical outcome were studied in 47 knees (43 patients) after implantation of prosthesis with the PCL resected. The knees had preoperatively the same deformities as in study 2 (Table 4). Four pa-

Table 1. Patient data. Median, *range* (when applicable)

	Type of polyethylene insert	
	Flat	Concave
Number of patients	11	11
Age (years)	69 *60–77*	66 *60–79*
Gender (M/F)	1 / 10	5 / 6
Type of arthrosis (M/L)	11 / 0	9 / 2
Ahlbäck grade 1 to 5	0 / 1 / 7 / 3 / 0	0 / 0 / 7 / 4 / 0

Table 2. Patient data. Median, *range* (when applicable)

	Type of polyethylene insert	
	Concave	PS
Number of knees	11	11
Age (years)	71 *60–80*	69 *53–81*
Gender (M/F)	7 / 4	6 / 5
Type of arthrosis (M/L)	7 / 4	8 / 3
Ahlbäck grade 1 to 5	0 / 0 / 3 / 4 / 4	0 / 0 / 4 / 4 / 3

Table 3. Patient data. Median, *range* (when applicable)

	Type of polyethylene insert	
	Flat	Concave[1]
Number of patients	20	20 (19)
Age (years)	70 *51–77*	68 *59–83*
Gender (M/F)	2 / 18	7 / 13
Type of arthrosis (M/L)	14 / 6	16 / 4
Ahlbäck grade 1 to 5	0 / 2 / 10 / 8 / 0	0 / 0 / 13 / 7 / 0
HKA-angle preop.	177 *173–182*	176 *175–185*

[1] One patient died between the 1- and 2-year follow-up.

Table 4. Patient data. Median, *range* (when applicable)

	Type of polyethylene insert	
	Concave	PS
Number of knees	25 (24)[1]	22 (19)[1,2]
Age (years)	71 *50–82*	70 *53–81*
Gender (M/F)	10 / 15	12 / 10
Type of arthrosis (M/L)	18 / 7	13 / 9
Ahlbäck grade 1 to 5	0 / 0 / 8 / 10 / 7	0 / 0 / 7 / 11 / 4
HKA-angle preop.	172 *166–197*	189 *166–208*

[1] Two patients (1 C, 1 PS) were revised before the 1-year follow-up.
[2] Two patients (PS) died between the 1- and 2-year follow-up.
[3] No correlation between preop. HKA-angle and migration/clinical results after 2 years.

Table 5. Patient data. Median, *range* (when applicable)

Age (years)	69 *53–80*
Type of arthrosis (M/L)	10 / 6
Ahlbäck grade 1 to 5	0 / 1 / 4 / 7 / 4
HKA-angle postop.	177 *170–185*
Type of insert	
Flat [1,2]	4
Concave [1,2]	1
Concave [3,4]	5
Posterior-stabilized [3,4]	6

[1] Varus/valgus deformity ≤ 5°.
[2] PCL retained.
[3] Varus/valgus deformity < 5° and/or fixed extension deformity > 10°.
[4] PCL resected.

tients (three male, one female) underwent bilateral TKAs but not with the same implant on the two sides. Two patients (male, PS implants) died before the two years follow-up of reasons not related to the knee replacements. Revision surgery was performed in two patients due to pain/instability (male, concave insert) and fracture of the tibial plateau (female, PS design), respectively. Two patients (concave plateaus) were excluded from the RSA evaluations, as too few markers were inserted peroperatively. RSA examinations were performed in two patients (1 C, 1 PS) between three months and two years (too few markers were seen postoperatively). Thus, complete radiostereometric examinations were undertaken in 39 knees (21 concave, 18 PS).

Study 5: The inducible displacement of the tibial component caused by active extension and clinical outcome were studied in 16 knees (15 patients). The patients were selected from the main study group of 87 knees. From the kinematic studies patients were selected on the basis of successful RSA examinations. Consequently in 16 of the knees where the kinematics were successfully examined it was also possible to evaluate the migration up to two years and the inducible displacements of the tibial component (Table 5).

Control group

Eleven normal knees in 11 patients (8 male, 8 female, median age 25 years, range 18–41) served as a control group in studies 1–2. These knees were marked with tantalum pellets primarily for comparison with the contralateral knee, which had a tear of the anterior cruciate ligament (Brandsson 2000). These patients were younger than those who received a knee arthroplasty because age-matched controls were not available.

Methods

Implants

All patients received a cemented AMK (DePuy, Johnson & Johnson, Warsaw, IN) total knee arthroplasty. The AMK knee replacement is a modification of the total condylar design (Figure 3–8). The femoral component has a comparatively short proximal flange on the ventral side. It is "box" shaped on the lateral view. The tibial component has a stem and two short metal pegs. It is polished on the proximal side and has grooves to fit with the tibial insert. The fixation of the polyethylene against the tibial component is also secured with a metal peg and a clip.

If the patella was resurfaced a cemented polyethylene patellar prosthesis was inserted. The choice of patellar resurfacing or not was made by the surgeon. In total 38 patients (PCL retained: 10 F, 8 C/PCL resected: 12 C, 8 PS) received a patellar prosthesis.

Randomisation

The patients were divided into two groups. Group 1 with a varus/valgus deformity of the knee of five degrees or less and group 2 with a corresponding deformity exceeding five degrees and/or a fixed flexion deformity of more than ten degrees. Within the groups a computer programme (Pocock 1983) based on a minimisation method was used to randomly allocate patients to one of the two polyethylene inserts. This allocation was based on age, (<70, ≥70 years), gender (male, female), walking distance (<500 m, ≥500 m), localisation of the arthrosis (medial/lateral) and presence of previous surgery or not. In patients who received a second implant in the same study (on the opposite side), the surface design that had *not* been used on the first operated knee was inserted. Thus, none of these patients in each study had the same joint area design on both sides.

Figure 3. The cemented AMK (DePuy, Johnson & Johnson) total knee arthoplasty.

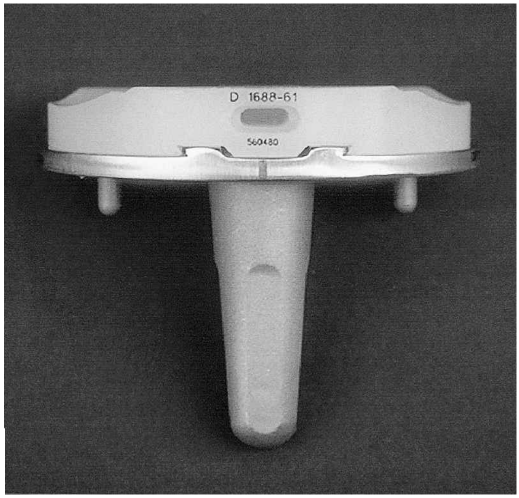

Figure 4. AP-view of the tibial component with a flat polyethylene insert.

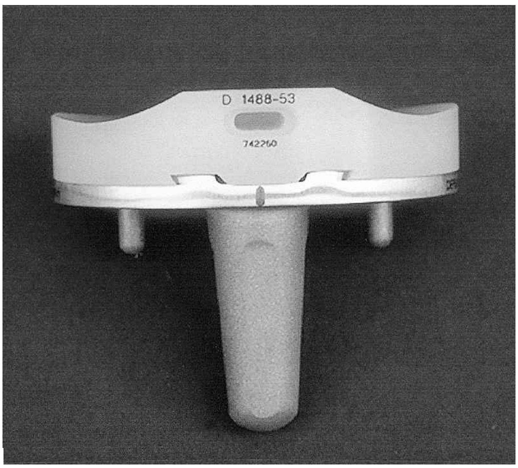

Figure 5. AP-view of the tibial component with a concave/constrained insert.

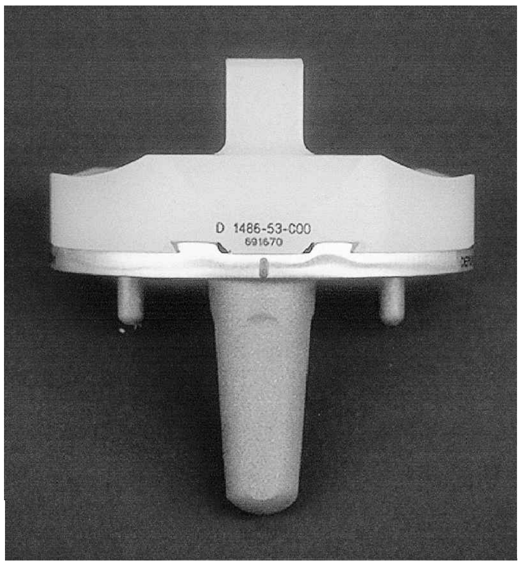

Figure 6. AP-view of the tibial component with a posterior-stabilised (PS) insert.

Surgical technique

Spinal or epidural anaesthesia and a tourniquet were used. The knee was approached medially through a standard anterior incision. Five surgeons did the operations. They had seven to more than 20 years experience of TKA. The PCL was retained in group 1 and resected in group 2. After preparation of the bone and before cementing of the tibial and femoral components, six to nine (size 0.8 mm) tantalum markers were inserted into the proximal tibia, and the same in the femur. The polyethylene insert was prepared with three 0.5 mm and three 0.8 mm tantalum spheres according to a specific protocol. Routine mobilisation with full weight bearing within pain limit began on the first day after operation.

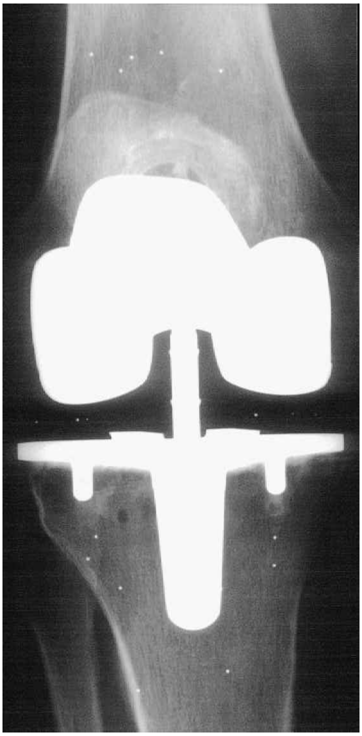

Figure 7. AP-view of the AMK prosthesis with a posterior-stabilised (PS) insert.

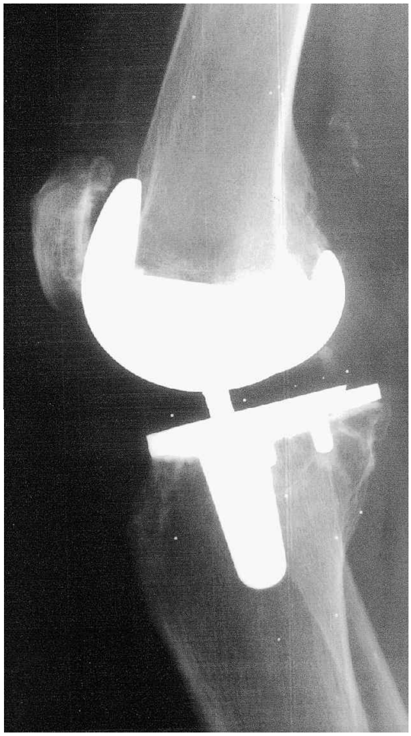

Figure 8. Lateral view of the AMK prosthesis with a posterior-stabilised (PS) insert.

Evaluation of stereoradiographs

Study 1 and 2: Kinematics

The kinematics of the knee after TKA was studied using film-exchangers. A new set-up was developed to enable recordings during active motion and weight bearing. Two film-exchangers were mounted on a frame with adjustable height and angular positions. All examinations were made at a constant angle of 90°, with the height of the set-up adjusted according to the length between the knee joint and the foot in the individual patient. Two reference plates (Kärrholm et al. 1988, Jonsson et al. 1989, Nilsson et al. 1990) made of Plexiglas and fitted with tantalum markers were fixed in front of the screen of each film exchanger. The Plexiglas cage, also fitted with tantalum markers (Kärrholm et al. 1988), and the reference plates were stereoradiographed to obtain a calibration exposure (Figure 9). Information from this examination was used to transform the laboratory coordinate system to the subsequent examinations of the patient using the position of the images of the reference markers. The calibration examination of the cage was also used to compute the position of the two roentgen foci. Thus, these positions and the positions of the film-exchanger had to be fixed after the calibration examination had been exposed.

The examination of the knee kinematics was performed in three steps:

1. With the patient supine and the knee straight a reference position at zero degrees of flexion was determined. At this examination we aimed to align the knee with the coordinate system defined by the calibration cage (Kärrholm et al. 1988). The posterior edge of the femoral condyles should be as parallel with the transverse axis as possible and the longitudinal axis should be parallel with the longitudinal axis of the tibia. This reference position was always used as a starting position for the subsequent dynamic examinations. Thus, in cases where the patient passed full extension during weight-bearing and active motion, the relative tibiofemoral positions could be different from those recorded in the supine position.

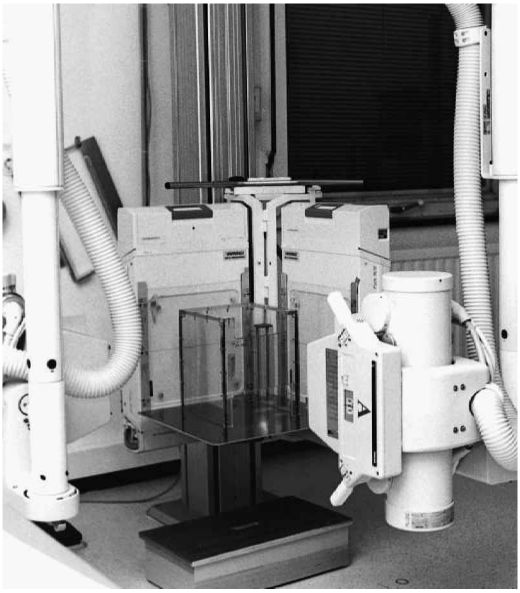

Figure 9. The radiographic set-up. Two film-exchangers angulated 90° in relation to each other are mounted on a stand, which enables adjustments in the proximal-distal directions to suit the length of the individual patient. Examination of the calibration cage and the reference plates is shown.

2. Then the patient positioned the operated knee on a platform (height eight cm) with the foot in a neutral position and performed trial extensions until those could be pursued in a comfortable way and at a fairly constant speed. The patient was also taught to maintain the knee within the limits of the aperture.

3. After three to six trials the knee was examined from the most flexed position possible to full active extension using sequential radiostereometric exposures (3–4 per second) over 1.5 to 4 seconds. This corresponded to six to 14 pairs of radiographs (Figure 10 and 11).

The tantalum markers in the *femur were used as a fixed reference segment to calculate the relative tibial rotations* (flexion/extension, internal/external rotation, abduction/adduction) *and translations* (at the centre of the tibia) as have been described earlier (Kärrholm et al.1988, Jonsson et al. 1989, Kärrholm 1989, Nilsson et al. 1990, Jonsson and Kärrholm 1994, Kärrholm et al. 1994, Jonsson and Kärrholm 1999).

In the normal knees we used a central point between the two tips of the tibial intercondylar eminence to calculate the translations of the tibia (Kärrholm et al. 1988, Jonsson et al. 1989).

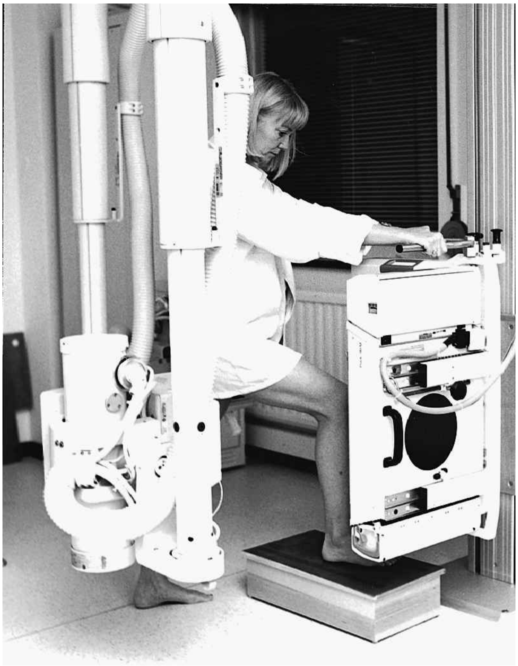

Figure 10. Starting position at the film-exchanger examination.

Figure 11. Final position at the film-exchanger examination.

At a second evaluation the tantalum markers in the proximal *tibia were used as a fixed reference segment to record the relative anterior-posterior translations of the femur*. The translations of a fictive point localised at the centre of a reconstructed circle described by the projection of the posterior part of the femoral condyles were measured. On the anterior-posterior view this point was located between the femoral condyles. The rotations (longitudinal and sagittal axes) and the translations were interpolated at intervals of five degrees of extension.

The reproducibility was tested in three patients, who repeated the whole procedure 15–30 minutes later. Between the two step-ups, the standard deviations of rotations and translation, respectively, varied from 1.6 to 2.3° and from 1.2 to 2.2 mm, when interpolated at 5° intervals of flexion.

The choice of evaluation was based on: 1) previous kinematic RSA studies which examined relative tibial motions, and 2) the presumption that studies of translations of the femur could add further information.

Study 3 and 4: Migration of the tibial component

Biplanar radiostereometric technique (Selvik 1974, reprint 1989, Ryd 1986) and the UmRSA 3.2 software was used (RSA Biomedical Innovations, Umeå, Sweden). Fictive points (artificial datum points) served as support to measure the translations of the tibial component (Kärrholm 1989, Nilsson et al. 1991).

The patients were studied one week postoperatively and after 3, 12 and 24 months. We evaluated the absolute rotations around the transverse, longitudinal and sagittal axes, maximum subsidence, maximum lift-off and maximum total point motion (Nilsson and Kärrholm 1992, Nilsson and Kärrholm 1993, Regnér et al. 1998, Nilsson et al. 1999).

The reproducibility of the RSA method has been tested in earlier studies at our department (Regnér et al. 1998). For the rotations and the proximal-distal translations precision varied between 0.15 to 0.30° and 0.07 mm, respectively (with 95% confidence limits). The accuracy is dependent on several factors; the most important being film quality, configuration and stability of the tantalum markers (Kärrholm 1989).

Study 5: Inducible displacements of cemented tibial components

In implants where at least three polyethylene markers could be identified between 45 and 15 degrees of flexion, motions of the insert were computed using the tibial bone markers as fixed reference segment. Thus, inducible motions were studied between the supine reference position and proceeding extension of the operated knee during weight bearing. The inducible motions were represented by rotations around the transverse, longitudinal and sagittal axes, maximum total point motion, maximum subsidence and maximum lift-off. The kinematics of the knee and the migration of the tibial component were evaluated as described above. The inducible displacements and the kinematics were interpolated at five degree intervals of extension.

Conventional radiography

The PT, PTS and FAP angles were determined in all knees (Figure 12). The AP position of the tibia in relation to the femur was determined on the reference examination (supine, extended knee).

The alignment of the leg; hip-knee-ankle angle (HKA), was measured on the standard radiographs preoperatively and at two years.

The radiolucent lines (RLL's) under the tibial tray and around the stem were examined at one and two years on the standard radiographs.

Clinical evaluation

The Hospital for Special Surgery knee score (HSS) was used preoperatively and at one (study 1–5) and two years (study 3 and 4) by two of the surgeons. Preoperatively the patients completed questionnaires about their expectations on the results of the operation. At the one (study 1–4) and two year (study 3 and 4) follow-ups the patients were asked if their expectations had been fulfilled or not. In addition a separate questionnaire about the stability and over-all function of the knee was completed. Presence of instability or not was assessed into two grades (Yes or No) in study 1, 2 and 5. In studies 3 and 4 the instability was divid-

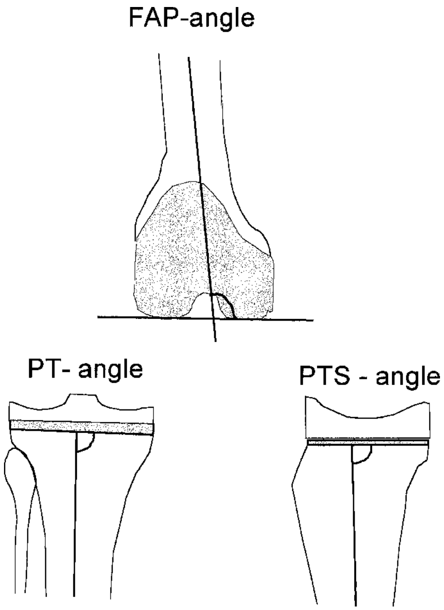

Figure 12. Diagram showing the femoral angle, AP view (FAP), and AP (PT) and lateral (PTS) tibial angles.

ed into three grades (always stable regardless type of activity/occasional instability when walking in stairs or on uneven ground/always instability when walking). The function of the knee was assessed by the patients as normal, almost normal or abnormal. The patients received the questionnaire by mail two weeks before their visit to the outpatient clinic (Appendix 1). The reproducibility of this questionnaire was evaluated in 18 patients who were asked to fill in the form a second time one to two weeks after the one or two years follow up. There was good agreement between the answers given at the two occasions (Kendall's tau = 0.9–1.0).

Statistics

In the results all values are presented as mean if not otherwise stated.

Study 1 and 2: Repeated measures ANOVA (MANOVA) was used to compare the three groups. This analysis was undertaken in the interval between 50° to 15° (study 1) and 45° to 15° (study 2) where observations from all 33 patients in each study were available. Due to multiple comparisons p-values less than 0.025 were considered to represent a significant difference. Evaluation of possible association between the positions of the components and the observed positions of the tibia or femur at 50° (study 1) and 45° (study 2) of flexion was pursued using non-parametric correlation (Spearman's rho). The Mann-Whitney U-test was used to compare the clinical outcome including the HSS score.

Study 3 and 4: Mann Whitney U-test was used to compare the RSA results at two years. Non-parametric tests (Mann-Whitney, Fisher's and Chi-Square) compared the clinical outcome including the HSS score. Spearman's non-parametric correlation evaluated possible associations between migration and extension of radiolucent lines or component positioning. P-values smaller than 0.025 were considered to representing a significant difference. Based on the scatter of data observed, the study design could detect a difference with 80% probability ($p<0.05$) in maximum subsidence of 0.2 mm. The same probabilities for MTPM were 0.2 (study 4) and 0.4 mm (study 3) and for rotations 0.3–0.4 degrees.

Study 5: Parametric tests (repeated measure ANOVA) were used for the rotations about the transverse and longitudinal axes (normally distributed data). The other parameters were not normally distributed and were evaluated using non-parametric tests. The values of the inducible displacements at the different degrees of knee extension were pooled in the statistical tests comparing concave and posterior stabilised inserts in group 2. The reason for this was to reduce the number of statistical tests. Stepwise linear regression was mainly used to study associations between the different RSA parameters.

Results

Study 1: In vivo kinematics of total knee arthroplasty. Flat versus concave tibial joint surface

Tibial motions with fixed femur

The tibia rotated slightly externally with increasing extension from 50°, but without any difference between the implants. The control knees (normals) had a more internally rotated position at 50° and during extension (F vs. N, C vs. N: p=0.005, 0.017). The varus/valgus angulation of the tibia did not differ between groups. The midpoint between the two tips of the tibial intercondylar eminence was positioned more medially in normals than in the knees with concave inserts (F vs. C: p=0.16, F vs. N: p=0.16, C vs. N: p=0.007) (Table 6).

Between 50 and 15° of flexion the group with concave inserts also had a more distal position than the controls (C vs. N: p=0.005, F vs. N: p=0.07). Posterior translation of the tibia was seen in all groups but was most pronounced when concave inserts had been used (mean=31.6 mm at 50°). The posterior displacement was also larger than normal in the group with flat implants (N=12.4 mm, F=24.7 mm) (50–15° of extension; F vs. C: p=0.001, F vs. N and C vs. N: p<0.0005) (Figure 13).

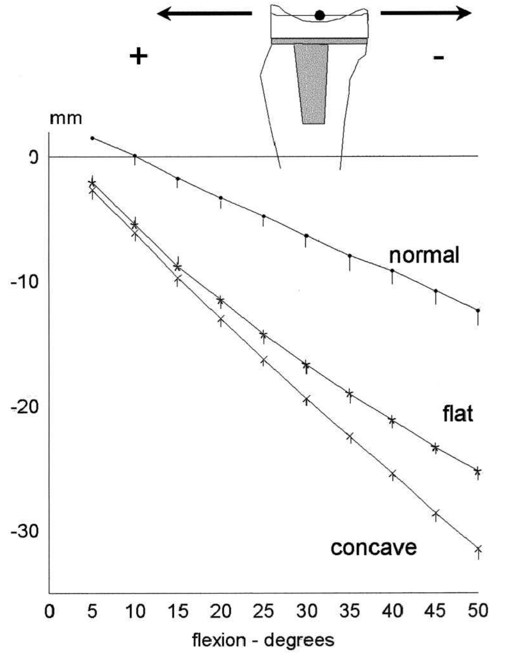

Figure 13. Anterior-posterior translation of the center of the tibial plateau.

Anterior-posterior femoral translations with fixed tibia

At 50° of flexion the central point between the two femoral condyles had translated 5.5 and 11.8 mm

Table 6. Relative tibial and femoral motions between 0° (supine reference position) and 50° of flexion in normal knees (N), and in knees with flat (F) and concave (C) polyethylene tibial inserts

	Mean			Minimum			Maximum		
	N	F	C	N	F	C	N	F	C
Rotations (degrees)									
Internal (+) – External (-)	4.7	1.4	2.4	-2.2	-3.1	-4.9	9.9	7.1	11.8
Varus (+) – Valgus (-)	-0.6	-1.1	-3.0	-4.7	-7.8	-13.1	6.4	3.9	1.9
Translations – Tibia (mm)									
Medial (+) – Lateral (-)	1.7	0.3	-1.5	-1.5	-2.5	-10.9	3.7	3.6	0.4
Proximal (+) – Distal (-)	5.2	4.0	5.8	2.7	-0.2	3.7	8.8	7.3	7.1
Anterior (+) – Posterior (-)	-12.4	-24.7	-31.6	-15.3	-30.2	-35.6	-8.2	-21.2	-25.1
Translations – Femur (mm)									
Anterior (+) – Posterior (-)	-0.7	5.5	11.8	-4.9	-0.1	6.7	2.8	11.8	17.7

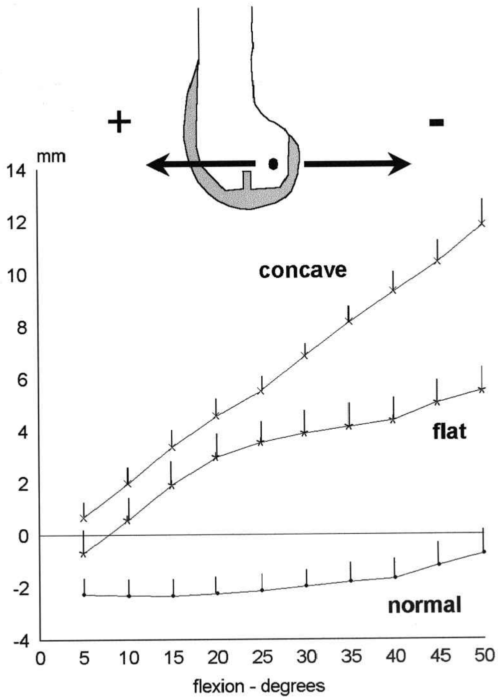

Figure 14. Anterior-posterior translation of a midpoint between the centers of the femoral condyles.

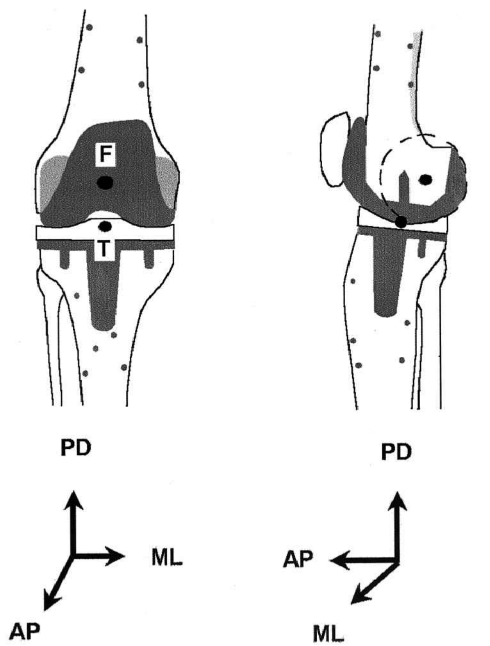

Figure 15. The extended reference position and the points used to measure tibial (T) and femoral (F) translations. The tibial and femoral coordinate system are aligned with each other. PD = proximal-distal, ML = medial-lateral and AP = anterior-posterior directions.

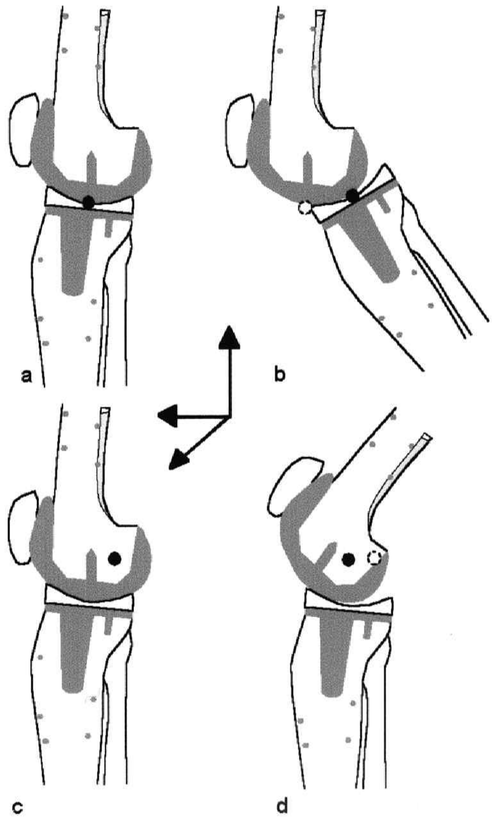

Figure 16. **(top, a and b).** Illustration of anterior-posterior and proximal-distal ***tibial*** translations. The femoral coordinate system is fixed and the tibial coordinate system follows tibia. This is achieved as follows. Between the reference position (a) and 50° of flexion the recorded absolute rotations of the femur are used to mathematically "replace" the femur to its initial position. The rigid body described by the tibial bone markers has also been rotated using the same rotation matrix. This procedure enables calculation of the relative tibial motions. Here the centre of the tibial plateau (initial position = black dot in **a** and white dot in **b**) has displaced posteriorly and proximally as an effect of tibial flexion (black dot in **b**).

(bottom, c and d) Illustration of anterior-posterior ***femoral*** translations. The tibial coordinate system is fixed and the femoral coordinate system follows femur. At this evaluation the absolute tibial rotation have been used to replace the tibia to its initial position. As in illustrations **a** and **b** the femur has been exposed to the same rotations to measure relative femoral motions. The landmark in the femur has displaced anteriorly corresponding to the distance between the white and black dots in figure d.

anteriorly in the groups with the flat and concave inserts, respectively. Minimal movements were recorded in the normal knees. (50–15° of extension; F vs. C: $p=0.004$, N vs. F and N vs. C: $p<0.0005$)(Figure 14–16).

Relative tibial position at extension, kinematics and component position

At the reference position (0°, supine), the tibia was positioned more anteriorly with concave inserts (F vs. C: p=0.2, F vs. N: p=0.1, C vs. N: p=0.02). In all three groups and at 50° of flexion, varus angulation of the tibia correlated to a medial position of the centre of the knee, whereas a lateral position was associated with a valgus angulation (rho=0.71–0.92, p=<0.0005–0.001). In the flat design the posterior translation of the tibial plateau centre decreased with increasing varus position of the tibial component (rho = -0.70, p=0.02). A corresponding positive correlation between the position of the femoral component and tibial rotation into valgus was noted in the group with concave inserts (rho=0.83, p=0.002).

Knee kinematics and clinical results

There was no significant difference in the clinical results between the two implants. In four patients (2 F, 2 C) who were the only ones to report occasional instability combined with abnormal function, the median displacement at 50º of flexion of the centre of the tibial plateau was 6.7 mm, compared to 4.4 mm for the rest of the patients (p=0.007). In two of these knees we found the most pronounced valgus tilt (50ºº of flexion: 7.7 and 13.1°).

Study 2: In vivo kinematics of total knee arthroplasty. Concave versus posterior-stabilised tibial joint surface

Tibial motions with fixed femur

In both groups the tibia was slightly internally rotated at 45° of flexion. During extension a small external rotation was recorded without any difference between the concave and the posterior-stabilised implants. Also in this study the tibia was more externally rotated in the two groups with TKA than in the normal knees (C vs. N, PS vs. N: p=0.008, 0.001). The tibial rotations around the sagittal axis of the knee did not differ between the three groups (Table 7).

The translations of the centre of the tibial plateau along the transverse axis did not differ between the three groups. The plateau centre did, however, occupy a more distal position in the knees with prostheses and especially when the PS design had been used (C vs. N: PS vs. N; p=0.001, <0.0005; C vs. PS, p=0.025). The knees with concave inserts displaced more posteriorly than did those with PS design (C vs. PS: p=0.002). The two designs showed 18 and 11 mm (C/PS) more than normal posterior displacement (C vs. N, PS vs. N; p<0.0005) (Figure 17).

Anterior-posterior femoral translations with fixed tibia

At 45º of flexion the point between the femoral condyles had displaced anteriorly in the knees re-

Table 7. Tibial rotations and tibial and femoral translations at 45° of flexion compared with extended position with the patient supine in normal knees (N), and in knees with concave/constrained (C) and posterior-stabilized (PS) polyethylene tibial inserts

	Median			Minimum			Maximum		
	N	C	PS	N	C	PS	N	C	PS
Rotations (degrees)									
Internal (+) – External (-)	6.3	2.8	-1.0	-2.2	-8.6	-7.3	9.9	9.7	7.3
Varus (+) – Valgus (-)	-1.2	0.2	-0.1	-4.7	-7.5	-9.7	6.4	7.6	5.9
Translations – Tibia (mm)									
Medial (+) – Lateral (-)	2.3	1.0	0.2	-1.5	-2.4	-4.8	3.7	5.8	5.3
Proximal (+) – Distal (-)	5.4	2.6	-0.6	2.7	-0.1	-4.7	8.8	8.2	3.3
Anterior (+) – Posterior (-)	-12.6	-30.3	-23.8	-15.3	-36.0	-26.5	-8.2	-19.7	-20.2
Translations – Femur (mm)									
Anterior (+) – Posterior (-)	0.0	10.2	5.9	-4.9	3.3	2.3	2.8	15.6	10.0

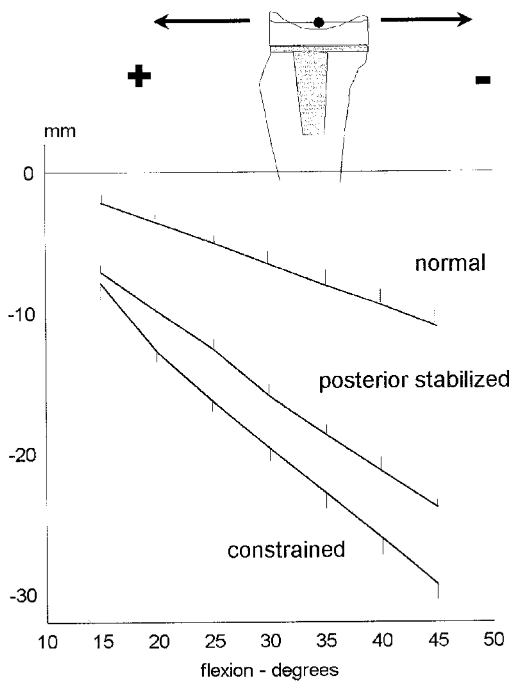

Figure 17. AP translation of the centre of the tibial plateau.

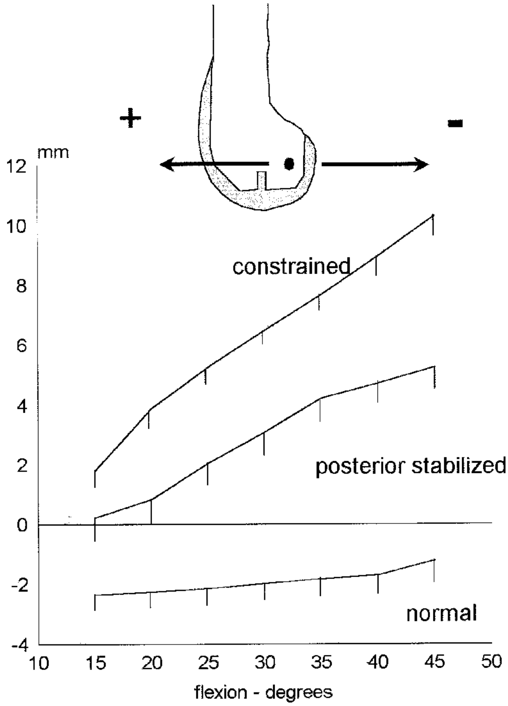

Figure 18. AP translation of a midpoint between the centres of the femoral condyles.

placed with prosthesis. It displaced posteriorly during extension, but maintained a more anterior position in the group with concave inserts (C vs. PS; P=0.003). As already noted in study 1 the corresponding motion in the normal knees was minimal (N vs. C and N vs. PS: p<0.0005) (Figure 18).

Relative tibial positioning at extension, kinematics and component position

In the reference position the tibia was translated more anteriorly than normal (C vs. N: p=0.002, PS vs. N: p=0.008). The scatter of these data was also more pronounced in the knees with prosthesis.

At 45° of flexion and in both designs there was a correlation between varus/valgus angulation of the joint and medial/lateral displacement of the centre of the tibial plateau (C: rho=0.80, p=0.003; PS: rho=0.85, p=0.001). In the concave design the posterior displacement of the tibial plateau centre decreased with increasing posterior tilt of the tibial plateau as measured on lateral radiographs (rho=0.76, p= 0.006). One patient with PS design had noted occasional instability, but there were no overall differences in the clinical results between the groups. There was no correlation between the relative tibial motion at 45° of flexion and the patient's opinion about the function of their operated knee.

Study 3: Flat versus concave tibial joint surface in total knee arthroplasty. Evaluation of 39 cases using radiostereometry

Migration

Two years postoperatively the median absolute rotations varied for the flat and concave inserts between 0.15 to 0.24 and 0.12 to 0.22 degrees, respectively, without any significant differences. The maximum total point motion (MTPM) was almost equal in the two groups. No differences between the implants were recorded for the maximum subsidence or lift-off (Table 8).

The pre- or postoperative HKA-angles and the position of the tibial and femoral components (FAP-, PTS- and PT-angles) did not differ between the two groups. With increasing posterior slope of the tibial component increased rotation

Table 8. Translations at 2 years for the flat (F) and concave (C) polyethylene inserts

	Median		95% confidence limits of mean [1]		Minimum		Maximum	
	F	C	F	C	F	C	F	C
Maximum total point motion (mm)	0.41	0.42	0.33–0.91	0.34–0.58	0.20	0.11	2.92	1.04
Maximum subsidence (mm)	-0.07	-0.13	-0.20– -0.04	-0.26– -0.03	-0.62	-0.86	0.11	0.16
Maximum liftoff (mm)	0.29	0.20	0.17–0.55	0.10–0.24	0.03	0.04	1.31	0.45

[1] mean value ± (2.086 x SE of mean)

Table 9. Expectations on the operation and results at 2 years

	Preoperatively Type of polyethylene insert		2 years Type of polyethylene insert	
	Flat[1]	Concave[1]	Flat[2]	Concave[2]
Number of patients	20	19	20	19
Relief of pain	0 / 0 / 5 / 15	1 / 1 / 1 / 16	3 / 1 / 7 / 9	1 / 0 / 6 / 12
Walking	0 / 0 / 0 / 20	1 / 0 / 3 / 15	2 / 1 / 8 / 9	0 / 0 / 8 / 11
Stair-climbing	0 / 0 / 4 / 16	1 / 1 / 1 / 16	3 / 5 / 7 / 5	1 / 3 / 7 / 8
Social activities	1 / 5 / 4 / 10	5 / 0 / 5 / 9	2 / 6 / 4 / 8	1 / 4 / 3 / 11
Stability	0 / 1 / 1 / 18	2 / 0 / 1 / 16	3 / 4 / 6 / 7	1 / 1 / 4 / 13
Sleep	2 / 3 / 6 / 9	3 / 4 / 3 / 9	2 / 9 / 3 / 6	2 / 5 / 5 / 7
Straight leg	4 / 4 / 2 / 10	5 / 3 / 1 / 10	3 / 7 / 1 / 9	2 / 1 / 2 / 14

[1] not / slight / rather / very important.
[2] worse / no change / better / as expected

around the longitudinal axis was recorded (F: r=-0.54, p=0.01; C: r=-0.56, p=0.02). In the group with concave inserts increasing rotations about the transverse axis were recorded with increasing varus position of the tibial component (r =-0.54, p=0.02).

Radiolucencies were seen most frequently medially under the tibial tray (i.e. zone 1) but with no relation to the migration results two years postoperatively.

Clinical results

At the two year follow up relief of pain was as expected in nine patients with flat and 12 with concave design (Table 9). In four patients with flat and in one patient with concave insert the pain was unchanged or worse compared with the preoperative evaluation. At two years eight patients (5F, 3C) reported occasional instability. Two patients with flat and four with concave inserts considered their knees equal to a normal knee. The HSS scores reached 82 and 86, respectively, for the flat and concave designs (p=0.2). The overall fulfilment of the expectations, i.e. almost or completely satisfied, was 68% (F) and 86% (C) in the two groups without any significant difference (Table 10). The expectation most consequently fulfilled was improved walking ability in the group with concave inserts. The patients who had

Table 10. Expectations on the operation and results at 2 years

	Preoperatively		2 years[1]		F vs. C Fishers' test
	Flat[2]	Conc.[2]	Flat[3]	Conc.[3]	
Relief of pain	0/**20**	2/**17**	**4**/16	**1**/16	p = 0.3
Walking	0/**20**	1/**18**	**3**/17	**0**/18	p = 0.2
Stair-climbing	0/**20**	2/**17**	**8**/12	**3**/14	p = 0.2
Social activities	6/**14**	5/**14**	**6**/8	**4**/10	p = 0.7
Stability	1/**19**	2/**17**	**7**/12	**1**/16	**p = 0.04**
Sleep	5/**15**	7/**12**	**8**/7	**5**/7	p = 0.7
Straight leg	8/**12**	8/**11**	**5**/7	**2**/9	p = 0.4

[1] only including answers from patients who preoperative ly selected this item as important/ very important
[2] not or minor importance/ rather or very important.
[3] worse or no change/ better or as expected.

Table 11. Translations at 2 years for the concave (C) and posterior stabilized (PS) polyethylene inserts.

	Median		95% confidence limits of mean [1]		Minimum		Maximum	
	C	PS	C	PS	C	PS	C	PS
Maximum total point motion (mm)	0.38	0.39	0.31–0.46	0.30–0.48	0.19	0.12	0.92	0.82
Maximum subsidence (mm)	-0.09	-0.02	-0.30–0.06	-0.10–0.06	-0.80	-0.38	0.31	0.17
Maximum liftoff (mm)	0.13	0.22	0.07–0.20	0.15–0.29	0.01	0.04	0.41	0.41

[1] = mean value ± (2.086 x SE of mean)

this design reported better fulfilment of their expectations on stability after the operation (C vs. PS: p=0.04).

Study 4: Concave versus posterior-stabilized tibial joint surface in total knee arthroplasty. Randomized evaluation of 47 knees

Migration

At two years the absolute rotations of the tibial component varied between 0.13 to 0.26 degrees in the group operated with concave inserts and 0.18 and 0.19 degrees in the group with PS design (p=0.1–0.7). The median translations were small without any difference (Table 11, Figure 19).

Two patients were revised. One prosthesis with concave insert was exchanged to a more constrained prosthesis because of instability. Preoperative RSA revealed minimum migration. The tibial component was found to be macroscopically fixed at revision. One patient with PS design was revised because of early postoperative fracture. The migration values (maximum rotation 6.81 degrees, MTPM 3.65 mm) indicated loosening, which was confirmed at the revision. Despite a randomised design the patients who received concave inserts had more pronounced varus angulation at the preoperative examination. This factor did, however, not influence any of the result parameters.

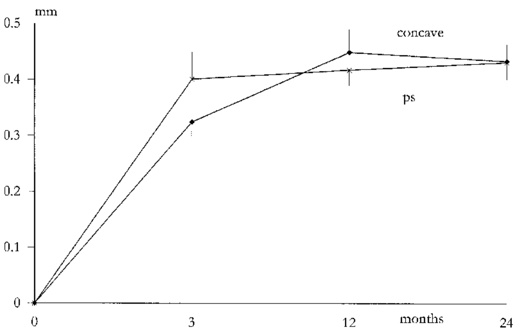

Figure 19. Maximum total point motion(mean, SE of mean) for the concave and posterior-stabilized inserts up to 2 years postoperatively.

In the knees implanted with the concave design there was a relation between the rotations around the anterior/posterior axis and the position of the tibial component. The greater the posterior slope of the tibial component the higher the migration into varus or valgus tilt at the two year follow up (rho=-0.51, p=0.015). There was no correlation between the extent of the radiolucent lines and the rotations or translations of the tibial component.

At two years the HSS scores reached 88 and 90 (C vs. PS, p=0.6). Pain relief was as expected in 17 and 13 patients (C/PS, Table 12). Two patients (both with PS design) answered in the questionnaire that they had more pain than preoperatively.

Ninety-one and 83% of the preoperative expectations had been fulfilled at two years (C/PS, Table 13). At one year three patients (all PS) had symptoms of instability. One year later symptoms of instability were only noted in one patient with a concave insert. Ten patients (11 knees: 7C, 4PS) considered their knees as normal at two years and nine patients (4C/5PS) as definitely abnormal.

Study 5: Inducible displacements of cemented tibial components. Observations during dynamic radiostereometry related to joint positions and 2 years history of migration in 16 TKR

On average there were no rotations of the tibial component around the transverse axis up to 35° of

Table 12. Expectations on the operation and results at 2 years

	Preoperatively Type of polyethylene insert Concave [1]	Preoperatively Type of polyethylene insert PS [1]	2 years Type of polyethylene insert Concave [2]	2 years Type of polyethylene insert PS [2]
Number of patients	24	19	24	19
Relief of pain	0 / 0 / 1 / 23	0 / 1 / 3 / 15	0 / 1 / 6 / 17	2 / 0 / 4 / 13
Walking	1 / 1 / 3 / 19	0 / 0 / 3 / 16	1 / 0 / 5 / 18	1 / 2 / 4 / 12
Stair-climbing	1 / 0 / 5 / 18	0 / 0 / 5 / 14	0 / 4 / 4 / 16	2 / 5 / 5 / 7
Social activities	3 / 5 / 6 / 10	3 / 2 / 6 / 8	1 / 4 / 4 / 15	2 / 4 / 3 / 10
Stability	2 / 1 / 2 / 19	1 / 2 / 2 / 14	2 / 1 / 5 / 16	1 / 2 / 2 / 14
Sleep	4 / 1 / 9 / 10	1 / 4 / 8 / 6	0 / 5 / 5 / 14	0 / 3 / 2 / 14
Straight leg	3 / 7 / 2 / 12	2 / 2 / 4 / 11	1 / 0 / 10 / 13	0 / 5 / 0 / 14

[1] not / slight / rather / very important.
[2] worse / no change / better / as expected

Table 13. Expectations on the operation and results at 2 years (divided in 2 groups)

	Preoperatively Conc.[1]	Preoperatively PS[1]	2 years Conc.[2,3]	2 years PS[2,3]	C vs. PS Fishers' test
Relief of pain	0/**24**	1/**18**	**1**/23	**2**/16	p = 0.6
Walking	2/**22**	0/**19**	**1**/21	**3**/16	p = 0.3
Stair-climbing	1/**23**	0/**19**	**4**/19	**7**/12	p = 0.3
Social activities	8/**16**	5/**14**	**3**/13	**5**/9	p = 0.4
Stability	3/**21**	3/**16**	**3**/18	**3**/13	p = 0.4
Sleep	5/**19**	5/**14**	**4** /15	**3**/11	p = 1.0
Straight leg	10/**14**	4/**15**	**0**/14	**3**/12	p = 0.2

[1] not or slight/ rather or very important (bald).
[2] worse or no change (bald)/ better or as expected
[3] patients with the opinion that the subject was important/ very important

flexion in all 16 knees. At 30° a minimum posterior tilt was recorded followed by anterior tilt, which at 15° degrees of flexion reached 0.07°. The implants with retained PCL (+PCL) showed the smallest movements. Comparison between the two groups both operated with PCL resection (-PCL) revealed that the rotation into recurvation started later in the PS-PCL group, at 25° instead of 30° as observed in the C-PCL group (PS-PCL vs. C-PCL at 25°, p=0.01; at 30–45°: p>0.1, Mann-Whitney test, Exact significance). Throughout extension (45 to 15°) and compared with the relaxed supine reference position, the tibial components with PS design were tilted posteriorly and those with concave inserts were tilted anteriorly (C-PCL vs. PS-PCL: p=0.04, repeated measurements ANOVA).

There was an association between the rotations of the tibial component around the transverse axis between 0 to 2 years (migration) and the corresponding inducible rotations at 25° (adjusted r^2=0.32, p=0.01). Implants that had slowly tilted anteriorly during the postoperative two years due to migration also showed an inducible rotation in the same direction.

During extension of the knee the tibial component rotated externally up to 20° and then internally without any difference between the two designs operated with PCL resection. The external/internal rotation of the knee joint or the corresponding migration of the tibial component 0 to 2 years did not influence the inducible rotations.

A slight change of the varus/valgus tilt of the tibial component occurred at 25° of flexion. There were no correlations to implant design, the pattern of varus/valgus rotation of the knee or the history of migration in terms of rotation around the sagittal axis.

The maximum subsidence was not obviously influenced by the position of the knee. The most pronounced lift-off was recorded at different points along the periphery of the tibial tray and especially at the beginning and end of the motion.

The median values for the inducible maximum total point motion varied from 0.37 to 0.52 mm when the knee was extended from 45° to 15° of flexion. The higher the MTPM in term of migration the higher the inducible MTPM at 20° during extension of the knee (Spearman's rho=0.54, p=0.03).

As the joint area design and the knee joint kinematics seemed to influence the inducible anterior-posterior tilt of the tibial component at 25° of flexion, this was further analysed using a stepwise linear regression analysis. Increasing anterior tilt correlated to a medial position of the tibial plateau centre (adjusted $r^2 = 0.62$, $p<0.0005$) and to the use of concave implants (increase of adjusted r^2 to 0.78, $p= 0.001$). The more medial the position of the tibial plateau the more the anterior tilt and especially in prostheses operated with a concave implant design.

Discussion

Study 1: In vivo kinematics of total knee arthroplasty. Flat versus concave tibial joint surface

We could for the first time study knee replacements with RSA during active motion and weight bearing. It should however, be noted that these studies were performed under standardised conditions. During active life, many other types of motions occur throughout the day and the speed of motion might be faster or slower. The deviations from normal might therefore be more pronounced than we observed. It is, however, somewhat astonishing that the pattern of kinematics does not diverge more from previous RSA studies (Nilsson et al. 1990, 1991, Kärrholm et al. 1994) despite their focus on other designs and measures supine or statically.

When walking upstairs or rising from a chair, stability of the implanted knee is crucial, which could be one important argument to choose the concave insert. According to Postak et al. (1992) concave tibial inserts of AMK design will provide higher resistance to internal/external rotation and anterior/posterior displacement than the same prosthesis when used with flat inserts. It should, however, be noted that these *in vitro* studies were undertaken at full or close to full extension. In our study the rotations during active motion did not differ. Moreover the concave inserts were associated with increased anterior/posterior displacement. At 50° of flexion the knees with a concave insert had between five to ten mm more *anterior* displacement of the femoral condyles, in contrast to the normal knees, which on average showed almost no anterior-posterior motion at all.

Decreasing contact between the femoral and tibial component with flexion of the knee joint could be one reason for this paradoxical finding. Our findings might even suggest that the femoral condyles do not always stay within the tibial trough, further destabilising the articulation. The slight built in posterior slope in the flat inserts may more effectively control the anterior-posterior motions. This is in accordance with the findings of reduced AP motions in the prostheses with concave inserts and posterior tilt of the tibial component in study 2 even though this comparison can be criticised because these patients were operated with resection of the PCL.

In patients who considered their operated knees as definitely abnormal and unstable, increased proximal tibial translation was recorded. The precise effect of this motion is unclear. It could indicate instability or medial lift-off in the flexed position, which reduces the contact area between the femoral component and the tibial insert. The choice between flat or concave designs did not have a major influence on the values of the tibial rotations around the longitudinal axis as reported in earlier RSA studies. Valgus angulation greater than the normal knees was noted in some of the operated knees. Imbalance of the medial ligaments causing medial separation of the joint is one probable explanation for this; another could be that the components were inserted with malalignment in rotation (Figure 20).

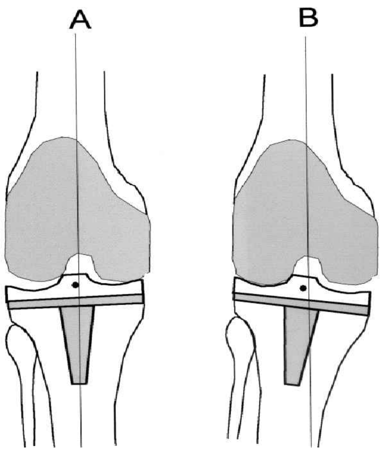

Figure 20. The tibia can be expected to rotate into varus (A) or valgus (B), when the central elevation moves laterally (away from the vertical line). In study 1 lateral displacement correlated to valgus rotation. Medial lift-off could be expected if the valgus angulation exceed a certain limit.

In our normal material, weight bearing resulted in a minimum mean posterior shift of the circular centre of the posterior condyles. This point moved minimally with increasing extension, corresponding to the findings by Andriacchi et al. (1999). When reviewing earlier studies some of the different outcomes compared to our results could have several explanations. The same parameters were not investigated and the techniques used had different resolutions in time and space. For example, we measured translations of a central point corresponding to the circular centre of the condyles and not contact points as measured by others.

To facilitate comparison with earlier RSA studies of the kinematics of the knee the anterior-posterior tibial translations were reported. The corresponding relative femoral translations might, however, be at least as informative. Previous RSA studies of prosthetic knees in standing and static positions or measured dynamically in the prone position have demonstrated that the tibia displaces at least 1.5 cm more posteriorly than normal at 80 degrees of flexion (Kärrholm et al. 1994). The findings in the AMK design implanted with retention of the PCL did not diverge from these previous observations (Uvehammer et al. 2000). Here we could also demonstrate that this abnormal motion corresponds to anterior displacement of a point located between the femoral condyles.

The reproducibility of the knee motions in our study was 10–30 times lower than that reported from migration studies (Nilsson et al. 1995, 1999). This finding implies that the knee does not have the same pattern of motion during extension despite the fact that the patient had the opportunity to perform a number of trials before the RSA recording. Difficulties in obtaining a reproducible neutral rotation of the foot between examinations are probably one reason for this variability (Kärrholm et al. 2000). Further more, the alignment of the knee in relation to the laboratory coordinate system may cause so-called kinematic "cross-talk" (Ramsey and Wretenberg 1999, Piazza and Cavanagh 2000). This means that inaccuracies in the alignment of the knee for example in relation to the longitudinal axis will result in recordings of a "pure" flexion of the knee not only as flexion (rotation around the transverse axis). If the leg is slightly externally rotated at the reference position, this rotation will also appear as a varus angulation. These types of errors are more or less unavoidable in any system, because an absolutely perfect alignment of an anatomical structure cannot be defined and might vary from patient to patient. In our studies we have approached this problem in two ways; randomised selection of patients and the use of what we think are sufficiently large study groups. Moreover, there is no reason to believe that these sources of errors should be unequally distributed between the two groups under study.

Another effect of the randomised design was that patients with symptoms of instability and abnormal function contrary to the situation in many previous studies were *not* excluded. To detect these problems self-assessment questionnaires were created and sent out to the patient two weeks before their visit to the outpatient clinic. We think that this time interval was important to obtain information with minimum bias. Finally, the findings of an association between abnormal kinematics and function or feeling of abnormality indicate that these questions were reasonably relevant.

Study 2: In vivo kinematics of total knee arthroplasty. Concave versus posterior-stabilized tibial joint surface

In patients with severe varus or valgus deformities resection of the PCL will make balancing of the soft tissues easier (Freeman and Railton 1988, Becker et al. 1991, Vinciguerra et al. 1994, Banks et al. 1997, Worland et al. 1997). Wilson et al. (1996) and Bolanos et al. (1998) considered the PS design as a satisfactory substitution for the PCL and several authors have reported excellent results for this type of implant (Insall et al. 1982, Aglietti and Buzzi 1988, Insall 1988, Groh et al. 1991). Incavo et al. (1997) found in cadaver knees, regardless of whether the PCL was substituted or not, that the kinematics were not restored when different designs of the tibial components were examined. We agree that proper soft tissue balancing is often difficult without PCL resection, which was the rationale for the design of our second kinematic study. Compared with the findings in study 1, no decrease of the internal/external tibial rotations during extension was noted. Thus, it seems that the design of the tibial plateau or whether the PCL is retained or resected will not have great influence on these rotations.

Increased medial loading after resection of the PCL has been reported by Dorr et al. (1988). Comparison of the varus/valgus angulation between the concave design with or without PCL in studies 1 and 2 did confirm this finding to some extent. In study 1, when the PCL was retained, a valgus angulation and lateral translation in the flexed position were noted. In Study 2 the same type of implant now operated with PCL resection showed mean rotation into varus and medial translation of the centre of the plateau. This is an interesting finding that might speak for retention of the PCL.

According to Stiehl et al. (1997, 1999) medial or lateral instability or subluxation of the femoral condyle could cause medial or lateral lift-off, which they relatively frequently recorded in some designs of TKA. We could not directly observe this type of movement, but pronounced rotations about the anterior-posterior axis in a few cases may very well indicate that such phenomena were present. The number of cases with extreme varus or valgus angulation in flexion did not however obviously differ between the groups.

Smaller AP translations were recorded with the PS design, but they were still not normal. Comparison between the knees with concave inserts in studies 1 and 2 (i.e. with and without PCL) did however, not reveal any difference. This finding supports previous presumptions that the PCL does not function normally in a TKR, perhaps due to the anatomy of the artificial joint, inadequate tension or resection of the ACL. Jonsson and Kärrholm (1999) found no difference in anterior-posterior translation during static extension in patients with a previous tear of the PCL. This finding and ours might suggest that the stabilising function in the AP direction of the PCL during controlled motion have been overestimated. The use of a central spine did, however, reduce the AP motion and might be one way to obtain motions closer to normal.

Study 3: Flat versus concave tibial joint surface in total knee arthroplasty. Randomized evaluation of 39 cases using radiostereometry

Retention of the PCL has been claimed to result in better function and reduced stresses at the cement-bone-implant interfaces (Andriacchi and Galante 1988). Other authors have raised concerns about high contact forces if the PCL is retained in a design with low conformity (Soudry et al. 1986). This risk could increase if a thin tibial plateau is used, especially in young and active patients (Wright et al. 1992, Bugbee et al. 1998). Also Blunn et al. (1997) have reported that tibial inserts with moderate conformity are most wear-resistant.

From a theoretical point of view a constrained implant should transmit higher forces to the interfaces. Our study could not, however, confirm increased migration in these cases. The reason for this is not clear. According to laboratory tests the constrained design will have more built in stability at full or close to full extension (Postak et al. 1992). With increasing flexion the configuration of the femoral joint area which faces the tibial component will change. This will result in reduction of stability as evidenced by the increased AP translations of the prostheses with concave insets according to the findings in study 1. These findings suggests that the tibial component will become more eccentrically loaded in the flexed positions. Thus the cement/bone interfaces might become subjected to loads as high as in the flat design. The correlation between tibial component migration in terms of tilt (anterior) and variations of the femoral component position (anterior) in the frontal plane further supports the conclusion that this really was the case in our study.

In study 1 we were able to show that the femoral component displaced anteriorly with increasing flexion. In this situation one of the femoral condyles could contact the anterior flange of the polyethylene due to tibial rotation, whereas the other lacks contact because of a more posterior position above the excavated part of the tibial joint area. Lack of contact due to excessive varus/valgus tilt of the knee or femoral component malposition could also be important. Thus, there are

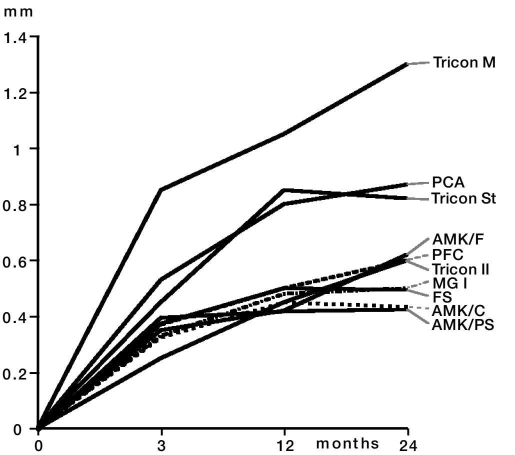

Figure 21. MTPM values up to 2 years for the AMK (flat, concave and PS inserts), Freeman-Samuelsson (Albrektsson et al. 1992), Tricon II (Nilsson et al. 1999), Tricon M (Nilsson et al. 1991), Miller-Galante I (Nilsson and Kärrholm 1993), PCA (Ryd et al. 1990), PFC (Önsten et al. 1998) and Tricon stem (Nilsson and Kärrholm 1992) prostheses.

reasons to believe that the transmission of forces from the knee joint to the interfaces varies depending on the position of the implant in a complicated pattern. The built in kinematics of a certain design are not the only factor of importance, but also the positioning of the components and certainly also the status of the soft tissue envelope (Blankevoort et al. 1988). The net effect of these forces over a period of two years was the same in the two groups in our study. It could, however, be that the choice of joint area configuration is more important in the long-term perspective. If so this factor might have a more significant influence on wear and especially its location.

We could not verify any correlation between the fixation and the deviation of the HKA angle from 180 degrees, maybe because minor deviations from the ideal position will not initiate a loosening process but only accelerates migration of implants with inadequate fixation already in the postoperative period. Thus, a slight malalignment might be tolerated provided that the surgeon has managed to attain an optimum fixation during the operation.

The migration of the AMK prosthesis in this study was of the same magnitude as reported earlier for similar designs fixed with cement (Ryd et al. 1990, Nilsson et al. 1991, Albrektsson et al. 1992, Nilsson and Kärrholm 1992, 1993, Önsten et al. 1998, Nilsson et al. 1999) (Figure 21). The hypothesis that a comparatively flat joint area would result in less migration of the tibial component after TKA could not be verified.

When evaluating the outcome after a knee replacement Murray and Frost (1998) recommended questionnaires. One argument for this was to avoid the surgeons influence, especially when recording the patients opinion regarding pain, which has high impact in most scoring systems, not least the HSS score. We had slightly inferior results compared to Bourne et al. (1988) when examining the HSS scores. This could be explained by our evaluation system as discussed above, but could also represent a true difference. As has been pointed out earlier, the questionnaire was sent to the patients two weeks before their visit to the outpatient clinic. Thus they could better review their opinion regarding the result after the knee replacement without interference from the observer.

Relief of pain, improved stability, walking and stair climbing ability were the most frequent expectations from the patients before the surgery. The concave design turned out to better fulfil the patients expectations. Instability could, however not be verified at the clinical examination in the eight patients (5 F, 3 C) who had the opinion that their operated knees were not stable in all situations. In study 1 we found a weak association between instability/feeling of abnormal knee and increased proximal displacement of the centre of the tibial component at 50 degrees of flexion, but this is probably very difficult to verify in a clinical examination.

At one year postoperatively none of the patients regarded the function of their knee replacements as normal. One year later six patients (2 F, 4 C) considered their knees as normal although the HSS scores only changed minimally. This could be a true change perhaps caused by improved muscular function, but could also represent an individual adaptation.

Study 4: Concave versus posterior-stabilized tibial joint surface in total knee arthroplasty. Randomised evaluation of 47 knees

There are a number of findings and opinions in favour of PCL resection. According to Insall exact tensioning of the PCL is difficult to achieve during surgery. Consistently several studies based on RSA measurements have concluded that the PCL will not function normally after TKR with retention of this ligament (Nilsson et al. 1991, Kärrholm et al. 1994, Uvehammer et al. 2000). Absent or insufficient function of other ligaments, soft tissue structures (Nilsson et al. 1997) and deficient proprioception (Skinner et al. 1984, Pap et al. 2000) can also be responsible for this observation. Resection of the cartilage will mean that any proprioception based on subchondral receptors will probably not function or will become severely disturbed. Several authors have argued for resection of the PCL to avoid problems with the collateral ligaments (Freeman and Railton 1988, Pereira et al. 1998, Worland et al. 1997). Further more, excellent results have been presented with PS designs not least in cases with advanced deformities (Aglietti and Buzzi 1988, Insall 1988, Groh et al. 1991).

In study 2 we found that the PS design of knee replacement had higher resistance to anterior posterior displacements than the concave design. This finding probably implies that the cement/bone interface is subjected to higher forces, resulting in increased rotation of the tibial tray around the transverse axis. On the other hand, increased anterior-posterior translations could result in a risk of increased asymmetrical loading of the tibial component. This is probably one explanation to the similar migration values recorded in the two groups with concave or PS implants. Whether the increased AP translations in the concave design would also result in more wear of the polyethylene needs to be documented in future studies.

Compared to previous studies of the PS implant, the HSS scores in our study were at the same level or slightly higher (Insall 1982, Aglietti and Buzzi 1988, Scott and Rubenstein 1986, Vinciguerra et al. 1994). They were also numerically higher compared to the results in study 3, where the preoperative deformities of the knee were less pronounced. We also recorded higher scores for the concave insert when the PCL was resected and more patients regarded their knee function as normal two years after the operation. One disadvantage in the study is of course that the observers were not independent.

Comparison between the two groups with concave inserts will be biased due to several reasons. The collection of patients in series two took longer time. Therefore, the overall surgical experience might have been superior, when the latter part of these patients were operated. Further, the selection of patients was not the same. The expectations in the group of patients with more advanced deformities could have been more modest and/or this patient population could have been less active. Our findings might, however, indicate that resection of the PCL really does improve the outcome, but this needs further study in the future.

Study 5: Inducible displacements of cemented tibial components. Observations during dynamic radiostereometry related to joint positions and 2 years history of migration in 16 TKR

Several authors have found a more or less strong correlation between migration during one to two years and inducible displacements (Hilding et al. 1995, Toksvig-Larsen et al. 1998, Regnér et al. 2000). Thus, there is evidence that indirect measurements of the interface quality in terms of inducible displacements will to some extent provide early information about the long-term fixation. Other factors such as bone remodelling and the forces acting on the prosthetic component will also have an influence. Further more, the inducible displacements do not only reflect the status of the interface. Deformation of the polyethylene, the cement and probably also the bone should be included (Regnér et al. 2000).

This study is the first to measure inducible displacement during active motion of the knee in humans. We could document a continuous change of the position of the tibial component during active extension, probably caused by the total sum of deformations in the polyethylene, cement and bone including interface motions. Obviously the inducible displacements turned out to be related to the kinematics of the joint and also to the design of the joint area. Our results should, however, be regarded with some caution because of a small sample size. Visualisation of sufficient number of tantalum markers in a metal-backed tibial component during motion is difficult and could only be achieved in about one third of the patients examined. We found a correlation between inducible displacements (anterior-posterior tilting, MTPM) and the corresponding migration up to two years. If these findings can be generalised, activities of daily living such as walking and above all stair climbing can be expected to influence the stability of the implant in the long run.

At about 25° of flexion increased anterior tilt was recorded in the knees with the PCL resected, probably due to an increase in or change of direction of the forces transmitted to the tibial component. Except from stressing the interface this motion could also increase the risk of polyethylene damage. Difficulties in achieving correct balancing of the ligaments in knees with severe deformity might have been of importance for its occurrence. Comparison between these groups revealed that the transition to anterior tilting was recorded at slightly more flexion for the concave implants. As has been reported in study 2, these implants had more pronounced AP translations and a more anterior position of the femoral condyles between 45 and 15° of flexion. When extending the knee the femoral condyles in these implants will probably contact the anterior slope of the polyethylene earlier, i.e. at a higher degree of flexion, which could explain this observation.

A relative medial translation was also found to increase this tilt. Close to extension the posterior capsule will become tenser resulting in transmission of higher pressure on the tibial insert from the femoral component. Medial positioning of the tibial component might cause the femoral condyles to articulate eccentrically against the concave trough, which will increase this pressure even more.

Increased resistance against anterior-posterior tilt seems to be of major importance for improvement of the fixation of the tibial component. This statement is probably not only valid for the AMK prosthesis, but also other implants of similar design. It is well known that this improved stability can be achieved by using a stemmed tibial component (Albrektsson et al. 1990).

Conclusions

Study 1: In vivo kinematics of total knee arthroplasty. Flat versus concave tibial joint surface

The hypothesis that a more concave joint area would result in smaller rotations and translations during active motions could not be verified. At one year correlation between abnormal kinematics and the patients opinion of abnormal function in the operated knee was detected. For the flat component posterior translation of the tibia correlated to the position of the tibial component. A correlation between positioning of the femoral component and sagittal rotations was noted for the concave design.

Study 2: In vivo kinematics of total knee arthroplasty. Concave versus posterior-stabilised tibial joint surface

The use of a central spine stabilized the knee, but only in the AP direction and not to normal values. No correlation between abnormal kinematics and clinical outcome was detected. In the concave group there was a correlation between the position of the tibial component and posterior translation of the tibia. When the results for the concave insert were compared with the corresponding design in study 1 no differences in the AP translation were found. Thus the PCL does not seem to play a major role in control of AP translation in many designs of knee replacements.

Study 3: Flat versus concave tibial joint surface in total knee arthroplasty. Randomized evaluation of 39 cases using radiostereometry

The hypothesis that implantation with a relatively non-conformed (flat) joint area would result in less migration of the tibial component two years after total knee arthroplasty could not be verified. The use of a concave insert was associated with a better fulfilment of the expectations on the stability. There was no correlation between radiolucent lines and migration of the tibial component.

Study 4: Concave versus posterior-stabilized tibial joint surface in total knee arthroplasty. Randomized evaluation of 47 knees

The hypothesis that the concave insert should migrate less than the PS design could not be verified. No differences in the clinical outcome between the two implants were recorded at two years. No correlation was detected between the radiolucent lines and the migration of the tibial component.

Study 5: Inducible displacements of cemented tibial components. Observations during dynamic radiostereometry related to joint positions and 2 years history of migration in 16 TKR

A continuous change of the position of the tibial component during active extension was recorded. The inducible anterior-posterior tilting and MTPM correlated to the corresponding migration measurements up to two years after the TKA. This finding could be related to the abnormal kinematics in the replaced knee and the choice of joint area configuration. Medial position of the tibial plateau centre and the use of a concave design were correlated to increasing anterior tilt.

Final comments and future perspectives

Despite the fact that the kinematics of the concave implants showed the most pronounced deviation from normal, the preoperative expectations in these patients were at least as well and on one item even better fulfilled. This could indicate that the kinematic pattern required of a knee prosthesis must not necessarily reproduce that of a normal knee. It is however obvious that the relative tibiofemoral motions have to stay within certain limits as documented in study 1.

There has indeed been an interest in the kinematics of TKR not least during the last decade. Despite this the association between the patients opinion or function of their TKA and the kinematics is not fully understood. Thus we still do not know the optimum kinematics required for a knee replacement. It could be that patients favour implants without any built in restriction of motion as long as this does not result in instability. Whether however, the more abnormal kinematics of the concave design also lead to a higher risk of wear of the polyethylene and loosening of the tibial component needs to be documented in further studies.

This study did not specifically address the role of the PCL in TKA. However, our findings suggest, that this ligament does not have a significant influence on the anterior-posterior translations, which is in accordance with previous observations. The clinical results seemed in fact to be slightly superior for one and the same design when the PCL was resected. As pointed out previously this comparison might be biased. The role of the PCL should therefore be further examined in studies with a randomised design. It might be that a more favourable loading pattern could be achieved with the PCL retained.

Andriacchi et al. (1982) and recently Stiehl et al. (2000) noted that ACL and PCL sparing prostheses were associated with better moment arms, closer to normal gait during stair climbing (increased quadriceps function) or closer to normal contact points. These types of implants can only be used in cases with no or mild degenerative changes of the ACL. Thus, as long the prosthetic designs cannot compensate for the absence of the ACL abnormal AP translations will probably remain unavoidable. Even if such prostheses will be available in the future, they might not necessarily solve the problem. In knees with advanced deformities, the soft tissue envelope might have become too severely changed to be compatible with a normal pattern of motion whatever implant is used. With present technology I think that the surgical procedure is considerably facilitated in severely damaged knees if the PCL is sacrificed. We could demonstrate that a PCL substituting design improved the kinematics, but not the clinical results. Others have, however, suggested reduced frequency of revisions due to instability with the use of "ultracongruent" polyethylene inserts (Hofmann et al. 2000).

In contrast to our hypotheses no differences between the implants regarding the fixation up to two years postoperatively were recorded. A possible explanation is that many replaced knees do not function as initially intended. Many theories and studies about the stability of knee prostheses and the forces transmitted to the interfaces only consider the situation at full extension and with full congruity between the components. As shown in this thesis the relative tibiofemoral positions may display a certain variability at full extension and the in vivo kinematics can be difficult to predict from a theoretical and laboratory model. If a new design of knee prosthesis is developed, my suggestion is that its fixation and kinematics are examined in vivo in a relatively small number of patients before large-scale production starts.

Today there are a number of standardised and validated systems to evaluate knee function. Due to the design of our studies we were especially interested in a few specific factors. Since the different designs of the joint area could be expected to have an influence on the stability, the patients expectations and fulfilment of these expectations regarding this parameter were judged to be especially interesting. The questionnaire used in our study could perhaps be improved to give a better understanding of the subjective function. Perhaps a better alternative would be to add a disease specific score. We were, however, reluctant to change the protocol during this study. Even if the HSS score has some value in the comparison with historical material, it has a comparatively poor inter-observer variability (Ryd et al. 1997). Thus, it should be supplemented with for example the Oxford score (Dunbar et al. 2000) or WOMAC (Söderman and Malchau 2000).

Kinematic evaluations of the knee with the use of RSA are still a fairly complicated procedure. In patients with total knee prostheses the metallic implant will easily hide one or several of the markers. It could be facilitated if the implants are premarked and with further development of the evaluation technique. Careful instructions and practical demonstrations for surgeons and radiographers involved in a project are mandatory steps to minimise dropouts during the follow up.

Since the kinematics for optimum clinical function of a knee prosthesis are still not fully understood, it is difficult to predict the design of a TKA which could be expected to give the best possible outcome. Improvements of laboratory models based on findings in clinical studies using RSA, fluoroscopy and gait analysis might be one approach. Many of the patients who participated in our study did not achive the pain releif they expected preoperatively. This indicates that there is indeed room for improvement in the design of the implants and the instruments used in knee replacements. Further improvement of the AMK prosthesis, and perhaps similar designs, should in my opinion focus on decreasing anterior-posterior tilt and on the shape of the femoral condyle. This would hopefully reduce the most obvious pathological findings in our studies.

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