50 years of total knee arthroplasty

INTRODUCTION AND HISTORY OF KNEE ARTHROPLASTY SURGERY

The advent of total knee arthroplasty (TKA) was an important milestone in the history of orthopaedic surgery. The development began in the late 1960s with the tibiofemoral condylar arthroplasties. In the 50 years since the advent of the first condylar knee implant, the design has evolved in order to provide better function and quality of life for millions of patients, with over 100 000 operations being carried out annually in the United Kingdom alone.[1]

This article, which coincides with the 50-year anniversary of the first condylar knee arthroplasty design, describes the developments that have been made to achieve better anatomical congruence, balance, and alignment with increasing accuracy and precision, while aiming to improve longevity, resistance to wear, and cost reduction (Fig. 1).

The first knees: hinged prosthesis

Theophilus Gluck implanted the earliest TKAs back in the 1890s, with an ivory hinged design with fixation achieved with plaster of Paris.[2] This rapidly failed, however, due to infection and inadequate fixation. The next major development was the hinge knee manufactured from cobalt chrome in 1958 by Walldius,[3] a design that was used until the 1970s (Fig. 2). The Bosquet–Trillat's prosthesis represented an evolution of the hinge at its introduction in 1971, as it allowed rotating movements.[4] This was the spherocentric knee. It provided the stability of a hinged unit by a contained ball-and-socket joint that obtained stability and allowed transaxial motion, thereby reducing torsional stresses at the prosthetic cement bone interface, and theoretically improving the longevity of the implants. The popularity of this design did not last long, however, as the implant tended to loosen and fail quickly, secondary to the amount of bone resection required.[5]

The use of the hinged prosthesis subsequently fell out of favour for primary arthritis due to the high mechanical failure rates from its inherent constraint, and thus newer designs with less constraint were sought. Its use is now reserved for special cases of complex primary, revision, and tumour surgery.

Making the implant more 'knee-shaped': the condylar knee design

Condylar knee arthroplasty essentially involves resurfacing the entire tibiofemoral joint, and the implants are mostly unconstrained. Therefore, they require instrumentation and less bone resection to aid soft-tissue balancing.

One of the first condylar implants was designed by Dr Frank Gunston, who worked with Sir John Charnley, gaining experience in high-density polyethylene as a bearing surface and polymethyl methacrylate cement fixation. Gunston first implanted the polycentric knee in 1968.[6] This was a highly conforming implant with separate medial and lateral stainless steel femoral components articulating with plastic tibial runners (Fig. 3). The collateral and cruciate ligaments were spared to help reduce implant stress and to allow for minimal bone resection, in order to enable arthrodesis should the arthroplasty fail. It was prone to failure due to minimal rotational freedom and high contact stresses from the small contact areas. Interestingly, 50 years on we are still trying to replicate implants with a similar appearance, albeit using technology to implant with more accuracy.

Professor Sav Swanson and Dr Michael Freeman of Imperial College London Hospital (ICLH) pioneered the ICLH Knee, which sacrificed both cruciate ligaments in order to correct large deformities and allow maximal contact area to reduce wear.[7] Knee kinematics were taken into account using the 'roller in trough' with a single radius of curvature. Freeman also introduced the concept of parallel and equal flexion and extension spaces, which were then termed "gaps" by John Insall.[8] He also introduced the concept of ligament balancing and soft-tissue release, which have become essential in contemporary knee arthroplasty surgery to maximize function and longevity.

Fine tuning: duocondylar and total condylar design

In 1971, Drs Chitranjan Ranawat, Allan Inglis, John Insall, and Peter Walker developed the duocondylar and unicondylar prosthesis.[9] The duocondylar had no anterior femoral flange, two separate tibial components, and preserved both cruciate ligaments. In 1974, this was modified to include the patellofemoral joint and

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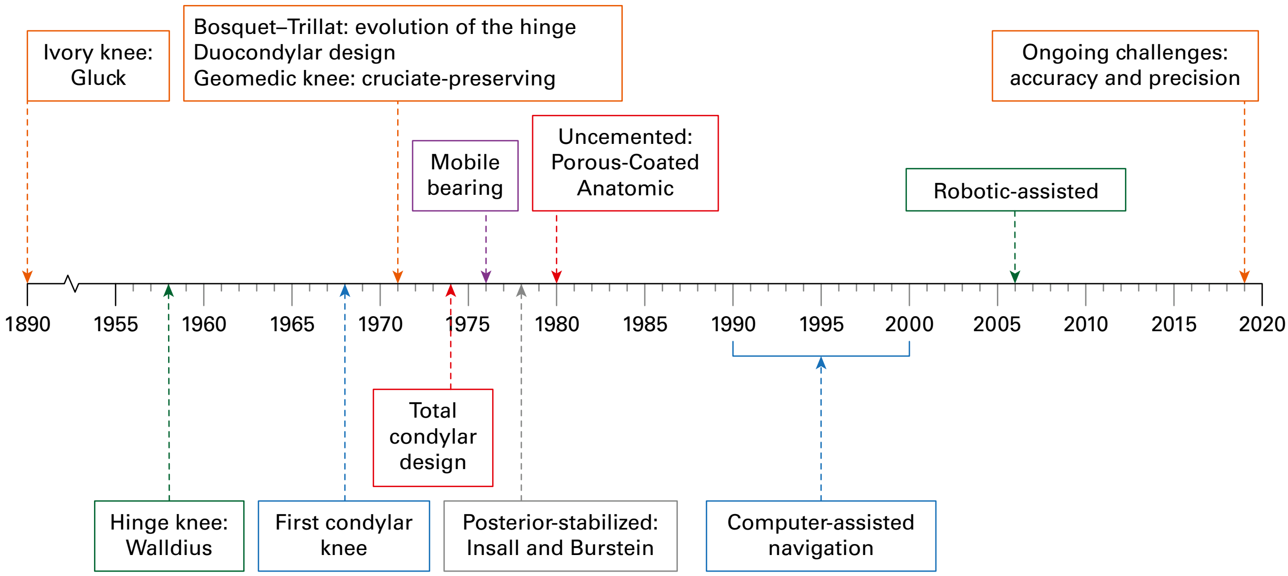

Fig. 1 A timeline showing important events in the history of total knee arthroplasty.

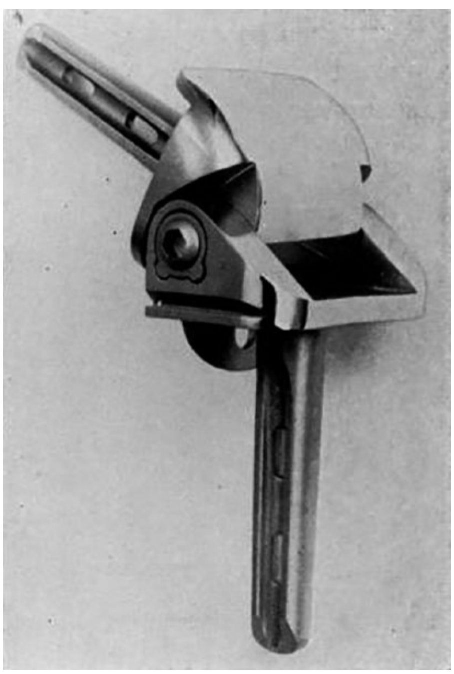

Fig. 2 Photograph of the Walldius knee. Reprinted from **Blundell JG.** Arthroplasty of the knee by the Walldius prosthesis. *J Bone Joint Surg [Br]* 1968;50-B:505-510.

preserve the posterior cruciate ligament. This was known as the Duopatella, which is the

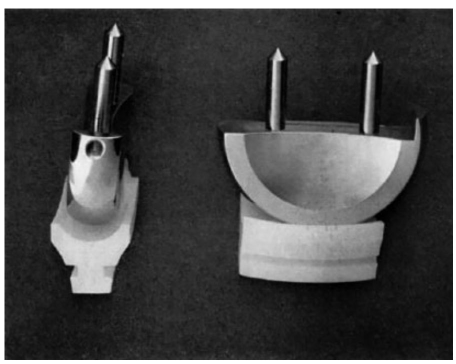

Fig. 3 Photograph of the Gunston knee. Reprinted from **Gunston FH.** Polycentric knee arthroplasty: prosthetic simulation of normal knee movement. *J Bone Joint Surg [Br]* 1971;53-B:272-277.

predecessor of many of the cruciate-retaining designs we use today.[9]

The same trio developed the more stable total condylar (TC) knee prosthesis in 1974, which became the first successfully marketed knee arthroplasty.[10] It had features that replaced all condylar surfaces and the patellofemoral joint. It also had an all-polyethylene tibial component with a large central tibial peg for fixation, with round-on-round geometry on the bearing surfaces with partial conformity, with multiple built-in radii of curvatures.

Early TC prosthesis did not allow roll back in flexion, and therefore the tibial portion was located more posteriorly, which reduced the range of movement, especially if the flexion gap was not balanced, and thus flexion was limited to between 90° and 100°.

To solve this, Insall and Burstein developed the posterior-stabilized knee in 1978, which was an adaptation of the TC design.[11] This knee tried to address the issues of anterior instability, insufficient flexion, and edge loading of the TC design. They added a cam to the femoral prosthesis and a post to the tibial prosthesis for posterior cruciate ligament substitution. This engages at around 70° of flexion to bring the femoral component forward, thus allowing more flexion and controlled roll back.

The first attempt at preserving the cruciate ligaments: Geomedic design

In a similar period between 1970 and 1973, another independent condylar knee was developed by Dr Mark Coventry (Fig. 4).[8] This Geomedic prosthesis incorporated a conforming tibial and femoral design that would reduce polyethylene wear. They preserved both cruciate ligaments but did not resurface the

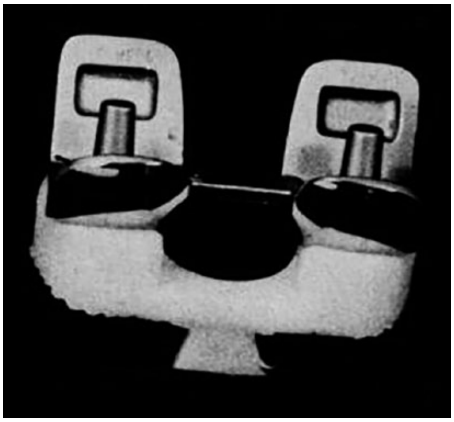

Fig. 4 Photograph of the Geomedic knee. Reprinted from **Bargren JH, Day WH, Freeman MA, Swanson SA.** Mechanical tests on the tibial components of non-hinged knee prostheses. *J Bone Joint Surg [Br]* **1978;60-B:256-261.**

patellofemoral joint, with the femoral condyles only attached to each other by a narrow bar. Although the tibial component had several pegs to enhance fixation, loosening was still a problem. The Geomedic knee was first implanted in 1971 with Simplex cement, and it was the United States Food and Drug Administration (FDA) approval of this cement that led to early success of many knee designs.[12]

Attempting to reduce wear and constraint: mobile- versus *fixed-bearing design*

Although traditional fixed-bearing components provide good results, issues with polyethylene wear were a concern in the long term, especially in young patients. Mobile-bearing articulations were therefore subsequently introduced in an attempt to improve polyethylene wear characteristics by decoupling rotation and translation forces while allowing for better freedom of movement. These designs were built on the concept of reducing contact stresses and increasing conformity between the femoral component and polyethylene,[13] while theoretically separating the movements of rotation and translation. The first, the unicompartmental Oxford Knee, was introduced in 1976 by Goodfellow and O'Connor.[14] In the United States, the low contact stress (LCS) knee was developed with a similarly conceived rotating platform mobile-bearing design to try to avoid the complication of dislocation of the meniscal bearing.

Issues with mobile-bearing components arise with reports of backside wear on the tibial bearing surface, as well as reports of loosening secondary to osteolysis.[15,16] The other issue is dislocation of the bearing, especially when the flexion and extension gaps have not been adequately balanced. The 15th annual National Joint Registry (NJR) report still shows that 65% of unicompartmental knee arthroplasties in the United Kingdom are implanted with a mobile bearing, although this is a downward trend since concerns of wear and fixation are less of a concern with modern implants.[17]

Fixation: to cement or not?

Concerns over the long-term outcome of bone-cement fixation led to the development of the uncemented bone ingrowth materials with the use of porous coated components. The first was the Porous-Coated Anatomic (PCA) knee arthroplasty, developed in 1980 by Hungerford and Kenna.[18] Although initial two- and five-year results were promising, the ultimate results of the PCA were dismal, because the flat articulation surfaces and heat-pressed polyethylene of the tibia promoted severe wear.[19]

In the most recent NJR, uncemented knee arthroplasties only account for 4.2% of all TKAs, with a ten-year revision rate of between 4% and 6%, compared with between 2% and 4% for a cemented TKA.[1] However, uncemented knee arthroplasty has made somewhat of a resurgence in recent years due to advances in prosthetic design, instrumentation, and operative technique, as well as the undying enthusiasm to try new technology in the hope it may lead to improvements.

MARKETING TOOLS? THE HIGH-FLEX AND SEX-SPECIFIC DESIGNS

High-flex designs

Theoretically, higher flexion is gained by means of posterior rolling and translation of the femoral prosthesis with an extended posterior condylar offset, allowing a wider contact surface with the bearing, reducing contact pressure and wear.

Although there are no consistently proven results, this design has been previously shown to provide approximately 10° greater flexion compared with a standard posterior-stabilized implant.[20] Often, however, these design features are essentially marketing strategies that had little effect on true kinematics in deep flexion. They were, however, effectively marketed at certain cultures where a greater degree of knee flexion is important.

Sex-specific design

The idea behind producing a sex-specific TKA design was to reduce the friction between the patella and the prosthesis, to eliminate anterior 'overstuffing', which can happen more commonly in women. This is gained by a more oblique trochlear groove, a thinner anterior profile, and a narrower contour, reducing bone loss.

Studies comparing this design with a traditional prosthesis essentially demonstrated no advantage in functionality or patient satisfaction.[21]

IMPROVING PRECISION AND ACCURACY: NAVIGATION, PATIENT-SPECIFIC INSTRUMENTATION, AND ROBOTICS

Computer-assisted navigation

This was developed in the late 1990s with advances in 3D sensor technology. The purpose is to provide precise implantation by means of digital mapping based on standard anatomical landmarks and kinematic analysis.[22] A 3D model of the knee is created intraoperatively using digital surface mapping, and the computer can then correlate this model with the surgical instruments to allow for precise cutting and implantation.

Multiple studies have demonstrated that computer-assisted navigation improves component alignment and restores the mechanical axis during TKA.[23] Controversy remains as to whether this leads to any actual clinical benefit.

Some studies have demonstrated no differences between this and conventional arthroplasty in terms of function or clinical outcome at ten years.[24-26] Equally, a meta-analysis of 21 studies found that along with improved alignment, computer-assisted navigation was associated with significantly better functional scores at three and 12 months postoperatively.[25]

The technology is useful in patients with extra-articular deformities that preclude the use of intramedullary guides, and in obese patients where achieving alignment can be difficult. It also does not directly address soft-tissue balancing, and thus the use of contact load sensors along with computer navigation may be employed in future.

Patient-specific instrumentation (PSI)

PSI is a more modern technique of performing TKA, aiming to facilitate the implantation and positioning of the prosthesis. This involves customized cutting blocks generated from a preoperative 3D model using CT or MRI. The PSI is designed to take into account any deformities and plans bone resection for a pre-determined implant size, position, and rotation, boasting more reproducible neutral alignment while reducing surgical time.

There is, however, no conclusive evidence that the precision of the PSI instrumentation is better than other methods in obtaining correct alignment of the components.[27]

Literature also suggests that there is no significant gain in functional improvement, reduction in perioperative blood loss, or surgical time with PSI compared with standard techniques.[28,29] However, there is a role for PSI in patients with femoral or tibial deformities.

Handheld navigation

Accelerometers and sensors increasingly utilize smartphone technology, making navigation more compact. Accelerometers measure the position of an object relative to a given axis and then use the information to calculate the mechanical axis of the tibia and femur, in order to assist the surgeon making the cuts.[30]

Pressure sensors are transducers that measure the contact load in the medial and lateral compartments of the knee. The dynamic sensor output through the full knee range of movement gives information about load in the compartments at all angles, as well as track pivot and rollback. Therefore, intraoperative osseous or ligamentous adjustments can be made to provide soft-tissue balance.[30]

This does not require preoperative imaging, but can potentially cost $1000 more per case.[31] There are mixed results in the literature with regards to its outcomes, and currently no randomized trials demonstrating improved balancing with sensor-based technologies compared with conventional instrumentation.

Robotic surgery

Robotic assistance has developed to facilitate the preparation of the bone surfaces. This requires a preoperative CT scan to plan the optimal component position based on sagittal, coronal, and rotational alignment. The robotic system then allows for 3D milling of the bone based on planning.

The majority of the literature on this is based on unicompartmental knee arthroplasty, where it is suited, since it is technically more challenging surgery. Here, it has been shown to improve component positioning and alignment.[32] For robotic-assisted TKA, most studies have demonstrated restoration of mechanical alignment, especially femoral rotation, to a greater degree than conventional surgery. However, this has yet to materialize into better clinical performance.[33]

In a recent study comparing robotic-assisted *versus* conventional TKA, the robotic group demonstrated no outliers in the mechanical axis (>3° from neutral) with no notching; however, clinical outcome scores were not different.[34] Larger and longer-term studies are still required for this technique.

Although robotics can more reliably reproduce mechanical alignment, this comes with additional operating time due to the learning curve, as well as a higher cost and the radiation exposure of the preoperative CT scan.

Which alignment? Mechanical versus kinematic

Mechanical alignment is an anatomical alignment (AA) technique, initially introduced in the 1980s by Hungerford and Krackow[18] as a compromise in an attempt to improve survivorship in early TKA designs, which aims for an oblique joint line (2° to 3° valgus) relative to the mechanical axis of the limb. This was deemed to provide a better load distribution on the tibial component, and better patella biomechanics. The technical challenge in the 1970s was to precisely achieve bone cuts, with the risk of having a supposedly deleterious excessive (> 3°) varus of the limb or tibial implant. Nowadays, this lack of surgical accuracy has been overcome by the use of precision tools for implant positioning, and by the development of TKA implant incorporating a 3° joint line obliquity in their design, which enables to obtain the effects of an AA technique by doing mechanical axis (MA) bone cuts. Good mid to long-term results have been published with this technique.[35]

The kinematic alignment (KA) technique is a 'true knee resurfacing' (fully anatomical positioning of TKA implants). It is a patient-specific and 'ligament-sparing' technique striving to restore the highly inter-individual variable native pre-arthritic limb and joint line alignment and stability. The KA technique is a pure bone procedure with predictable expected thickness of bone cuts, and intraoperative ability to check (caliper measurement) and correct them. Early results of KA have been comparable to MA.[36]

MATERIALS AND TRIBOLOGY

There had been a drive to develop materials to reduce bearing wear and increase resistance to stresses. Highly crosslinked and Vitamin E stabilized polyethylenes are now being used as the bearing insert, which has oxidation resistance and minimized free radical formation. This highly crosslinked polyethylene has better wear properties than conventional polyethylene.[37]

New solutions for the femoral and tibial component materials have also been developed. Alumina was the ceramic forerunner first used in 1980 by Oonishi,[38] the advantages being that it is very hard and stable, with a low coefficient of friction, but the initial designs failed early due to loosening.[38] In the 1990s, an alumina femoral component was used with a metal tibial component. From 1993, cemented alumina was introduced.

Initial alumina evolution was with zirconia stabilized with yttrium in TKA from 2001.[39,40] Currently, Biolox Delta ceramic is the highest performing, which combines the stability, biocompatibility, and low wear of alumina, along with the superior mechanical strength and fracture toughness of zirconia.[41]

Oxinium is a zirconium alloy metal that transitions into a ceramic zirconium oxide outer surface. A zirconia and niobium alloy is used to create Oxinium. Oxinium is highly biocompatible and has been shown to be twice as hard, with less wear debris generated when articulating with UHMWPE *versus* cobalt chromium. Although good results and survival of up to 94% at 15 years have been demonstrated, its use has widely been limited by production costs.[42] It is likely that condylar knee arthroplasty will continue to be a resurfacing operation of cobalt chromium on polyethylene with cemented implants, due in part to the excellent current results, and in part to the conservatism resulting from joint registries, as well as the natural conservatism in the arthroplasty community caused by the recent catastrophic failure of some implants used in hip arthroplasty.

QUALITY CONTROL AND PERFORMANCE MONITORING

The National Joint Registry (NJR) was formed in the United Kingdom by the Department of Health in 2002.[1] It collects information on knee as well as other joint arthroplasty operations to monitor the performance of joint arthroplasty implants and effectiveness of different types of surgery, with the aim of improving clinical standards. It provides comparative data to identify outlying hospitals, surgeons, or implants with regards to survivorship or surgical practice.[1]

Similarly, the Orthopaedic Data Evaluation Panel (ODEP) was established in 2002 initially for hips, but since 2014 for knees also, to track performance of implants with less than ten years of data.[43] This also allows manufacturers to take responsibility for the implants they sell, as they are required to register the implant through ODEP and allow monitoring through the NJR. Surgeons in the United Kingdom are encouraged to only use ODEP rated implants through the Getting It Right First Time (GIRFT) project.[44] The rating is the number of years of evidence for the implant followed by the letter 'A' for "strong evidence" or 'B' for "acceptable evidence". If not a "10A" rated implant, it would be followed by ODEP through the manufacturer.[43]

In order to encourage innovation while still maintaining safety, new implants should go through the 'Beyond Compliance' process where they are given a 'pre-entry' ODEP rating, and then monitored more closely until obtaining an acceptable rating.[45]

SUMMARY

There have been tremendous advances in the design and development of TKA over the last 50 years. These improvements have been more incremental than revolutionary.

At present, new technologies using robotics are too costly to justify their routine use in place of conventional TKA. Longer-term evidence is required to demonstrate that this improved accuracy and precision, combined with 3D imaging and optimal component position, leads to superior clinical outcomes.

Along with surgical and implant advances, better outcomes in TKA involves improvements in patient selection, anaesthesia, recovery, and pain relief post-surgery, as well as rehabilitation protocols.

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 DOI: 10.1302/2048-0105.82.360688