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The Evolution of Modern Total Knee Prostheses

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1. Introduction

Many types of prosthesis are used for total knee arthroplasty, and the evolution of knee arthroplasty, which has a history of almost 40 years, involves repetitious cycles of failure and development. During its early stage (1970-1974), instruments of the unicondylar, duocondylar, or hinged types were used, but these were eventually abandoned due to low success rates. A replacement for the total condylar type was successfully developed and became the model for total knee arthroplasty. Recently, unicondylar arthroplasty has produced good results in selected patients, and arthroplasty of the constrained or hinged type have been proven useful for revision surgery or combined surgery, respectively. To solve the problem of the fixed bearing joint, a mobile bearing joint has been developed, and non-cemented fixed knee arthroplasty is receiving renewed attention. Much effort is being expended on the developments of new materials, such as, ceramics and cross-linked polyethylene, on new designs that maximize function and endurance, and on minimally invasive surgery.

2. History of the evolution of total knee arthroplasty

2.1. Interposition and resurfacing knee arthroplasty

During the late 19th and early 20th century, interposition arthroplasty was attempted using soft tissues. In 1860, Verneuil proposed interposition arthroplasty, involving the insertion of soft tissue to reconstruct the joint surface. Since then, pig bladder, nylon, femoral sheath, anterior bursa of the knee, cellophane, and many other materials have been used, but results have been disappointing. The use of metallic interposition arthroplasty began in the late 1930s. Having obtained successful results for mold arthroplasty in the hip joint, Campbell

and Smith-Peterson proposed metal femoral mold arthroplasty[2], and McKeever and MacIntosh proposed hemiarthroplasty of the tibia, but all produced unsatisfactory results in terms of minimizing pain, and high rate of failures of the interposition [3], and thus, these procedures were not widely recognized.

Ferguson [1] attempted resection arthroplasty for ankylosis or severe deformity caused by tuberculosis or infection. This procedure involved resecting cartilage from the knee joint and allowing knee joint movement along the subchondral surface. When too little bone was removed, knees spontaneously fused, and when more bone was removed, knee had good motion but poor stability. Accordingly, these operations were attempted in only the most severe cases because their results were poor.

2.2. The hinged prosthesis

In the 1950s, Walldius [4] developed a hinged prosthesis that replaced the joint surfaces of the femur and tibia, as subsequently, modifications of the basic hinged prosthesis design were made by many surgeons. The hinged prosthesis allows the intramedullary stem to align with the artificial knee joint by itself, and is technically easy to perform since all ligaments and soft tissues can be removed due to the mechanical and structural stability of the prosthesis. During the 1950s and 1960s, hinged total knee arthroplasty provided satisfactory results for a longer period of time in more patients than any other knee arthroplasty design used. However, this method could not be widely used since this type of simple hinged prosthesis cannot replace the complex movements of the knee joint and because of a high failure rate due to early loosening caused by overloading the prosthesis and bone contact surface or by infection.

2.3. The bicompartamental prosthesis

In 1971, Gunston [5] developed polycentric knee arthroplasty. This was done by adopting the concepts of low friction hip arthroplasty espoused by Charnley. Gunston's knee arthroplasty retained the collateral and cruciate ligaments to help absorb stress, and consisted of relatively flat tibial interposition of high-density polyethylene and a round femoral prosthesis, which replaced the posterior portion of femoral condyles. These components were fixed to bones with bone cement, and replaced the complex movements of 'femoral roll-back'. Polycentric knee arthroplasty was initially successful due to improved mobility and movement range, but the fixation it provided was not sufficient.

Geomedic knee arthroplasty was introduced by Coventry et al. at the Mayo Clinic in 1972[6], and consisted of a polyethylene tibial instrument which was of one structure and was in joint with the femoral condyles. This design was initially devised to sustain the cruciate ligament, but joint mobility was limited because of pathologic posterior cruciate ligament in some cases. The main limitation of this design was rapid and excessive loosening.

Freeman et al.[7] at Imperial College Hospital (London) designed a femoral and tibial prosthesis to work in a 'roller-in-trough' manner by the strength of collateral ligament. The anterior and posterior cruciate ligaments were usually removed, and the tibial prosthesis did not

have an intramedullary stem to minimize the risk of infection and to maximize knee joint function for salvage procedures. However, the loosening of the tibial prosthesis became a major drawback.

In the mid 1970s, duocondylar interposition was designed to resemble the anatomic structure of the knee joint [8]. The femoral prosthesis connected with two unicondylar prostheses via an anterior bridge, and formed a joint, which was considerable wider than previous polycentric knee arthroplasties, with two flat tibial instruments. However, the design had the drawbacks of frequent destruction or deformity of the tibial prosthesis.

2.4. The tricompartmental prosthesis

In the early 1970s, three types of condylar prostheses were developed, which opened the era of modern knee arthroplasty. First, in 1976, Ranawart et al. [8] at the Hospital for Special Surgery, developed the duocondylar prosthesis; second, Coventry et al. [6] developed the geometric prosthesis; and third, Townley [9] developed the anatomic prosthesis. The condylar prosthesis developed by Ranawart et al. preserved the anterior and posterior cruciate ligaments, provided stability of the knee joint, and used bone cement for fixation to bone. However, the geometric and anatomic types were not produced continuously due to early loosening of fixation. The duocondylar type was further developed to produce the first total condylar prosthesis with a tibial stem by Walker et al. in 1976 [10] at the Hospital for Special Surgery and became the early model for today's posterior cruciate ligament substitution knee arthroplasty. The total condylar prosthesis is a design that removes anterior and posterior cruciate ligaments. The femoral prosthesis, which is made of chrome cobalt, has a symmetric femur with a double curve, which has a flat patellar trochlear groove. The tibial prosthesis is completely made of polyethylene, has good conformity in the flexion and extension states, has anterior and posterior lips in the tibial joint surface, and has eminence in the mid joint surface which provides anteroposterior and mediolateral stability. There is also a stem in the tibial prosthesis, which can endure asymmetric loading. The patellar prosthesis is of the half-ball type and is completely made of polyethylene, with a fixation lug in the middle, which is fixed with bone cement. The features of this early total condylar knee are used in most of today's prostheses. Along with these total condylar prostheses, the duopatellar prosthesis was developed, which preserves the posterior cruciate ligament. This prosthesis is anatomically similar to the normal knee joint with respect to the femoral prosthesis trochlear groove, and forms a joint with a polyethylene patellar prosthesis. The early tibial prosthesis model could be separated into medial and lateral parts, but later a form communicating the bilateral parts was developed. The duopatellar prosthesis was developed into the kinematic condylar prosthesis, which was widely used in the 1980s [11]. Early total condylar prostheses did not allow roll-back in the flexed position and the tibial portion was located posteriorly, which reduced the mobility range when the flexion gap was not balanced. According to early clinical reports, the average mobile angle was 90-100 degrees. To solve this problem, Insall et al. [12] added a cam to the femoral prosthesis and a post to the tibial prosthesis for posterior cruciate ligament substitution knee arthroplasty to accelerate the posterior location of the femoral prosthesis when flexed at about 70 degrees, thus enhancing

flexion. These Insall-Burnstein and kinematic interpositions became the foundation of modern knee arthroplasty. Despite the developments of modern joint replacement designs, complications of the femoro-patellar joint were frequent after knee arthroplasty in the 1980s and 1990s, which led to the development of today's knee arthroplasty which increases contact surface in the femoro-patellar joint and prevents lateral displacement of patellar bone.

2.5. Unicompartmental knee arthroplasty

Although it has been used since its introduction in 1950s, the results of unicompartmental knee arthroplasty (Figure 1) remain controversial. In the early 1970s, several authors reported unsatisfactory results for unicompartmental knee arthroplasties but over the next decade, better surgical techniques and proper patient selection improved results [13]. Unicompartmental knee arthroplasty can be used in cases with up to moderate arthritis and when diseased is confined to one compartment. Along with Repicci and Eberle's [14] minimally invasive techniques, unicompartmental knee arthroplasty has aroused much interest. As compared with total knee arthroplasty, the unicompartmental knee arthroplasty has the advantage of preserving anterior and posterior cruciate ligaments and of recovering almost the full range of motion of the normal knee joint. It also boasts a small amount of bone loss and theoretically enables easier revision surgery [15]. The recently reported long-term endurance of unicompartmental knee arthroplasty is about 85-95%, which is similar to that of total arthroplasty. Therefore, if patients are properly selected and an adequate technique is used, it may be a good surgical option.



Figure 1. Unicompartmental Knee System (Courtesy of Zimmer)

2.6. Patellar resurfacing

Patellar resurfacing was described as early as 1955. The first patellar resurfacing materials were metallic components, but this design was limited because of problems concerning metal to cartilage articulation. Subsequently, the polyethylene patellar prosthesis was developed and satisfactory results were obtained. Present day knee arthroplasty became total knee replacement when patellar component was added.

3. Spectrum of prosthesis designs

Nowadays, many types of prostheses are used for total knee arthroplasty. However, controversy exists regarding which prostheses are the most appropriate for individual surgeons and specific patients. Therefore, we compare the advantages and disadvantages of each type of interposition knee arthroplasty.



Figure 2. Posterior cruciate ligament retention type prosthesis (Courtesy of DePuy)

3.1. Posterior cruciate ligament retention versus substitution

All knee arthroplasties require anterior cruciate ligament removal, but retention of the posterior cruciate ligament depends on the type of arthroplasty. The preservation type, in which posterior cruciate ligament is preserved, is considered better than the replacement type for performing functions, such as, climbing stairs, and has the advantage of simplifying revision surgery due to less loss of bone (Figure 2). However, knee joints with degenerative

arthritis usually show soft tissue contracture, and when preserving the posterior cruciate ligament, the soft tissue balance is not easy to achieve, which possibly increases the risk of early failure due to polyethylene insert overloading caused by posterior cruciate ligament unbalanced tension [16].



Figure 3. Posterior-substitution prosthesis showing that the post-and-cam mechanism offers no restraint to varus or valgus stability (Courtesy of Biomet)

When the posterior cruciate ligament substitution type is used, even degenerative knee joints with relatively severe deformities can achieve ligament balance, and when flexed at 60-70 degrees, the post of the tibial polyethylene contacts the cam of the femoral component and induces posterior placement of femoral bone, which allows relatively satisfactory roll-back and can achieve sufficient knee joint flexion (Figure 3) [17]. However, bone loss at the intercondylar notch makes revision surgery difficult, and fracture may occur intra-operatively or post-operatively in patients with small femurs. From the biomechanical perspective, neither posterior cruciate ligament preservation nor substitution types can totally replace the biomechanics of the normal knee joint. Furthermore, many clinical studies have concluded that there is no significant difference between these two types of prosthesis.

3.2. Mobile versus fixed bearing total knee arthroplasty

Traditional fixed bearing knee arthroplasties have produced good clinical results at 10-15 years postoperatively. Unfortunately, problems associated with polyethylene wear can occur in the long-term, especially in young patients. This wear can be reduced by reducing

contact stress at the joint surface and by improving the wear characteristics of the material used. Contact stress may be reduced by increasing conformity between the femoral component and the polyethylene insert. The development of mobile-bearing articulating polyethylene surfaces in implants for patients undergoing total knee arthroplasty reflects the efforts made by designers to optimize wear while addressing the complexities of function. However, the trade-off for conformity and free mobile range in fixed bearing knee arthroplasty makes marked improvements in contact stress near impossible. To solve this problem, mobile bearing interposition knee arthroplasty was invented to reduce contact stress but to preserve freedom of movement. In 1986, Goodfellow and O'Connor [18] invented Oxford knee arthroplasty, which is a mobile bearing knee arthroplasty of the bicondylar type (Figure 4), and subsequently, Beuchel and Pappas [19] invented the meniscus sustaining bearing, which boasts low contact stress. However, in the case of the mobile bearing insert, the bearing can be dislocated when flexion extension gaps are inadequate. In Europe, this mobile bearing prosthesis has been used for decades with good clinical results, but recent reports have found no significant differences between this mobile bearing prosthesis and fixed bearing polyethylene.



Figure 4. Mobile bearing knee prosthesis, which reduces contact stress but preserves freedom of movement (Courtesy of Biomet)

3.3. Non-cemented versus cemented knee prostheses

Concern over the long-term tolerance of bone cement fixation led to the development of a non-cemented fixation design in 1980. Hungerford et al. [20] invented the initial porous-coated anatomic design, others include, the Miller-Galante, Miller-GalanteII, Tricon-M, Genesis, and Ortholoc prostheses. These implant designs have a surface topography that is

conducive to bone ingrowth. Most are coated or textured so that the new bone actually grows into the surface of the implant. They may also use screws or pegs to stabilize the implant until bone ingrowth occurs. However, because they depend on new bone growth for stability, non-cemented implants require a longer healing time than cemented replacements.

Non-cemented implants, unfortunately, showed higher failure rates than cemented knee arthroplasties due to aseptic loosening and bone loss. In all knee replacement implants, metal rubs against the polyethylene insert, and although the metal is polished and the polyethylene is treated to resist wear, the loads and stresses of daily movements generate microscopic particle debris, which in turn, can trigger inflammatory responses that result in osteolysis or loosening.

Because non-cemented implants have not been used as long as cemented implants, comparisons after long-term use are not possible. However, some studies have shown that non-cemented fixation has success rates comparable to those of cemented fixation [21]. Nevertheless, non-cemented knee arthroplasty has not widely adopted, but recent material developments have resulted in materials that enhance bone ingrowth which has led to the use of non-cemented knee arthroplasty in young patients.

3.4. Constrained condylar knee prostheses

Revision total knee arthroplasty is often associated with poorer outcomes due to bone loss and ligament damage, which can result in ligamentous laxity and imbalance. A constrained condylar knee design was developed to resist coronal moments in the plane caused by soft-tissue deficiency. Constrained condylar knee designs have the advantage of allowing changes in the center of rotation during flexion, and thereby, theoretically impart less tangential anterior-posterior stress across the prosthetic interface [22]. An early model of constrained condylar knee design was proposed by Insall et al, although similar to posterior cruciate ligament substitution knee arthroplasty, the polyethylene post is thicker and longer, which provides stability for valgus and varus movements as well as not posterior movements [23]. These early models were developed into Legacy Constrained Condylar Knee (Figure 5)[24]. Excessive constraint is a problem when the LCCK is used and this causes failure by loosening the prosthesis. Thus, in difficult knee arthroplasty cases, usage may be determined during surgery by taking into consideration the need for constraint. For example, in severe valgus knee joints, the LCCK polyethylene insert may be a good candidate, but posterior cruciate substitution tibial bearing is recommended over the constrained type.

3.5. Cross-linked polyethylene bearing

The development of arthroplasty design and materials has led to long-term endurance, but the not infrequent need for revision due to polyethylene wear has been a cause of patient dissatisfaction. To reduce polyethylene wear, a cross-linked polyethylene bearing was developed and used in hip replacements in 1990s, and thus, its effectiveness has been proven. Its resistance to wear provides a promising solution for arthroplasty patients, especially today's more active, physically demanding patients. However, in knee arthroplasty, it has nei-

ther been widely used nor widely studied. Recently improved resistance in posterior cruciate substitution knees have been reported to lead to cam and post delamination, pitting, cracking or fractures [25].



Figure 5. The Legacy Constrained Condylar Knee Prosthesis (Courtesy of Zimmer)

3.6. High flexion type knee prostheses

Generally, postoperative knee motion range for total knee arthroplasty is less than 120 degrees. Recently, to obtain motion ranges similar to those of the normal knee joint, high flexion femoral prostheses with a thickened posterior portion of femoral prosthesis and a wider contact surface with the bearing are being used to reduce contact pressure and wear (Figure 6). To prevent collision between the patellar ligament and bearing at high degrees of flexion, a high flexion bearing with an oblique cutting of the anterior bearing has been developed. Furthermore, many authors have reported that high flexion knee arthroplasty can result in smaller contact loadings and wider ranges of motion than previous knee arthroplasties. For example, Huang et al. [26] found that mean flexion in patients with a high-flexion prosthesis was approximately 10° greater than in patients with a standard posterior stabilized implant. Laskin [27] has also published similar findings. In addition to pain reduction and restoration of function, survivorship is also a decisive contributor to the success of TKA. Thanks to its extended posterior condyle radius, which has been broadened all round, the NexGen CR-Flex system offer a larger contact surface during deep bending, and therefore, spreads contact stress over a large area. However, some authors [28, 29] have reported no increase of flexion when using high-flexion prostheses.

In particular, in a clinical study that used both knee implants, high flexion knee arthroplasty did not show a significant increase in knee joint flexion range. This issue needs to be proven by long-term follow up over 10 to 15 years [30].



Figure 6. High flexion type prosthesis (Courtesy of Zimmer)

3.7. Ultracongruent polyethylene bearings

The most important thing to remember when performing posterior cruciate ligament preserving knee arthroplasty is to balance the posterior cruciate ligament and prevent instability by ligament disruption when flexed. For these reasons, deep-dished polyethylene insert (also called ultracongruent insert) was developed. This bearing insert has moderate conformity in coronal and sagittal planes, which can prevent edge loading caused from paradoxical anterior translation due to elevation of the anterior lip of the prosthesis, prevent elevation in flexion, and prevent posterior subluxation (Figure 7). Ultracongruent bearings can reduce cam-and-post wear or fracture that may occur after posterior cruciate ligament substitution knee arthroplasties, and can prevent bone loss at the intercondylar cutting site. This bearing represents a new concept in that it can also maintain the posterior cruciate ligament and provide moderate conformity in total knee arthroplasty. Further long-term clinical follow-up is required along with comparative clinical trials of posterior cruciate ligament preservation, substitution, and sacrificing techniques.



Figure 7. Ultracongruent polyethylene bearing (Courtesy of Biomet)

4. Conclusion

The history of prostheses evolution follows a repetitive course of development and failure. The continuous and rapid developments of biomechanics and of materials in the 20th century hugely expanded the information available. Furthermore, spectrums of designs are currently being used for total knee arthroplasty.

Most knee replacements are now being performed with PCL-retaining or PCL-substituting prosthesis that have their merits and limitations, as discussed above. New mobile-bearing devices, which address the issue of functional complexity, have been developed and have the potential to prolong implant durability. Nonetheless, prosthesis materials and the historical and current results of different types of prosthesis remain topics of discussion with respect to their indications and contraindications. In the future, the new implant will be developed by applying the pros and removing the cons based on the implant history.

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