Prostheses option in revision total knee arthroplasty, from the bench to the bedside: (1) basic science and principles

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• The number of primary and revision total knee arthroplasties (rTKAs) continues to increase annually. To date, most of the literature has focused on the surgical technique and outcome of revision prostheses. Thanks to the contributions of surgeons, engineers, and researchers, the design of prostheses has reached a prominent milestone. However, very limited discussion regarding the design, rationale and constitution of prostheses has been documented at present.

• An electronic search of four online databases (Embase, MEDLINE, PubMed, and Google Scholar) was conducted to identify eligible resources. Forty-four review articles were acquired by searching the terms ‘prosthesis selection’, ‘prosthesis option’, and ‘prosthesis determination’ in rTKA. Sixty-eight research articles investigating the factors affecting prosthesis options in rTKA were screened and integrated with the authors’ perspective to reach a final recommendation.

• This article first discusses the pathological, individual, and other factors affecting prosthesis options in rTKA and further illustrates the classification, geometry, biomechanics, and constitution of the revision system from the authors’ perspective. An evidence-based recommendation in the form of a matching algorithm was formulated.

• This review offers special value for decision-making regarding prosthesis options in rTKA. Particularly, it presents specific recommendations regarding unclear practical issues, such as the optimal level of constraint, individualized design, length, and fixation of extension stem, as well as the pros and cons of modularity.

Introduction

Total knee arthroplasty (TKA) has been acknowledged as an effective intervention for patients with advanced knee arthrosis. There has been a steady increase in the number of TKAs over the past decade due to the rapid increase in global aging and profound insight into the disease pathology, including consistent improvement of implants, technical innovation, and clinical outcomes (1). The increased numbers of primary TKA (pTKA) have also resulted in an increased incidence of failure, which is usually solved via revision TKA (rTKA) by addressing the pathologies and consequences resulting from failure. Studies to date have demonstrated a significant increase in the requirement for revision procedures (2, 3, 4, 5) frequently caused by septic or aseptic loosening, instability, polyethylene (PE) wear, and osteolysis. Projected estimates made for the United States showed that the demand for rTKA will likely increase by 601% by 2030 from the base level in 2005 (2), and a similar trend has been predicted in other national registries (3, 4, 5). Based on these forecasts, knee surgeons have an urgent requirement for evidence-based guidelines for prosthesis options in managing rTKA.

The revision procedure usually requires a comprehensive understanding of the design rationale of a revision system, which is characterized by a high degree of modularity, offset adjustment, metallic augmentation, stem biomechanics and fixation methods, and grade of constraint, according to the disease pathology, patient specificity, and availability of arthroplasty (6). However, there is very limited knowledge in terms of implant selection and instrumentation, and little regarding the
design, rationale, and constitution of prostheses has been discussed from a knee surgeon’s perspective, resulting in confusion, misunderstanding, and operative errors with further deleterious results (7, 8), which translates to a mean revision rate of 6% after 5 years and 12% after 10 years in a current analysis of worldwide joint registers (9).

This review aims to provide strategic support and process demonstrations for the selection of revision prostheses by explaining basic principles, implant design (geometry, biomechanics), and evidence-based guidelines. In particular, it presents specific decision aids regarding unclear issues such as the optimal level of constraints, individualized design, length, fixation of extension stems, and the pros and cons of modularity.

We conducted a systematic search of the online databases Embase, MEDLINE, PubMed, and Google Scholar from inception through November 2014 to identify eligible works. We used database-appropriate search terms, including ‘prosthesis selection in rTKA’, ‘prosthesis option in rTKA’, and ‘prosthesis determination in rTKA’. Forty-four review articles and 68 research articles were identified, and the results were carefully extracted and integrated with the authors’ understanding to reach a final recommendation.

Specific factors affecting decision-making regarding prosthesis options in rTKA

The prerequisite for rational selection of a revision system is to identify the mechanism for pTKA failure, risk factors, individual variables, specific goals, and surgical challenges, followed by conducting specific assessments of key factors, such as bone loss/ligament insufficiency/instability, and further identifying individualized solutions.

Cause and etiology

The preoperative plan of rTKA usually comes from etiology analysis, which might be the preliminary predictor for the choice of prosthesis option. The most frequent causes for rTKA are as follows: (i) Aseptic loosening (10), which is the leading cause for failure in Western countries. Loosening of the tibial component is the most common type and is induced by the cumulative effect of shearing forces for various reasons. (ii) Instability (11, 12) is another cause for failure. The most common forms are asymmetrical extension gaps and lax flexion gaps, which result from bone resection errors, malposition of the prostheses, and undersized or hyperextension placement of the femoral component. (iii) Septic loosening, another cause of failure, is a consequence of the failed treatment of periprosthetic joint infection and is reported as the leading cause of rTKA in developing countries (13). Increasing evidence has revealed that antibiotic-resistant bacteria and fungi constitute the major pathogens of recurrent infection. (iv) PE wear and osteolysis (14) are common causes of late revisions. Several implant and surgical factors have been identified as contributing to the development of wear, including nonanatomic articular geometry, bearing surface of first generation, poor knee kinematics, and patient-related factors, such as younger age and high activity. Empirically, most mechanical or septic loosening can be addressed using standard posterior-stabilized (PS) prostheses combined with defect or fixation augmentation. However, ligament insufficiency and bone loss are usually difficult to predict in cases of instability and osteolytic wear. Except for elaborate techniques of retuning a balanced knee under incompetent ligaments and restoring the bony structure under massive defects, multiple revision options should be a backup, including varus/valgus constrained and even hinged prostheses.

Occult obstacles and challenges

Three main issues demanding solutions in rTKA are ligament insufficiency, instability, and bone defects (15). In addition to the aforementioned causes, there are other occult factors affecting the prosthesis option, for example, abnormal patellar height, joint line deviation, abnormal range of motion (including recurvatum and flexion contracture), soft tissue defects, neurovascular impairment, and local deformity (16, 17). Park et al. applied multiple regression to investigate the correlation between prosthesis options and patient variables, including age, sex, BMI, postoperative time, revision causes, Anderson Orthopedic Research Institute (AORI) classification, changes in joint line height, and patella height. They found that two causes (loosening and instability), abnormal joint lines and patellar height, are independent factors that affect the use of constrained prostheses (18). A parallel study investigated the value of primary diagnosis, cause of revision, surgical approach, and AORI grade of bone defects and found that the femoral bone defect grade was the only significant factor affecting the choice of prostheses between PS and varus–valgus constrained (VVC) implants (19).

Individual factors

Individual factors significantly affect the performance of prostheses. Except for demographic variables (sex, age, BMI, career, race, cigarette, and alcohol consumption), comorbidities (diabetes, osteoporosis, thyroid disease, rheumatoid arthritis, and idiopathic bone necrosis) and medication (20) may significantly impair bone support at the metaphysis and further influence the initial stability. rTKA in such patients is recommended to expand the fixation zones from an articular surface (zone 1, Morgan-Jones classification (21)) to metaphysis (zone 2), occasionally to
diaphysis (zone 3), either by augmented design of a wider keel or sleeve for sufficient contact or stem extension for enhanced metaphyseal engaging or diaphyseal press-fit (Fig. 1). For patients with obesity and a femoral shaft with a laterally bowed deformity, a diaphyseal-engaging press-fit stem is usually helpful to offload the excessive shearing stress on the tibia and further improve longevity (22, 23, 24). High-constrained prostheses are appropriate to avoid early failure in neuromuscular diseases caused by poliomyelitis. (25, 26).

**Bone quality**

The role of bone defects in decision-making of rTKA affects lower limb alignment and further influences implant longevity. Although bone defects do not represent a predominant factor for the constraint of the prostheses, in certain cases of massive bone loss involving avulsion, absorption, or absence of the attachment of ligament, they can further improve the constraint of the implant. A widely used assessment system is the AORI classification (27). This system is divided into two subcategories: tibia (T) and femur (F). Each subcategory is divided into three grades according to the location and dimension of the bone defect. In terms of prosthesis options, type I and type IIa bone defects can be solved using a standard PS system with routine reconstruction methods, such as bone cement and screws, autologous bone grafting, or metal augmentation.

If the collateral ligament cannot be properly balanced, a VVC system can be an option. For types IIb and III, it is necessary to use blocks, wedges, metaphyseal sleeves, cones, or custom-made augments to restore the integrity of the metaphysis. VVC and even unlinked rotating hinge knee (RHK) are recommended (28).

**Ligament condition**

The essential determinant of prostheses in rTKA is the ligamentous status, including the major stabilizers of medial and lateral compartments, posterior cruciate ligament (PCL), and extension mechanism, as well as other secondary ligaments. The condition of the ligament is generally classified as lax (referring to fiber tear), insufficient (loss of partial function), or absent (structural loss) (29). From the author’s perspective, protocols presented by Krackow and Ranawat for evaluating the medial collateral ligament in genu valgus could be a valuable reference (30, 31). They advised balancing the lax ligaments by releasing the contralateral ligament, so a standard PS and even CR prosthesis is suitable for regular rTKA. However, for ligament insufficiency, an initial step-by-step release of the contralateral ligament can be attempted; if it is still difficult to balance, a supplementation of bone management, such as reduction osteotomy (reducing the volume of the medial tibial condyle to relax the medical collateral ligament (MCL)) in a fixed varus knee (32) or an expansion osteotomy (increasing the volume of the medial tibial condyle to tighten the MCL) is proposed for a type II–III valgus knee (33). If gap balancing can be achieved, standard PS with or without stems is an option for completing rTKA. If the balancing fails, VVC or RHK should be considered. There are great controversies regarding the treatment of ligament absence, and highly constrained prostheses, such as RHK, usually provide excellent short-term results in terms of pain relief, immediate weight-bearing, and improved patient-reported functional scales (34, 35). Satisfactory outcomes were also observed by hybrid procedures of ligament repair, augmentation, and reconstruction with arthroplasty using low-constraint prostheses for young and active patients (36).

**Instability**

Instability in rTKA is a very complex state that results from multiple influencing factors, such as ligament deficiency, bone quality, intraarticular deformity, and infection status. A classification of type I–III presented by Petrie is advisable for managing instability (11). There are usually two manifestations of symmetrical and asymmetric instability (referring to medial and lateral imbalance in type I (extension instability)). Symmetric instability is usually caused by excessive bone cutting at the distal femur or posterior condyle or an undersized femoral component,
so the instability can be solved by a standard PS prosthesis (37), with specific bone augmentation at the distal femur or posterior condyle, or soft tissue retensioning with a thick PE insert. In contrast, asymmetric instability is relatively difficult to handle. An initial soft tissue release at the contralateral ligament and a standard PS implant can be attempted to access the gap balance. If it fails, a condylar constrained knee (CCK) is recommended.

However, if the instability is caused by MCL injury, there are some supplementary choices, such as MCL repair supplemented with the PS or VVC system or hinged knee without MCL treatment. Shahi et al. found that MCL repair combined with VVC may be a better alternative for a satisfactory outcome (38). In the same way, instability of type II (flexion instability) or type III (mid-flexion instability) resulting from gap imbalance and joint line deviation, routine corrective techniques, and low constrained prostheses are usually helpful in correcting the instability (39). However, standard PS and VVC prostheses exhibit a high rate of failure in type IV (genu recurvatum) or type V (global instability) Petrie’s classification (11), and higher constrained implants, such as RHK, might be a satisfactory solution (40, 41).

**Design and rationale of prostheses in rTKA**

*Classification and constraint grading*

The definition of constraint refers to a design of restricting the motion of an object in a particular direction. In TKA, the more the original ligaments maintain their original function, the less constraint is required. The increased level of constraint stabilizes the knee by replacing the deficient or absent ligament function. A classification of revision prostheses is summarized to illustrate their respective constraint mechanism in Fig. 2.

(1) Unconstrained prostheses include bicruciate-retaining, unicompartment knee replacement (UKR), and cruciate-retaining (CR) prostheses (42) (Fig. 2A), which are rarely used in revision scenarios. Theoretically, a CR prosthesis can be considered for a revision of UKR.

(2) Minimally constrained prostheses include PS knee, ultracongruent or deeply dished articulation, and a third condylar design (Fig. 2B, C, and D) (41). The primary indicator of PS prostheses for rTKA is the lack of PCL, but the collateral ligaments are functionally intact. If the tension of the PCL cannot be ideally tuned with a CR prosthesis, highly conforming, anterior–stabilized bearing can be an alternative for favorable outcomes (Fig. 2C) (43). Although these low-constrained prostheses can be indicated in case of isolated change of the PE insert, it is often necessary to convert to a higher constrained prosthesis due to bone weakening or ligament incompetence.

(3) Semiconstrained prostheses, primarily referring to VVC, also known as CCK knees, belong to constrained unlinked prostheses. They feature a higher and broader central post on the tibia that fits closely against the femoral cam (Fig. 2E). If the medial and lateral ligaments are still unable to balance after sufficient soft tissue release or the difference between medial or lateral gaps is greater than 3–5 mm, a VVC is strongly recommended. The restrictions on side translation, varus/valgus angulation, and internal/external rotation differ according to various designs of the manufacturers (44).

(4) High-constrained prostheses include fixed (rigid) hinge knees and RHGs (Fig. 2F and G). Rigid-designed hinge knees are now rarely used in clinical practice due to the high rate of loosening (34). While a modern rotating design significantly reduces this complication, a yoke design on the tibial component allows the tibial platform to rotate around the femur, thereby offloading the shearing force on the prostheses–bone interface (45). This property enables excellent mid- to long-term survival rates of RHG in both pTKA and rTKA (46, 47). This indication is generally acceptable but still controversial: (i) massive bone loss sacrifices

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**Figure 2**

An overview of revision knee prostheses on the market illustrating different constraint mechanisms. (A to G) Represent bicruciate-retaining, posterior cruciate-retaining, highly congruent (anterior-stabilized), posterior-stabilized, varus–valgus constrained (condylar constrained knee), rotating hinge, and pure (rigid) hinge prostheses. The upper line indicates the polyethylene insert, and the lower line indicates the contact pattern of condylar and tibial components.
the attachment of the collateral ligament; (ii) gross ligamentous incompetence is defined as the clinical absence of all four major knee ligaments; (iii) severe bone osteolysis or soft tissue defects are caused by sepsis debridement or component removal; (iv) severe valgus or varus deformity is combined with flexion contracture or recurvatum; and (v) severe gonarthrosis is combined with neuromuscular diseases, such as polio and syphilis (6, 35). A particular species of hinge knee called segmental defect prostheses, also known as tumoral prostheses, can be considered in salvage conditions, such as bone tumor en bloc resection and monolithic segmental bone defects (48).

(5) Custom-made prostheses, where customization is needed when the structural loss of bone and soft tissue cannot be solved by traditional techniques or serious deformities and lesions cannot be addressed with a uniformly designed commercial prosthesis. A few reports that can be retrieved are 3D printed irregular high-porosity metal cones or metaphyseal sleeves, or whole femur/tibia, combined with the RHK system for knee revision (49, 50).

Although the improved constraint of prostheses enhances the intrinsic instability of the implant, the stress transmitted onto the implant–host surface and interface of a modular system is also amplified. The heightened stress may result in increased fretting and corrosion in modular components and implant loosening. Most authors therefore recommend using the least amount of implant constraint necessary to achieve a satisfactory result (51, 52).

**Component rationale**

A thorough understanding of the mainstay and auxiliary parts of a revision system can ensure the successful conduction of the surgery highly complies with preoperative planning. The following is a concrete illustration of the accessory components of the current mainstream revision system (Fig. 3A).

**Offset adaptor**

An offset adaptor is a Z-shaped connector between the tibial/femoral component and the stem extension. The offset is defined as the distance between the center of the metaphysis and the axis of the diaphysis. The original intention of the design is the anatomical nonaxial property between the femoral/tibial metaphysis and the medullary cavity of the diaphysis. The design philosophy of offset is the anatomical nonaxial property between the femoral/tibial metaphysis and diaphysis (53) (Fig. 3B). The offset design is convenient for maintaining satisfactory coverage of the prostheses on the bone-cutting surface at the metaphysis and accurate contact of the stem in the medullary cavity to reduce the incidence of coronal or sagittal malalignment.

Currently, the adapter can also be applied when (i) bone defects are classified as AORI IIa, which is helpful for adjusting the position of the prostheses to maximize the prostheses–bone contact surface, with the additional benefit of reducing the overhang and soft tissue irritation (54) (Fig. 3C); (ii) when combined with extra-articular deformity.

**Figure 3**

An overview of tibial revision systems on the market describing component constitution. (A) Different components for tibial baseplate stabilization, wedge/block augmentation, metaphyseal sleeve and cone for bone defect repair, offset adaptor for anatomical connection, and stem extension for metaphyseal or diaphyseal engagement are shown. (B) The design philosophy of offset is the anatomical nonaxial property between the femoral/tibial metaphysis and the medullary cavity of the diaphysis. The medullary center of the proximal tibia was located laterally and posteriorly to the center of the tibial plateau, and the center of the femoral condyle surface was located medially and posteriorly to the medullary center of the femur diaphysis. (C) The offset adaptor serves to adjust the position of the prosthesis to maximize the prostheses–bone contact surface with the additional benefit of reducing the overhang and soft tissue irritation, occasions of bone loss (AORI II), and extra-articular deformity.
deformities at the metaphyseal-diaphyseal junction, the eccentric design helps the prostheses bypass the deformity and achieve accurate implantation (Fig. 3C); (iii) occasions requiring precise translation of the components to balance the flexion and extension gaps to restore the natural joint line and posterior condyle offset also warrant adaptor application. However, the current problem is that the design diversity of manufacturers cannot meet the continuously adjustable configurations in terms of offset distance and rotational angle (55).

Augment

The metal augment, either block or wedge in shape (Fig. 3A), is designed to solve mild to moderate structural defects (thickness <15–20 mm) at the metaphysis and to achieve anatomical reconstruction following the requirement of measured resection as pTKA. This is critical to avoid adverse effects such as joint line deviation, insufficiency of posterior condyle offset, undersized femoral component, and patellofemoral overstuffing. Most of the augmentations are made of solid titanium 6 aluminum 4 vanadium alloy with a blasted surface. The thickness of the blocks is usually increased by 5 mm, and the total thickness generally does not exceed 15 mm because a block thicker than 20 mm has difficulty offloading the shearing force concentrated at the stem extension (56).

Although wedge augmentation is more beneficial for bone sparing, block augmentation holds multiple biomechanical advantages in stress unloading and resistance to compression and deformation (57). One study identified that metal block augmentation for the medial tibia was not inferior to that for varus knees without bone defects in terms of knee scores and survival rates at the 3- to 6-year follow-up, but a nonprogressive radiolucent line (RLL) beneath the metal was detected at 30.3% (58). The failure rate of wedge augmentation in rTKA was higher, as evidenced by 44.8% exhibiting radiological changes and 17.2% needing revision due to tibial implant migration. The reported rate of RLLs beneath the metal wedge is 46.4–52.0% (58, 59).

Metaphyseal sleeve and cone

If the bone defect is primarily manifested as substantial cavitory loss of cancellous bone at the metaphysis and the surrounding cortical bone is relatively intact, then augmentation, either in block or wedge, is not recommended for defect reconstruction (60). Instead, metaphyseal sleeves and cones are ideal alternatives to ensure a preferable clinical outcome (61, 62). Generally, the geometry and appearance of sleeves and cones are analogous, but they have different design concepts and surgical techniques (Fig. 3A).

The sleeve is a solid component made of titanium alloy with a thin porous external layer made of titanium sintered beads or microfragments. The gradual-step geometry ensures maximal contact with metaphyseal bone in regions 2 and 3 (21). The philosophy is stepped to compressively load the bone and form a strong foundation for reliable stability, avoiding excessive bone resection, and preserving the anatomical joint line (63). This design can achieve a tight press-fit between the sleeve and the bone through intraoperative impaction and further achieve bone ingrowth through Wolf’s law.

The inside of the sleeve is highly polished and tapered, which facilitates the formation of Morse fixation with stem extension. The general indication of the sleeve includes (i) metaphyseal cavitory defect needing increased fixation range from zone I to zone II or III; (ii) massive bone defect which is prone to fail by metal augmentation; and (iii) stability of construct requiring multiple corrections of extension and flexion gaps, and the joint line (64). Problems with sleeves include malalignment, subsidence, septic or aseptic loosening, and intraoperative fracture (65).

Comparably, the cone is in a porous structure made of tantalum or titanium. The combination of solid and porous structures allows for reduced cone augmentation of cross-sections while still meeting fatigue strength requirements (66). Due to its excellent osteoinductive properties (67), the cones play a crucial role in addressing metaphyseal cavitory defects. Notable advantages compared to sleeves include a high friction coefficient, free stress shielding, and reduced bacterial adherence. Because the whole body of the cone is designed with 3D pores, biological fixation only exists on the external surface contacting the host bone, while internal fixation contacting stem extension is achieved by cement fixation.

Both sleeves and cones are designed to repair metaphyseal cavitory defects by biological fixation, and they are beneficial for eliminating the concerns associated with traditional autogenous bone grafting, such as graft resorption, disease transmission, improper graft size, and allograft fracture (61, 62). However, the cone tends to work as augmentation and plays a minimal role in the initial stabilization of the core implant, while the sleeve has the dual characteristics of fixation and augmentation. One study demonstrated that cones and sleeves have few differences in survival indicators after revision, such as rates of intraoperative fractures, noninfectious loosening, periprosthetic infection, and septic failure (68). A meta-analysis revealed no loosening of 18 cases of rTKA with trabecular metal cones with a follow-up of 6 years and a low revision rate (2.5%) of metaphyseal sleeves with a follow-up of 4.8 years (69).
Stem extension

Stem extension, which has load-sharing capability and protects the remaining host bone from excessive stress and migration, can provide additional support for the femoral or tibial component. Its role is ‘bridging’ and ‘offloading’ to bypass the defects in the metaphysis and diaphysis and to offload the stresses to healthy bone. It is recommended in the following scenarios: (i) the remaining bone stock is not sufficient to support the implant, (ii) demand for increased constraint of the prostheses (70), and (iii) demand to correct the hyperextension of the femoral component (71).

Although stem extensions have various morphological and geometric designs, they can be divided into two main categories, metaphyseal-engaging stems (MESs) and diaphyseal-engaging press-fit stems (DESs) (72). MESs are usually 30–75 mm in length, made of cobalt–chromium alloy, and require bone cement to be fixed over the entire length. One superiority of MES is that it can be conveniently adjusted toward each direction to fit the contour of the metaphysis without the offset adapter. The disadvantage is the potential risk of massive bone defects (73). In contrast, DESs are made of titanium alloy and are greater than 75 mm in length. A hybrid technique is recommended by fixing the proximal section with bone cement and the distal section with biological engaging (74). Their disadvantages include stress shielding, periprosthetic fracture, and end-of-stem pain, as well as cost-effectiveness (75, 76).

The geometry of the stems, variable lengths, with or with offset options, and supplemented with either/and cement and porous augments have their benefits and must be individualized to each revision situation present. The determination of the variables of stem extension in rTKA has always been a focus of debate.

(i) How is the length of the extension determined? Factors affecting the length include individual factors (sex, height, weight, bone quality, etc.), underlying diseases (obesity, hypothyroidism, osteoporosis, rheumatoid arthritis, etc.), and residual cancellous bone in the metaphysis supporting capacity of the device, the material and design of the stem, the constraint of the prostheses, etc. (20) Among them, biomechanics plays a pivotal role. First, the balance between micromotion and stress shielding at the prosthetic–bone interface depends on the length of the stem extension. A finite element analysis showed that the longer the stem is the larger its ability to reduce the micromotion of the prosthesis–bone interface. Compared to the 40 mm-long extension, the 60 mm-long extension reduces micromotion by 12.5%. The stress shielding effect with a length of less than 40 mm is negligible, while stress shielding effects longer than 60 mm increase exponentially (76, 77).

Second, the higher the material stiffness is the more frequent stress shielding will occur. A stem made of titanium alloy less than 40 mm in length is an ideal choice for rTKA. Third, the stem should efficiently offload the shearing force transmitted from the tibial tray to the tibial cortical bone. According to Wolff’s law, a healthy bone will adapt and remodel itself to the loads under which it is placed, and the ideal intensity of bone regeneration at the proximal tibia is 50–1500 με. If it is less than 50 με, excessive stress shielding will accelerate bone resorption. In addition, above 3000 με, the risk of microfractures is greatly increased (73). Unfortunately, there is no quantitative study to explore how much microstress the stem length exerts on the surrounding bone.

(ii) How can the diameter of the stem extension be determined? The diameter of MESs is usually specific, and no intraoperative selection is required. However, DESs, including the traditional conical and splined design, need to meet the press-fit between the stem and the medullary cavity. Therefore, the diameter of the medullary cavity is accurately determined by intraoperative measurement. However, for newer generation prostheses, such as the splined stem with a distal stab (Vanguard 360, Biomet, USA), sufficient initial stability can be achieved by single spot welding when the stab is embedded into the inner bone or single surface support between the distal end and the cortical bone (76, 78).

Parsley et al. introduced canal filling rate (CFR) to determine the applicable parameters of stem extension (79). Lee et al. further utilized receiver-operating characteristic curve analysis to evaluate the cut-off value for stem length and diameter in 17 of 65 aseptic loosening pTKAs. They found protective factors for prosthesis survival, including CFR >0.85 or CFR >0.7 and canal filling length (CFL) >2 cm for the femoral component and CFL >0.85 or CFL >0.7 and CFL >4 cm for the tibial component (80).

Tibial insert

As PE is the most frequent component to be worn and fails among all parts of TKA, this choice is more critical for the clinical result of rTKA. Most manufacturers offer two types of inserts for rTKA, low-constrained and high-constrained PS inserts (81) (Fig. 4A and B). The modified geometry of the intercondylar box and PE post and the enhanced contact mechanism of the cam post determine the range of valgus/varus angularity, lateral translation, internal/external rotation, and femoral lift-off (jump) movement (42) (Fig. 4C and D). The design parameters and constrained motion in the three mainstay systems available in the clinic are illustrated in Table 1.

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Table 1

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Due to complicated rolling, sliding, and rotational motions between the material and the bearing surface \(^{(41)}\), the anti-resistance property of PE insert in rTKA is much higher than that in pTKA. However, there have been limited substantial advances in updating the biochemomechanical properties of the base material. The main type of PE in rTKA is ultrahigh-molecular weight polyethylene (UHMWPE). A recent study from the National Joint Registry of England, Wales, and Northern Ireland revealed significantly lower unadjusted rates of all-cause revision and aseptic revision of conventional PE compared to highly cross-linked polyethylene (HXLPE) after a maximum duration of follow-up of 12 years \(^{(14)}\).

However, there have been many attempts to modify newer HXLPEs, such as vitamin E reformation in second-generation HXLPEs, \(\alpha\)-tocopherol-modified UHMWPE, which are supposed to be more resistant to wear, delamination, and oxidation \(^{(82, 83, 84)}\). However, the available results are conflicting, and future long-term follow-up reports are required to provide insights into persistence and potential complications. Novel materials, such as carbon fiber-reinforced-polyether-ether-ketone (CFR-PEEK), were found to reduce the wear volume by nine-fold and wear depth by three-fold compared to UHMWPE \(^{(85)}\). These studies shed light on the orientation of PE development in rTKA.

PE thickness as well as diagnosis and BMI have been proven to be risk factors for insert failure \(^{(86)}\). Studies have shown that the thickness of the PE insert must be 8 mm, and the wear of the PE increases by three-fold for every 1 mm reduction \(^{(87)}\). This is evidence for why a
minimal 8-mm thickness in pTKA and 10-mm thickness in rTKA are recommended for PE inserts (88, 89). Although the increase in PE thickness may be helpful in eliminating bone defects and reducing instability, the benefit comes at a price. The increment from 5 to 25 mm was found to decrease both articular peak contact pressure (4%) and articular wear (5%) but also increases peak cumulative sliding distances (101%) and backside wear (38%) in a static element infinite model (90). Identical results were found by another dynamic simulation analysis in vivo by Bei (91). In addition, a PE insert greater than 10 mm in thickness is beneficial for conserving a physiological joint line of approximately 10–12 mm because the cruciate ligaments are usually sacrificed in rTKA (92).

Modularity

The successful implementation of rTKA relies strongly on the modular design in rTKA (Figs 1 and 2). Modular options are beneficial for addressing complex reconstructions, providing customization to remedy bony deficits, deformity, malalignment, and instability. However, these benefits come at a price (93). The more complex a modular system is, the more interfaces are generated, and the more shear force, micromotion, and wear can be induced. Chronic inflammation following the generation of wear particles, either PE or metal, has been identified as the primary biological mechanism leading to implant failure (94). One study found that approximately 12% by weight of the wear products were metallic, and these particles and ions may become clinically relevant for patients sensitive to these materials (95). Modern design noted decreased interface and micromotion are as important as intensified baseplate roughness and locking mechanism for the longevity of implant (96).

One aspect that should not be neglected in rTKA is that the modular design of the revision system results in hidden problems in terms of fretting and corrosion. Because of the increased contact area, the fretting wear on the nonarticulating surface is thought to be of greater significance than that on the articular surface and interfaces at the modular junction, such as back-side wear and the related locking mechanism between the PE and metal baseplate. One study compared different designs of lock mechanisms between the tibia insert and baseplate and found that 100% of IB II® implants (anterior/posterior dovetails plus interlocking pin, Zimmer, USA) and Advance® (posterior locking rail plus anterior metallic locking post, Wright Medical Technologies, USA) exhibited evidence of burnishing, scratching, pitting, and deformation. However, 17% of the Optetrak® (full peripheral locking, Exactech, USA) had no backside wear (97).

These studies highlight the significance of optimal modularity in implant selection in rTHA: (i) The smallest modularity should be favored, as it is the least risky. (ii) Each revision system used should be studied before using it to identify the insufficiency of the fixation between the parts of the assembly to avoid insecure assemblies. (iii) A full locking peripheral locking, or a hybrid of central and anterior–posterior locking mechanism between PE insert and tibial baseplate to restrain motion in all directions shows a significant reduction in backside wear (Fig. 5). (iv) The use of nonmetallic materials should be avoided, as they are imperfectly validated. Nonmodular design (all PE or metal-backed monoblock tibia (98, 99)) and nonmetallic materials (PEEK, ceramics, or advanced coatings (100, 101)) may be promising alternatives for high-risk revision procedures.

Decision-making regarding prosthesis options in rTKA and clinical outcomes

The structural determinants for prostheses options in rTKA include extension mechanism (quadriiceps tendon and patellar and patellar tendon), PCL, MCL, and posterolateral complex (lateral collateral ligaments, iliotibial bands, popliteal tendons, popliteal oblique ligaments, etc.). The matching of these structures results in different statuses of extension/flexion gap balancing, which dominate the prosthesis option in rTKA. Bone defects only influence the constraint of revision prostheses when the severity develops to AORI type III when MCL and LCL attachments at the distal femur or proximal tibia are absent. The algorithm of each prosthesis is described in Table 2.

An upgrade of the degree of a constraint is postulated to be associated with the risk of component loosening.
and the failure rate. Therefore, minimally constrained prostheses are advocated for rTKA. Nevertheless, there are indeed occasions when unconstrained prostheses, such as standard PS, cannot offer sufficient stability; therefore, the use of a more constrained implant is inevitable. Unfortunately, the optimal degree of constraint for rTKA with ligamentous insufficiency still lacks evidence.

(1) PS vs VVC prostheses. Lee et al. evaluated the outcome of 79 cases of VVC compared to 42 cases of PS prostheses. Clinical results, including range of motion (ROM), Knee Society Knee Score (KSS), function score (KSFS), and incidence of an RLL, on radiographs displayed no significant differences. Complication rates were 9.5% in the PS and 10.1% in VVC, and Kaplan–Meier survival analysis revealed 8-year component survival rates of 83.1 and 93.0%, respectively (24). Haas et al. reported that the clinical scores with PS were higher than those with CCK, but the difference was not significant and might reflect the fact that CCK was used in cases with greater collateral ligament damage (102). Gofton et al. found no significant differences in the postoperative clinical measures in comparing the outcomes of rTKA with PS and VVC prostheses, even though differences in the preoperative functional scores were identified (103).

(2) VVC vs RHK prostheses. A retrospective study enrolled 85 revision patients needing rTKA due to ligamentous laxity, and RHK achieved equivalent results to mobile-bearing VVC prostheses. No significant difference between the two groups was observed for any of the clinical scores (WOMAC, VAS, KSS, FJS, and Lysholm). Both prostheses exhibited equally good clinical outcomes with regard to stability, mobility, and satisfaction (104). Another meta-analysis revealed that 87.4% of RHK and 83.8% of CCK prostheses survived in the short term (<5 years), while 81.3% of RHK and 75.0% of CCK prostheses survived in the midterm (5–10 years) (105).

(3) PS vs VVC vs hinge prostheses. A study performed by Pavizzi et al. investigated the prosthetic options in cases of different degrees of bone defects. This series included rTKA cases of 183 AORI type I knees, 168 type II knees, 124 type III knees utilizing PS, unlinked constrained (UC), or hinged prostheses. The results indicated that PS prostheses displayed superior KSS scores in both aseptic and septic revision with AORI type I compared to UC prostheses, and hinged prostheses offer better outcomes of KSS, SF-36, and WOMAC scores in septic revision with AORI type II, than the unlinked constrained group, while unlinked constrained prostheses had better outcomes in aseptic revision with AORI type III (106). Another Korean study reviewed 36 rTKAs using PS, CCK, and RHK prostheses with a mean follow-up period of 30 months. The average KSS improved from 28 before the revision to 83, and the average KSFS improved from 42 to 82 at the final follow-up. There was no significant difference in the average KSS (PS (average 78), CCK (average 81), and RHK (average 83)) or in the average KSFS (PS (average 79), CCK (average 85), and RHK (average 81)) between different types of prostheses (107).

In general, although a less constrained system and lower modularity are the ideal choices for revision procedures, there is currently no definite evidence or consensus (108, 109, 110) on which types of prostheses exhibit better performance in rTKA. Paradoxical findings have shown that unanticipated, highly constrained prostheses yield better results in certain circumstances.

Conclusions
rTKA is a complicated procedure requiring the surgeon to choose an accurate prosthesis by considering the etiology, hidden obstacles, individual factors, bone and soft tissue quality, anticipated lifespan, and patient comorbidities. The constitution of a revision system, geometry of the stem, variable lengths, diameters and offset options, and supplementation with augments or bone substitute must be individualized to each revision occasion based on their pros and cons. Current studies comparing prostheses of different degrees of constraint in rTKA are equivocal and inconclusive. The optimal degree of constraint and modularity for rTKA with ligamentous insufficiency or bone loss must be carefully tailored to ensure satisfactory outcome and prosthetic longevity.

Table 2 The descriptive algorithm of prostheses option in rTKA.

| Prostheses type          | CR | PS | UC | VVC | RHK | PHK |
|--------------------------|----|----|----|-----|-----|-----|
| Extension mechanism      | +  | +  | +  | +   | +/- | +/- |
| Posterior cruciate ligament | +  | -  | -  | -   | -   | -   |
| Medical collateral ligament | +  | +  | +  | -   | -   | -   |
| Posterolateral complex   | +  | +  | +  | -   | -   | -   |
| Gap balance              | -  | -  | -  | +   | +   | +   |
| Asymmetry                | +/− | -  | +/− | -   | -   | +   |
| Difference               | +/− | -  | +/− | -   | -   | +   |
| Bone loss                | +/− | +/-| +/-| +/- | +/- | +/- |
| AORI II                  | +/-| +/-| +/-| +/- | +/- | +/- |
| AORI III                 | +/-| +/-| +/-| +/- | +/- | +/- |

+Prerequisite (mandatory requirement); − nonessential condition; *gap difference: flexion-extension >3–5 mm; #gap difference: flexion-extension >30 mm.
CR, cruciate retaining; PS, posterior stabilizing; PHK, pure hinge knee; RHK, rotational hinge knee; UC, ultra-congruence; VVC, varus–valgus constrained.

ICMJE Conflict of Interest Statement
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.
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