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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.

Keywords
- total knee arthroplasty
- revision procedure
- prosthesis options
- constraint
- decision-making
- modularity

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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

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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 rection 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.

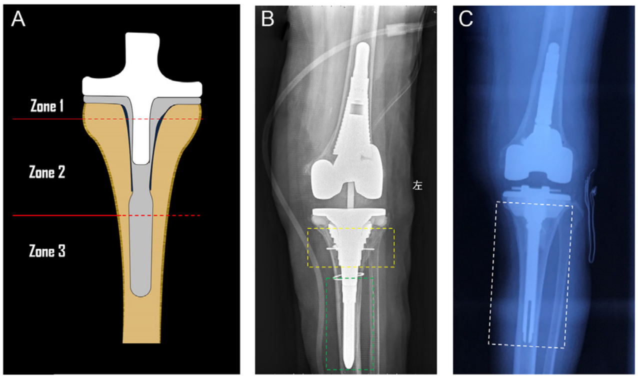

Figure 1
Morgan-Jones classification of fixation zones in the revision procedure. (A) Schematic illustration of the zones for stem fixation in the tibia: zone 1, articular surface; zone 2, metaphysis; zone 3, diaphysis. (B) A revision case due to periprosthetic joint infection. Massive bone defects were observed in the proximal tibia (AORI type III). Solid fixation was achieved by sleeve fixation in zone 2 (yellow dotted rectangle) and distal stem fixation in zone 3 (green dotted rectangle). (C) A revision case due to aseptic loosening. Bone defects were observed in the medial proximal tibia (AORI type IIa), solid fixation was achieved by metal trays and keels in zone 1, and diaphyseal-engaging cemented stems were achieved in zones 2 and 3 (white dotted rectangle).

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 inset 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 RHKs (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 RHK in both pTKA and rTKA (46, 47). This indication is generally acceptable but still controversial: (i) massive bone loss sacrifices

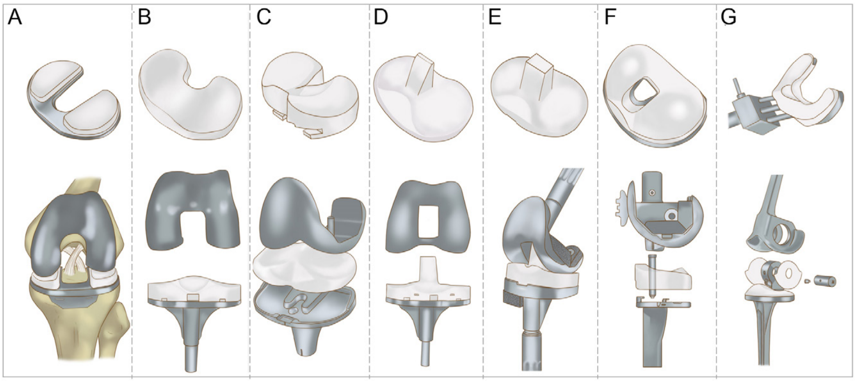

Figure 2
An overview of revision knee prostheses on the market illustrating different constraint mechanisms. (A to G) Represent bicruciate-retaining, posterior cruciate-retaining, highly congruent (anterior-stabilized), posterior-stabilized, varus–valgus constrained (condylar constrained knee), rotating 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 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

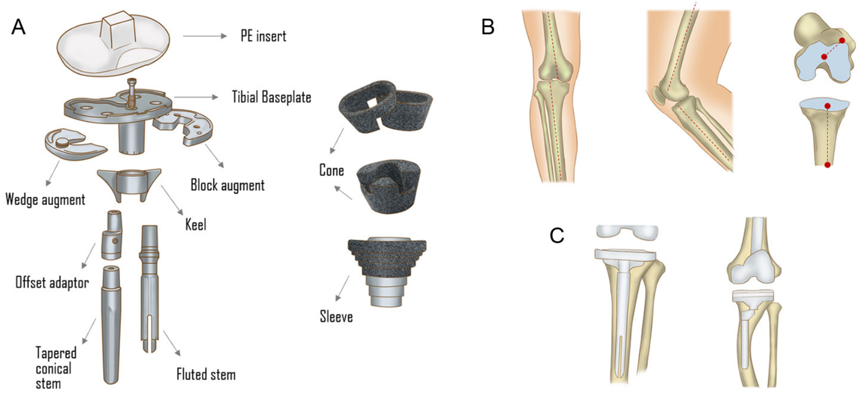

Figure 3
An overview of tibial revision systems on the market describing component constitution. (A) Different components for tibial baseplate stabilization, wedge/block augmentation, metaphyseal sleeve and cone for bone defection repair, offset adaptor for anatomical connection, and stem extension for 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 prosthesis–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 cavitary 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 analogical, 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 Wolff'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 cavitary 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 cavitary 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 cavitary 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 prosthesis–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 $\mu\varepsilon$. If it is less than 50 $\mu\varepsilon$, excessive stress shielding will accelerate bone resorption. In addition, above 3000 $\mu\varepsilon$, 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 CFR >0.85 or CFR >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.

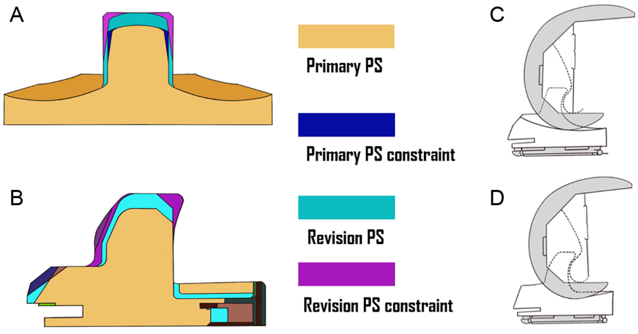

Figure 4

Tibial insert designs are illustrated, and their interaction with condylar components determines the constraints of different revision systems. (A, B) The anterior–posterior view and lateral view of the polyethylene insert in different degrees of constraint. Note that four different colors represent two inserts for pTKA and two for rTKA. (C, D) The contact mechanism of the regular and constrained design of posts on the tibial insert with the femoral condylar box during knee extension-flexion has a significant influence on knee kinematics, such as varus/valgus angulation, internal/external rotation, and femoral lift-off movement (data are shown in Table 1).

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, α-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

Table 1 Influence of different constraints of primary and revision prostheses on the motion of the knee.

	Depuy tibial insert				Zimmer-Biomet tibial insert				Smith & Newphew tibial insert			
	Primary knee		Revision knee		Primary knee		Revision knee		Primary knee		Revision knee	
Dimension of constraint	Sigma PS	Sigma PS plus	TC3 FB	TC3 RP	Vanguard PS	Vanguard PS plus	Vanguard 360 PS	Vanguard 360 PSC	Legion PS	Legion PS plus	Legion revision PS	Legion revision PSC
Internal/external rotation at 0°	7.5°	2.2°	4.3°	None*	15.0°	2.0°	15.0°	0.5°	None	4.0°	None	3.0°
Internal/external rotation at 90°	7.5°	2.2°	5.4°	None*	15.0°	2.0°	15.0°	0.5°	None	4.0°	None	3.0°
Varus/valgus at 0°	None	1.9°	2.2°	2.0°	None	2°	None	1°	None	3.0°	None	2.0°
Jump distance/lift-off height	16.3 mm	16.3 mm	20.3 mm	20.3 mm	18.0 mm	18.0 mm	23.0 mm	23.0 mm	19.5 mm	19.5 mm	23.5 mm	25.0 mm
Post-cam contact	70.0°	70.0°	55.0°	–#	65.0°	65.0°	45.0°	45.0°	75.0°	75.0°	50.0°	50.0°
Hyperextension constraint	12.5°	10.0°	5.0°	–#	10.0°	10.0°	5.0°	5.0°	1.05°	13.0°	15.0°	10.0°

* 'none', no restriction on the motion. # '-', data not available.
FB, fixed bearing; PS, posterior-stabilized; PSC, posterior-stabilized constraint; RP, rotational bearing.

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 (quadriceps 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

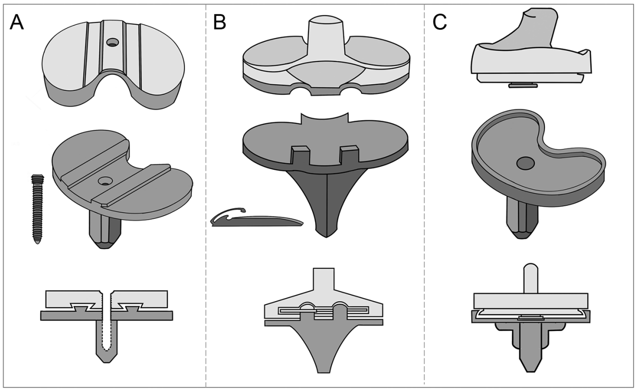

Figure 5

An overview of knee prostheses on the market illustrating various locking mechanism between PE insert and tibial baseplate. (A) Lateral and anteroposterior views of a central locking system; (B) lateral and anteroposterior views of a hybrid system of central and anterior–posterior locking; (C) lateral and anteroposterior views of a full peripheral locking system.

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 (KSKS), 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 KSKS 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 KSKS (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).

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 lgament	+	+	+	+	–	–
Posterolateral complex	+	+	+	+	–	–
Gap balance						
Asymmetry	–	–	–	+	+	–
Difference	+/–*	–	+/–*	–	–$^{\#}$	+
Bone loss						
AORI I	+/–	+/–	+/–	+/–	–	–
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.

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 prosthesis longevity.

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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References

1. Delanois RE, Mistry JB, Gwam CU, Mohamed NS, Choksi US & Mont MA. Current epidemiology of revision total knee arthroplasty in the United States. *Journal of Arthroplasty* 2017 **32** 2663–2668. (https://doi.org/10.1016/j.arth.2017.03.066)

2. Kurtz S, Ong K, Lau E, Mowat F & Halpern M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *Journal of Bone and Joint Surgery: American Volume* 2007 **89** 780–785. (https://doi.org/10.2106/JBJS.F.00222)

3. Patel A, Pavlou G, Mujica-Mota RE & Toms AD. The epidemiology of revision total knee and hip arthroplasty in England and Wales: a comparative analysis with projections for the United States. A study using the National Joint Registry dataset. *Bone and Joint Journal* 2015 **97-B** 1076–1081. (https://doi.org/10.1302/0301-620X.97B8.35170)

4. Feng B, Zhu W, Bian YY, Chang X, Cheng KY & Weng XS. China artificial joint annual data report. *Chinese Medical Journal* 2020 **134** 752–753. (https://doi.org/10.1097/CM9.0000000000001196)

5. Huang SL, He XJ & Wang KZ. Joint replacement in China: progress and challenges. *Rheumatology* 2012 **51** 1525–1526. (https://doi.org/10.1093/rheumatology/kes077)

6. Thienpont E. Revision knee surgery techniques. *EFORT Open Reviews* 2016 **1** 233–238. (https://doi.org/10.1302/2058-5241.1.000024)

7. Massin P. How does total knee replacement technique influence polyethylene wear? *Orthopaedics and Traumatology, Surgery and Research* 2017 **103** S21–S27. (https://doi.org/10.1016/j.otsr.2016.06.024)

8. Sharkey PF, Lichstein PM, Shen C, Tokarski AT & Parvizi J. Why are total knee arthroplasties failing today – has anything changed after 10 years? *Journal of Arthroplasty* 2014 **29** 1774–1778. (https://doi.org/10.1016/j.arth.2013.07.024)

9. Labek G, Thaler M, Janda W, Agreiter M & Stöckl B. Revision rates after total joint replacement: cumulative results from worldwide joint register datasets. *Journal of Bone and Joint Surgery: British Volume* 2011 **93** 293–297. (https://doi.org/10.1302/0301-620X.93B3.25467)

10. Lenguerrand E, Whitehouse MR, Beswick AD, Kunutsor SK, Foguet P, Porter M, Blom AW & National Joint Registry for England, Wales, Northern Ireland and the Isle of Man. Risk factors associated with revision for prosthetic joint infection following knee replacement: an observational cohort study from England and Wales. *Lancet: Infectious Diseases* 2019 **19** 589–600. (https://doi.org/10.1016/S1473-3099(18)30755-2)

11. Petrie JR & Haidukewych GJ. Instability in total knee arthroplasty: assessment and solutions. *Bone and Joint Journal* 2016 **98-B** (Supplement A) 116–119. (https://doi.org/10.1302/0301-620X.98B1.36371)

12. Vajapey SP, Pettit RJ, Li M, Chen AF, Spitzer AI & Glassman AH. Risk factors for mid-flexion instability after total knee arthroplasty: a systematic review. *Journal of Arthroplasty* 2020 **35** 3046–3054. (https://doi.org/10.1016/j.arth.2020.05.026)

13. Cram P, Lu X, Kates SL, Singh JA, Li Y & Wolf BR. Total knee arthroplasty volume, utilization, and outcomes among Medicare beneficiaries, 1991–2010. *JAMA* 2012 **308** 1227–1236. (https://doi.org/10.1001/2012.jama.11153)

14. Partridge TCJ, Baker PN, Jameson SS, Mason J, Reed MR & Deehan DJ. Conventional versus highly cross-linked polyethylene in primary total knee replacement: a comparison of revision rates using data from the National Joint Registry for England, Wales, and Northern Ireland. *Journal of Bone and Joint Surgery: American Volume* 2020 **102** 119–127. (https://doi.org/10.2106/JBJS.19.00031)

15. Schairer WW, Vail TP & Bozic KJ. What are the rates and causes of hospital readmission after total knee arthroplasty? *Clinical Orthopaedics and Related Research* 2014 **472** 181–187. (https://doi.org/10.1007/s11999-013-3030-7)

16. van Lieshout WAM, Valkering KP, Koenraadt KLM, van Etten-Jamaludin FS, Kerkhoffs GMMJ & van Geenen RCI. The negative effect of joint line elevation after total knee arthroplasty on outcome. *Knee Surgery, Sports Traumatology, Arthroscopy* 2019 **27** 1477–1486. (https://doi.org/10.1007/s00167-018-5099-8)

17. Prudhon JL, Caton JH, Aslanian T & Verdier R. How is patella height modified after total knee arthroplasty? *International Orthopaedics* 2018 **42** 311–316. (https://doi.org/10.1007/s00264-017-3539-6)

18. Park CH, Bae JK & Song SJ. Factors affecting the choice of constrained prostheses when performing revision total knee arthroplasty. *International Orthopaedics* 2019 **43** 1831–1840. (https://doi.org/10.1007/s00264-018-4200-8)

19. Lee JK, Lee S, Kim D, Lee SM, Jang J, Seong SC & Lee MC. Revision total knee arthroplasty with varus-valgus constrained prostheses versus posterior stabilized prostheses. *Knee Surgery, Sports Traumatology, Arthroscopy* 2013 **21** 620–628. (https://doi.org/10.1007/s00167-012-1998-2)

20. Kremers HM, Lewallen EA, van Wijnen AJ & Lewallen DG. Clinical factors, disease parameters, and molecular therapies affecting osseointegration of orthopedic implants. *Current Molecular Biology Reports* 2016 **2** 123–132. (https://doi.org/10.1007/s40610-016-0042-6)

21. Morgan-Jones R, Oussedik SI, Graichen H & Haddad FS. Zonal fixation in revision total knee arthroplasty. *Bone and Joint Journal* 2015 **97-B** 147–149. (https://doi.org/10.1302/0301-620X.97B2.34144)

22. Steere JT, Sobieraj MC, DeFrancesco CJ, Israelite CL, Nelson CL & Kamath AF. Prophylactic tibial stem fixation in the obese: comparative early results in primary total knee arthroplasty. *Knee Surgery and Related Research* 2018 **30** 227–233. (https://doi.org/10.5792/ksrr.18.022)

23. Song MH, Yoo SH, Kang SW, Kim YJ, Park GT & Pyeun YS. Coronal alignment of the lower limb and the incidence of constitutional varus knee in Korean females. *Knee Surgery and Related Research* 2015 **27** 49–55. (https://doi.org/10.5792/ksrr.2015.27.1.49)

24. Zhang Z, Chai W, Zhao G, Zhang Q, Chen Z, Wang X, Wei P, Zhang Y, Jin Z & Qiu Y, *et al.* Association of HSS score and mechanical alignment after primary TKA of patients suffering from constitutional varus knee that caused by combined deformities: a retrospective study. *Scientific Reports* 2021 **11** 3130. (https://doi.org/10.1038/s41598-021-81285-6)

25. Gan ZJ & Pang HN. Outcomes of total knee arthroplasty in patients with poliomyelitis. *Journal of Arthroplasty* 2016 **31** 2508–2513. (https://doi.org/10.1016/j.arth.2016.04.019)

26. Gu A, Wei C, Robinson HN, Sobrio SA, Liu J, Sculco TP & Sculco PK. Postoperative complications and impact of diabetes mellitus severity on revision total knee arthroplasty. *Journal of Knee Surgery* 2020 **33** 228–234. (https://doi.org/10.1055/s-0038-1677542)

27. Lei PF, Hu RY & Hu YH. Bone defects in revision total knee arthroplasty and management. *Orthopaedic Surgery* 2019 **11** 15–24. (https://doi.org/10.1111/os.12425)

28. Hommel H, Wilke K, Kunze D, Hommel P & Fennema P. Constraint choice in revision knee arthroplasty: study protocol of a randomised controlled trial assessing the effect of level of constraint on postoperative outcome. *BMJ Open* 2017 **7** e012964. (https://doi.org/10.1136/bmjopen-2016-012964)

29. Cho KJ, Seon JK, Jang WY, Park CG & Song EK. Objective quantification of ligament balancing using VERASENSE in measured resection and modified gap balance total knee arthroplasty. *BMC Musculoskeletal Disorders* 2018 **19** 266. (https://doi.org/10.1186/s12891-018-2190-8)

30. Krackow KA, Jones MM, Teeny SM & Hungerford DS. Primary total knee arthroplasty in patients with fixed valgus deformity. *Clinical Orthopaedics and Related Research* 1991 **273** 9–18. (https://doi.org/10.1097/00003086-199112000-00004)

31. Ranawat AS, Ranawat CS, Elkus M, Rasquinha VJ, Rossi R & Babhulkar S. Total knee arthroplasty for severe valgus deformity. *Journal of Bone and Joint Surgery: American Volume* 2005 **87** (Supplement 1) 271–284. (https://doi.org/10.2106/JBJS.E.00308)

32. Ahn JH, Yang TY & Lee JY. Reduction osteotomy vs pie-crust technique as possible alternatives for medial release in total knee arthroplasty and compared in a prospective randomized controlled trial. *Journal of Arthroplasty* 2016 **31** 1470–1475. (https://doi.org/10.1016/j.arth.2016.01.018)

33. Cheng X, Wang Z, Zhang Y, Wang M & Zhang X. Tightening medial collateral ligament during total knee arthroplasty for patients with fixed valgus deformity: a novel technique. *Journal of Orthopaedic Surgery* 2019 **27** 2309499019834695. (https://doi.org/10.1177/2309499019834695): 30862275.

34. Kouk S, Rathod PA, Maheshwari AV & Deshmukh AJ. Rotating hinge prosthesis for complex revision total knee arthroplasty: a review of the literature. *Journal of Clinical Orthopaedics and Trauma* 2018 **9** 29–33. (https://doi.org/10.1016/j.jcot.2017.11.020)

35. Barrack RL, Lyons TR, Ingraham RQ & Johnson JC. The use of a modular rotating hinge component in salvage revision total knee arthroplasty. *Journal of Arthroplasty* 2000 **15** 858–866. (https://doi.org/10.1054/arth.2000.9056)

36. Ni M, Sun JY, Fu J, Du YQ, Shen JM, Yang XX, Zhou YG, Zhang GQ & Chen JY. Management of medial collateral ligament insufficiency during total knee arthroplasty with a screw and rectangular spiked washer: a case series of 14 patients. *Orthopaedic Surgery* 2020 **12** 1784–1791. (https://doi.org/10.1111/os.12818)

37. Chang MJ, Lim H, Lee NR & Moon YW. Diagnosis, causes and treatments of instability following total knee arthroplasty. *Knee Surgery and Related Research* 2014 **26** 61–67. (https://doi.org/10.5792/ksrr.2014.26.2.61)

38. Shahi A, Tan TL, Tarabichi S, Maher A, Della Valle C & Saleh UH. Primary repair of iatrogenic medial collateral ligament injury during TKA: a modified technique. *Journal of Arthroplasty* 2015 **30** 854–857. (https://doi.org/10.1016/j.arth.2014.12.020)

39. Stambough JB, Edwards PK, Mannen EM, Barnes CL & Mears SC. Flexion instability after total knee arthroplasty. *Journal of the American Academy of Orthopaedic Surgeons* 2019 **27** 642–651. (https://doi.org/10.5435/JAAOS-D-18-00347)

40. Athwal KK, Willinger L, Manning W, Deehan D & Amis AA. A constrained-condylar fixed-bearing total knee arthroplasty is stabilised by the medial soft tissues. *Knee Surgery, Sports Traumatology, Arthroscopy* 2021 **29** 659–667. (https://doi.org/10.1007/s00167-020-05995-6)

41. Abdel MP & Haas SB. The unstable knee: wobble and buckle. *Bone and Joint Journal* 2014 **96-B** (Supplement A) 112–114. (https://doi.org/10.1302/0301-620X.96B11.34325)

42. Uvehammer J. Knee joint kinematics, fixation and function related to joint area design in total knee arthroplasty. *Acta Orthopaedica Scandinavica: Supplementum* 2001 **72** 1–52. (https://doi.org/10.1080/000164702760300299)

43. Peters CL, Mulkey P, Erickson J, Anderson MB & Pelt CE. Comparison of total knee arthroplasty with highly congruent anterior-stabilized bearings versus a cruciate-retaining design. *Clinical Orthopaedics and Related Research* 2014 **472** 175–180. (https://doi.org/10.1007/s11999-013-3068-6)

44. Vasso M, Beaufils P & Schiavone Panni A. Constraint choice in revision knee arthroplasty. *International Orthopaedics* 2013 **37** 1279–1284. (https://doi.org/10.1007/s00264-013-1929-y)

45. Rodriguez-Merchan EC. Total knee arthroplasty using hinge joints: indications and results. *EFORT Open Reviews* 2019 **4** 121–132. (https://doi.org/10.1302/2058-5241.4.180056)

46. Hintze JV, Niemelainen M, Sintonen H, Nieminen J & Eskelinen A. Good mid-term outcome of the rotating hinge knee in primary total knee arthroplasty – results of a single center cohort of 106 knees with a median follow-up of 6.3 years. *Knee* 2021 **28** 273–281. (https://doi.org/10.1016/j.knee.2020.12.016)

47. von Hintze J, Niemelainen M, Sintonen H, Nieminen J & Eskelinen A. Outcomes of the rotating hinge knee in revision total knee arthroplasty with a median follow-up of 6.2 years. *BMC Musculoskeletal Disorders* 2021 **22** 336. (https://doi.org/10.1186/s12891-021-04205-9)

48. Ippolito JA, Thomson JE, Rivero SM, Beebe KS, Patterson FR & Benevenia J. Management of large segmental bone defects at the knee with intramedullary stabilized antibiotic spacers during two-stage treatment of endoprosthetic joint infection. *Journal of Arthroplasty* 2021 **36** 2165–2170. (https://doi.org/10.1016/j.arth.2021.01.026)

49. McNamara CA, Gosthe RG, Patel PD, Sanders KC, Huaman G & Suarez JC. Revision total knee arthroplasty using a custom tantalum implant in a patient following multiple failed revisions. *Arthroplasty Today* 2017 **3** 13–17. (https://doi.org/10.1016/j.artd.2016.08.003)

50. Burastero G, Pianigiani S, Zanvettor C, Cavagnaro L, Chiarlone F & Innocenti B. Use of porous custom-made cones for meta-diaphyseal bone defects reconstruction in knee revision surgery: a clinical and biomechanical analysis. *Archives of Orthopaedic and Trauma Surgery* 2020 **140** 2041–2055. (https://doi.org/10.1007/s00402-020-03670-6)

51. Czekaj J, Fary C, Gaillard T & Lustig S. Does low-constraint mobile bearing knee prostheses give satisfactory results for severe coronal deformities? A five to twelve year follow up study. *International Orthopaedics* 2017 **41** 1369–1377. (https://doi.org/10.1007/s00264-017-3452-z)

52. Morgan H, Battista V & Leopold SS. Constraint in primary total knee arthroplasty. *Journal of the American Academy of Orthopaedic Surgeons* 2005 **13** 515–524. (https://doi.org/10.5435/00124635-200512000-00004)

53. Nielsen CS, Nebergall A, Huddleston J, Kallemose T, Malchau H & Troelsen A. Medial overhang of the tibial component is associated with higher risk of inferior knee injury and osteoarthritis outcome score pain after knee replacement. *Journal of Arthroplasty* 2018 **33** 1394–1398. (https://doi.org/10.1016/j.arth.2017.12.027)

54. Oh SM, Bin SI, Lee BS & Kim JM. The entry point of intramedullary tibia cutting guide should vary according to the individual tibia morphology in TKA. *Archives of Orthopaedic and Trauma Surgery* 2020 **140** 391–400. (https://doi.org/10.1007/s00402-019-03324-2)

55. Lee J, Wang S & Kim K. Is there a difference in joint line restoration in revision total knee arthroplasty according to prosthesis type? *BMC Musculoskeletal Disorders* 2018 **19** 382. (https://doi.org/10.1186/s12891-018-2295-0)

56. Innocenti B, Fekete G & Pianigiani S. Biomechanical analysis of augments in revision total knee arthroplasty. *Journal of Biomechanical Engineering* 2018 **140** 111006. (https://doi.org/10.1115/1.4040966)

57. Kang KS, Tien TN, Lee MC, Lee KY, Kim B & Lim D. Suitability of metal block augmentation for large uncontained bone defect in revision total knee arthroplasty (TKA). *Journal of Clinical Medicine* 2019 **8** 384. (https://doi.org/10.3390/jcm8030384)

58. Tsukada S, Wakui M & Matsueda M. Metal block augmentation for bone defects of the medial tibia during primary total knee arthroplasty. *Journal of Orthopaedic Surgery and Research* 2013 **8** 36. (https://doi.org/10.1186/1749-799X-8-36)

59. Pagnano MW, Trousdale RT & Rand JA. Tibial wedge augmentation for bone deficiency in total knee arthroplasty. A followup study. *Clinical Orthopaedics and Related Research* 1995 **321** 151–155. (https://doi.org/10.1097/00003086-199512000-00023)

60. Rand JA. Bone deficiency in total knee arthroplasty. Use of metal wedge augmentation. *Clinical Orthopaedics and Related Research* 1991 **271** 63–71. (https://doi.org/10.1097/00003086-199110000-00009)

61. Klim SM, Amerstorfer F, Bernhardt GA, Sadoghi P, Hauer G, Leitner L, Leithner A & Glehr M. Excellent mid-term osseointegration and implant survival using metaphyseal sleeves in revision total knee arthroplasty. *Knee Surgery, Sports Traumatology, Arthroscopy* 2020 **28** 3843–3848. (https://doi.org/10.1007/s00167-020-05865-1)

62. Jacquet C, Ros F, Guy S, Parratte S, Ollivier M & Argenson JN. Trabecular metal cones combined with short cemented stem allow favorable outcomes in aseptic revision total knee arthroplasty. *Journal of Arthroplasty* 2021 **36** 657–663. (https://doi.org/10.1016/j.arth.2020.08.058)

63. Martin-Hernandez C, Floria-Arnal LJ, Muniesa-Herrero MP, Espallargas-Doñate T, Blanco-Llorca JA, Guillen-Soriano M & Ranera-Garcia M. Mid-term results for metaphyseal sleeves in revision knee surgery. *Knee Surgery, Sports Traumatology, Arthroscopy* 2017 **25** 3779–3785. (https://doi.org/10.1007/s00167-016-4298-4)

64. Klim SM, Amerstorfer F, Bernhardt GA, Sadoghi P, Gruber G, Radl R, Leithner A & Glehr M. Septic revision total knee arthroplasty: treatment of metaphyseal bone defects using metaphyseal sleeves. *Journal of Arthroplasty* 2018 **33** 3734–3738. (https://doi.org/10.1016/j.arth.2018.08.017)

65. Bonanzinga T, Akkawi I, Zahar A, Gehrke T, Haasper C & Marcacci M. Are metaphyseal sleeves a viable option to treat bone defect during revision total knee arthroplasty? A systematic review. *Joints* 2019 **7** 19–24. (https://doi.org/10.1055/s-0039-1697611)

66. Rao BM, Kamal TT, Vafaye J & Moss M. Tantalum cones for major osteolysis in revision knee replacement. *Bone and Joint Journal* 2013 **95–B** 1069–1074. (https://doi.org/10.1302/0301-620X.95B8.29194)

67. Boureau F, Putman S, Arnould A, Dereudre G, Migaud H & Pasquier G. Tantalum cones and bone defects in revision total knee arthroplasty. *Orthopaedics and Traumatology, Surgery and Research* 2015 **101** 251–255. (https://doi.org/10.1016/j.otsr.2014.11.020)

68. Zanirato A, Formica M, Cavagnaro L, Divano S, Burastero G & Felli L. Metaphyseal cones and sleeves in revision total knee arthroplasty: two sides of the same coin? Complications, clinical and radiological results-a systematic review of the literature. *Musculoskeletal Surgery* 2020 **104** 25–35. (https://doi.org/10.1007/s12306-019-00598-y)

69. Kim HJ, Lee OS, Lee SH & Lee YS. Comparative analysis between cone and sleeve in managing severe bone defect during revision total knee arthroplasty: a systematic review and meta-analysis. *Journal of Knee Surgery* 2018 **31** 677–685. (https://doi.org/10.1055/s-0037-1606564)

70. Xie S, Conlisk N, Hamilton D, Scott C, Burnett R & Pankaj P. Metaphyseal cones in revision total knee arthroplasty: the role of stems. *Bone and Joint Research* 2020 **9** 162–172. (https://doi.org/10.1302/2046-3758.94.BJR-2019-0239.R1)

71. Ettinger M, Savov P, Balubaid O, Windhagen H & Calliess T. Influence of stem length on component flexion and posterior condylar offset in revision total knee arthroplasty. *Knee* 2018 **25** 480–484. (https://doi.org/10.1016/j.knee.2018.02.011)

72. Patel AR, Barlow B & Ranawat AS. Stem length in revision total knee arthroplasty. *Current Reviews in Musculoskeletal Medicine* 2015 **8** 407–412. (https://doi.org/10.1007/s12178-015-9297-4)

73. Kang SG, Park CH & Song SJ. Stem fixation in revision total knee arthroplasty: indications, stem dimensions, and fixation methods. *Knee Surgery and Related Research* 2018 **30** 187–192. (https://doi.org/10.5792/ksrr.18.019)

74. Sheridan GA, Garbuz DS & Masri BA. Hybrid stems are superior to cemented stems in revision total knee arthroplasty: a systematic review and meta-analysis of recent comparative studies. *European Journal of Orthopaedic Surgery and Traumatology* 2021 **31** 131–141. (https://doi.org/10.1007/s00590-020-02752-w)

75. Barrack RL, Stanley T, Burt M & Hopkins S. The effect of stem design on end-of-stem pain in revision total knee arthroplasty. *Journal of Arthroplasty* 2004 **19** (Supplement 2) 119–124. (https://doi.org/10.1016/j.arth.2004.06.009)

76. El-Zayat BF, Heyse TJ, Fanciullacci N, Labey L, Fuchs-Winkelmann S & Innocenti B. Fixation techniques and stem dimensions in hinged total knee arthroplasty: a finite element study. *Archives of Orthopaedic and Trauma Surgery* 2016 **136** 1741–1752. (https://doi.org/10.1007/s00402-016-2571-0)

77. Gustke K. Optimal use of stems in revision TKA. *Seminars in Arthroplasty* 2018 **29** 260–264. (https://doi.org/10.1053/j.sart.2019.01.016)

78. Baldini A, Balato G & Franceschini V. The role of offset stems in revision knee arthroplasty. *Current Reviews in Musculoskeletal Medicine* 2015 **8** 383–389. (https://doi.org/10.1007/s12178-015-9294-7)

79. Parsley BS, Sugano N, Bertolusso R & Conditt MA. Mechanical alignment of tibial stems in revision total knee arthroplasty. *Journal of Arthroplasty* 2003 **18** (Supplement 1) 33–36. (https://doi.org/10.1016/s0883-5403(03)00302-4)

80. Lee SH, Shih HN, Chang CH, Lu TW, Chang YH & Lin YC. Influence of extension stem length and diameter on clinical and radiographic outcomes of revision total knee arthroplasty. *BMC Musculoskeletal Disorders* 2020 **21** 15. (https://doi.org/10.1186/s12891-019-3030-1)

81. Lee JK, Kim SJ, Choi CH & Chung HK. Revision total knee arthroplasty using a constrained condylar knee prosthesis in conjunction with a posterior stabilized articular polyethylene. *Journal of Arthroplasty* 2013 **28** 566–569. (https://doi.org/10.1016/j.arth.2012.07.017)

82. Gigante A, Bottegoni C, Ragone V & Banci L. Effectiveness of vitamin-E-doped polyethylene in joint replacement: a literature review. *Journal of Functional Biomaterials* 2015 **6** 889–900. (https://doi.org/10.3390/jfb6030889)

83. Oral E, Rowell SL & Muratoglu OK. The effect of alpha-tocopherol on the oxidation and free radical decay in irradiated UHMWPE. *Biomaterials* 2006 **27** 5580–5587. (https://doi.org/10.1016/j.biomaterials.2006.07.017)

84. Lambert B, Neut D, van der Veen HC & Bulstra SK. Effects of vitamin E incorporation in polyethylene on oxidative degradation, wear rates, immune response, and infections in total joint arthroplasty: a review of the current literature. *International Orthopaedics* 2019 **43** 1549–1557. (https://doi.org/10.1007/s00264-018-4237-8)

85. Koh Y, Lee J & Kang K. Prediction of wear on tibial inserts made of UHMWPE, PEEK, and CFR-PEEK in total knee arthroplasty using finite-element analysis. *Lubricants* 2019 **7** 30–30. (https://doi.org/10.3390/lubricants7040030)

86. Conditt MA, Thompson MT, Usrey MM, Ismaily SK & Noble PC. Backside wear of polyethylene tibial inserts: mechanism and magnitude of material loss. *Journal of Bone and Joint Surgery: American Volume* 2005 **87** 326–331. (https://doi.org/10.2106/JBJS.C.01308)

87. Kuster MS & Stachowiak GW. Factors affecting polyethylene wear in total knee arthroplasty. *Orthopedics* 2002 **25** (Supplement) s235–s242. (https://doi.org/10.3928/0147-7447-20020202-07)

88. Berend ME, Davis PJ, Ritter MA, Keating EM, Faris PM, Meding JB & Malinzak RA. 'Thicker' polyethylene bearings are associated with higher failure rates in primary total knee arthroplasty. *Journal of Arthroplasty* 2010 **25** (Supplement) 17–20. (https://doi.org/10.1016/j.arth.2010.04.031)

89. Edwards SA, Pandit HG, Ramos JL & Grover ML. Analysis of polyethylene thickness of tibial components in total knee replacement. *Journal of Bone and Joint Surgery: American Volume* 2002 **84** 369–371. (https://doi.org/10.2106/00004623-200203000-00006)

90. O'Brien ST, Turgeon TR & Bohm ER. Effects of insert thickness on contact pressure, sliding distances and polyethylene wear in total knee replacements. In *ORS 2014 Annual Meeting* Poster No. 0971. The Orthopaedic Research Society .

91. Bei Y, Fregly BJ, Sawyer WG, Banks SA & Kim NH. The relationship between contact pressure, insert thickness, and mild wear in total knee replacements. *Computer Modeling in Engineering and Sciences* 2004 **6** 145–152. (https://doi.org/10.3970/cmes.2004.006.145)

92. Pijls BG, Van der Linden-Van HM & Nelissen RG. Polyethylene thickness is a risk factor for wear necessitating insert exchange. *International Orthopaedics* 2012 **36** 1175–1180. (https://doi.org/10.1007/s00264-011-1412-6)

93. Makhdom AM & Parvizi J. Modular versus nonmodular tibial inserts in total knee arthroplasty: what are the differences? *Annals of Translational Medicine* 2017 **5** 225. (https://doi.org/10.21037/atm.2017.02.25)

94. Babis GC, Trousdale RT & Morrey BF. The effectiveness of isolated tibial insert exchange in revision total knee arthroplasty. *Journal of Bone and Joint Surgery: American Volume* 2002 **84** 64–68. (https://doi.org/10.2106/00004623-200201000-00010)

95. Kretzer JP, Reinders J, Sonntag R, Hagmann S, Streit M, Jeager S & Moradi B. Wear in total knee arthroplasty – just a question of polyethylene? Metalion release in total knee arthroplasty. *International Orthopaedics* 2014 **38** 335–340. (https://doi.org/10.1007/s00264-013-2162-4)

96. Ebramzadeh E. CORR insights(R): current total knee designs: does baseplate roughness or locking mechanism design affect polyethylene backside wear? *Clinical Orthopaedics and Related Research* 2018 **476** 615–617. (https://doi.org/10.1007/s11999.0000000000000156)

97. Jayabalan P, Furman BD, Cottrell JM & Wright TM. Backside wear in modern total knee designs. *HSS Journal* 2007 **3** 30–34. (https://doi.org/10.1007/s11420-006-9033-0)

98. Bettinson KA, Pinder IM, Moran CG, Weir DJ & Lingard EA. All-polyethylene compared with metal-backed tibial components in total knee arthroplasty at ten years. A prospective, randomized controlled trial. *Journal of Bone and Joint Surgery: American Volume* 2009 **91** 1587–1594. (https://doi.org/10.2106/JBJS.G.01427)

99. Ritter MA, Keating EM, Sueyoshi T, Davis KE, Barrington JW & Emerson RH. Twenty-five-years and greater, results after nonmodular cemented total knee arthroplasty. *Journal of Arthroplasty* 2016 **31** 2199–2202. (https://doi.org/10.1016/j.arth.2016.01.043)

100. Meier E, Gelse K, Trieb K, Pachowsky M, Hennig FF & Mauerer A. First clinical study of a novel complete metal-free ceramic total knee replacement system. *Journal of Orthopaedic Surgery and Research* 2016 **11** 21. (https://doi.org/10.1186/s13018-016-0352-7)

101. Du Z, Zhu Z, Yue B, Li Z & Wang Y. Feasibility and safety of a cemented PEEK-on-PE knee replacement in a goat model: A preliminary study. *Artificial Organs* 2018 **42** E204–E214. (https://doi.org/10.1111/aor.13101)

102. Haas SB, Insall JN, Montgomery WR & Windsor RE. Revision total knee arthroplasty with use of modular components with stems inserted without cement. *Journal of Bone and Joint Surgery: American Volume* 1995 **77** 1700–1707. (https://doi.org/10.2106/00004623-199511000-00009)

103. Gofton WT, Tsigaras H, Butler RA, Patterson JJ, Barrack RL & Rorabeck CH. Revision total knee arthroplasty: fixation with modular stems. *Clinical Orthopaedics and Related Research* 2002 **404** 158–168. (https://doi.org/10.1097/00003086-200211000-00028)

104. Rohner E, Benad K, Zippelius T, Kloss N, Jacob B, Kirschberg J & Matziolis G. Good clinical and radiological results of total knee arthroplasty using varus valgus constrained or rotating hinge implants in ligamentous laxity. *Knee Surgery, Sports Traumatology, Arthroscopy* 2019 **27** 1665–1670. (https://doi.org/10.1007/s00167-018-5307-6)

105. Yoon JR, Cheong JY, Im JT, Park P-S, Park J-O & Shin Y-S. Rotating hinge knee versus constrained condylar knee total knee arthroplasty: a meta-analysis. *PLoS ONE* 2019 **14** e214279. (https://doi.org/10.1371/journal.pone.0214279)

106. Shen C, Lichstein PM, Austin MS, Sharkey PF & Parvizi J. Revision knee arthroplasty for bone loss: choosing the right degree of constraint. *Journal of Arthroplasty* 2014 **29** 127–131. (https://doi.org/10.1016/j.arth.2013.04.042)

107. Hwang SC, Kong JY, Nam DC, Kim DH, Park HB, Jeong ST & Cho SH. Revision total knee arthroplasty with a cemented posterior stabilized, condylar constrained or fully constrained prosthesis: a minimum 2-year follow-up analysis. *Clinics in Orthopedic Surgery* 2010 **2** 112–120. (https://doi.org/10.4055/cios.2010.2.2.112)

108. Scuderi GR. Revision total knee arthroplasty: how much constraint is enough? *Clinical Orthopaedics and Related Research* 2001 **392** 300–305. (https://doi.org/10.1097/00003086-200111000-00039)

109. Luttjeboer JS, Bénard MR, Defoort KC, van Hellemondt GG & Wymenga AB. Revision total knee arthroplasty for instability-outcome for different types of instability and implants. *Journal of Arthroplasty* 2016 **31** 2672–2676. (https://doi.org/10.1016/j.arth.2016.06.062)

110. Indelli PF, Giori N & Maloney W. Level of constraint in revision knee arthroplasty. *Current Reviews in Musculoskeletal Medicine* 2015 **8** 390–397. (https://doi.org/10.1007/s12178-015-9295-6)