Recent Advances in Knee Arthroplasty: A Narrative Review

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Abstract:

Total knee arthroplasty (TKA) has undergone significant advancements since its inception in the late 19th century. However, nearly 20% of patients report unsatisfactory outcomes. This review summarises the recent advances and practices aimed at improving the results of primary TKA. Implant designs have evolved to enhance longevity, address diverse patient needs, and align with specific alignment philosophies. Smart sensor implants offer the potential for real-time monitoring of implant function and patient activity levels. Advancements in implant materials focus on enhancing longevity, biocompatibility, and functionality. Multiple alignment philosophies are being adopted to better replicate knee anatomy and kinematics. Robotic-assisted surgery (RAS) has emerged as a promising approach, enhancing precision through a robotic arm after creating a 3D model of the knee joint. Effective perioperative pain management is crucial for promoting early mobilisation and expediting hospital discharge. New patient specific multimodal perioperative pain control techniques, such as targeted surgical local infiltration analgesia, adductor canal blockade, genicular nerve blocks, and the infiltration between the popliteal artery and capsule of the knee (iPACK) block, have shown promise in improving postoperative pain relief and reducing opioid consumption. With these advanced practices, we hope to reduce the unsatisfactory outcomes and improve implant survivorship.

Key words: Knee Arthroplasty, Recent Advances, Implant Design, Material, Philosophies, Robotic, Pain Management.

Introduction

Knee arthroplasty is a surgical treatment offered to patients with knee arthritis who do not respond to conservative therapy. Numerically, it is the most common major surgical procedure in orthopaedic surgery around the world. It includes a variety of surgical procedures ranging from partial knee arthroplasty, primary total knee arthroplasty, complex primary knee arthroplasty, and revision knee arthroplasty. The concept of knee arthroplasty can be traced back to the late 19th century when Themistocles Gluck attempted the first artificial joint replacement using ivory components in 1890.[1] The modern era of knee replacement began in the 1950s and 1960s. In 1951, Börje Walldius introduced a hinged prosthesis made of acrylic, which was later replaced with cobalt-chrome in 1958.[2] A significant breakthrough came in the 1970s with the introduction of the total condylar knee by John Insall and colleagues.[3]

The 1980s saw further refinements in implant design and materials. The introduction of modular components allowed for greater flexibility in addressing individual patient needs. Improvements in polyethylene manufacturing processes led to more durable implants, reducing wear and extending implant longevity.

In the 1990s, minimally invasive surgical techniques began to emerge, offering potential benefits such as reduced postoperative pain and faster recovery. This period also saw the development of computer-assisted surgery, which aimed to improve the accuracy of implant positioning.[4] The turn of the 21st century brought significant advancements in implant materials and designs. Highly cross-linked polyethylene was introduced to further reduce wear and improve longevity.[5] Gender-specific and high-flexion designs were developed to better accommodate anatomical variations and functional demands.[6]

Recent years have witnessed the rise of personalised implants[7] and robotic-assisted surgery (RAS). Advances in perioperative pain management have also played a crucial role in improving outcomes. Enhanced recovery protocols, including multimodal pain management and early mobilisation, have significantly reduced hospital stays and accelerated rehabilitation.

Despite these advancements, challenges remain, and nearly 20% of patients report unsatisfactory outcomes. Issues such as implant loosening, infection, and persistent pain continue to be areas of ongoing research and development. The pursuit of the "forgotten knee"–a replacement that feels and functions like a natural knee–remains a key goal in the field. In this article, we have summarised the recent advances and practices aimed at improving the results of TKA. We have limited our purview to include only primary total knee replacement.

Implant Design

Total knee arthroplasty (TKA) implant designs have evolved significantly over time to improve patient outcomes, enhance implant longevity, and address diverse patient needs while also aligning with specific alignment philosophies. There are several implant designs available in current practice (Table 1) (Figure 1).

In the future, we may have smart sensor implants that will offer significant potential for real-time monitoring of implant function, wear, and patient activity levels. These intelligent devices can provide diagnostic capabilities along with therapeutic benefits.

Intraoperatively, smart sensor-assisted TKA can objectively assess ligament and soft tissue balancing while maintaining proper alignment to achieve desired kinematic targets. Post-implantation, these sensors can monitor implant performance under natural conditions and track the patient's clinical recovery during rehabilitation. This real-time data could help detect early signs of complications like polyethylene wear, which is a major cause of TKA failure.[8]

Implant designs	Functions	Advantages	Alignment targets
Fixed bearing designs	Traditional design with a fixed polyethylene insert	Provides stability and reduces wear	Suitable for mechanical alignment approaches
Mobile-bearing designs	Allows rotation between the tibial tray and polyethylene insert	Aims to reduce polyethylene wear and improve kinematics	Can accommodate anatomical and kinematic alignment philosophies
Posterior-stabilised designs	Incorporates a cam-post mechanism to prevent posterior tibial translation	Compensates for the absence of the posterior cruciate ligament	Compatible with various alignment approaches
Cruciate-retaining designs	Preserves the posterior cruciate ligament	Aims to maintain more natural knee kinematics	Often used in kinematic and anatomical alignment strategies
Medial-pivot designs	Mimics the natural pivoting motion of the knee around the medial compartment	Designed to improve stability and patient satisfaction	Aligns with functional and kinematic alignment principles
Gender-specific implants	Tailored to address anatomical differences between male and female knees	Aims to improve fit and function in female patients	Can be used with various alignment philosophies
High-flexion designs	Modified femoral component geometry to allow greater flexion	Aims to improve range of motion and functional outcomes	Compatible with multiple alignment approaches
Patient-specific implants	Custom-designed based on individual patient anatomy[9]	Aims to optimise fit and restore natural kinematics	Often used in conjunction with kinematic alignment principles
Cementless fixation designs	Utilise porous coatings or trabecular metal for biological fixation	Aims to improve long-term implant survival and bone preservation	Can be applied to various implant types and alignment philosophies
Unicompartmental knee implants	Designed for partial knee replacement in cases of isolated compartment disease	Preserves more natural knee kinematics and bone stock	Often aligned using kinematic or functional principles

Table 1: Implant designs in current practice.

Figure 1: A- Smart knee implant, B- Medial pivot knee, C- Cement-less knee, D- Unicondylar knee.

Implant Material

Recent advancements in implant materials for TKR have focused on enhancing longevity, biocompatibility, and functionality. Several key developments have emerged (Table 2) (Figure 2).

Highly cross-linked polyethylene (HXLPE)	This material demonstrates superior wear resistance compared to conventional polyethylene, potentially extending implant lifespan
Vitamin E-infused polyethylene	The incorporation of vitamin E as an antioxidant aid in maintaining mechanical properties and reducing oxidative degradation of the polyethylene component[10]
Ceramic coatings	Zirconia and alumina ceramic coatings applied to metal components contribute to reduced wear and enhanced biocompatibility
Porous metals	Materials such as trabecular metal (tantalum) and 3D-printed titanium structures facilitate improved osseointegration and fixation
Oxidised zirconium (OXINIUM)	This material combines the strength of metal with the wear resistance of ceramic, potentially offering enhanced durability
Hypoallergenic materials	Nickel-free alloys and ceramic-coated implants address metal sensitivity concerns in certain patients
Antimicrobial coatings	Surface modifications utilising silver ions or antibiotics aim to mitigate the risk of periprosthetic joint infections
Biodegradable scaffolds	These materials support tissue regeneration and gradually degrade as new bone forms, potentially improving long-term outcomes
Hydrogel-based cartilage substitutes	Ongoing research focuses on developing materials that more closely mimic the properties of natural cartilage

Table 2: Implant materials.

Figure 2: Oxinium knee.

Alignment Philosophy

The importance of coronal alignment in TKA has become increasingly recognised as a crucial factor in enhancing clinical outcomes. In response to patient dissatisfaction and the perception of an "unnatural knee" following TKA, various alignment strategies and philosophies have been developed to better replicate knee anatomy and kinematics. Currently, several principles and surgical techniques have been described. (Table 3)

		Mechanical alignment[11] (MA)	Kinematic alignment[12.13] (KA)	Inverse kinematic alignment (iKA)[14]	Restricted kinematic alignment[15]	Functional alignment (FA)
Femoral component	**Flexion**	Follows distal femoral bowing Target: 0 to 5° of flexion	Follows distal femoral bowing Target: 2 ± 3° flexion	Follows distal femoral bowing Target: 2 ± 3° flexion	Follows distal femoral bowing Target: 2 ± 3° flexion	Follows distal femoral bowing Target: 0 to 5° of flexion
	Distal cut	Systematic and perpendicular to femoral mechanical axis target 0°	Parallel to the distal femoral joint line (considering wear)	Parallel to the distal femoral joint line (considering wear)	Correct to <5°, then parallel to the distal femoral joint line (considering wear) target <5°	Parallel to the distal femoral joint line (considering wear) Target 0° to 5°
	Posterior cut	External or neutral rotation relative to posterior condylar line Measured resection or gap-balancing techniques Posterior or anterior referencing techniques	Parallel to the posterior condylar line	Parallel to the posterior condylar line	Parallel to the posterior condylar line	Surgical transepicondylar axis ±3°
	Mediolateral	Slightly lateralised	Centred on the notch	Centred on the notch	Centred on the notch	Centred on the distal femur
Tibial component	**Coronal Cut**	Systematic and perpendicular to the tibial mechanical axis Target 0°	Parallel to proximal tibial joint line (considering wear) Target -6° to 9°	Parallel to proximal tibial joint line (considering wear) within safe zone of 84° to 92° Target -6 ° to 2°	Correct to <5°, then parallel to proximal tibial joint line (considering wear) Target <5°	Perpendicular to tibial mechanical axis Target 0° ± 3°
	Slope	Systematic. Between 2° and 7° relative to sagittal tibial mechanical axis	Parallel to the medial plateau slope	Parallel to lateral plateau long axis	Parallel to lateral plateau long axis	Parallel to the medial plateau slope Target 0° to 3°
	Rotation	Towards the medial third of the tibial tuberosity				
Knee balancing		Soft tissues	Tibial cut	Femoral cut (distal and or posterior)	Tibial cut + soft tissues	Femoral and tibial positioning + soft tissues
Soft tissue release	**Femorotibial**	Frequent	None	None	Sometimes	Sometimes
	Lateral retinaculum	Sometimes	Rarely	Rarely	Rarely	Rarely
Technologies		All	All	Robotic-assisted	All	Robotic-assisted

Table 3: Alignment philosophies.

Robotic-Assisted Surgery

Conventional jig-based TKA is based on preoperative radiographs, intraoperative anatomical landmarks, and manually positioned alignments jigs to guide bone resections and implant positioning. Conventional TKA poses a risk of poor reproducibility, soft tissue iatrogenic injuries and limited intraoperative data on gap measurements and ligament tensioning. Computer-assisted surgery (CAS) uses a computer system to obtain live on-screen information about patient anatomy and knee kinematics during surgery (Figure 3). CAS provides the surgeon with patient-specific anatomical data and indications for bone resections and optimal implant positioning, but the computer system does not actively intervene in the operation. RAS intervenes in surgery, improving accuracy through a robotic arm after creating a 3D model of the knee joint based on the patient's anatomical landmarks. A brief summary of robotic systems in current practice is provided below (Table 4) (Figure 4).

Figure 3: Computer navigation assisted total knee replacement.

	MAKO® (STRYKER LTD, KALAMAZOO, MI, USA)	CORI® (SMITH AND NEPHEW, ANDOVER, TX, USA)	ROSA®(ZIMMER INC, WARSAW, IN, USA)	CUVIS®(SOUTH KOREA)	VELYS (DePUY SYNTHES, WARSAW, USA)
Level of surgeon involvement	Semi-active	Semi-active	Semi-active	Automatic	Semi-active
Image based	CT scan (image based)	Imageless	X rays (imageless possible)	CT scan (image based)	Imageless
UKA/TKA/THA	UKA/TKA/THA	UKA/TKA	TKA	TKA/UKA	TKA/UKA
Platform	Closed	Open	Closed	Closed	Closed
Implant choice	1. Triathlon	All implants	1. Persona 2. Vanguard 3. Nexgen	1. Maxx-meril	1. Attune
Workflow	1.Measured resection 2. Gap balancing	Measured resection	1. Measured resection 2. Gap balancing 3. Hybrid	1. Measured resection 2. Gap balancing	1. Measured resection 2. Gap balancing
Bone cuts	Saw directly assembled on the robotic arm	Handheld burr	Surgeon holds the external saw and the system controls the cutting guides	Milling tool attached to the robotic arm	Controlled saw cuts without cutting blocks
Soft tissue protection	Haptic feedback/ virtual boundaries	Smart burr/ virtual boundaries	Handheld saw	Virtual boundaries	Haptic feedback/ virtual boundaries
Accuracy	****	**	*	**	***

Table 4: Robots in current practice.

Abbreviations: CT: computed tomography; UKA: unicompartmental knee arthroplasty; THA: total hip arthroplasty; TKA: total knee arthroplasty.

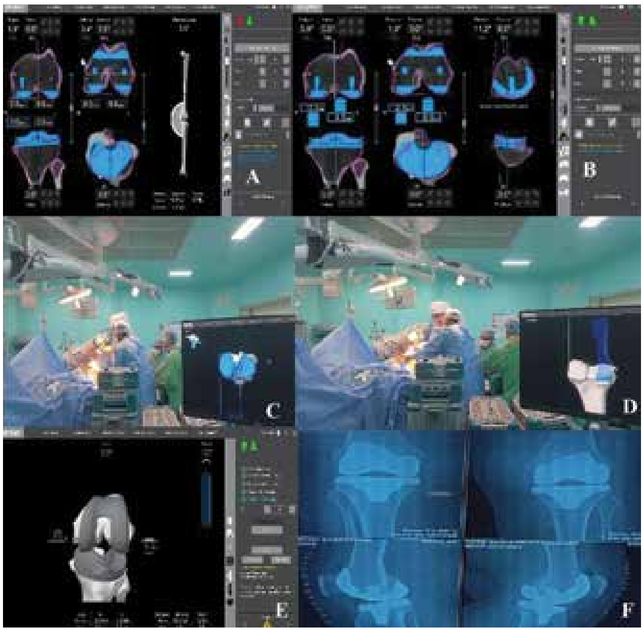

Figure 4: Robotic knee replacement A- Implant planning, B- Ligament balancing, C- Execution by robotic arm (tibia), D- Femur, E- Trailing with assessment of laxity, F- Final X ray.

Perioperative Pain Management

Severe postoperative pain is a common consequence of TKA. Effective pain management is crucial for promoting early mobilisation and expediting hospital discharge following this procedure. Recent advancements in motor-sparing regional anaesthesia techniques have enhanced recovery after TKA. Several promising approaches have emerged to improve postoperative pain relief, including targeted surgical local infiltration analgesia, adductor canal blockade, genicular nerve blocks, and the iPACK block. These motor-sparing regional anaesthesia methods contribute to a multimodal analgesic strategy, which aims to decrease opioid consumption and enhance functional recovery. Advent of liposomal bupivacaine as local anaesthetic agent gives analgesia up to 72 hours in single shot nerve block techniques (Table 5) (Figure 5).

Blocks	Description	Mechanism of action	Benefits
Local infiltration analgesia (LIA)	Intraoperative infiltration of large volumes of dilute local anaesthesia solutions to periarticular soft tissues	Multifactorial: in addition to direct sensory blockade, there might also be dilution of inflammatory mediators or direct anti-inflammatory effects	Opioid-sparing postoperative analgesia, shorter hospital stay, higher range of motion at 24 h and higher patient satisfaction.
Adductor canal block	Procedure involves locating the superficial femoral artery (SFA) dorsolateral to the sartorius muscle and identifying the target saphenous nerve anterolateral to the SFA	Block is administered distal to the efferent branches supplying the quadriceps muscle	Comparatively better preservation of quadriceps muscle strength than femoral nerve block
Genicular nerve block[16]	Superolateral genicular nerve (SLGN) Superomedial genicular nerve (SMGN) Inferomedial genicular nerve (IMGN) Inferolateral genicular nerve (ILGN)	Targets the sensory nerves around the knee joint	Improved pain control, enhanced early mobilisation by preserving quadriceps strength, reduced opioid use, longer-lasting analgesia
Interspace between the popliteal artery and capsule of the knee (iPACK) block[17]	Technique involves injecting local anaesthetic between the popliteal artery and the posterior knee capsule	Block targets the sensory nerves innervating the posterior knee capsule, which are not adequately covered by traditional nerve blocks	Improved posterior knee pain control, reduced opioid consumption, enhanced early mobilisation and rehabilitation, shorter hospital stays

Table 5: Perioperative pain management.

Figure 5: Adductor canal block.

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Conclusion

Knee arthroplasty continues to evolve, with efforts to improve postoperative function and increase implant survivorship. Advanced techniques and materials offer promising benefits; however, but they must demonstrate superiority over current practices and prove value for money before being widely adopted for patient care.

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