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Current Concept Update on Robotic Technology in Arthroplasty- A Narrative review

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Abstract

Ensuring precise prosthesis positioning is one of the key elements for improving long-term survival rates in knee arthroplasty. The evolution of Total knee arthroplasty surgeries from Computer assisted navigation to robotic assisted techniques has improved the precision of bone preparation, component positioning and has reduced alignment outliers and surgeon-related errors. The present article gives an overview of the existing robotic arthroplasty systems available.

The present review describes the types of robots, their classification system, comparisons between various robotic assisted devices available in the market. This review highlights the key steps involved in using various systems, current concepts and the future scope of development in this field. This review also proposes the concept of intelligent alignment philosophy which is more patient specific combining different philosophies.

Keywords: Robotic Assisted techniques; current updates; intelligent alignment; total knee arthroplasty

Introduction

Total knee arthroplasty remains a popular procedure even though there are ongoing improvements in surgical methods and implant technology. However, despite its technical success, a significant percentage of patients do not achieve the intended or expected functional results. Newer TKA designs have had mixed results in improving functional outcomes, particularly when meeting the needs of younger, more active patients[1]. According to a study that examined more than 60,000 revision TKA cases in the U.S., the most common reason for the revision was infection (25.2%), which was followed by mechanical loosening (16.1%) and implant failure/breakage (9.7%)[2]. This study highlighted the relationship between inadequate prosthesis positioning and the ensuing post-operative lower limb misalignment as major predictors of failure from prosthesis loosening and poor functional outcomes[3]. Ensuring precise prosthesis positioning is thus one of the key elements to improve long-term survival rates in knee arthroplasty[4].

The use of technological strategies that prevent malalignment may play a critical role in enhancing overall success. Computer-assisted navigation was introduced to enhance TKA outcomes by improving implant positioning and alignment. Two main categories within computer-assisted surgery (CAS) are passive (navigated TKA) and semi-active or active (robotic TKA). Passive CAS has demonstrated better alignment results in TKA compared to traditional methods, yet it poses potential complications such as registration errors, pin site issues, prolonged surgical time, and a steeper learning curve.

To overcome this, robotic-assisted knee arthroplasty has been developed to enhance the precision of bone surface preparation and component positioning, reduce alignment outliers, and minimize surgeon-related errors. In short, apart from improved software that helps in better planning workflow, modern Robotic systems also offer the opportunity to execute it to perfection. The incorporation of artificial intelligence (AI) in these systems is also likely to bring about a paradigm shift in this man-machine interface and interplay[4].

Orthopedic robotic systems are typically classified into two main categories: Active and semi-active. In active systems, the robot acts independently without direct surgeon involvement. In contrast, in semi-active systems, the surgeon performs the procedure with feedback from the robot to prevent errors in bony cuts-a technology often termed 'haptic system[5].

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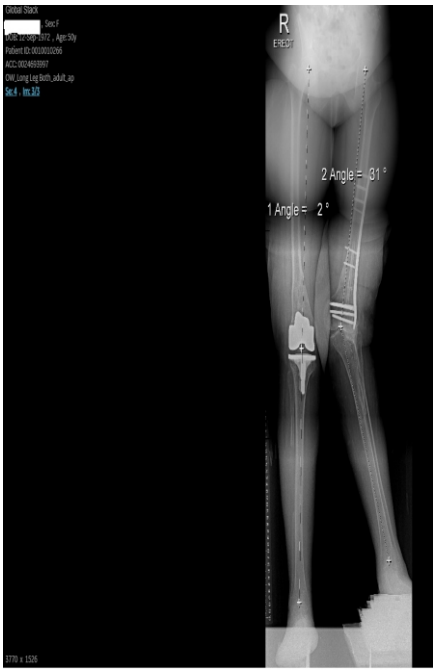


Figure 1a: Pre-operative X-ray scannogram

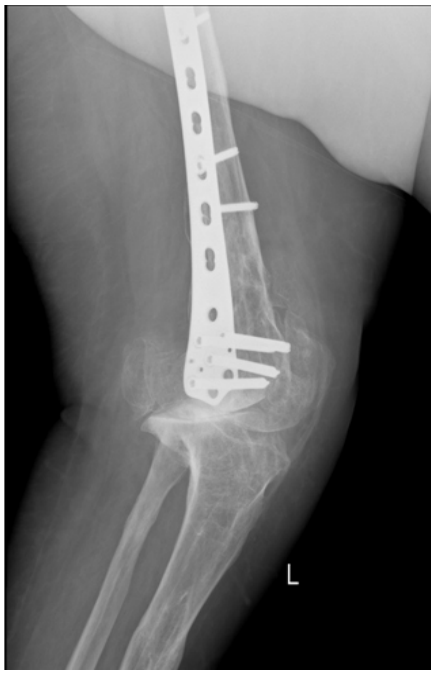


Figure 1b: Pre-operative X-ray of left knee – Lateral view

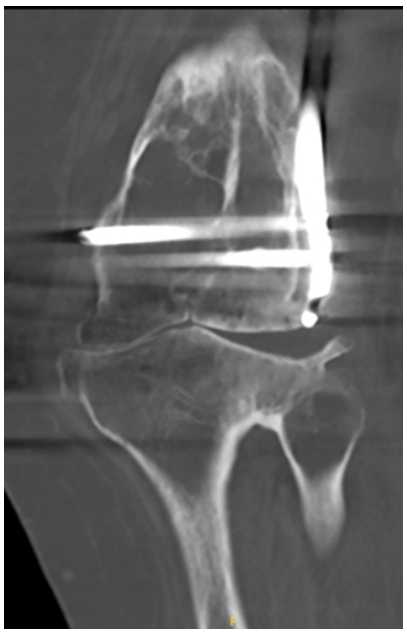


Figure 2a: Pre-operative CT scan of left knee – Coronal view

The majority of early robotic TKA systems were active, which resulted in significant surgical and technical problems as the operating surgeons had no control over what were the "early prototypes". However, unlike traditional arthroplasty and previous technologies, modern robotic total joint arthroplasty systems are primarily semi-active and use haptic feedback to reduce iatrogenic soft-tissue injury5. Another way of classifying them is whether they are image based or imageless. Image based systems require pre-operative radiological imaging and imageless do not require any pre-operative imaging. A brief overview of the existing robotic arthroplasty systems is as follows:

Types of Robots

The categorization of robotic surgical

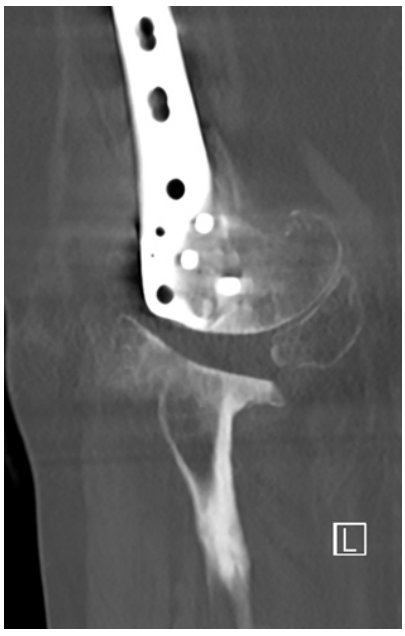


Figure 2b: Pre-operative CT scan of left knee – lateral view

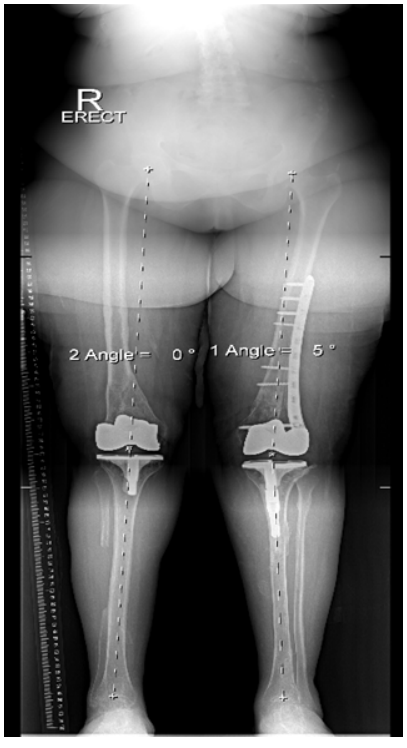


Figure 3a: Post-operative X-ray scannogram

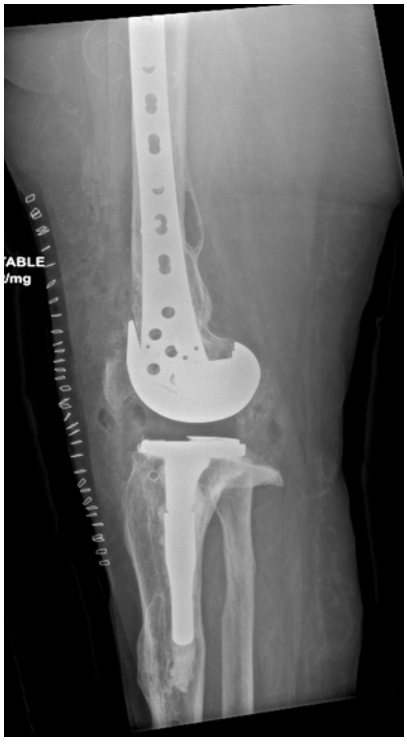


Figure 3b: Post-operative X-ray left knee – lateral view

Table 1: Comparing different available robots

	Active/Semi-active	Image-based or imageless	System	Disadvantages
ROBODOC	Autonomous	Image-based		1. The time needed for registration and milling is greater than others.
				2. Milling, compared with cutting, creates excessive heat that could damage the surrounding bone.
				3. Intraoperative flexibility, and therefore surgeon's involvement, is very limited.
				4. 4. Software does not allow for live kinematic joint assessment or final implant position information.
MAKO	Semi-active	Image-based (C.T. Scans)	1. Provides haptic feedback that constrains the movement of the cutting instrument guided by the surgeon.	
			2. For the UKR, it is a high-speed burr, and for the TKR an oscillating saw.	
ROSA	Semi-active	Image-based (X-rays) or imageless	Imageless system but can be supplemented with pre-operative radiographs to create a 3D model of the patient's knee.	Poor modeling precision in individuals with anatomical abnormalities (major dysplasia, post-traumatic malunion, fracture fixation devices in place, etc.)
CUVIS	Fully Autonomous	3D C.T. Base surgical planning	1. Fully automatic cutting (Milling).	
			2. No cutting guides (jigs) required.	
VELYS		Imageless	Consists of bone-mounted arrays and a bed-mounted robotic arm that positions a surgical saw to perform bony resections	
CORI	Semi-active	Imageless	1. Handheld robotics	
			2. High-speed cutting burr.	
			3. Allow for real-time planning and gap assessment, optimized alignment and balance.	

systems includes three main types:

Passive

Based on computer-assisted or navigation technology, passive robotic systems give the surgeon positional direction through an overhead monitor; however, because the surgeon performs bone cuts using traditional instruments and they lack safety limitations (haptic feedback) on bone surface preparation and component location, their application in TKA is restricted. Although it works directly with the surgeon, the system is still managed by the surgeon[6].

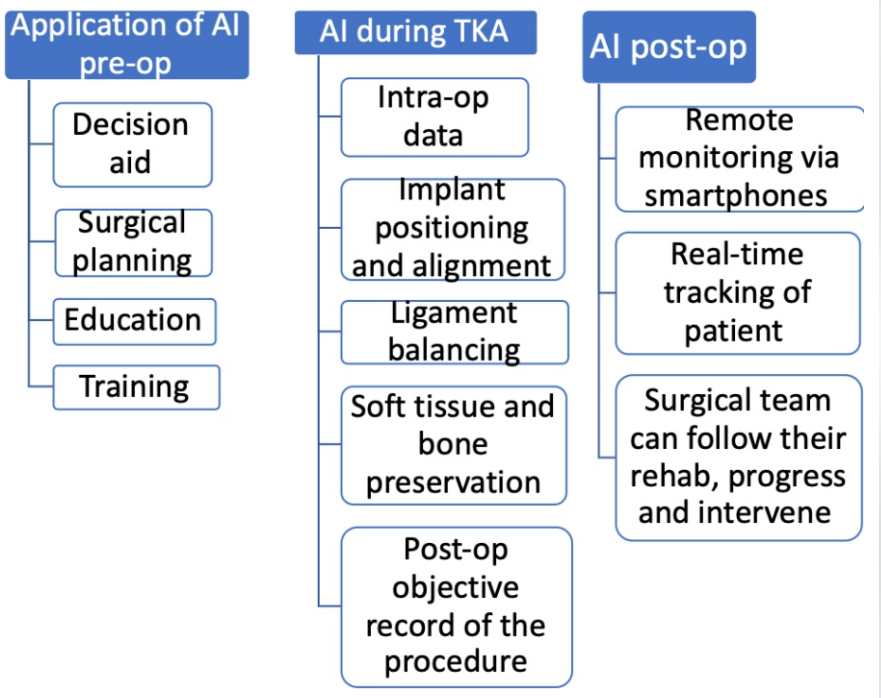
Semi-active

Semi-active systems require continuous surgeon input to guide the robotic arm within predetermined haptic constraints. They use controlled robotic instruments in which a task is restricted by the system to a predefined set of parameters. In semi-active systems, haptic feedback can be visible (color changes on the computer screen), tactile (vibratory), or auditory (beeping). Certain semi-active technologies regulate the depth and speed of the working instrument, preventing unintentional modifications by retracting or slowing down the cutting tool if the surgeon deviates from the predetermined margins[7].

Active

In contrast, active systems operate autonomously under surgical supervision, configuring the surgical

Table 2: Application of AI pre-op, intra-op and post-op Total knee arthroplasty (TKA)



plan based on pre-operative imaging (X-rays, C.T. scans, or MRI scans)[8].

The surgeon initiates the robotic arm, which performs bony resections independently, with the surgeon maintaining control through a manual override button but without direct intervention from the surgeon. Examples include tools for drilling or milling. A platform and a surgical treatment plan that has been authorized are necessary for any orthopedic robotic system. Pre-operative imaging or intraoperative landmark registration may serve as the foundation for surgical planning. By mapping points on the bone, the anatomy of the patient is registered, and a three-dimensional frame of reference is produced.

Another way to classify these systems is whether they use pre-operative imaging or not:

Image-Based Modality

Construct three-dimensional models using pre-operative C.T. or MRI images.

The benefit of pre-operative planning – which enables the surgeon to select implant size and orientation – is provided by image-dependent systems. Pre-operative imaging does come with increased expenditures and risk of radiation, so the benefits should be considered carefully9.

This modality is commonly used in knee surgery.

Image-Free Modality

It does not require imaging; anatomical landmarks are collected directly during surgery to create a patient-specific model. Using a database of knee C.T. scans, the surgeon can create a 3D knee model using intraoperative anatomical registration points obtained when using image-free systems. After that, the cutting jig and knee position are matched to the reference frame that was established using the registered anatomical landmarks. One benefit of image-free systems is that they rely on real-time intraoperative data instead of pre-operative imaging.

Because imageless systems depend on the surgeon to provide data intraoperatively, there is a chance for human error[10].

Based on the permissibility of a particular robotic system for different company implants, robotic systems may have "closed" or "open" platforms, allowing only one manufacturer (CLOSED) or different companies (OPEN) to be implanted. While most platforms are essentially open, commercial considerations often restrict them.

Closed platforms may limit implant options, requiring surgeons to weigh the benefits of the robotic system against familiarity with the implant. Open systems, while more universal, may sacrifice some specificity and functionality. For instance, many open systems may not optimally predict kinematics for implant positioning (Table 1).

Various types of robotic total knee replacement systems that exist are:

1. Haptic Interface System:

- Utilizes a robotic arm to assist in TKA through a haptic interface.
- Stops the saw if bone resection deviates from predetermined parameters.
- Creates a 3D model from C.T. images for precise calculation of bone resection, prosthesis size, and position.

2. Handheld Robotic Burr System:

- A semi-active system manually controlled by the surgeon for partial knee arthroplasty and TKA.
- Follows the navigation field's burring tool trajectory, controlling exposure, and speed to prevent undesired resection.
- No pre-operative C.T. scan is required.

3. CT-Based Autonomous Active System:

- An autonomous active system is suitable for any prosthesis.
- Pre-operative planning is based on a C.T. scan, allowing the surgeon to decide on bone resection size, prosthesis sizing, and positioning.
- Robotic tools perform femoral and tibial cuts.

4. Motor-Powered Robotic System:

- Assists the surgeon in precise tibial and femoral cuts using a pre-operative plan.
- Does not use a pre-operative C.T. scan but is suitable for specific knee prosthesis.

These systems vary in their approach, affecting soft-tissue damage potential. Surgeons remain responsible for the appropriate positioning of retractors and soft-tissue protection. The adoption of robotic systems introduces financial costs, time-consuming aspects, and additional intraoperative steps compared to conventional TKA. The systems require setup, draping, stab incisions, and frequent calibration to ensure accuracy. Despite these challenges, robotic systems aim to enhance precision and outcomes in total knee replacement surgery.

Key Steps in the Robotics

Robotic-assisted TKA utilizes computer software to create a virtual three-dimensional (3D) model of the patient's unique bony anatomy. Surgeons pre-plan bone cuts, component size, and positioning using this model, and the plan is then applied intraoperatively to the patient's anatomy through navigational software. Image-dependent systems derive the 3D model from pre-operative imaging, while imageless systems use detailed intraoperative registration of bony surfaces and joint kinematics.

Steps in using Robotics Systems

Registration: Registration of bony landmarks and hip/knee/ankle joint is performed. Kinematic knee range of motion is registered in neutral, as well as varus and valgus stress and mapping of the femoral and tibial condyles. A 3D stereolithographic model of the patient's limb is generated and displayed on the screen, which is used for the planning of

the alignment, component positioning, implant sizing, and gap balancing in real time.

2. Planning: Considered a critical step that is feasible due to robotic system software. Surgeons can use a more personalized alignment technique in which the alignment and balancing are tailor-made according to the patient's stressed/unstressed range of motion and their natural anatomy instead of generalized conventional or kinematic alignment philosophies.

3. Execution: The robotic burr or saw is subsequently used for executing the bony resection according to our pre-operative and intraoperative plan.

Key Concepts in Robotic-Based Alignment

Concept of Intelligent Alignment

The idea of replicating knee structure within pre-determined target ranges is based on functional alignment principles. In an effort to provide personalized TKA, surgeons adhere to guiding principles that take into consideration the distinct anatomical differences of each patient. In order to achieve balanced joint forces in flexion and extension, the principles include preserving joint-line obliquity and height, reestablishing dynamic sagittal alignment, restoring native coronal alignment, sizing implants to match anatomy, and carefully placing implants to release the least amount of soft tissue. Finding balance throughout the knee joint is the ultimate goal[11].

Future Development in Robotics

1. Incorporation of CPAK

In knee surgery, determining the ideal coronal alignment for TKA is a big challenge. Although the gold-standard alignment principle used traditionally was mechanical alignment (MA) which emphasizes a neutral mechanical axis, it ignores the individual heterogeneity in coronal alignment. Some surgeons follow the goal of the kinematic alignment (KA) approach, which mimic a patient's pre-arthritic knee joint movement. Uncertainties still exist, though, about patient selection, surgical methods, and alignment targets. To address these issues, the Coronal Plane Alignment of the Knee (CPAK) classification was developed. It permits tailoring of pre-operative alignment planning for joint line obliquity (JLO) and anatomical hip-knee-ankle (aHKA) based on unique, surgeon-defined boundaries. Whether a patient is a good candidate for functional alignment techniques, MA TKA, KA TKA, or anatomic alignment (AA) TKA depends on the classification.

This system facilitates communication and encourages further research, offering surgeons a pre-operative method to choose the best alignment strategy based on individual patient characteristics and priorities such as soft-tissue balance optimization[12].

2. Incorporation of AI (Table 2)

A 360-degree view of different surgical techniques is provided by immersive virtual reality, an AI-based teaching tool that allows surgeons to evaluate implant decisions, placement, procedural errors, efficiency, and optimal use of instruments and operating equipment simultaneously. Surgeons can practice both technical and cognitive aspects, which reduces implant malalignment and surgical complications in knee arthroplasty[13].

The assistive mode in immersive virtual reality provides feedback on key steps, aiding surgeons in planning bone resection, implant positioning, sizing, virtual range of motion assessment, and gap balancing. This anticipatory feedback helps surgeons overcome difficulties and achieve surgical targets[14].

Combining the benefits of an autonomous robotic system and a navigation system, the semi-autonomous robotic-assisted system is an AI-based tool. Through this integration, the surgical team's capabilities are improved, showcasing A.I.'s potential to improve knee arthroplasty precision and results.

3. Usage of Wireless/5g Network In TKA:

This wireless technology uses a multimodal sensing device to measure contact forces and take pictures of the femoral component to improve TKA procedures. It offers force imbalance assessment (< ±5N) and real-time, accurate pose reconstruction (errors < 1.73°). Surgery accuracy is improved by a unique 3D motion trajectory output that is not found in single-modal systems. Surgeons seeking better results can simply integrate it into routine clinical practices because it is used seamlessly during TKA and causes minimum disruption to the process[15].

Significant progress has been made in knee replacement surgery with the introduction of a "smart" knee implant. The first knee replacement with a smart sensor that measures steps taken, walking speed, and range of motion was done by orthopedic surgeons at the Hospital for Special Surgery (HSS). This breakthrough enables real-time data to be securely sent to a cloud-based platform, enabling remote monitoring of a patient's recuperation. The Persona I.Q. is a smart knee that is the first implantable device to be approved by the FDA in the United States. It gathers data after surgery and provides orthopedic doctors with useful information on their patients' development outside of routine office visits. With the addition of objective, real-world data, this technology improves patient care without completely replacing the necessity for in-person check-ups.

Conclusion

Enhanced accuracy and precision in TKA have been proven using computer-assisted navigation (CAS). Consistent component placement and attaining the desired alignment are among the objectives of CAS. When hardware restricts the femoral canal, when extra-

articular abnormalities need to be corrected intra-articularly, or for research, CAS is especially helpful. Although CAS has consistently demonstrated improvements in coronal and sagittal plane mechanical axis alignment, its effect on rotational placement is still unclear. Furthermore, although CAS does not directly address soft-tissue balancing, it may help achieve balance when combined with contact load sensors or soft-tissue laxity measurements.

The adoption of CAS varies globally, with an increase in usage reported in countries such as Australia and some European nations, while South American and U.S. surgeons show lower adoption rates. As CAS procedures become faster and less expensive, broader adoption is expected.

More attention is being given to adding further control over ligament balance and bone cuts in robotic surgery. Robotic assistance has reduced variability and increased consistency, and preliminary data is beginning to show better clinical results. Clinical benefit demonstration is hampered by things like the meticulousness of soft-tissue balance. Patient-specific arthroplasty with alignment targets is becoming more accessible through robotic surgery, but more study is required to fully understand the costs and advantages of this procedure in everyday medicine[16].

The previous active robotic TKA systems demonstrated better alignment and decreased blood loss after surgery, but they were less cost-effective due to enhanced risks, longer surgical times, and complications[17].

Current predominantly semi-active robotic systems offer greater technical reliability and haptic feedback, providing superior soft-tissue protection and early functional benefits.

It is still necessary to compare these modern robotic systems with traditional methods to get long-term functional results. The chosen platform (open or closed) has a significant influence on surgeon preferences and implant compatibility, and the reported incidence of periprosthetic joint infection in robotic total joint arthroplasty is low[18].

While newer robotic systems show promise in minimizing soft-tissue damage and improving short-term outcomes, the economic impact and long-term benefits warrant careful consideration. Ongoing investment in this technology should be justified by continued evaluation of long-term functional outcomes and survivorship.

A key consideration in robotic TKA is the kind of platform. Although open platforms can be used with different types of implants, they might not have the depth of detailed design specificity and biomechanical data needed for the best component location and kinematics. Closed systems, on the other hand, restrict the variety of implants available, which may force doctors to abandon their favorite prostheses. This creates a learning curve specific to using new implants, distinct from the robotic technology learning curve. Since a center is unlikely to use two different robotic systems at the same time, it is difficult to assess if using diverse platforms would result in significant clinical disparities[5].

Case

A 50-year-old female is a known case of rheumatoid arthritis who had succumbed a polytrauma in 2009 and had undergone multiple fixations which included left tibia and bilateral distal femur fixation. The left femur fracture had gone into non-union and so had revised with fibula bone grafting and plating.

The patient came to us with healed fractures, progressive knee deformity in the left knee, bilateral knee pain, and difficulty in walking and doing daily activities.

In the first step, we did right total knee replacement and left tibia nail removal.

In 2nd step, she was posted for left total knee replacement.

Her pre-operative X-rays and CT scan showed severe valgus deformity of left knee and arthritis of knee with distal femur plate in-situ (Fig. 1a, 1b, 2a and 2b).

Using robotic technology, we were able to accomplish left total knee replacement without requiring to remove distal femur plate (Fig. 3a and 3b).

Declaration of patient consent: The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given his consent for his images and other clinical information to be reported in the Journal. The patient understands that his name and initials will not be published, and due efforts will be made to conceal his identity, but anonymity cannot be guaranteed.

Conflict of Interest: NIL; **Source of Support:** NIL

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