MENTORS IN ORTHOPEDICS

TOTAL KNEE REPLACEMENT: ON THE PATH TO A PERFECT ALIGNMENT!

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SUMMARY

Background: Total knee arthroplasty (TKA) has evolved significantly since 1968; however, patient dissatisfaction rates persist between 10% and 20%. Current research to improve these outcomes focuses on optimizing limb alignment strategies and integrating robotic technology to achieve precise gap balancing and functional restoration.

Objective: This review aims to delineate various limb alignment philosophies in TKA, including mechanical, kinematic, and functional approaches, while evaluating the modern methodologies and technologies utilized to optimize component positioning.

Key Points: Mechanical alignment remains the conventional standard, targeting a neutral hip-knee-ankle axis of 180° ± 2°, though it often necessitates soft tissue release. Alternative strategies include kinematic alignment, which restores native pre-arthritic anatomy to minimize ligamentous intervention, and restricted kinematic alignment, which applies specific boundaries to avoid extreme phenotypes. Inverse kinematic alignment prioritizes the restoration of joint line obliquity. Functional alignment utilizes robotic assistance to customize bone resections based on individual soft tissue laxity. Technological adjuncts for achieving these targets range from conventional manual instrumentation and patient-specific instrumentation to computer-assisted navigation and robotic systems. These tools offer varying degrees of precision, with robotic and navigation systems providing real-time intraoperative feedback on alignment and gap symmetry.

Conclusion: Selecting an optimal alignment strategy is essential for achieving a balanced knee and improving clinical outcomes. While mechanical alignment is widely practiced, personalized approaches supported by robotic technology and advanced navigation are increasingly utilized to accommodate individual patient anatomy and potentially address persistent dissatisfaction rates.

KEYWORDS

Arthroplasty, Replacement, Knee; Robotic Surgical Procedures; Surgery, Computer-Assisted; Knee Joint; Prosthesis Implantation

INTRODUCTION

The inaugural “modern” total knee arthroplasty (TKA) designed and performed by Dr. Franck Gunston, a Canadian surgeon in 1968, marked the beginning of an era. Now six decades later, we can appreciate the extensive journey that has led to enhancements in both the longevity and functional outcomes of knee replacements (Figure 1). Advances in surgical techniques and implant design have been instrumental in improving patient satisfaction. Despite these improvements, literature reveals that dissatisfaction rates among patients post-TKA hover between 10 to 20% [1] The primary avenues of research to diminish these statistics focus on the use of robotics and the pursuit of optimal alignment. Since the nascent stages of TKA, alignment has been a pivotal concern: In the 1980s, Insall & Hungerford presented divergent alignment philosophies—anatomical versus mechanical—which laid the groundwork for the myriad of alignment methods we see emerging today. Bellemans et al.’s introduction of the constitutional varus concept in 2012 [2], paved the way for a more “physiological TKA” preserving a minor degree of the original deformity in patients with preexisting varus conditions. John Insall posited that TKA was a soft tissue operation, underlining the significance of knee laxity on functional outcomes. The overarching goal of all alignment strategies remains consistent: obtaining a perfectly balanced knee.

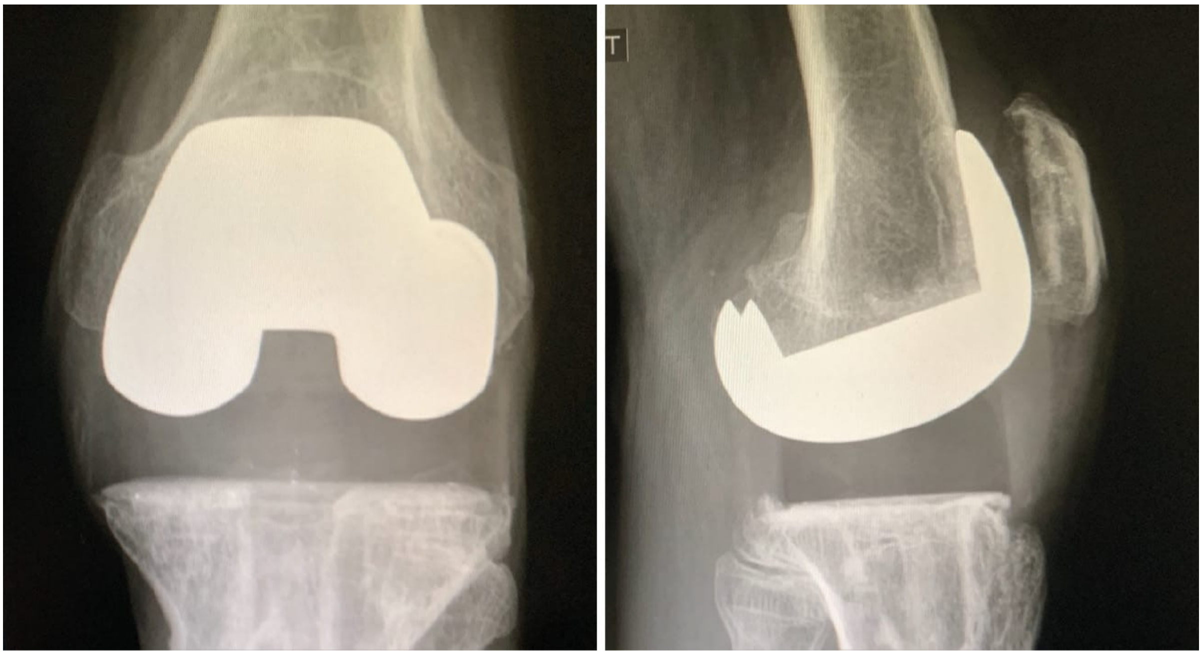

Figure 1: Full polyethylene tibial tray

This article aims to delineate the varying philosophies of limb alignment in total knee arthroplasty, offering insights to knee surgeons. We will discuss the principles of mechanical alignment, kinematic alignment, and functional alignment, along with modern methodologies that strive to optimize TKA positioning, such as robotics, custom cutting guides, and navigation.

ANATOMICAL ALIGNMENT

Anatomical alignment in TKA strives to replicate the "normal" native knee's anatomical landmarks. Hungerford et al. first detailed this approach in their 1982 publication, "the porous-coated anatomic total knee," suggesting that by cutting the femur to achieve a Lateral Distal Femoral Angle (LDFA) of 87° and a Medial Proximal Tibial Angle (MPTA) of 87°, one could mirror the most common knee anatomy found in the general population [3]. This concept laid the initial groundwork for what would later evolve into kinematic alignment. While rooted in solid anatomical reasoning, the approach did not gain widespread acceptance, largely due to technical inaccuracies and suboptimal functional outcomes in patients with atypical anatomies—limitations likely a consequence of the imprecise tools available in the 1980s. Concurrently, mechanical alignment provided a more reliable and patient-safe option (Figure 2).

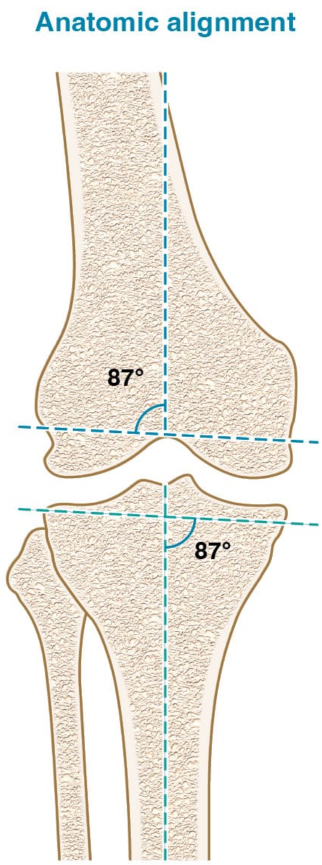

Figure 2: Adjusted Mechanical Alignment

MECHANICAL ALIGNMENT

Mechanical alignment (MA) in TKA aims for a straight alignment of 180° ± 2° along the mechanical axis of the lower limb. This axis extends from the center of the femoral head, through the knee, and to the center of the ankle —forming the Hip-Knee-Ankle angle. Precise cuts are made at 90° to both the femur's and the tibia's mechanical axes. (Figure 3) This surgical technique, outlined by Insall et al. in 1982, is widely regarded as the gold standard for TKA [4]. The rationale for these perpendicular cuts is to ensure even load distribution across the prosthesis, thus reducing wear and risk of aseptic loosening. Nonetheless, this technique has been critiqued for its necessitation of ligament release, which can result in suboptimal gap balancing—potentially contributing to the dissatisfaction experienced by 10-20% of TKA patients. These challenges with gap balancing have led surgeons to explore new alignment strategies that better balance the gap while more closely approximating the patient's native knee anatomy.

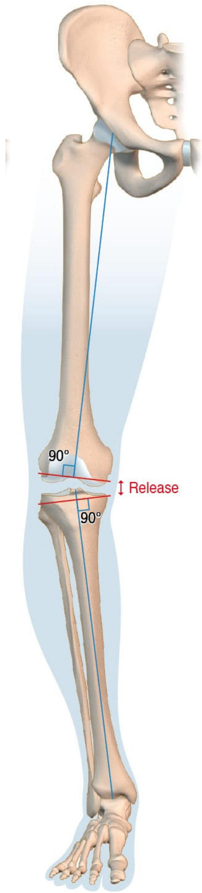

Figure 3: Mechanical Alignment

ADJUSTED MECHANICAL ALIGNMENT

Adjusted mechanical alignment (aMA) emerged from the need for reproducible instrumentation that could sidestep the failures associated with anatomical alignment and still accommodate individual varus or valgus knee phenotypes. The approach can be executed using standard mechanical alignment tools.

The goal is to attain optimal gap balancing by modifying the distal femoral cut, while the tibia is cut at 90°. The technique's ease of execution is balanced by its drawback: the implants are not positioned anatomically (Figure 4).

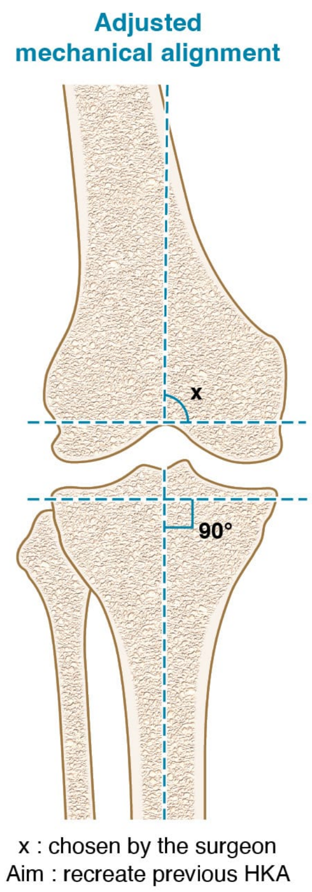

Figure 4: Adjusted Mechanical Alignment

In their paper, Vanlommel et al [5]studied a cohort of 132 patients at 7 years of follow up : the varus patient left in mild varus : 4.5° had better functional results based on KSS and WOMAC scores.

KINEMATIC ALIGNMENT

Kinematic alignment (KA) represents the pinnacle of achieving perfect gap balancing with bone cuts. Howell, in 2014, described this method with the goal of restoring the patient's pre-arthritic knee anatomy through precise femoral and tibial cuts, thereby obviating the need for ligament release [6]. The femoral distal cut is tailored to the patient's LDFA, while the tibial proximal cut matches the patient's MPTA. Using "calipered instrumentation," Howell's technique measures resected bone to ensure the prosthetic components fit perfectly into the created gap. (Figure 5) This technique is the most conservative for the anatomy of the patient however it could lead to recreate patho-anatomy and reproducing poorly aligned lower limbs.

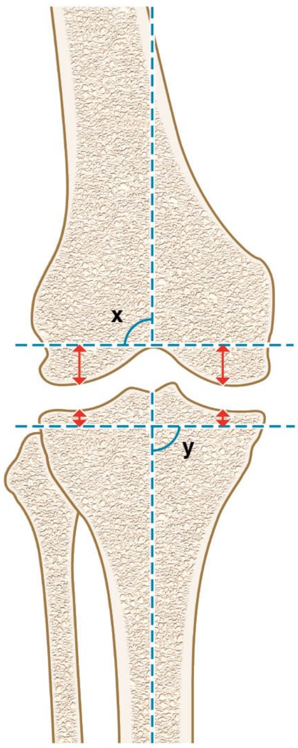

Figure 5: Kinematic Alignment

Some studies reported improved of the functional outcomes related to KA compared to MA: McEwen et al published a series of bilateral TKA with on knee KA and one MA for each patient. The patient tended to prefer their KA knee compared to their MA knee [7] These results were also depicted in the paper of Dossett et al [8] in their randomized control trial with increased satisfaction for KA vs MA at 13 years follow up. Notwithstanding, the literature is not fully supportive of this philosophy: Waterson et al [9] found no differences at one year follow up and Young et al [10] no differences at five years follow up.

RESTRICTED KINEMATIC ALIGNMENT

Restricted kinematic alignment (rKA) is a modified form of KA introduced by Venditolli et al. to prevent recreating extreme anatomies [11]. While adhering to the principles of kinematic alignment, rKA sets limits: the Hip Knee Ankle (HKA) angle must fall within 180° ± 3°, and the LDFA and MPTA should not deviate beyond 5° of varus or valgus. One of the principles is to correct the most contributing bone to the deformation: Usually varus patients will be corrected in the tibia settled at maximum 5° of varus and valgus patients will be corrected in the femur settled at maximum 5° of valgus. A precise algorithm is depicted in the surgical technique (Figure 6). This technique is probably the less risky of the various alignment strategy although is requires specific instrumentation to perform one-degree precision cuts of the femur and tibia. (Figure 7)

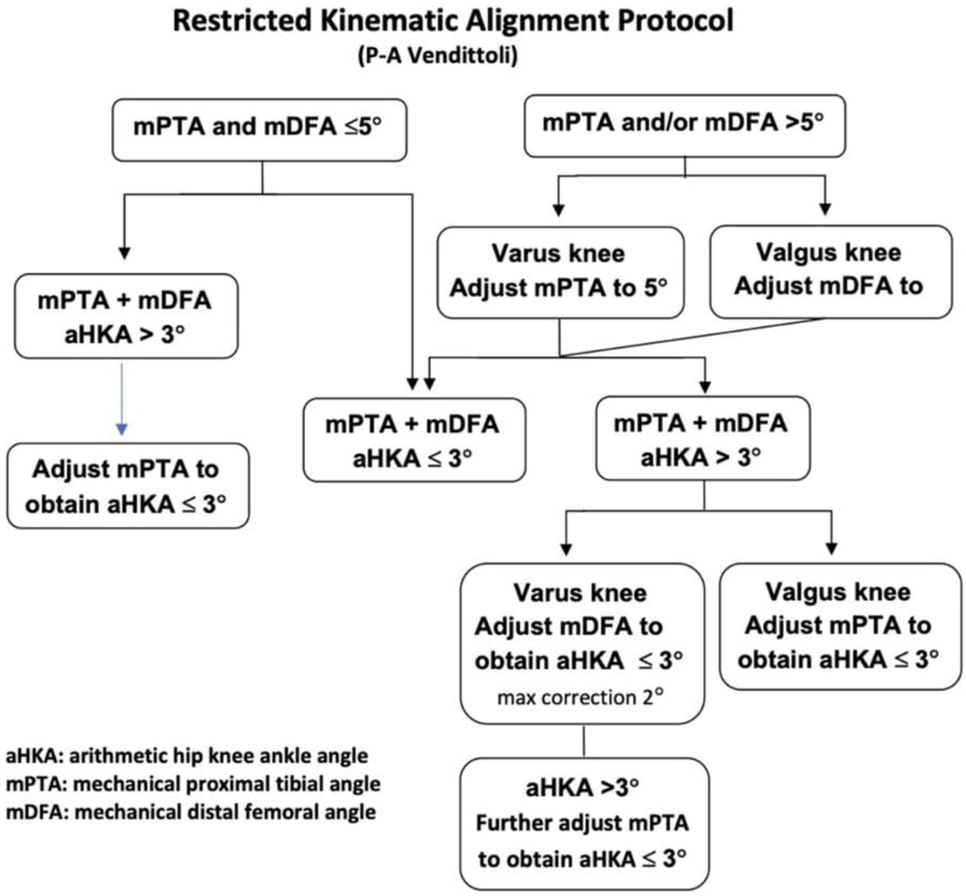

Figure 6: Restricted kinematic alignment algorithm

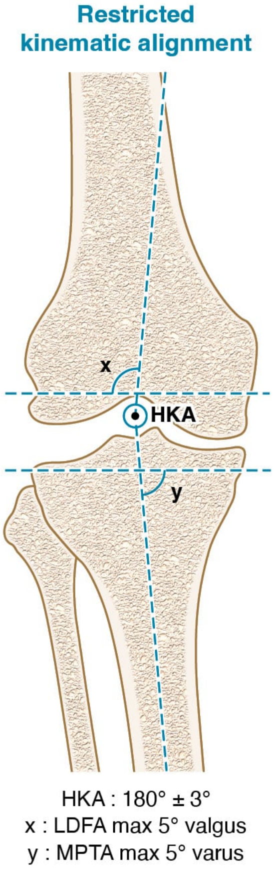

Figure 7: Kinematic Alignment

INVERSE KINEMATIC ALIGNMENT

Another version of kinematic alignment is called inverse kinematic alignment (iKA). Described by Philippe Winnock de Grave in 2022 [12] this technique focuses on the recreation of the joint line obliquity (JLO). Some papers have already depicted the importance of reproducing the JLO to improve functional results [13]. Recreating the joint line obliquity of the patient : apex distal or apex femoral permits to reproduce its original knee phenotype according to MacDessi et al [14].

In this technique the tibia is cut first with equal medial and lateral resection to reproduce the native JLO. The gap balancing is then adjusted in the femur after the tibial cut. (Figure 8) The inventor of the technique published a series of 40 iKA vs 40 aMA showing better functional results at one year of follow up for varus patient and lower pain score for iKA vs aMA.

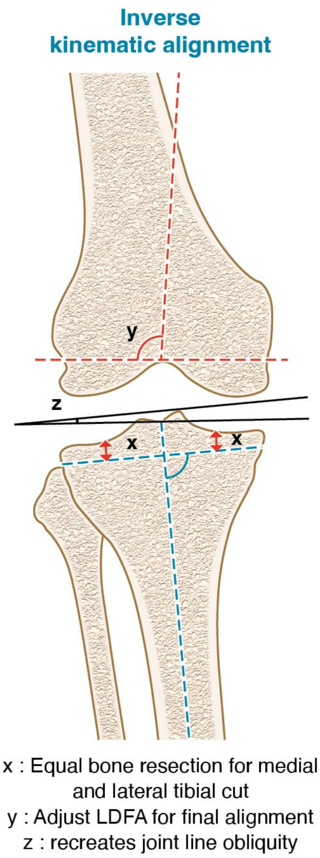

Figure 8: Inverse Kinematic Alignment

FUNCTIONAL ALIGNMENT

Functional Alignment is intrinsically linked to the advancement of robotic surgery. The fundamentals of the technique are based on the previous alignment philosophy mentioned before: achieving perfect gap balancing with personalized bone cuts. Robotic surgery is a key tool for this technique allowing one degree precision bone cuts. It is promoted by several authors : Sebastien Parratte **[15]**, Sebastien Lustig**[16]**, Fares Haddad **[17]**.

The surgeon chooses the femoral distal angle and proximal tibial angle that he wants to recreate during the surgery. Knee laxity is measured before the bone cuts, with spacer and with the trials implants to fine-tune knee laxity. One of the key advantages of this technique is to be able to play with parameters as rotation and flexion of the femoral component for gap balancing. (Figure 9) However, this technique's limitation lies in its reliance on the availability of robotic surgery, which is not yet widespread.

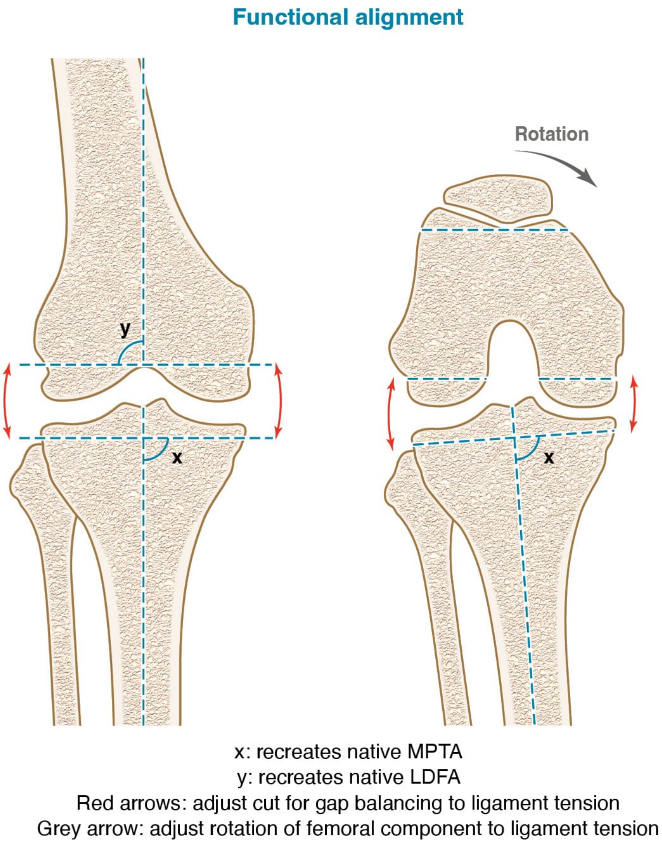

Figure 9: Functional Alignment

TECHNIQUES FOR OPTIMIZING TKA POSITIONING

Conventional instrumentation

With the evolving precision of alignment theories, new tools have become necessary. Mechanical and adjusted mechanical alignment were meant to be done with conventional instrumentation. These instrumentations include cutting guides with intra- or extra-medullary rods. They are still the most widespread use for TKA and their precision could be considered between 1° and 3° [18]. Howell designed a conventional instrumentation specially made for kinematic alignment called the "caliper technique" which aims to measure the bone resections and create a space of the size of the tibial and femoral component. [19]Using these types of instrumentation, the measure of the laxity remains in the hand of the surgeon which makes it no very reproducible.

Patient Specific Instrumentation

Cutting guides based on the anatomy of the patients were designed by surgeons aiming for more precision in their bone cuts. These 3D printed guides are based on pre-op CT-Scan to match the bony anatomy of the patients. The surgeons decide the orientation of the cuts doing a surgical planning based on the CT scan that will be reproduced during the "real life" surgery. The precision reported of these guides is less than 1° [20] allowing precise aims such as restricted kinematic alignment requires. In case of mismatch or change in the surgical planning the surgeon could switch to conventional instrumentation with "re-cutting guides" to modify the cuts. The other advantages of PSI are the reproducible positioning of the jig and reducing the learning curve for less experienced surgeons. Ng et al published a series comparing PSI vs conventional instrumentation for mechanical alignment: they found 9% of outliers in the PSI group and 22% in the conventional instrumentation group. [21]

Custom Made Implants

An alternative to off the shelf implant associated to personalized bone cut is custom made total knee arthroplasty. Its objective is to standardize the surgical technique, but use patient-specific implants to create a personalized alignment strategy. The Symbios company is leader on this market with its prosthesis called Origin®. Their creators published 94% satisfaction rate and comparable functional outcomes to off the shelf TKA at two years of follow up. [22]

Computer-Assisted Navigation

In the 2000's the era of informatic and new technologies has enabled the invention of computer-assisted navigation systems. They provided real-time feedback to the surgeon during TKA, aiding in implant positioning and alignment. These systems used infrared cameras and reflective markers placed on the patient's anatomy to track instrument movement and guide surgical navigation. Research has demonstrated the effectiveness of computer-assisted navigation in improving implant alignment, reducing component malpositioning, and enhancing overall surgical accuracy. Some other systems of navigation use accelerometers to measure the gaps in flexion and extension. They also provide information about the laxity with the trial implants. [23] (Figure 10)By minimizing errors in implant placement, navigation systems contribute to improved implant longevity and patient outcomes. [24] These informatic systems have been the first step to robotic assisted surgery therefore they are less and less in use.

Figure 10: Accelerometer Navigation Device: Orthoalign®

Robotic-Assisted Total Knee Arthroplasty

Robot-assisted total knee arthroplasty has emerged as a promising technology in knee replacement surgery. The robotic system is made of three pieces: navigation system, control screen and a robotic arm. (Figure 11) It provides to the surgeon real-time feedback and assistance in achieving precise bone cuts and optimal implant positioning. By using preoperative imaging data based on CT-Scan and intraoperative navigation, the robotic arm helps performing precise cuts. The robotic system also gives precise information concerning the laxity in flexion and extension aiming for a perfectly balanced knee. Nevertheless, scientific proofs of the benefits of robotics surgery still need to be done [25]. Robot-assisted surgery offers increased precision in implant placement, and it will probably improve clinical outcomes and prosthesis durability.

Figure 11: MAKO Robot Stryker®

CONCLUSION

Accurate prosthesis alignment is paramount in knee replacement surgery for achieving a well-balanced knee and ensuring satisfactory long-term clinical results. From the advent of mechanical alignment, numerous alignment philosophies and technologies have emerged, igniting ongoing debate over the optimal strategy and tools for achieving it. As the field progresses, the comprehension of various alignment techniques and their clinical implications becomes crucial for orthopedic surgeons seeking to tailor their approach to the unique requirements of each patient. All techniques are still considered efficient and future scientific research is expected to define the most effective strategies for TKA.

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