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Alignment Strategies in Total Knee Prosthesis: The Robotic Era Changed the Game

Estrategias de alineamiento en prótesis total de rodilla: La era robótica cambió el juego

Sebastián Monge[1] David Figueroa[1] Jorge Isla[2]

[1] Traumatology Department, Knee, and Clinical Arthroscopy Unit, Clínica Alemana, Universidad del Desarrollo, Santiago, Chile.
[2] Knee Surgery Fellow, Clínica Alemana, Universidad del Desarrollo, Santiago, Chile.

Address for correspondence Jorge Isla, MD, Knee Surgery Fellow, Clínica Alemana, Universidad del Desarrollo, Chile (email: drjorgeisla@gmail.com).

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Abstract

Total knee arthroplasty is a widely used surgery to treat moderate to severe knee osteoarthritis, usually with favorable outcomes but a controversial patient dissatisfaction rate. Potential multiple causes of this dissatisfaction have been extensively studied, with a recent growing debate surrounding the type of alignment for knee arthroplasty, especially considering the advent and advantages brought by robotic surgery.

Over the years, mechanical alignment has been the gold standard in knee arthroplasty. However, in the 21st century, new rationales have emerged, many resulting from robotic surgery. In this study, we categorized alignments into three major groups, discussing the general characteristics of each one and the current approach used in our institution, believing robotic surgery is a game changer.

Keywords
- alignment
- knee prosthesis
- robotic surgery
- knee osteoarthritis
- dissatisfaction with knee prosthesis
- functional alignment

Resumen

La prótesis total de rodilla es una cirugía ampliamente utilizada en el tratamiento de la gonartrosis moderada y severa, con resultados en general favorables, pero con una controversial tasa de insatisfacción entre los pacientes. Se han estudiado las posibles múltiples causas de esta insatisfacción, tomando mucha fuerza en el último tiempo el debate en torno al tipo de alineamiento utilizado en cirugía protésica de rodilla, sobre todo, considerando el advenimiento y las ventajas que trajo consigo la cirugía robótica. El alineamiento mecánico, se ha considerado a lo largo de los años como el estándar de oro en prótesis de rodilla, pero durante el siglo XXI se han creado nuevas filosofías, muchas de ellas gracias a los avances en cirugía robótica. En el presente trabajo dividiremos los alineamientos en 3 grandes grupos, se comentarán las características generales de cada uno, así como también el enfoque actual utilizado en nuestra institución, donde creemos que la cirugía robótica llegó para cambiar el juego.

Palabras clave
- alineamiento
- protesis de rodilla
- cirugía robótica
- artrosis de rodilla
- insatisfacción en prótesis de rodilla
- alineamiento funcional

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Why Continue Innovating if Mechanical Alignment Works?

Total knee prosthesis is a surgery with good outcomes and high survival rates in patients with moderate and severe gonarthrosis. Mechanical alignment is the gold standard for prosthetic coronal alignment. Its rationale is creating sections perpendicular to the mechanical axes of the femur and tibia to generate a load distributed homogeneously throughout the implant. Gap balance relies on ligamentous releases, a potentially relevant factor of patient dissatisfaction.[1]

The literature reported disagreement rates ranging from 10% to 20%. This data prompts us to delve deeper into the discomfort caused and seek solutions for what they perceive as an "unnatural knee" sensation after surgery.[1]

Current studies suggest that the "one-size-fits-all alignment" strategy may not be appropriate since each patient has a different anatomy. Bellemans et al. reported that from 1,000 knees studied, 17% of women and 32% of men, both asymptomatic, had a genu varus higher than 3°.[2] In contrast, the Coronal Plane Alignment of the Knee (CPAK) classification showed that 46.6% of patients with knee osteoarthritis have a neutral axis and that only 14.6% have an interline perpendicular to the ground (►**Fig. 1**).[3]

Hirschman et al. identified five femoral and five tibial phenotypes, resulting in 25 potential knee phenotypes (►**Fig. 2**). The most prevalent phenotype (with a 24.7% prevalence) is the NEU femur (third valgus) and NEU tibia (third varus), followed by (18.8%) the NEU femur (third valgus) and VAL tibia (0° or "neutral").[4] As mechanical alignment relies on sections perpendicular to the mechanical axes, it replicates the anatomy of 3.2% of the patients. This fact makes us question whether the systematic and generic alignment is optimal for all patients.

Classification of Coronal Alignments in Total Knee Prosthesis

We divided the alignments into three large groups: systematic, patient-specific, and hybrid alignments.

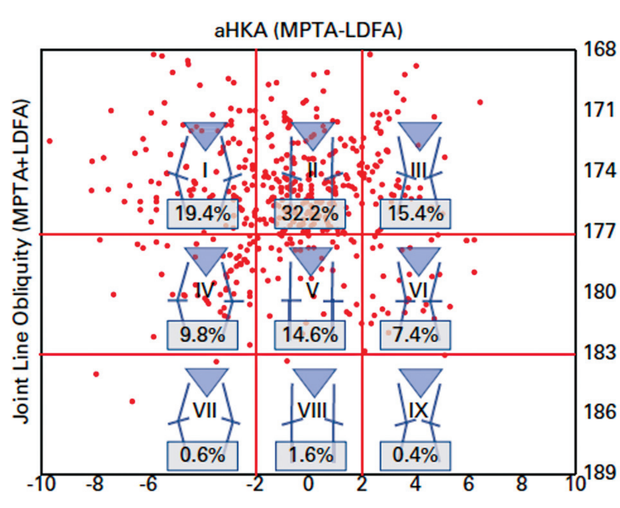

Fig. 1 Coronal plane alignment of the knee (CPAK) classification and its nine potential knee types.

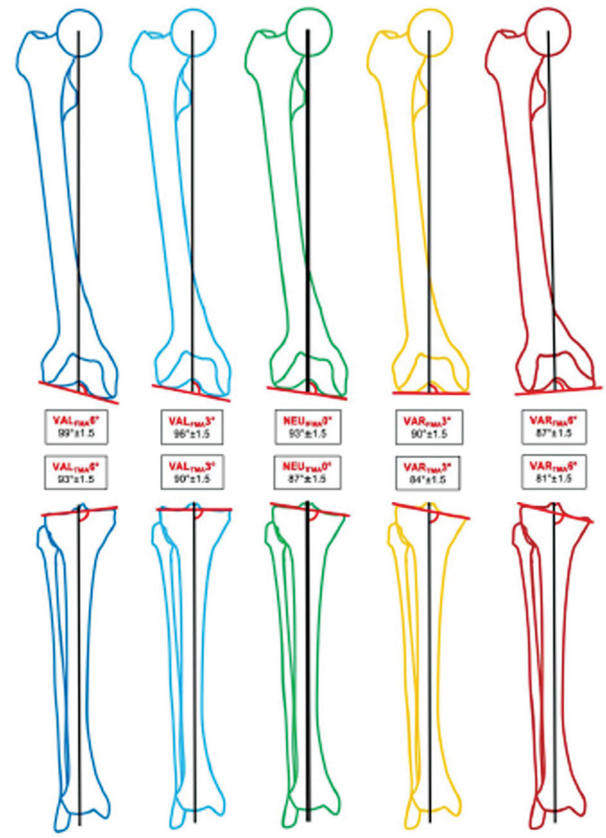

Fig. 2 Tibial and femoral phenotypes characterized by the distal femur and proximal tibia angulations described by Hirschman et al.

Systematic alignments are a uniform approach, aiming for an ideal 180° angle between the hip and knee for all patients. This group includes mechanical alignment (MA) and anatomical alignment (AA). Patient-specific alignments aim to reestablish the native alignment and joint line, diversifying the axes. This group also presents kinematic alignment (KA), which seeks to replicate the patient's preoperative kinematics and their specific alignment (as described by Howell), adjusting to the unique alignment of each person.

Finally, hybrid alignments combine principles from both systematic and patient-specific approaches.[5,6] These methods aim to maintain a hip-knee angle within a "safety zone" ranging from 177° to 183°, offering a compromise solution potentially adaptable to the patient's specific requirements.

Mechanical Alignment

Developed by Ranawat and Insall, MA is the gold standard in prosthetic knee surgery. As mentioned, the components are perpendicular to the tibial and femoral mechanical axes to obtain a hip-knee angle of 180° and ensure a symmetrical load distribution through the prosthesis. As a result, implant wear or the potential loosening of the cement-bone interface should be symmetrical. A controversial factor of this technique is that the gap balance for a balanced knee requires soft tissue releases, which may be difficult to achieve and reproduce. The 10- and 20-year survival rates range from 89% to 99% and 85% to 97%, respectively, depending on the series. However, prolonged survival does not necessarily imply satisfied patients; despite the good durability, one in five subjects presents dissatisfaction.

Technically, the tibial section removes a large part of the tibia on the lateral side, while the femoral section removes more bone from the medial side of the femur. This implies that to balance the gaps and compensate for lateral laxity in flexion, the femur must be rotated 3° externally,[7] thus reproducing the anatomy of only 3.2% of patients, according to the previously mentioned studies by Hirschmann.

Anatomical Alignment

AA is known as the forgotten alignment. This technique, developed by Hungerford and Krackow in the 1980s, reestablishes an oblique joint interline through the measured resection technique (third valgus femur and third varus tibia) and obtains a hip-knee angle of 180°. Theoretically, it reduces the release rate by sectioning a smaller part of the lateral tibia and performing the femoral section in 3° valgus, avoiding external rotation of the femoral component. However, the difficulty in executing precise 3° sections of tibial varus and the accelerated wear of the polyethylene components lead to unexpected outcomes, resulting in the abandonment of their practice. Despite this, AA is the precursor of KA, which today belongs to the personalized alignment group.

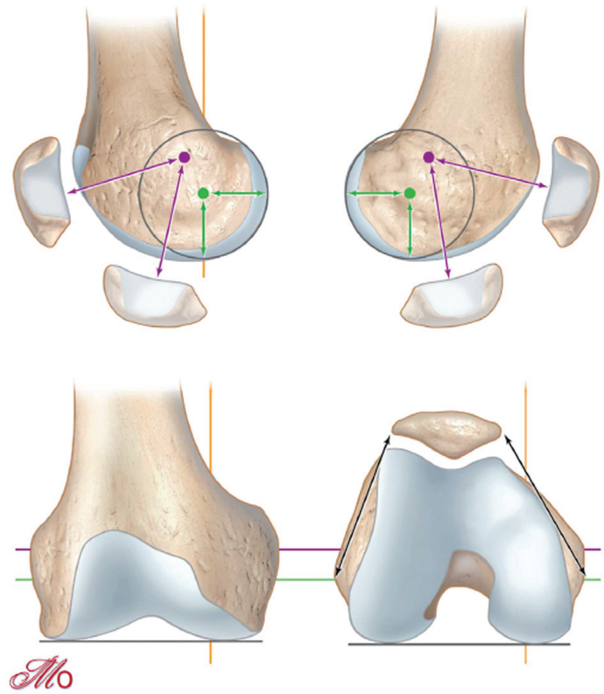

Fig. 3 The graph shows the three planes of potential knee mobilization. The most distal transverse green line reflects the plane of tibial flexion and extension to the femur. Purple lines are the axis of patellar extension and flexion to the femur. Yellow lines show the internal and external tibial rotation axis to the femur, passing through the medial femorotibial space. (Image reproduced with permission of the author).

Kinematic Alignment

Introduced by Howell et al. in 2013, KA is also known as the true femoral resurfacing technique. Its primary objectives include restoring the knee-hip angle, the parthritic joint interline obliquity, and the patient's native ligament balance. In this technique, the knee has three kinematic axes concerning the joint lines of the posterior and distal part of the femur (►**Fig. 3**).[8] Procedural tailoring is key: cartilage removal depends on the thickness of the implant, and resection is adjusted based on the patient's specific cartilage wear. In this technique, the femoral section occurs before tibial adjustments to correct and tune the gap balance with no need for release. The most significant concept is returning the knee rotation at its native axes (tibiofemoral, femoropatellar, and axial rotation), hence the name KA. Although there has been criticism about the incidence of tibial varus, this technique has not been shown to increase the risk of aseptic loosening. Additionally, there is concern that the lack of femoral external rotation (regarding the posterior condylar line) could negatively impact patellar tracking; however, this assertion has not been supported by compelling scientific evidence. However, it has been reported that this alignment can fail to balance the prosthesis in up to 50% of cases.[9] Another feature of this technique is that resections follow the measurement of the bone sections of the medial distal femur, made with a caliper, an element that may not be error-free.

Reverse Kinematic Alignment

Reverse KA, developed by Winnock and Grave, is the true tibial plating technique. This rationale is based on the equitable resection of the tibial plateau considering the pre-arthritic state of the cartilage. The key to this technique is performing ligamentous balance through femoral sectioning. The advent of robotic surgery and navigation allows precise sections, achieving balanced knees with the help of artificial intelligence in the surgical ward. This approach has precise limits on tibial sectioning, with margins ranging from 6° varus to 8° valgus. Research has suggested that reverse KA may offer satisfaction levels comparable to MA, marking an important milestone in the personalization of prosthetic knee surgery.

Restricted Kinematic Alignment

It is a KA with tighter limits. This alignment follows the KA rationale. However, in severe deformities, it is difficult to determine the pre-arthritic state of the patient. So, restricted KA establishes certain limits for a safer surgical technique concerning the implant and its survival. Therefore, the technique is feasible for subjects with mild deformities. The hip-knee angle is limited to +/- 3°, and the lateral distal femoral and medial proximal tibial angles are limited to +/- 5°. Given the absence of long-term studies, we recommend a cautious approach when adopting this alignment technique.

Functional Alignment

FA, an evolution of the KA introduced by Kayani, focuses on restoring the native joint interline obliquity and achieving prosthetic balance through fine adjustments in component positioning, avoiding extensive ligamentous releases. This technique requires computed axial tomography (CAT) planning and robotic surgery. The additional precision offered by robotic surgery means that non-neutral limb alignment goals are more reproducible, minimizing the possibility of undesired outcomes and unusual alignments.

This technique takes the best of the measured resection and gap balance and begins with the femoral component alignment to MA. Intraoperative limb alignment assessment occurs after osteophyte removal, allowing coronal correction by manually applying varus and valgus forces to correct the pre-existing deformity. This allows the software to determine the size of the potential spaces, both in extension and in the different degrees of flexion deemed appropriate to evaluate. Then, the robotic arm can make precise section adjustments. The sagittal plane is adjusted to prevent notching, respecting the anterior femoral curvature, and maintaining the axial plane within a +/- 3° range concerning the transepicondylar axis. The precision of robotic surgery allows the balance of joint gaps with subtle modifications to bone section, resulting in a knee objectively balanced in flexion and extension and significantly decreasing the need for ligamentous releases.

Patient-Specific Alignment

Knee prosthesis has historically been defined as a soft tissue surgery since the technical complexity is in the ligament balance, not component positioning. Advanced alignment techniques emerged recognizing the surgeon's judgment regarding balance can be imperfect and that each knee presents a unique anatomy. These techniques aim to replicate the individual anatomical constitution of each patient, considering the bone structure, residual cartilage, and ligamentous balance.

Mark Clatworthy has refined this approach by introducing the patient-specific alignment technique, a progression of Howell's kinematic method, but starting at the tibia and adjusting the femoral sections with the help of robotics to achieve proper balance (inverse kinematics). A notable aspect of this technique is eliminating the need for preoperative CT scanning, as the robot directly records the patient's anatomy during surgery. In his technique, Mark Clatworthy shows how tibial sectioning alters previously balanced spaces (►**Fig. 4**). This occurs mainly due to meniscal resection, capsular release, and posterior cruciate ligament release (even in prostheses with posterior cruciate ligament retention).

The lateral space in flexion is left 2 mm laxer to favor the native roll-back of the femur on the tibia. Its limits are 5° of varus-valgus of tibial and femoral sections and a +/- 5° mechanical axis. This approach minimizes the need for ligamentous releases, potentially leading to higher patient satisfaction. In this type of alignment, the hip-knee angle is no longer a "central" issue in surgery. In addition, it shows promising results in patient-reported outcome measures (PROMs, including satisfaction and performance of a new surgery) of 100% per year.[10]

Batailler et al. reported improved postoperative pain and equal or slightly better functional outcomes at one year of follow-up in surgeries performed with the MAKO robot

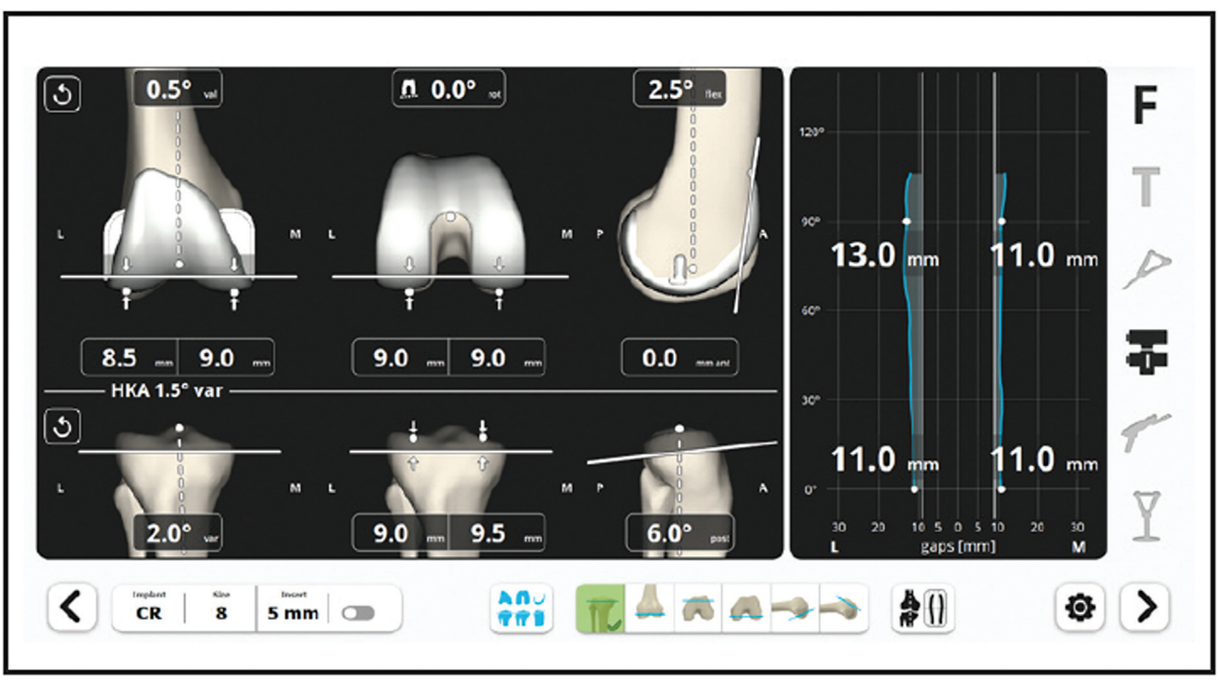

Fig. 4 This scheme demonstrates the access to different parameters during robotic surgery, adjusting bone sections at the surgeon's discretion and avoiding excessive ligamentous releases.

(Stryker) following the doctrine of personalized alignment. These authors also objectively established that the robot improves implant positioning.[11] In contrast, Mancino et al. concluded that surgery with robotic assistance improves short-term functional outcomes and reduces radiolucent lines and atypical radiographic images. At the same time, it reduces the risk of soft tissue injuries by reducing bleeding and drain discharge.[12] Although there are evident improvements in implant survival in the robotic group, this study showed no significant differences in complication rates and surgical times. Figueroa et al., in 2023, showed the first Latin American series of robotic surgery. This study compared different parameters of 72 knees operated with robotic assistance versus 123 knees operated with conventional technique. It showed a reduction in opioid use and early ambulation in the robotically assisted group with no differences in complication rates between groups. It is worth noting the conventional prosthesis group required more transfusions (20.3% versus 13.9%) without a statistically significant difference, potentially due to less soft tissue damage with robotic surgery.[13]

Robotic-assisted surgery has changed how we conceive prosthetic surgery, allowing the surgeon to have absolute control of sections, axis, and ligament balance in vivo, providing the possibility of implant adjustment to the patient and not the other way around. Even though it has not yet been proven that the long-term survival of prostheses with this type of alignment exceeds the gold standard (MA), theory suggests that more precise adjustments to the patient's anatomy and the reduction of soft tissue releases may increase satisfaction and durability. Current studies indicate short-term improvements and tangible benefits from its application. Only time and future research will confirm whether long-term outcomes and implant survival improve over traditional techniques. Despite this, we can say that in the era of artificial intelligence and data science, robotics came to change the game.

Conflict of Interest
None.

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