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Advancements and Prospects in Personalized Navigation Systems for Knee Arthroplasty: A Literature Review

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Summary. Introduction. *Traditional methods of knee arthroplasty are based on mechanical alignment, which ensures long-term component survival but does not always meet patients' functional needs. Recent studies indicate that personalized alignment approaches, such as kinematic and functional alignment, can improve functional outcomes and reduce complication rates. These methods consider the natural axes of movement and the anatomy of the knee joint, contributing to the restoration of joint anatomy and function. Individualized navigation systems represent a modern approach to knee arthroplasty using three-dimensional preoperative models based on CT or MRI. This method improves the accuracy of fitting the prosthesis components, considering the patient's individual anatomical features and biomechanical parameters.* ***Objective.*** *The objective of this literature review is to analyze the literature on using advanced navigation systems and evaluate their effectiveness, advantages, and prospects in personalizing knee joint arthroplasty.* ***Material and Methods.*** *Using PubMed, Scopus, and Web of Science databases, we reviewed 22 scientific studies on various navigation systems for knee joint arthroplasty. Studies were selected based on patient numbers, statistical significance, clear inclusion and exclusion criteria, and availability of objective treatment outcome data. This allowed for a detailed analysis and comparison of different navigation methods.* ***Results.*** *Total knee arthroplasty (TKA) is one of the most effective surgical treatments for knee osteoarthritis. However, the accuracy of prosthesis implantation remains a critical factor for the long-term success of the surgery. Deviations in placement can lead to increased wear of components and a higher risk of complications. Traditionally, standard tools and techniques based on anatomical landmarks are used for prosthesis placement. In recent years, individualized navigation systems (INS) based on preoperative three-dimensional modeling of the patient's individual anatomy have been introduced. INS aim to improve the accuracy of knee joint component placement, reduce time of surgery, and lower the risk of complications.* ***Conclusions.*** *The use of patient-specific surgical instruments and resection tools in primary and revision knee joint arthroplasty improves surgical and rehabilitation outcomes. This development allows for a 30% improvement in implant positioning accuracy and a 10% reduction in CO2 emissions. Standardizing research methods and increasing surgeon experience may contribute to a better understanding of the long-term benefits of individualized navigation systems in knee joint arthroplasty. Despite the identified advantages of INS, further research is needed to determine the long-term clinical outcomes and cost-effectiveness of these systems. The application of INS is especially important in cases of significant deformities and bone defects.*

Key words: *total knee arthroplasty; individualized navigation systems; three-dimensional modeling; patient-specific tools; kinematic alignment.*

Introduction

A navigation system is a modern technique and set of tools used for primary, complex, and revision knee joint arthroplasty. Each navigation technique aims to improve prosthetic component placement accuracy depending on the specific prosthetic model's design and mechanical principles. Classic navigation systems primarily use mechanical alignment. This type of alignment for valgus or varus deformities does not take into account the patient's unique anatomical features but focuses on creating a new biomechanics for the prosthetic knee joint. During preoperative planning and model prototyping, collaboration between the engineer and the surgeon is essential to input data on the placement of prosthetic components that account for the kinematic and biomechanical axes, ligamentous apparatus, and muscle function [2].

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Traditionally, neutral alignment has been the standard principle for total knee arthroplasty (TKA) [3-5]. For mechanical alignment, the femoral and tibial components are positioned at a 90° angle to the mechanical axes of the tibia and femur. This alignment principle in knee arthroplasty was based on distributing mechanical load on the implant to reduce wear and aseptic instability, rather than restoring normal kinematics and knee function. Mechanical alignment (MA) in TKA has demonstrated good long-term implant survival but not always satisfactory functional outcomes [4, 6, 7].

Individualized navigation systems are based on preoperative three-dimensional models created using CT or MRI scans [1]. When developing a personalized navigation system, various individual characteristics of the knee joint are considered, such as the kinematic axis, ligament balance, and biomechanical axis. Proper preoperative planning is crucial in total knee arthroplasty. For the design of a personalized navigation system, the detailed bone surface relief of the distal epiphysis of the femur and the proximal epiphysis of the tibia is used.

However, the functional results of TKA with navigation systems remain controversial. Bonnin et al. found that 75-89% of patients with TKA reported significant discomfort after surgery with the restoration of the knee joint's mechanical axis [8]. Other studies have shown that discomfort during daily activities is a major cause of patient dissatisfaction with kinematic alignment TKA [9-10].

A systematic review by Moser et al. reported that the mean angle between the hip, knee, and ankle (HKA) ranged from 176.7° to 180.7° in non-arthritic knees. Most studies in the review did not report neutral limb alignment at 180°, except for Hovinga and Lerner, and Khattak et al. [11-13]. The variability in anterior knee joint alignment without osteoarthritis raises the question of whether 180° limb alignment is «normal». Such alignment may not be a suitable goal for all TKA patients. Hess et al. reviewed the femorotibial alignment in osteoarthritic knees and concluded that there are large differences in overall limb alignment, as well as in isolated femoral and tibial alignment. This observation continues to stimulate debate and classification of limb alignment. In a randomized cohort of 250 adults, Bellemans et al. identified neutral alignment as 180 ± 3°, constitutional varus as below 177°, and constitutional valgus as above 183° [14, 15].

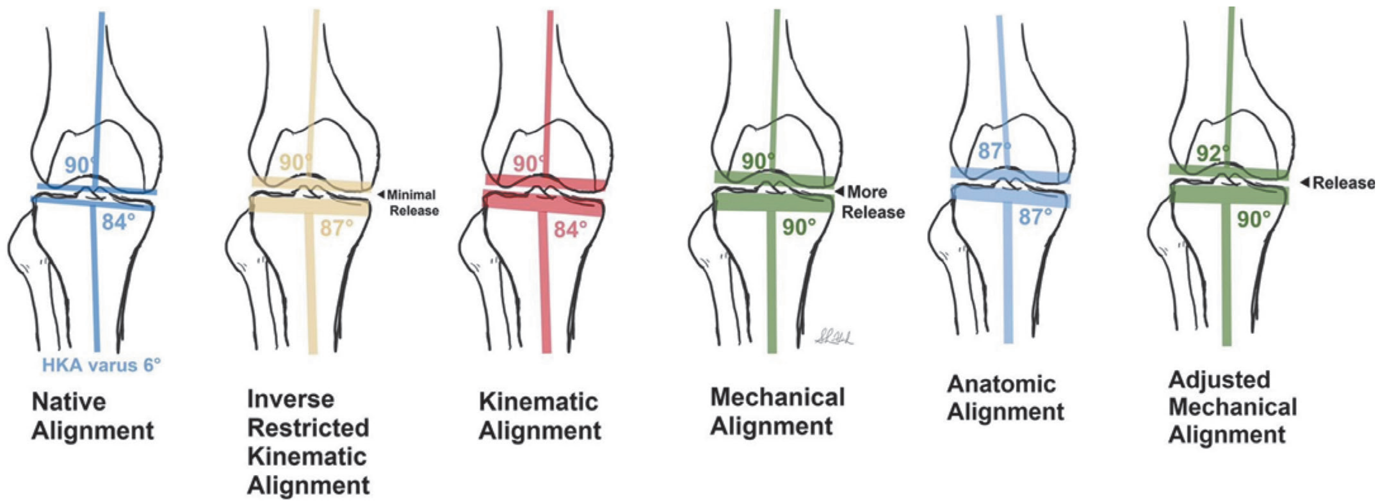
Later studies further classified TKA positioning by including femoral and tibial mechanical angles (FMA and TMA, respectively). This classification is more useful and explains how modern concepts of altering femoral and tibial bone cuts affect final alignment and improve knee arthroplasty outcomes [16-18].

Since the MA concept was challenged in the 1980s, Krakow and Hungerford described anatomical alignment to improve functionality by more accurately restoring the knee's original position, though the alignment was the same for all and not personalized. This led to the development of several individualized alignment concepts (kinematic, inverse kinematic, restricted kinematic, and functional). The distinction between these alignment concepts can sometimes be difficult to interpret, and the literature presents conflicting reports on them [3, 19].

The use of individualized navigation systems allows for more accurate positioning of prosthetic components, accounting for various factors such as valgus, varus, angular, and rotational deformities, deformities of joint surfaces from fractures of the femoral and tibial condyles, deformities from osteotomies, and congenital dysplasia of knee joint bones.

Kinematic alignment (KA), described by Howell et al. in 2006, is a method that restores anatomy prior to arthritic changes and preserves the ligamentous apparatus and biomechanics of movement [20]. In this method, the knee is viewed along three kinematic axes relative to the femur's posterior and distal joint lines. Figure 1 shows the types of alignment: one transverse axis in the femur, around which the tibia extends and flexes; one axis around which the patella extends and flexes; and one axis around which the tibia rotates externally and internally on the femur. All three axes are either parallel or perpendicular to the joint lines [21].

By addressing the knee joint, the KA method aims to align the axes and joint lines of the implants with the three «kinematic» axes and joint lines of the native knee. The surgeon performs a femoral resection while maintaining pre-arthritic angles, femoral joint lines, and adjusts the extension and flexion gaps by resecting the proximal tibia. Sometimes, KA involves complex algorithms for balancing extension and flexion gaps using resections and tenotomies [22]. Tibial compensation may lead to more oblique varus tibial resections with a greater medial cut of the tibia compared to MA (mechanical alignment). The thickness of the tibial and femoral resections is verified with calipers and must correspond to the thickness of the implants after the resections. Kinematic alignment (KA) restores the ligament extension observed before the development of arthritis, avoids creating ligament imbalances, and minimizes the need for ligamentotomies. KA requires precise surgical technique and can be performed using several methods: traditional instruments, computer navigation, personalized instruments, or



LDFA	Reconstruction	**Reconstruction**	Full-correction	Reconstruction	Over-correction
MPTA	Reconstruction	**Under-correction**	Full-correction	Full-correction	Full-correction
Overall Limb alignment	No bone correction	**Under-correction**	Full-correction	Full-correction	Under-correction
Medial Release	Nil /Minimal	**Nil /Minimal**	+	+	+

Fig. 1. Types of lower limb axis alignment.

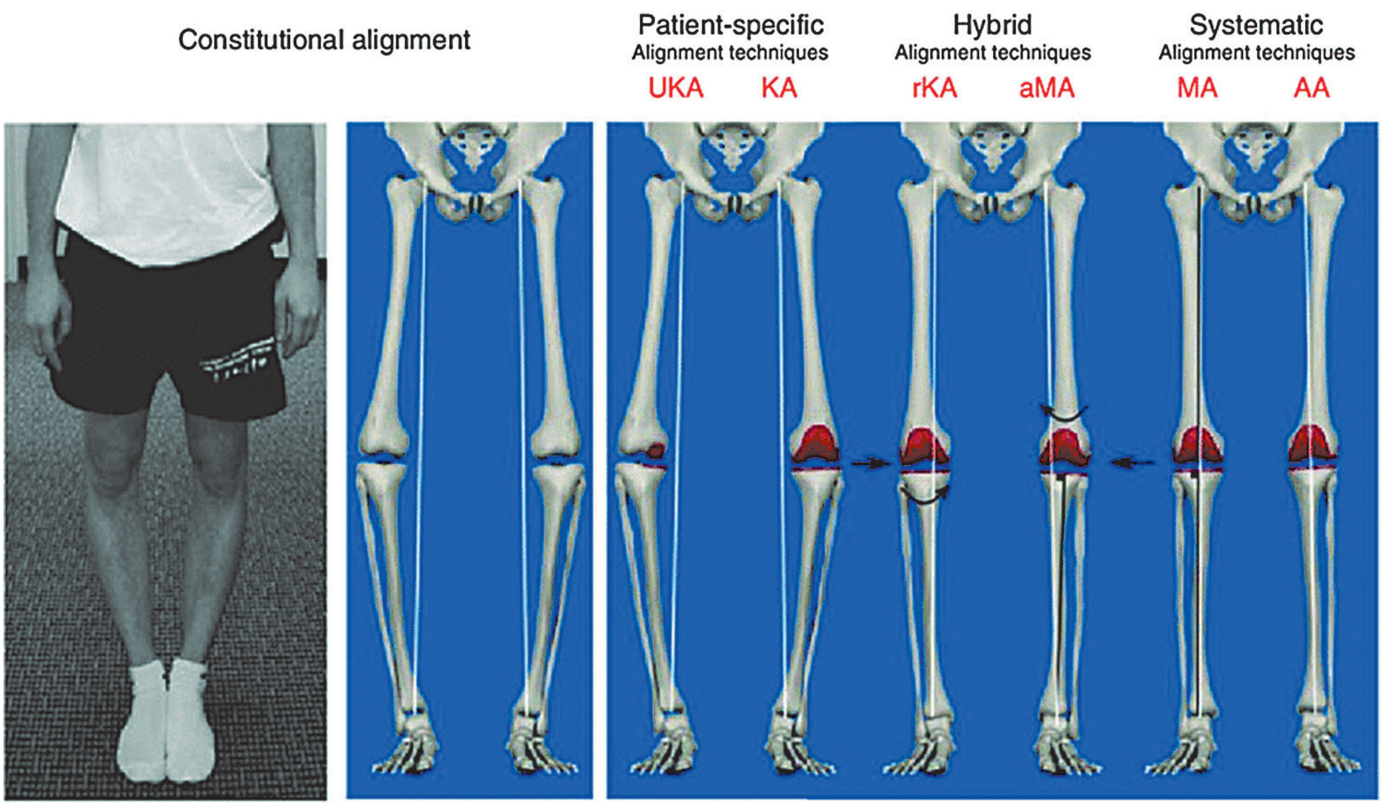


Fig. 2. Types of lower limb alignment.

robotic navigation systems [23-25]. Figure 2 shows the different types of alignment in a prosthetic knee joint.

Taking into account the latest trends in the development and design of personalized navigation systems for knee arthroplasty, we can say that this technology has rapidly advanced over the past 5 years. Currently, this technology has been significantly refined and shows promising results, but it is not yet the gold standard. Advocates of personalized knee arthroplasty emphasize the potential of using a personalized navigation system to improve the accuracy of prosthesis component positioning (Fig. 3).

Objective: The objective of this literature review was to analyze literary sources on the use of modern navigation systems and determine their effectiveness, advantages, and prospects in the individualization of knee joint arthroplasty.

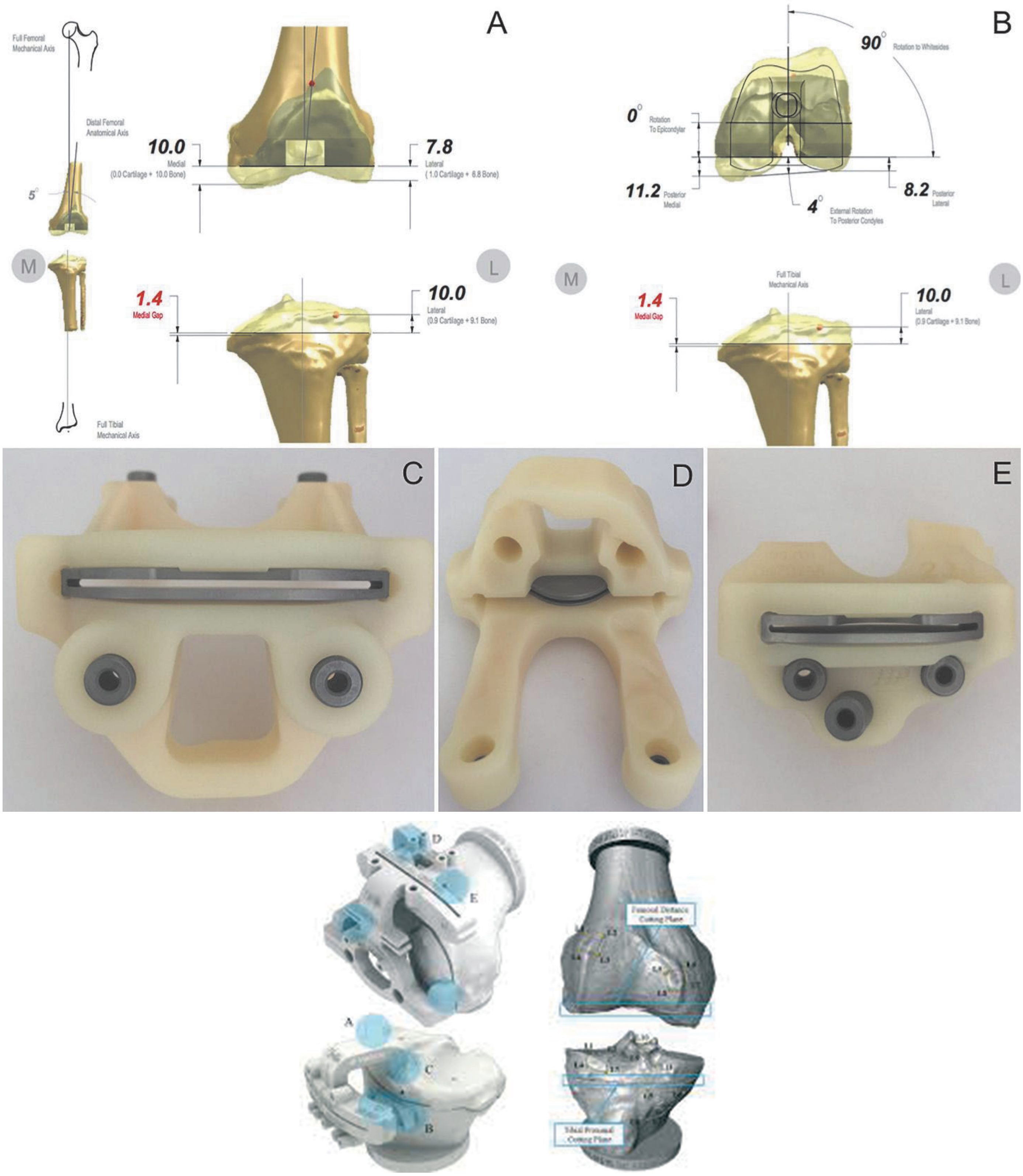


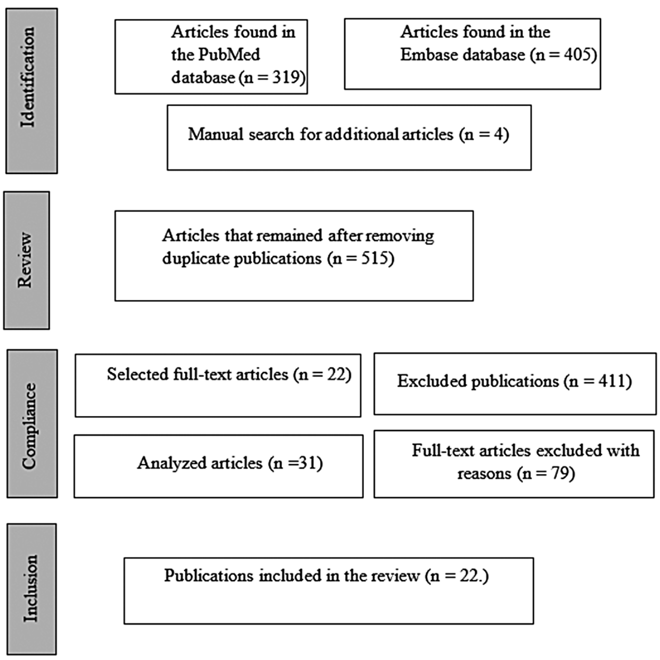
Fig. 3. Individualized navigation systems.

Materials and Methods

A review of the use of various navigation systems, including classic mechanical navigation systems, combined and individualized navigation systems for knee joint arthroplasty, was conducted. The review included studies available in recognized databases such as PubMed, Scopus, and Web of Science. During the selection of material for the review, key terms such as «total knee arthroplasty,» «patient-specific instrumentation,» «conventional instrumentation,» «kinematically aligned,» «native alignment,» and «treatment outcomes» were used to ensure maximum objectivity and representativeness of the results. The selection of specific articles was based on quantitative data and an objective comparative analysis of the outcomes. Special attention was given to studies that included a large number of patients and provided sufficient statistical significance. Only those studies with clear inclusion and exclusion criteria, as well as objective data on treatment outcomes, were included in the review. In total, 22 scientific publications were selected for further consideration, allowing for a comprehensive review and comparison of methods. The results of the literature search are described in Table 1.

Table №1

Results of the literature search



Results and Discussion

Total knee arthroplasty is one of the most effective surgical methods for treating knee osteoarthritis. The accuracy of implant placement remains a critical factor for achieving long-term surgical success. Misalignment can lead to increased wear of components and a higher risk of complications. Traditionally, standard instruments and techniques based on anatomical landmarks have been used for implant placement. In recent years, individualized navigation systems (INS) based on preoperative three-dimensional modeling of the patient's specific anatomy have been introduced. INS aim to improve the accuracy of knee joint component placement, reduce surgery time, and lower the risk of complications.

In the context of improving outcomes in total knee arthroplasty, modern technologies such as patient-specific instruments (PSI) and computer-assisted surgery play an important role. Patient-specific instruments (PSI) are designed based on preoperative images, allowing the creation of specially tailored tools for each patient. This ensures more precise alignment and implantation, reducing the risk of mechanical errors and improving implant stability. The use of INS is particularly effective in kinematic alignment (KA), where alignment accuracy is critical for restoring the natural kinematics of the knee joint [26].

The computer-assisted navigation system (CAS) provides surgeons with real-time detailed information about the patient's anatomy, allowing for adjustments to the implant positioning during surgery. This ensures high accuracy and predictability of outcomes, reducing the risk of deviations from the planned alignment. CAS is especially useful in functional alignment (FA), where achieving an optimal balance between bone structures and soft tissues is crucial [27].

The integration of INS and CAS into various alignment methods, such as KA (kinematic alignment), inverse kinematic alignment (iKA), restricted kinematic alignment (rKA), FA (functional alignment), and mechanical alignment (MA), significantly improves the accuracy of implant positioning. This contributes to better preservation of the joint line, optimal patellar kinematics, reduced complication rates, and improved functional outcomes in the postoperative period.

Despite the potential advantages, research results regarding the effectiveness of navigation systems in knee joint arthroplasty remain ambiguous due to the significant variability and diversity of the studies conducted. Researchers used different concepts, clinical and instrumental evaluation methods, as well as varying techniques and instruments for arthroplasty. The evaluation considered both clinical and instrumental data. Clinical outcome comparisons remain a subject of active discussion among orthopedic surgeons. The key criteria for different types of alignment are presented in Table 2 ananalyzed.

Table №2

Comparison of alignment types

Parameter	Kinematic Alignment (KA)	Inverse Kinematic Alignment (iKA)	Restricted Kinematic Alignment (rKA)	Functional Alignment (FA)	Mechanical Alignment (MA)
Method Features	Restores kinematics	Personalized approach to the patient	Hybrid approach	Restores functional mechanics	Aligns the mechanical axis
Complication rate (%)	3.9%	3.5%	3.7%	3.8%	4.4%
Use of technologies	More often uses PSI and CAS	Use of robotic assistance	Use of individual CT scans	Robotic assistance for accuracy	Standard instruments
Bone resection	Minimal resection	Individualized resection	Similar to KA	Individualized resection, focus on preservation	Significant resection required
Radiological parameters	Better alignment than MA	Similar to KA	Similar to KA	Balanced alignment	Strong correlation with outcomes
Soft tissue release	Better balance compared to MA	Similar to KA	Similar to KA	Improved balance through robotic assistance	Additional corrections may be needed
Patellar kinematics	Better tracking and fewer patellofemoral complications than MA	Improved tracking and stability compared to MA	Similar to KA	Similar to KA, but better balance than KA	Possible tracking issues, additional corrections may be needed
Axis preservation	Better preservation compared to MA	Preservation with correction options	Similar to KA	Similar to KA, but better alignment than MA	More difficult correction, potential for complications

As seen in Table 2, the study by Courtney et al. showed significantly higher Knee Society Score (KSS) and Oxford Knee Scores (OKS) for KA compared to MA [29]. In the study by Grave et al., iKA and rKA demonstrated promising results similar to KA, with a significant improvement in OKS for both techniques [29]. Functional alignment also shows improved knee scores, with higher Knee injury and Osteoarthritis Outcome Score (KOOS) and OKS compared to MA [30]. However, Waterson et al. did not find significant differences in KOOS between KA and MA, suggesting the need for further research [31].

The complication rate is an important factor in evaluating the safety and effectiveness of alignment techniques in TKA. Studies show that KA, iKA, rKA, and FA slightly increase the complication rate compared to MA. A systematic review by Klasan et al. found no significant differences in complication rates between KA and MA [26]. Courtney et al. also reported similar complication rates for KA and MA (3.9% versus 4.4%) [28]. iKA and rKA show comparable complication rates with KA, according to the study by Grave et al. (3.5% and 3.7%, respectively) [29]. FA, using robotic assistance, also shows a low complication rate (3.8%) [27].

Patellofemoral kinematics and its tracking are important for the longevity and functionality of the knee prosthesis. KA, iKA, rKA, and FA demonstrate promising results in improving patellar kinematics compared to MA. Dossett et al. found that KA provides better patellar tracking and fewer complications compared to MA [32]. Similar results were shown in the study by Chang et al. for FA, which demonstrated better patellar kinematics with robotic assistance [32]. iKA and rKA also show improved patellar kinematics, highlighting improved tracking and stability of the prosthetic knee joint. These results suggest that alternative alignment techniques may offer benefits in patellar kinematics, potentially reducing the risk of complications [29].

Axis preservation is critical for maintaining the natural biomechanics of the knee. Studies show that KA, iKA, rKA, and FA may better preserve the axis compared to MA. Hutt et al. showed that KA better preserves the axis, leading to more natural kinematics [34]. Steer et al. also reported better axis preservation results for FA compared to FA [27]. iKA and rKA also show comparable axis preservation results with KA [29]. These results highlight the potential benefits of alternative alignment techniques in preserving the joint line, which is important for long-term knee function.

The use of modern technologies such as individualized navigation systems (INS) and computer-assisted navigation systems (CAS) is common in KA and MA techniques. These technologies improve the accuracy of implant positioning and alignment. Klasan et al. highlighted the use of INS in

KA, which allows for more precise alignment of the implant and better outcomes. Steer et al. also noted the advantages of using robotic assistance in FA to achieve precise alignment and improve functional outcomes [26, 27].

Soft tissue mobilization is an important aspect that affects postoperative pain, function, and recovery. Studies show that KA may require fewer soft tissue releases compared to MA. An et al. reported that KA required fewer soft tissue releases, resulting in less trauma and better postoperative outcomes [35]. Abhari et al. also found that KA led to fewer soft tissue releases compared to MA, contributing to higher patient satisfaction. These results suggest that KA may offer advantages in soft tissue management, leading to improved recovery and patient outcomes [36].

Bone resection affects the stability and durability of the implant. Studies show that KA requires less bone resection compared to MA. An et al. reported that KA required less total bone resection compared to MA (16.7 mm versus 18.9 mm, $p < 0.0001$). This reduction in bone resection helps preserve bone stock and potentially improves long-term outcomes [35].

Radiological parameters are critical for assessing the accuracy and success of alignment techniques. Studies show that KA leads to better radiographic outcomes compared to MA. Hirschmann et al. found that KA leads to better radiographic alignment with less deviation from the intended alignment compared to MA [18]. Steer et al. also reported that KA achieves better radiographic outcomes, which more closely match the patient's natural knee anatomy [27]. Longstaff et al. also reported that KA achieves better frontal alignment, contributing to better balance and reducing the risk of implant instability [37].

Conclusions

The use of custom-made tools and resection guides in primary and revision knee arthroplasty improves surgical and rehabilitation outcomes. The development of this approach allows for up to 30% improvement in implant positioning accuracy and a 10% reduction in CO_2 emissions.

Standardizing research methods and increasing surgeons' experience can help better understand the long-term benefits of custom navigation systems in knee arthroplasty. Despite the identified advantages of INS, further research is needed to determine the long-term clinical outcomes and cost-effectiveness of these systems. The use of INS is more important in cases of significant deformities and bone defects.

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Досягнення та перспективи персоналізованих навігаційних систем для ендопротезування колінного суглоба: огляд літератури

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Анотація. Вступ. *Традиційні методи ендопротезування колінного суглоба засновані на механічному вирівнюванні, яке забезпечує довгострокове виживання компонентів, але не завжди задовольняє функціональні потреби пацієнтів. Останні дослідження показують, що персоналізовані підходи до вирівнювання, такі як кінематичне та функціональне вирівнювання, можуть покращити функціональні результати та зменшити частоту ускладнень. Ці методи враховують природні осі руху та анатомію колінного суглоба, що сприяє відновленню анатомії та функцій суглоба. Індивідуальні навігаційні системи представляють сучасний підхід до ендопротезування колінного суглоба, використовуючи тривимірні передопераційні моделі на основі КТ або МРТ. Цей метод підвищує точність підгонки компонентів протеза, враховуючи індивідуальні анатомічні особливості та біомеханічні параметри пацієнта.* ***Мета дослідження*** *— проаналізувати літературу щодо використання передових навігаційних систем і оцінити їхню ефективність, переваги та перспективи в персоналізації ендопротезування колінного суглоба.* ***Матеріали та методи.*** *За допомогою баз даних PubMed, Scopus і Web of Science ми провели огляд 22 наукових досліджень, присвячених різним навігаційним системам для ендопротезування колінного суглоба. Дослідження відбиралися на основі кількості пацієнтів, статистичної значущості, чітких критеріїв включення та виключення, а також наявності об'єктивних даних щодо результатів лікування. Це дозволило провести детальний аналіз і порівняння різних навігаційних методів.* ***Результати.*** *Тотальне ендопротезування колінного суглоба (ТЕПК) є одним із найефективніших хірургічних методів лікування остеоартриту коліна. Однак точність імплантації протеза залишається критичним фактором для довгострокового успіху операції. Відхилення у встановленні можуть призводити до підвищеного зносу компонентів та збільшення ризику ускладнень. Традиційно для встановлення протеза використовуються стандартні інструменти та методики, що ґрунтуються на анатомічних орієнтирах. Останніми роками були впроваджені індивідуальні навігаційні системи (ІНС), засновані на передопераційному тривимірному моделюванні специфічної анатомії пацієнта. ІНС спрямовані на підвищення точності розташування компонентів колінного суглоба, скорочення часу операції та зниження ризику ускладнень.* ***Висновки.*** *Використання індивідуальних хірургічних інструментів і засобів для резекції при первинному та ревізійному ендопротезуванні колінного суглоба покращує хірургічні та реабілітаційні результати. Ця технологія дозволяє на 30% підвищити точність позиціонування імплантату та на 10% знизити викиди CO2. Стандартизація методів дослідження та підвищення досвіду хірургів можуть сприяти кращому розумінню довгострокових переваг індивідуальних навігаційних систем у ендопротезуванні колінного суглоба. Незважаючи на виявлені переваги ІНС, необхідні подальші дослідження для визначення довгострокових клінічних результатів та економічної доцільності цих систем. Застосування ІНС особливо важливе у випадках значних деформацій і дефектів кісток.*

Ключові слова: *тотальне ендопротезування колінного суглоба, індивідуальні навігаційні системи, тривимірне моделювання, індивідуальні інструменти, кінематичне вирівнювання.*