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ROBOTICS APPLIED TO ORTHOPEDICS: A SCOPING REVIEW OF THE MAIN ROBOT-ASSISTED SURGICAL SYSTEMS

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ABSTRACT

Introduction: *orthopedic surgery has undergone remarkable technological advances in recent decades, with robotics being one of the most relevant developments. Its implementation has transformed procedures such as total knee and hip arthroplasty by enhancing surgical precision and enabling personalized planning.*

Objective: *to conduct a descriptive scoping review of the main robotic systems used in orthopedics, focusing on their technical characteristics, clinical applications, benefits, limitations, and associated costs.*

Methodology: *a narrative bibliographic review was carried out between January 2015 and August 2025 by consulting databases such as PubMed, Scopus, Web of Science, Embase, and SciELO. Original articles, systematic reviews, and observational studies related to robotic systems in orthopedic surgery were included. Preclinical studies, editorials, and publications without full-text access were excluded.*

Results: *the systems analyzed include ROSA®, Mako®, NAVIO®, TSolution One®, and ExcelsiusGPS®. All demonstrated advantages in terms of mechanical alignment, surgical accuracy, reduced postoperative pain, and faster functional recovery. The learning curve for some systems, such as ROSA®, is shorter than expected, facilitating clinical adoption. However, high costs, the need for specialized training, and infrastructure requirements remain major barriers. Further long-term evidence is needed to confirm definitive functional and economic benefits.*

Conclusions: *robotics in orthopedics provides tangible clinical improvements and greater surgical precision. Nevertheless, its implementation should be rational and evidence-based, taking into account costs, available resources, and patient profiles. The future of the field is closely linked to the development of artificial intelligence and technologies that enhance personalized surgery.*

KEYWORDS: *Orthopedic Surgery, Robotics, ROSA, Mako, Artificial Intelligence, Surgical Precision.*

INTRODUCTION

In recent decades, technological advancements have profoundly transformed the field of orthopedic surgery. Among the most significant developments is the integration of robotic surgical systems, which have enabled greater precision, personalization, and safety in complex procedures, particularly in total knee and hip arthroplasty. Robotic technology in orthopedics has evolved from passive navigation systems to semi-active platforms that assist surgeons in real time, enhancing both the planning and execution of surgical procedures(1,2).

The use of systems such as ROSA® (Robotic Surgical Assistant), Mako SmartRobotics®, Navio®, and TSolution One®, among others, has grown significantly in specialized centers with the aim of optimizing clinical outcomes, reducing complications, and increasing patient satisfaction. However, the adoption of these technologies varies considerably across regions and countries due to factors such as high costs, the learning curve, and the availability of specialized training.

Despite the growing enthusiasm for these tools, there is still debate about their actual clinical and economic impact compared to conventional techniques. Furthermore, the scientific literature is heterogeneous in terms of results, making it difficult to reach a definitive conclusion about their superiority(3).

In light of this situation, the present work aims to conduct a scoping review of the main robotic systems used in orthopedic surgery, describing their technical characteristics, clinical applications, advantages, limitations, and costs based on the current scientific literature. This review seeks to provide a comparative overview that serves as a reference for healthcare professionals, hospital administrators, and academics interested in technological innovation applied to orthopedics.

METHODOLOGY

A descriptive bibliographic review of a narrative or scoping type was conducted with the aim of identifying and analyzing the main robotic platforms used in orthopedic surgery, as well as their technical characteristics, clinical benefits, limitations, and economic aspects. The article search was carried out between January 2015 and August 2025 in the databases PubMed/MEDLINE, Scopus, Web of Science, Embase, and SciELO, using descriptors in English, Spanish, and Portuguese such as "robotic surgery," "orthopedic robots," "ROSA robotic system," "Mako SmartRobotics," "TSolution One," "robot-assisted arthroplasty," and "robotic knee surgery."

Included were original articles, systematic reviews, observational studies, and technical reports published in English, Spanish, or Portuguese that addressed the use of robotic systems in orthopedic procedures, especially in knee and hip arthroplasties. Excluded were duplicate articles, preclinical studies, studies in animals or simulators, opinions, editorials, letters to the editor, and publications without full-text access.

The study selection was performed in three stages: reading titles and abstracts, full-text review, and extraction of relevant information. The collected data were organized into thematic categories that included the robotic system name, manufacturer, type of robotic assistance, clinical indications, reported advantages, limitations, estimated costs, and clinical outcomes. The findings are presented narratively and in tabular form for comparative and explanatory purposes.

RESULTS AND REVIEW

Main Robotic Systems in Orthopedics.

The development of robotic surgery in orthopedics has enabled the incorporation of various platforms designed to improve precision in procedures such as total and partial knee and hip arthroplasty. Below are descriptions of the main systems currently available in clinical practice.

ROSA® Knee System (Zimmer Biomet)

The ROSA® (Robotic Surgical Assistant) system is a robotic platform primarily used for total knee arthroplasty. It integrates preoperative imaging and intraoperative sensors to assist the surgeon in the precise planning and execution of bone cuts, ligament balancing, and implant alignment. Its design allows for real-time adjustments during surgery without the need for rigid fixation to the bone, which may reduce the risk of complications. The system offers a moderate learning curve and is compatible with conventional surgical workflows. ROSA® is a semi-autonomous platform for total knee arthroplasty that combines preoperative planning with intraoperative point acquisition, providing precise bone cuts, reproducible ligament balance, and optimal alignment without replacing the surgeon's control(4).

Mako SmartRobotics™ (Stryker).

Mako is one of the most established robotic systems worldwide and is used for total and unicompartmental knee arthroplasties, as well as total hip arthroplasties. It operates through preoperative planning based on computed tomography (CT) and allows controlled execution via a semi-active robotic arm that guides the surgeon during bone milling, enabling millimetric precision and proven improvements in alignment, postoperative pain, and faster recovery. The AccuStop™ technology provides millimetric accuracy by limiting intervention outside predefined boundaries. Studies have demonstrated improvements in component alignment, reduced postoperative pain, and faster recovery(5).

NAVIO™ Surgical System (Smith & Nephew).

NAVIO is a portable system that does not require preoperative CT imaging, as it performs anatomical mapping intraoperatively using optical sensors. It is primarily used in unicompartmental and total knee arthroplasties. Its imageless surgery approach reduces radiation exposure and speeds up the surgical process, although it may have limitations compared to systems that use preoperative three-dimensional models. Its main advantages are portability and lower cost compared to other systems(5).

TSolution One® (Think Surgical).

TSolution One is an autonomous robotic system designed to perform automated bone milling in knee arthroplasties. Unlike other semi-active systems, it allows a more automated execution of bone cuts based on precise three-dimensional planning. Although less widely used globally, its technical precision is comparable or superior to other systems, and it has shown promising results in implant alignment and stability(6).

Other Systems and Emerging Technologies.

There are different robotic systems, each with unique features for planning and executing surgery, as well as other systems in development or with more specific applications, such as OrthAlign, ExcelsiusGPS® (specialized in spine surgery), and hybrid platforms with integrated computer navigation. Additionally, some companies are incorporating artificial intelligence and machine learning to enhance personalized surgical planning. Each system has its own particularities and should be evaluated on its individual merits(7).

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Figure 1. Robotic surgical system (ROSA®).

Source: Photograph by the authors.

Advantages and Clinical Benefits

The introduction of robotic systems in orthopedic surgery, especially in knee and hip arthroplasties, has brought a series of clinical benefits documented in the literature. One of the main contributions is greater precision in bone cuts and implant alignment, which has been associated with better long-term functional outcomes and reduced prosthetic wear. In particular, systems like ROSA® and Mako® enable individualized surgical planning and real-time intraoperative adjustments, contributing to more precise placement of prosthetic components.

Another widely reported benefit is the reduction of immediate postoperative pain and improvement in early functional recovery. Some studies have shown that patients operated on with robotic assistance require fewer analgesics and achieve more effective early ambulation compared to conventional techniques. These advantages have been attributed to less soft tissue trauma and the precision of the cuts, which optimizes ligament balancing.

Furthermore, robotics has proven useful in reducing outliers (cases outside the desired mechanical axis), which improves implant longevity and decreases complication rates related to poor alignment. Lower rates of hospital readmission, fewer early revisions, and higher patient satisfaction have also been observed in some clinical series.

It is important to note that, although these benefits are well documented in observational studies and some systematic reviews, more long-term evidence from randomized clinical trials is still needed to confirm their definitive impact on implant survival and overall healthcare costs(1,2,4,7)**.**

Advantages and Clinical Benefits

Robot-assisted orthopedic surgery has demonstrated greater precision in alignment and bone cuts, especially in knee arthroplasties, resulting in a significant reduction of mechanical deviations and alignment outside the desired ranges (outliers) compared to manual surgery. This contributes to a more uniform implantation and potentially greater implant durability(8,9)**.**

Additionally, patients undergoing robotic arthroplasty report less postoperative pain, require fewer opioids, and experience faster functional recovery, enabling earlier ambulation and shorter hospital stays(10).

Systems like MAKO and ROSA combine three-dimensional planning based on tomography with intraoperative guidance, allowing the surgical procedure to be adapted with the goal of preserving soft tissues and achieving better ligament balance, thereby optimizing early rehabilitation.

Finally, studies indicate that the learning curve to achieve technical competence with systems like ROSA is completed after only a few cases, allowing surgical times to stabilize quickly without compromising implant precision(11).

Table 1. Comparative Table of Robotic Systems in Orthopedics.

Robotic System	Type of Assistance	Main Applications	Planning Method	Advantages	Limitations
ROSA® (Zimmer Biomet)	Semi-active	Total knee arthroplasty	Pre-op with X-rays or CT; intraoperative planning	High precision without invasive fixation, short learning curve	High cost, initial learning curve
Mako® (Stryker)	Semi-active	Total and unicompartmental knee and hip arthroplasty	Pre-op CT and 3D modeling	High precision in bone cuts, tissue preservation	Requires CT, high cost, tech dependency
NAVIO® (Smith & Nephew)	Imageless, semi-active	Total and unicompartmental knee arthroplasty	Intraoperative anatomic mapping, no pre-op imaging	Portable, no CT required, lower initial costs	Lower precision vs. CT-based systems, technical training required
TSolution One® (Think Surgical)	Autonomous	Total knee arthroplasty	Pre-op CT with detailed 3D planning	Automated milling, minimal human variability	Limited global adoption, specialized training needed
ExcelsiusGPS® (Globus Medical)	Spinal robotic navigation	Spine surgery	CT + real-time image-guided navigation	High precision in pedicle screw placement	Limited to spine, costly infrastructure

Source: created by the authors.

DISCUSSION

This descriptive analysis of the main robotic systems used in orthopedics confirms the growing interest in this technology, particularly in high-demand procedures such as total knee arthroplasty (TKA) and hip arthroplasty. The results show that platforms like ROSA®, Mako®, and NAVIO® have improved precision in implant placement, resulting in better mechanical alignment, a lower rate of outliers, and potentially greater prosthetic longevity(2,8)**.**

One of the most relevant contributions of robot-assisted surgery is its ability to individualize surgical planning, adapting to the specific anatomy of each patient. This has been associated with better early functional outcomes, reduced postoperative pain, and higher patient satisfaction. In particular, the Mako® system has shown strong evidence of improvements in bone precision and ligament balancing compared to manual techniques(1,4,7).

However, although the technical advantages are clear, their long-term clinical impact remains a subject of debate. Some meta-analyses indicate that while robotics improves radiological parameters, the long-term functional benefits and implant survival are not yet significantly superior compared to conventional techniques. This suggests that robotics should be understood as a complementary tool, not as an absolute substitute for surgical experience.

Authors suggest that the ideal robot should be portable, imageless, semi-active, template-free, open-source, and possibly implemented with artificial intelligence to facilitate preoperative and postoperative decision-making, thereby improving clinical outcomes and patient satisfaction. Currently, numerous robots are available that represent promising solutions(12).

The high acquisition, maintenance, and operational costs of these systems represent a significant barrier, especially in developing countries or public institutions. In addition, the need for specialized training and the adaptation of surgical infrastructure limit their widespread adoption. However, recent studies indicate that the learning curve is shorter than expected (6–11 cases for ROSA®), which facilitates the transition to routine use(8,11).

On the other hand, orthopedic robotics represents a fertile field for the development of artificial intelligence (AI), machine learning, and data-driven personalized surgery. The future use of platforms that integrate AI could enable more precise predictions about the best implant and surgical technique for each patient, based on thousands of previous cases and individual biomarkers(13).

Robotic systems in orthopedics offer real clinical advantages and greater surgical precision, although their adoption should be rational, considering factors such as cost, training, and patient profile. Long-term comparative studies are needed to definitively define their clinical, economic, and functional impact.

CONCLUSIONS

The introduction of robotic systems in orthopedics represents a significant technological advance that has improved surgical precision and enabled greater personalization in procedures such as total knee and hip arthroplasty. Platforms like ROSA®, Mako®, NAVIO®, and TSolution One® have demonstrated concrete clinical benefits, including better mechanical alignment, reduced postoperative pain, early ambulation, and potential reduction in complication rates related to poor implant placement.

However, despite these advantages, important limitations persist, such as high acquisition costs, the need for specialized infrastructure, and technical training for the surgical team. Additionally, long-term functional benefits are not yet fully established, and high-quality prospective studies are necessary to evaluate prosthetic survival, patient satisfaction, and the real economic impact of these technologies.

In this context, robotics should be seen as a complementary tool to clinical judgment and surgical experience, rather than a replacement. Its successful integration will depend on a critical evidence-based evaluation, cost-benefit analysis within each institution, and ongoing development of associated technologies such as artificial intelligence, which could further enhance its impact on future orthopedic practice.

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Declaration of Conflict of Interest

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