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Robot-Assisted Joint Replacement Surgery: A Comprehensive Review of Applications and Advances

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Abstract: *Robot-assisted joint replacement surgery represents a significant technological advancement in orthopedic practice, aimed at enhancing procedural precision and improving patient outcomes. This review synthesizes current evidence to evaluate the underlying principles, clinical benefits, persistent challenges, and future trajectories of robotic systems in joint arthroplasty. Technical approaches are categorized by interaction modality—including active, semi-active, and passive systems—and reviewed through widely adopted platforms such as MAKO and ROBODOC. Clinically, robotic assistance has demonstrated improved implant positioning, reduced postoperative pain, optimized learning curves, and enhanced capacity for personalized surgery and soft tissue preservation. Despite these advantages, limitations including high costs, additional surgical incisions, and restricted implant compatibility continue to pose barriers to widespread adoption. Looking forward, the integration of artificial intelligence for image processing, advancements in robotic arm design, and the thoughtful incorporation of surgical expertise into automated workflows are identified as key avenues for progress. By addressing current constraints and leveraging evolving technologies, robot-assisted joint replacement is poised to expand its role in achieving reproducible, patient-specific surgical outcomes.*

Keywords: *Robot-Assisted Surgery; Joint Arthroplasty; Orthopedic Robotics; Clinical Outcomes; Review*

1. Introduction

Joint diseases, which can arise from degenerative changes, autoimmune reactions, infections, trauma, and other causes, impose a significant burden on patients, families, and society. Joint replacement surgery, including total hip arthroplasty (THA) and total knee arthroplasty (TKA), is the most effective treatment for end-stage joint disease, effectively alleviating pain, improving mobility, and enhancing quality of life [1]. Although traditional joint replacement techniques have matured, studies show that 7% of patients are dissatisfied with outcomes after conventional THA, and up to 20% express dissatisfaction after conventional TKA [2, 3]. This is partly attributed to factors such as surgical experience, individual variations in bone structure, and patient positioning [4, 5]. Critical steps in traditional joint replacement, such as osteotomy and prosthesis placement, rely heavily on the surgeon's intraoperative judgment and standardized techniques, making precision susceptible to anatomical variability and surgical experience, often lacking reliable objective metrics. To further improve patient satisfaction and clinical outcomes, surgical assistive robots have been developed and widely adopted in joint replacement surgery. This review provides a comprehensive analysis of the principles, advantages, challenges, and future directions of robot-assisted joint replacement technology.

2. Robotic Systems and Technical Principles in Joint Replacement Surgery

2.1 Classification of Robotic Systems for Joint Replacement

2.1.1 Classification by Interaction Mode

Based on the human-robot interaction during surgery, robotic systems can be categorized as active, semi-active, or passive. Active systems execute pre-programmed plans autonomously to perform osteotomies, with ROBODOC being a representative system. Passive systems, also known as computer-assisted or navigation systems, provide precise positioning and danger-zone monitoring for saw cutting, but the actual osteotomy is performed by the surgeon. Semi-active systems are the most widely used orthopedic robotic systems currently; they provide real-time feedback, assist in osteotomy via a robotic arm, and offer features such as cutting boundary constraints and dynamic soft-tissue gap monitoring. These are often referred to as "haptic" feedback systems, with MAKO being a representative example [6].

2.1.2 Classification by Compatibility

Based on prosthesis compatibility, robotic systems can be classified as closed or open. Closed systems are compatible only with specific prostheses provided by the manufacturer, limiting surgeon choice. MAKO is a representative closed system. Open systems incorporate detailed biomechanical data for a wider range of prostheses, offering greater flexibility in implant selection. ROBODOC is a representative open system. Additionally, systems can be categorized based on whether preoperative imaging is required for modeling.

2.2 Current Clinically Applied Robotic-Assisted Systems

2.2.1 MAKO RIO System (Robotic Arm Interactive Orthopaedic)

The MAKO orthopedic robot is one of the most widely used closed, semi-active, image-based robotic systems. Developed by MAKO Surgical Corp., it received FDA approval in 2008 [7]. It utilizes preoperative CT-based modeling for surgical planning, determining osteotomy levels and assessing implant size and orientation. During surgery, the surgeon guides the robotic arm's burring tool, with the arm providing real-time haptic feedback to prevent deviation from the planned cutting boundaries. The system also provides real-time 3D bone imaging and knee kinematics, allowing assessment of deformity and ligament laxity through range of motion. Batailler et al., in a systematic review, demonstrated that MAKO robotic-assisted TKA improves implant positioning compared to conventional TKA, with comparable early clinical outcomes [8]. Kayani et al. reported significantly lower pain scores on postoperative day 3 in the MAKO-assisted TKA group compared to the conventional TKA group, indicating its potential for early pain reduction [9].

2.2.2 ROBODOC System

Introduced in the United States in 1992, the ROBODOC system was among the earliest orthopedic surgical robots, designed for surgical path planning and positioning. Evolving from ROBODOC, the TSolution-One system is an open-platform, active, CT image-based robotic system. It uses preoperative CT data to create a surgical plan via the ORTHODOC workstation, generating a 3D joint model and selecting an appropriately sized implant. Intraoperatively, an automated robotic arm equipped with sensors and cutting tools performs the milling osteotomy. Yang et al. found that the ROBODOC-assisted TKA group had significantly superior postoperative radiographic outcomes compared to the conventional TKA group [10].

2.2.3 NAVIO System

The NAVIO system is a closed-platform, semi-active, imageless robotic system featuring a retractable saw blade and an infrared camera. It intraoperatively registers the tibia and femur using the infrared camera and an imageless mapping system to create a patient-specific 3D knee model [11]. The surgeon uses a semi-active hand-held cutting tool; if the cut deviates from the plan, the system reduces saw speed or retracts the blade to prevent error [12].

2.2.4 ROSA System

The ROSA system is a closed-platform, semi-active robotic system designed specifically for TKA, operating in either image-based (using X-rays to generate 3D models) or imageless modes (using intraoperatively collected registration points). Zhou G et al., comparing 20 patients who underwent MAKO-TKA and 20 who underwent ROSA-TKA, found similar accuracy, precision, and comparable clinical outcomes at 1-year follow-up [13].

2.2.5 Honghu Orthopedic Robotic System

The "Honghu" orthopedic robot is an open, semi-active, CT image-based system developed in China with proprietary robotic arm technology. It analyzes preoperative CT data to provide preoperative planning information (e.g., osteotomy volume, implant size/position) and intraoperatively assists with semi-active cutting and soft-tissue gap monitoring, characterized by high precision and a lightweight design. Qiao Hua et al., in a multicenter clinical study, reported satisfactory postoperative radiographic outcomes for Honghu robot-assisted TKA.

2.3 Technical Principles of Robot-Assisted Joint Replacement Surgery

2.3.1 Preoperative Planning

Detailed 3D images of the joint are obtained via CT or MRI. These images are imported into planning software where the surgeon designs a personalized surgical plan, determining optimal implant size, position, and orientation. Systems like NAVIO and ROSA can perform real-time intraoperative registration and mapping, eliminating the need for preoperative imaging.

2.3.2 Intraoperative Execution

Intraoperative execution begins with a registration phase, wherein specialized tracking devices identify fiducial markers placed on the patient to calibrate the robotic system's spatial position relative to the surgical anatomy. Following this registration, the robotic arm proceeds to perform precise bone cutting and drilling under continuous surgeon supervision. This stage leverages high-precision navigation and the inherent stability of the robotic platform to minimize human error and ensure that the prepared bone surfaces closely match the preoperative plan. Once bone preparation is completed, the surgeon then proceeds to implant the prosthesis into the accurately shaped anatomical site.

3. Advantages of Robot-Assisted Joint Replacement Technology

3.1 Improved Implant Placement Accuracy

Accurate lower limb alignment is crucial for long-term implant survival and function. The mechanical alignment (MA) concept aims for a hip-knee-ankle (HKA) angle of 180° [14]. Studies indicate that HKA deviations within ±3° are associated with significantly lower rates of implant loosening, better functional recovery, and superior KSS, VAS, and WOMAC scores compared to deviations beyond ±3° [15]. In a prospective randomized controlled trial, Li et al. found that the robotic-assisted TKA group had a postoperative varus angle (1.801±1.608)° closer to the ideal 180° than the conventional TKA group (3.017±2.735)°, enabling more precise coronal alignment reconstruction [16]. Sergio Chávez-Valladares et al., in a single-center retrospective study, observed that among cases with postoperative HKA deviation >3°, the robotic-assisted TKA group had better KSS and WOMAC scores and a lower incidence of such deviations [17]. Furthermore, a prospective RCT on cementless femoral stems suggested that ROBODOC-assisted THA improved femoral stem positioning and limb length accuracy while reducing intraoperative fracture risk compared to conventional THA [18]. Through preoperative planning and intraoperative navigation, robots enable highly precise and accurate prosthesis placement in both TKA and THA.

3.2 Optimized Learning Curve

While robot-assisted surgery often prolongs operative time initially due to additional steps like tracker pin placement and bone registration, the learning curve shows significant improvement with increasing case volume. A study of 240 Mako-assisted TKAs found no significant difference in operative time between the final 20 robotic cases and conventional TKA (70 min vs. 68 min) [19]. Zhi Xin et al. demonstrated that surgical time for robot-assisted TKA decreased significantly after a certain number of cases, with the learning curve plateau for the Honghu robot reached by the 7th case [20]. Neira I et al., analyzing the learning curve for surgeons with varying experience using the ROSA robot, found that experienced surgeons achieved operative times comparable to conventional TKA after the initial learning phase, indicating that prior TKA experience shortens the robotic learning curve [4]. Experienced surgeons adapt more confidently, making minor technical adjustments that can reduce the need for additional gap verification and expedite planning, thereby shortening operative time [6]. The robotic learning curve pertains primarily to efficiency and speed of robotic use. For lower-volume surgeons, robotic assistance may help overcome the learning curve associated with conventional techniques, avoiding poor implant positioning due to inexperience [21].

3.3 Personalized Surgery

Howell et al. introduced the kinematic alignment (KA) concept in 2006, aiming to individually restore the knee's native joint line and alignment, preserving inherent ligament laxity and tibiofemoral compartment loading for more physiological TKA [22, 23]. Some studies suggest KA-TKA offers superior early outcomes compared to MA-TKA [15, 24]. However, achieving true KA is challenging with conventional instruments. Robotic systems enable more precise execution of surgical plans, including control of femoral/tibial component placement, osteotomy volume, and angles [25]. Some studies indicate higher patient satisfaction with KA-guided TKA. Elbuluk et al. in a study of 200 patients with varus osteoarthritis, reported higher Forgotten Joint Scores at 1- and 2-year follow-up for robot-assisted KA-TKA compared to MA-TKA.

3.4 Soft Tissue Protection

In conventional TKA, factors such as surgeon inexperience, visual errors, and instrument inaccuracies can compromise osteotomy precision and soft-tissue balance . Robotic systems, using preoperative or intraoperative data to generate personalized plans and provide real-time feedback on bone resection and flexion/extension gaps, help reduce osteotomy errors and imbalance, minimize collateral ligament releases, preserve native ligament tension, and offer advantages in early recovery and patient satisfaction [26].

4. Discussion

Recent years have witnessed rapid interdisciplinary development, including in orthopedic surgery. The integration of artificial intelligence (AI), big data, and other modern technologies into healthcare has accelerated, enriching clinical applications and fostering cross-disciplinary convergence [27]. Joint replacement robots exemplify the successful integration of big data, advanced manufacturing, biosensing, and other cutting-edge technologies within the AI domain. The core design philosophy of these robots is to enhance the accuracy and precision of prosthesis placement, thereby improving clinical outcomes, reducing revision rates, and increasing patient satisfaction. While short-term benefits of robot-assisted joint replacement are well-documented [28-30], long-term efficacy requires further validation through extended follow-up [14].

Nevertheless, current robotic systems have limitations: 1. High costs: Robotic systems are expensive to acquire and maintain. Studies indicate significant fixed costs for preoperative imaging, system setup, and consumables, with annual maintenance for most systems reaching approximately $40,000 [31]. However, Sarrel K et al., in a systematic review of 21 health economic studies comparing robotic and conventional TKA, reported that nearly all studies indicated positive health economic impacts for robotic TKA [32]. The emergence of domestically produced surgical robots in China may help address cost barriers. 2. Additional incisions: Robotic assistance typically requires fixation of tracking pins and reference arrays to bony structures (e.g., femur, tibia), creating extra incisions. Thomas et al., following over 7,366 robot-assisted TKA patients for more than one year, reported a pin-related complication rate of approximately 1.4% [31]. 3. Limited implant compatibility and system interoperability: Most current robotic systems are closed platforms with restricted prosthesis options. Further development of open-platform systems is needed to accommodate diverse patient needs and implant preferences.

Future technological development should focus on optimizing AI-based medical image processing, improving robotic arm configurations, and effectively integrating valuable surgical experience with robotic intelligence to enhance autonomous operational performance.

In conclusion, robotic systems for joint replacement have seen rapid clinical adoption in recent years. While inherent limitations persist, continued technological advancement and iterative optimization of robotic algorithms are expected to drive even broader clinical application in the future.

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