

Current Concepts

Advancements in Robotic Orthopaedic Surgery: A Current Concept

Anish K Ponna, BS¹^a, Alec M Giakas, MD², Anthony A Khoudary, MS¹, Ahmed Siddiqi, DO, MBA³

¹ Drexel University College of Medicine, Philadelphia, PA, USA, ² Rothman Orthopaedic Institute, Philadelphia, PA, USA, ³ Hackensack Meridian School of Medicine, Nutley, NJ, USA

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Robotic systems are revolutionizing the field of orthopaedic surgery by enabling new approaches to joint reconstruction and spine procedures, with the latest technologies in other sub-specialties continuing to emerge. Improvements in system capabilities have enhanced preoperative planning and intraoperative precision, contributing to the growing adoption of robotic technology. With the global surgical robotics market projected to reach \$7.42 billion by 2030, the integration of these systems in orthopaedic practice has expanded significantly. Robotic platforms vary in design, functionality, and level of automation, offering advantages such as improved anatomical accuracy and reduced intraoperative variability. This review evaluates recent advancements in robotic-assisted orthopaedic surgery, comparing different platforms, their clinical benefits, and their impact on surgical workflows.

Additionally, the role of robotics in reducing complications, optimizing rehabilitation, and improving long-term prosthetic surgery is explored. While challenges such as cost and system limitations persist, ongoing innovation continues to drive the integration of robotics into mainstream orthopaedic practice. The future of robotic surgery lies in its ability to refine procedures, expanding indications, and enhance patient care across diverse orthopaedic subspecialties.

INTRODUCTION

Orthopaedic robotic-assisted surgery has been increasingly adopted due to its potential to enhance precision, reduce recovery times, and improve surgical outcomes. As of 2023, the global surgical robots market was valued at \$3.92 billion and is estimated to reach \$7.42 billion by 2030.¹ Significant advancements in robotic orthopaedic surgery have developed over the last 30 years, with its leading utility in adult joint reconstruction and spine surgery.² The shift towards robotics is driven by technology and motivated by its undeniable impact on diagnosing and treating musculoskeletal conditions. Robotics provide advanced imaging and real-time feedback that improves precision in the operating room and allows for personalized procedures that strive to reduce complications and improve outcomes.³

Surgical robots come equipped with arms and tools to assist the surgeon in implementing preoperative plans.⁴ These systems can perform specific surgical tasks, with or without the surgeon at the operating table.⁴ Robotic sys-

tems can be categorized based on several criteria: open vs. closed platforms, image-based vs. imageless systems, and active vs. passive vs. semi-active systems.²

Open platforms, like the TMINI System (formerly known as ROBODOC) (THINK Surgical, Fremont, CA), work with a broad range of prosthetic implants, offering flexibility in surgical decision-making. While these open platforms allow for a different range of implants to be sourced from various manufacturers, these implant manufacturers are smaller companies rather than the prominent and more available manufacturers in the industry. Conversely, closed platforms, such as the Robotic Surgical Assistant (ROSA) Knee System (Zimmer-Biomet, Warsaw, IN), the Mako SmartRobotics (Stryker, Kalamazoo, MI), the CORI (Smith & Nephew, London, UK), and the Apollo (Corin, Cirencester, UK), are only compatible with their own manufacturer-specific implants. While open platforms provide more freedom for surgeons in selecting prosthesis model choices, closed systems offer higher specificity and integrated functionalities tailored to specific implants, which may allow for

^a Corresponding Author:

Anish K. Ponna, BS

Drexel University College of Medicine, Philadelphia, USA

1111 Donovan Way, Chester Springs, PA 19425, USA

akp94@drexel.edu

better balancing and alignment and surgeon interface.² Additionally, some open systems rely on anatomic landmarks rather than actual patient images. This prevents them from being able to consider individual patient anatomic variations, which can negatively impact specificity.² Surgeons must, therefore, carefully weigh the benefits of increased freedom of choice with lower specificity in deciding between open and closed systems.

Another critical distinction among robotic systems lies in how patient data is acquired. Image-based systems rely on preoperative imaging, such as computed tomography (CT) or magnetic resonance imaging (MRI), for anatomical data acquisition, allowing for detailed surgical planning. This approach, seen in systems like TMINI, ROSA, and Mako, provides accurate anatomical references but involves higher costs and potential radiation exposure.² Imageless systems, such as CORI and Apollo, gather anatomical data intraoperatively, reducing preoperative costs and avoiding radiation but relying heavily on the surgeon's intraoperative accuracy.²

Robotic systems also differ in the level of interaction required from the surgeon. Active systems, such as the early ROBODOC and Computer Assisted Surgical Planning And Robotics (CASPAR) (Ortho-Maquet/URS, Schwerin, Germany), perform the bony resection autonomously. While active systems offer high precision, they have historically faced issues with longer operation times and complications during surgery, such as iatrogenic fractures and ligament injuries.^{2,5} The robot guides passive systems, but the surgeon performs the resection. One example is the Apollo system, which offers adjustable cutting guides and real-time feedback, enhancing precision while maintaining significant surgeon control.² Combining active and passive systems features, semi-active systems like Mako and CORI allow the surgeon to operate the cutting tool with robotic guidance and control mechanisms to ensure precision. These systems offer a balance between surgeon control and robotic precision, with haptic feedback and safety features to prevent deviations from the planned resection.²

Currently, most robotic applications in orthopaedic surgery are in knee and hip arthroplasties. However, systems have also been developed for spine, shoulder, ankle, and fracture care. These systems have been increasingly studied and have been found to have distinct advantages and disadvantages.

REVIEW

1. JOINT AND RECONSTRUCTIVE SURGERY

1A. HIP

Active robots were first used in total hip arthroplasty (THA) in the 1990s.⁶ Recently, the new generation of active robot-assisted systems, such as TMINI and other new technologies like non-positioning needle navigation and miniature robots, have made robotic surgery less invasive and more user-friendly.⁶⁻⁸ The latest generation of pre-operative assistant design platforms improves surgeons' ability to de-

termine the optimal position, anteversion angle, and abduction angle of the prosthesis, as well as to evaluate bone defects. For instance, the Mako Total Hip combines computer navigation with a semi-active boundary-constrained robot reaming system to achieve precise acetabular reaming and accurate cup placement based on spinopelvic dynamic parameters.⁶ As of 2022, the Mako Total Hip is the most widely used THA robot globally, and these surgical robots have performed more than 500,000 knee and hip replacement procedures.^{1,6,9}

Robotic systems may also offer better control over femoral prosthesis positioning and lower limb leg length discrepancies. El Bitar *et al.*¹⁰ reported 91.8% of offsets within 10mm, effectively reducing complications like claudication and Trendelenburg gait.^{6,10} Both El Bitar *et al.*¹⁰ and Domb *et al.*¹¹ found that robot-assisted systems maintain lower limb length discrepancy (LLD) within 10mm, comparable to traditional methods, ensuring patient comfort and successful results.⁶ Additionally, studies have indicated significant reductions in postoperative dislocation rates with robot-assisted THA and computer navigation compared to manual methods.¹²⁻¹⁴ Even in technically challenging cases, such as obese patients or those with severe hip dysplasia, studies have demonstrated accurate and reproducible component positioning.^{7,15,16}

Despite the several proposed benefits, robotic-assisted total hip arthroplasty has been associated with certain drawbacks. Some studies have demonstrated longer operative times and increased blood loss with the implementation of robotic surgery compared to conventional THA due to the increased time needed to calibrate the system and anchor the detector.^{17,18} One retrospective cohort study demonstrated an increased risk of intraoperative periprosthetic fracture and requiring blood transfusion. However, this same study found reduced odds of postoperative vascular complications in the robot group compared to conventional hip arthroplasty.¹⁸ Other systematic reviews demonstrate mixed results in this regard, with either less or no differences in perioperative complications.^{9,17}

1B. KNEE

Early active robots used in total knee arthroplasty (TKA), like CASPAR and the original ROBODOC, were less efficient and inaccurate. However, modern, semi-active robots, such as the Active Constraint ROBOT (ACROBOT), Mako, and CORI, offer improved performance through advanced feedback mechanisms⁶ compared to their predecessors. Patient interest in this technology is also rising, with one study using Google Trends open-source analytics showing that patient interest in robotic TKA is outpacing conventional TKA.¹⁹ This study is limited in scope due to the lack of demographic data provided by Google Trends, but this trend is likely multifactorial. One key driver may be direct-to-patient marketing efforts, such as Stryker's campaign to promote awareness of its Mako SmartRobotics platform in August 2023 to enhance patient engagement and education.¹

Some studies show that robot-assisted unicompartmental knee arthroplasty (UKA) and TKA may lead to better component alignment, improved soft-tissue protection,

and prosthesis positioning compared to traditional methods.²⁰⁻²² For example, robotic systems may significantly reduce positioning errors of the tibial²³ and femoral prostheses.^{24,25} In a review by Inabathula *et al.* found that robotic systems provide consistent and precise implant alignment and resection, with several studies demonstrating reduced variability, fewer alignment outliers, and more accurate bone cut angles.²⁶ While these studies demonstrated improved cut consistency, interestingly, this did not translate to superior patient-reported outcomes. Other studies indicate that this improved precision may help to maintain joint line height and preserve more bone, reducing the risk of complications and revisions.²⁷ Postoperatively, studies have demonstrated lower pain scores and improved physical function, patient satisfaction, and activity compared to manual TKA.²² Some studies also showed that robotic TKA surgery may require less inpatient therapy, faster hospital discharge times, and less postoperative therapy, all of which are major contributors to healthcare costs.²²

As with most robotic applications in orthopaedic surgery, robotic-assisted TKA is associated with increased procedure times. This includes the time required for checkpoints, tibia and femur pin placement and removal, and bone registration.^{28,29} Additionally, a systematic review of 21 studies found mixed results regarding the incidence of iatrogenic soft-tissue injuries during bone cutting when comparing robotics to conventional TKAs.²⁹ These included patellar and popliteal tendon rupture, patellar dislocation, peroneal nerve injury, and damage to the medial and lateral ligaments. Damage to these ligaments can lead to an imbalance in knee extension/flexion while also damaging the extensor mechanism.²⁸ Furthermore, RA-TKA presents with several inherent system limitations. Pin insertion and movement of the leg with the leg holder are difficult in patients with obesity and those of short stature. Vibration during the procedure from cutting can also lead to intermittent function of the robotic-arm-assisted saw. The saw follows planned cutting lines, so if there is disruption from the knee movement from vibrations, the procedure stops.²⁸

1C. SHOULDER

Robotic systems have not yet fully emerged in shoulder surgery, but work is underway. Many systems being developed are currently in preclinical and clinical trials and are focused on procedures such as soft tissue surgeries around the shoulder. For instance, tendon transfers, arthroscopies, and brachial plexus surgeries have been conducted using the da Vinci robot (Intuitive Surgical, Sunnyvale, CA).³⁰ These trials are still in their early stages but demonstrate potential for the future of robotic surgery within the shoulder and elbow subspecialty.

Novel robots designed for total shoulder arthroplasty (TSA) are currently being developed, but many remain in the proof-of-concept stage using prototypic robotic technology on cadavers. Currently, the ROSA Shoulder (Zimmer-Biomet) is the first and only robot to receive approval from the U.S. Food and Drug Administration (FDA) for shoulder arthroplasty.³¹ It received its approval in February 2024. In April 2024, Zimmer-Biomet announced the suc-

cessful completion of the world's first robotic-assisted shoulder replacement surgery using this system, performed at Mayo Clinic by Dr. John W. Sperling.³² Given the novelty of this machine, literature is sparse regarding its efficacy in clinical practice.

Robotic technology in shoulder arthroplasty also presents practical challenges. During robotic surgery, placement of registration trackers on the glenoid and humerus may require additional coracoid and proximal humerus exposure, adding complexity and time to the procedure. Additionally, robotic devices, screens, and sensors can reduce working space, leading to potential instrument crowding and requiring surgical teams to adapt their workflows. While robotics can enhance precision and aid in perioperative planning and intraoperative adjustments, the surgeon's experience, judgment, and role in final component implantation are irreplaceable for successful outcomes.³³

1D. FOOT AND ANKLE

In foot and ankle surgery, cadaveric studies have demonstrated the efficacy of robotic systems over traditional methods by allowing for multi-dimensional testing of forces and movements. For example, robots have been used to assess ankle motion in specimens with total ankle arthroplasty (TAA) and have demonstrated greater consistency in outcomes and a broader range of motion compared to conventional systems.³⁴⁻³⁷ This advanced testing capability provides deeper insights into the biomechanics of the foot and ankle joints.

One of the primary challenges in the widespread adoption and clinical utility of robot-assisted surgeries in this field is the complex three-dimensional anatomy and small surgical spaces of the foot and ankle. The restricted space within the surgical field and the inherent complexity of some procedures, such as those that necessitate precise screw placement, further limit the effectiveness of robotic systems. Currently, these systems are difficult to justify implementing for more streamlined procedures where the surgeon cannot achieve accuracy alone.³⁷ The lack of versatile, open-platform systems also limits the adaptability of current robotics to the diverse needs of foot and ankle surgery, including trauma management, arthrodesis, and deformity correction.^{37,38}

2. SPINE

In spine procedures, robotics have primarily been utilized in pedicle screw placement in the context of thoracolumbar degenerative diseases that use posterior, transforaminal, or lateral approaches.³⁹ Currently, there are several spine robotic systems available, including SpineAssist (Mazor-Robotics, Caesarea, Israel), Renaissance (Mazor-Robotics, Caesarea, Israel), Mazor X (Mazor-Robotics, Caesarea, Israel), ROSA SPINE (Zimmer-Biomet Robotics, Montpellier, France), ExcelsiusGPS (Globus Medical, Inc., Audubon, PA).⁴⁰ The most common indication for these systems is minimally invasive surgery-transforaminal interbody fusion (MIS-TLIF), where robots may enhance accuracy and reduce invasiveness compared to freehand technique.³⁹ Ro-

botic assistance may also be beneficial in treating thoracolumbar fractures, offering higher screw placement accuracy.³⁹ A 2021 review by McKenzie *et al.*⁴⁰ of 34 studies showed that robotic accuracy ranged from 94.6% to 99%, while a 2022 review by Lopez *et al.*³⁹ of 76 studies found that robotic-assisted techniques provided higher precision in screw placement compared to the freehand group, achieving up to 94% to 98% accuracy in optimal trajectories (Gertzbein-Robbins scale grades A and B).³⁹ This precision reduced the incidence of cortical breaches and superior facet joint violations, leading to better outcomes and fewer complications.³⁹ Additionally, robotic systems streamlined the surgical process, cutting down placement time by an average of 90s per screw.⁴¹

Currently, the use of robotic systems in spine surgery has only been approved for pedicle screw insertion. To be more widely adopted, applications of these systems must expand to include complex spinal deformities, tumor resections, and craniovertebral junction surgeries where the surgeon could benefit the most from robotic assistance. Furthermore, most of the current evidence supporting the adoption of robotic spine surgery comes from retrospective studies, with the few randomized control trials showing inconsistent results regarding improvements over traditional methods. These studies typically demonstrate equal efficacy and accuracy between robotic and traditional techniques but often show mixed results regarding procedural time and intra- and post-operative complications.^{39,42,43} Without proven clinical benefits, cost-effectiveness studies remain challenging, as the high initial cost of these systems can typically only be justifiable for large, high-volume academic institutions.⁴²

3. TRAUMA

Robotic-assisted fracture reduction (RAFR) is an emerging technology with significant promise for enhancing the precision and effectiveness of orthopaedic surgeries, particularly for complex fractures. To date, the clinical applications of robotics in orthopaedic trauma procedures have primarily been studied in China. A 2021 review by Schuijt *et al.*⁴ examined eight studies focused on robotic-assisted fracture fixation in orthopaedic trauma patients in China, utilizing the TiRobot System (TINAVI Medical Technologies, Beijing, China). The review included a diverse set of studies from 2017 to 2019 encompassing 437 patients and included several retrospective cohort studies, prospective cohort studies, a case series, and a randomized control trial.⁴ These studies investigated various types of fractures, including those to the pelvic ring, proximal femur, and one nondisplaced scaphoid fractures.⁴ The findings indicated that robotic-assisted surgery could significantly reduce radiation exposure for both surgeons and patients, enhance the accuracy of percutaneous screw placement, and result in considerably less intraoperative blood loss.⁴ Furthermore, postoperative performance and functional outcomes were comparable to traditional methods, and fracture healing was not adversely affected.⁴ Despite the limited number of included studies, this review highlights the potential benefits of robotic-assisted fracture care, sug-

gesting a promising future for RAFR in improving surgical outcomes and patient safety in orthopaedic trauma.

4. ORTHOPAEDIC ONCOLOGY

Recent studies from China have investigated the use of the TiRobot in treating osteoid osteomas. Percutaneous CT-guided radiofrequency ablation (CT-RFA) has replaced surgical resection as the reference treatment for osteoid osteomas, as it salvages more bone with high clinical success, brief recovery, and low complication rate as compared to traditional open surgical resection.⁴⁴ However, repeated CT scans are needed during the procedure to guide the needle to the nidus, which increases operating time and radiation exposure. To combat this, the TiRobot has been implemented in a few studies to propose a new method of osteoid osteotomy using robot-assisted RFA.^{44,45} In a study of 62 patients, Wang *et al.*⁴⁵ found that, when compared to CT-RFA, patients receiving robot-assisted RFA had lower operating times, lower radiation exposure, and fewer K-wire adjustment times. While still in its infancy, robot-assisted osteotomies show promise for future development.

5. LIMITATIONS OF ROBOTIC SURGERY

Robotic systems have become well-established in hip and knee arthroplasty, with notable milestones like Stryker's announcement in March 2023 of over one million Mako total knee procedures performed.⁴⁶ This milestone underscores the maturity and success of robotic technology in knee arthroplasty. However, robotics in other orthopaedic subspecialties, such as shoulder, foot, and ankle, trauma, and orthopaedic oncology, remain at the frontier of innovation. While these emerging applications offer exciting potential, robotics presents unique challenges and limitations that must be addressed as the technology evolves.

While long-term outcomes for robotic-assisted surgery are starting to emerge in well-established fields like hip and knee arthroplasty, thanks to their longer presence in the market, data remains limited or largely unavailable in newer applications in other orthopaedic subspecialties. In a recent review, one multicenter study found that at two years, robotic TKA showed consistent enhancement in patient-reported measures across institutions, while another study noted superior pain reduction and function in cementless robotic TKA compared to manual procedures, also at two years.²⁶ One 10-year study from this review evaluating clinical outcomes in robotic TKAs found no significant differences in activity levels or implant survivorship in a South Korean population.²⁶ Most existing studies focus on short-term results, leaving a gap in understanding the enduring benefits and potential risks over time. Additionally, the availability of robotic systems for orthopaedic procedures is currently limited. These systems are only used for specific indications and are not yet widely implemented across all orthopaedic surgeries.

Robotic systems pose a significant investment to health-care systems, presenting another considerable barrier to their widespread adoption. In one study, direct costs per case for robotic TKA were \$11,615, while manual proce-

dures cost \$8,674 (excluding preoperative imaging, labor, acute stay, and supply/implant cost).⁴⁷ In hip arthroplasty, another study found that the average inpatient hospital cost for a robotic THA was \$20,046 (SD=6,165) compared to \$18,258 (SD=6,147) for conventional THA ($P < 0.001$).⁴⁸ These robotic systems require healthcare systems to make substantial initial investments, with additional pressure to recover costs over time through increased procedural volumes. Studies have shown that cost-efficacy improves through increased procedural volumes, with high-volume TKA centers (≥ 200 cases/yr) able to reduce costs to as low as \$3,931 per procedure.⁴⁹ However, the largest cost of implementing robotic surgery is the cost of the robot itself.²⁶ Many practices or hospitals enter into negotiated payment agreements with vendors or negotiate payment strategies utilizing rebates. Robotic systems are currently more prevalent in larger, well-funded hospitals, limiting availability in underserved areas and for patients with lower socioeconomic status and increased comorbidities.²⁶ Minimizing costs and ensuring equitable access to robotic surgery remain important goals for surgeons implementing these technologies.

CONCLUSION

Robotic-assisted orthopaedic surgery is an evolving and transformative field that has demonstrated significant benefits in enhancing surgical precision, optimizing patient outcomes, and expanding the scope of minimally invasive procedures. Over the past three decades, advancements in robotic technology have refined surgical techniques across multiple orthopaedic subspecialties, particularly in joint reconstruction and spine surgery. As robotic platforms continue to integrate real-time feedback mechanisms and improved imaging capabilities, their role in surgical planning and execution will likely expand. Emerging applications in shoulder, foot and ankle, trauma, and orthopaedic oncology further underscore the untapped potential of robotics in addressing complex surgical challenges. Despite cur-

rent limitations, including cost and accessibility, ongoing research and technological advancements will shape the future trajectory of robotic-assisted surgery, driving further refinement and adoption. As surgeons continue to harness these innovations, improved clinical outcomes, reduced clinical complication rates, and enhanced patient satisfaction can be anticipated, reinforcing the integral role of robotics in the future of orthopaedic surgery.

DECLARATION OF CONFLICT OF INTEREST

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Table 1. Currently Available Orthopaedic Robot Systems

Company	Device	Specialty	Degree of Automation	Procedure(s) (US Indication, if approved)	First FDA Clearance	Older generation	Notes
Alphatec	REMI	Spine	Passive	open spinal procedures, percutaneous spinal procedures, placement of pedicle screws in vertebrae in the posterior lumbar region (L1-S1), lumbar pedicle screw placement	2021		
Brainlab	Cirq	Spine	Passive	spinal screw placement	2020		
Carnegie Mellon University	MBARS	Knee	Semi-active	total knee arthroplasty	never approved		*no longer commercially available
Corion	Apollo	Knee	Passive	total knee arthroplasty	2017	OMNIBotics	
Curexo	CUVIS-spine	Spine	Passive	spinal screw placement	2021		
DePuy Synthes (Johnson & Johnson)	VELYS Robotic-Assisted Solution	Knee	Semi-active	total knee arthroplasty	2021		
eCential robotics	SURGIVISIO Platform	Spine	Passive	for conditions of the spine, pelvis, or articulation structures in which the use of stereotactic surgery may be appropriate, positioning of surgical instruments in vertebrae with a posterior approach in the thoracolumbar region	2021		
Globus Medical	ExcelsiusGPS	Spine	Passive	placement of spinal and orthopedic bone screws and interbody spacers	2017		
Hangzhou Lancet Robotics	RobPath Total Hip Application	Hip	Semi-active	total hip arthroplasty	2022		
Intuitive Surgical	da Vinci	Soft-Tissue***	Teleoperated	ulnar nerve decompression, supraclavicular brachial plexus dissection, nerve root grafting, ALIF spine surgery	2001		
Mazor Robotics, Medtronic	Mazor X (Stealth Edition)	Spine	Passive	general spinal surgery, spinal implant	2011	Renaissance X	
MicroPort	SkyWalker (Honghu) Orthopedic Surgical Robot	Knee	Semi-active	total knee arthroplasty	2022		

Company	Device	Specialty	Degree of Automation	Procedure(s) (US Indication, if approved)	First FDA Clearance	Older generation	Notes
OrthoMaquet	CASPAR	Knee, Hip	Active	total knee arthroplasty, total hip arthroplasty	never approved		*no longer commercially available. Acquired by Getinge in 2000 and further acquired and discontinued by Universal Robot Systems in 2001
Point Robotics MedTech	POINT Kinguide Robotic-Assisted Surgical System	Spine	Passive	stereotactic spinal surgery where reference to a rigid anatomical structure can be identified relative to images of the anatomy, pedicle screw implantation posterior to L1-L5 or sacral vertebrae S1	2022		
Smith and Nephew	CORI Surgical System	Knee, Hip	Semi-active	unicondylar knee replacement, total knee arthroplasty, total hip arthroplasty	2012	Navio	
Stryker	Mako	Knee, Hip	Semi-active	total knee arthroplasty, total hip arthroplasty, unicondylar knee replacement, patellofemoral knee replacement	2007	ACROBOT, RIO	
Think Surgical	Tmini	Knee	Active	total knee arthroplasty	2023		
Think Surgical	Tsolution One	Knee, Hip	Active	total knee arthroplasty, total hip arthroplasty	2008	ROBODOC	
TINAVI Medical Technologies	TiRobot	Spine	Semi-active	spinal screw placement, intramedullary nail fixation for intertrochanteric fractures	2016**		
Zimmer Biomet	ROSA Robotics, ROSA ONE	Knee, Hip, Spine, Shoulder	Semi-active	total knee arthroplasty, total hip arthroplasty, partial knee arthroplasty, placement of pedicle screws in vertebrae with a posterior approach in the thoracolumbar region, anatomic total shoulder arthroplasty, reverse total shoulder arthroplasty	2009		

Adapted from Lee *et al.*,⁵⁰ Li *et al.*,⁵¹ and the FDA 510(k) Premarket Notification Database⁵²

*No longer commercially available

**Received China FDA Approval

***Da Vinci is currently FDA-approved for laparoscopic surgery, with expanded approval for prostate surgery, mitral valve repair, and gynecological procedures



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