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Review

Robotics in Arthroplasty: A Comprehensive Review

David J. Jacofsky, MD [*], Mark Allen, DO

The CORE Institute, Phoenix, Arizona

A R T I C L E I N F O

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ABSTRACT

Robotic-assisted orthopedic surgery has been available clinically in some form for over 2 decades, claiming to improve total joint arthroplasty by enhancing the surgeon's ability to reproduce alignment and therefore better restore normal kinematics. Various current systems include a robotic arm, robotic-guided cutting jigs, and robotic milling systems with a diversity of different navigation strategies using active, semiactive, or passive control systems. Semiactive systems have become dominant, providing a haptic window through which the surgeon is able to consistently prepare an arthroplasty based on preoperative planning. A review of previous designs and clinical studies demonstrate that these robotic systems decrease variability and increase precision, primarily focusing on component positioning and alignment. Some early clinical results indicate decreased revision rates and improved patient satisfaction with robotic-assisted arthroplasty. The future design objectives include precise planning and even further improved consistent intraoperative execution. Despite this cautious optimism, many still wonder whether robotics will ultimately increase cost and operative time without objectively improving outcomes. Over the long term, every industry that has seen robotic technology be introduced, ultimately has shown an increase in production capacity, improved accuracy and precision, and lower cost. A new generation of robotic systems is now being introduced into the arthroplasty arena, and early results with unicompartmental knee arthroplasty and total hip arthroplasty have demonstrated improved accuracy of placement, improved satisfaction, and reduced complications. Further studies are needed to confirm the cost effectiveness of these technologies.

Robotic-assisted orthopedic surgery has been available clinically in some form for over 2 decades, claiming to improve total joint arthroplasty by enhancing the surgeon's ability to reproduce alignment and therefore better restore normal kinematics. However, recently, robotic surgery has gained increasing attention as its adoption has grown along with its approved surgical indications and a growing body of supporting literature [1,2]. As robotic products have been appearing in various technology types and platform varieties, many surgeons are finding it challenging to parse out marketing claims from fiction and to understand the differences in these products. This article is intended to serve as both an historical reference and a review of the current state of robotics in arthroplasty.

According to experts such as Roger Bohn, every industry, from aviation to manufacturing to financial services to firearms safety to military activity, has followed the 5 phases of the development. These 5 phases are (a) consideration of the industry as an “art” by experts in the field, (b) development of “rules plus instruments,” (c) development of “standardized procedures and templates,” (d) automation, and (e) computer integration [3]. Industries move through these phases predictably, often to the surprise of those in the field. The things that aircraft are now capable of, for example, and the massive increase in safety and cost effectiveness seen as a result, would never have been believed to be possible by pilots of the past. Aircraft autopilot systems, for example, use real-time data related to wind speed, humidity, barometric pressure, altitude, weight distribution, turbulence, moments of inertia, and a near infinite number of electronic and system setting combinations to determine how to follow a flight path that is changing in real time. Importantly, this computer is calculating these variables not only where the aircraft currently is but also where it will be in the future, across all the possible flight paths it may take. It then also considers how to move through the flight path to optimize fuel efficiency and passenger comfort. Autopilot does this with

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[*] Reprint requests: David J. Jacofsky, MD, The CORE Institute, 18444 N 25th Ave, Phoenix, AZ 85023.

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redundancy as well, to minimize the chance of system failure leading to errors. In these industries, outcomes improve as intuition is replaced by accurate real-time data and as science and evidence replace the concept of “art” [3]. The health care industry is hovering in or around stage 3, and as is typical in other industries, the forward rate of movement through the stages seems to be accelerating. Although the timing of when automation and computer integration become the unequivocal and required standard is never prospectively clear, health care is undeniably on this forward path [3].

Despite dramatic improvements in complication rates, morbidity, and mortality, total joint arthroplasty procedures still remain major surgical undertakings and are accompanied by significant risks. The recovery period can also be challenging for total knee arthroplasty (TKA) and total hip arthroplasty (THA) patients, including stiffness, weakness, significant impairment in ambulation in the near term, and postoperative pain sometimes requiring narcotic analgesics to manage pain in the months following [4-12]. In addition, arthroplasty outcomes may be limited in some cases due to technical errors, which can lead to early implant failures such as premature implant loosening, instability, and increased rates of dislocation [13]. Furthermore, even a seemingly well-executed arthroplasty may not be associated with high patient satisfaction for reasons that still sometime are elusive [14-16].

Motivated by a desire to reduce complications and to improve patient satisfaction, there have been many technological advances, such as computer navigation, patient-specific cutting guides, and semicustom patient-specific implants in the adult reconstruction arena in recent years. However, as new technology continues to be incorporated into practice, it is imperative to examine the reproducibility, precision, and accuracy of these advances. Improved patient outcomes are mandatory to justify added surgical time, integration into surgical flow, and increases in direct cost that these changes inevitably cause. Health care reform initiatives are of growing importance, as well, amid concerns over providing care to increasing numbers of patients with chronic conditions. By 2019, an estimated 19.3% of the U.S. gross domestic product will be devoted to health care [17]. The field of health care and current payment systems in the United States must fundamentally change to contain this spending while improving quality of care. Improving the delivery of surgical care will aid tremendously in helping hospitals to improve the experience of patient care and reduce health care costs, as surgical care currently accounts for an estimated 52% of hospital admission expenses in the United States [17]. As the landscape of health care evolves, there is an inherent responsibility to be critical of the results and cost effectiveness of new technology that may be unproven with level I evidence.

Robotic surgery has become an increasingly popular tool for orthopedic surgeons in the operative suite. These robotic platforms have been shown to increase accuracy and precision of component placement during unicompartmental knee arthroplasty (Mako, Navio), TKA (TSolution One Surgical System (formerly called Robodoc)), iBlock, and THA (TSolution One Surgical System, Mako). Improved alignment has been shown to increase implant survival and decrease revision surgery [18]. Over the long term, no industry has ever seen robotic technology be introduced and ultimately not show an increase in production capacity, improved accuracy and precision, and lower cost. As in all development efforts, robotics in other industries generally undergoes a period of development and refinement before rapid adoption, which occurs after the benefits of the technology become clear. Robotics is now being introduced in the arena of arthroplasty in ways that seem likely to portend viable improvements over prior failed robotic technologies in the health care space.

History of Robotics

Several definitions of “robot” exist. According to the Robot Institute of America, a robot is defined as a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks [19]. Webster's Dictionary describes a robot as an automatic device that performs functions normally ascribed to humans or a machine in the form of a human [20]. Mike Brady is perhaps the world's most-respected robotics engineer and is the endowed BP Professor of Information Engineering in the Department of Engineering Science at University of Oxford, where he founded the Robotics Research Laboratory. The field of robotics, according to Mike Brady, is that field concerned with the intelligent connection of perception to action [21]. One of the first instances of a mechanical device built to regularly carry out a particular physical task occurred around 3000 BC where Egyptian water clocks used human figurines to strike the hour bells. Giovanni Torriani created a wooden robot that could fetch the Emperor's daily bread from the store in 1557 [22]. Although these early inventions may have sparked some inspiration for the modern robot, the scientific progress made in the field of robotics in the 20th century has obviously surpassed previous advancements significantly.

The earliest robots, were created in the early 1950s by Devol, from Louisville, KY [22]. He invented and patented a reprogrammable manipulator called “Unimate,” but he was unable to sell his product in the industry. In the late 1960s, the “Father of Robotics,” Joseph Engleberger, acquired Devol's robot patent and was able to modify it into an industrial robot and form a company called Unimation to produce and market the robots [22]. This robot was the standard hydraulic robot in industry until electrically driven robots were developed.

This work completed in the 1950s and 1960s led to robotic advancements in the surgical field. The first robotic surgical system, Puma 560, was used in conjunction with computed tomography (CT) guidance during neurosurgical biopsies in 1985, allowing the procedures to be performed with greater precision [23]. In 1988, the same system was used for a transurethral resection of a prostate and eventually led to the development of the ProBot system, designed to specifically aid in the resection of prostatic tissue, which proved that predictable soft tissue surgery was feasible with robotics [24]. Since then, the field of medical robotics has grown tremendously.

Technology Platform Types

Passive, Active, and Semiactive

Different types of robots are used in robotic surgery, allowing for different methodologies of execution. These robotic approaches have been classified into 3 main categories: passive, semiactive, and active [25,26]. Passive systems complete a portion of the procedure under continuous and direct control of the surgeon. Active systems perform a task independent of any surgeon involvement. Semiactive systems require surgeon involvement, but providing feedback, usually tactile, to augment the surgeon's control and, theoretically, operative safety. These semiactive systems are also known as “haptic systems.” In contrast to computer-assisted surgery, which provides passive guidance and feedback, the robotic system provides passive haptic restraints for surgical resection. Therefore, the surgeon cannot, for example, burr bone outside the preset volumetric parameters, confining the treatment to only the planned level of resection in 3 dimensions. Haptic sensation is provided to the surgeon through auditory (beeping), tactile (vibratory), and visual (color change on the computer screen). These alerts trigger and provide feedback to the surgeon as the defined resection parameters are approached; this prevents over resection and malpositioning during the procedure. The process relies on quantitative data rather than surgeon feel and intuition to facilitate clinical decision-making.

Another form of semiactive technology controls the speed and depth of the working instrument. Once a defined bone resection plan is created and the procedure is begun, the semiactive system correlates the position of the burr within the operative field. When the burr approaches the border of the planned resection (ie, depth or medial/lateral), the computer system will slow the speed of the burr or retract the burr into the hand piece, effectively decreasing the potential for over resection of the bone. This technology allows the surgeon to perform the bone resection within defined parameters with feedback and controls that limit error and improve accuracy.

Image Based vs Imageless

All orthopedic robotic systems currently require a platform and “preapproved” plan on which to base the surgical procedure. The presence of a plan to execute is one aspect of robotic orthopedic surgery that differentiates it from other specialties that speak about the use of robots. Having a specific plan to reproduce that allows the surgeon to preoperatively (or in the case of imageless systems, just before bone resection) think about and approve the end result is a major advantage of these systems. Other robotic system types that function simply as a tool for a surgeon who is thinking about the end result as he operates in real time do not portend this benefit. These systems can be either image based or imageless. Patients' anatomy must be registered via mapping points on the bone with a navigated tool during the registration process in both system types so that the “robot” knows where the cutting tools are in space in relation to the anatomy. In image-based systems, this registration is directly tied to the preoperative imaging, currently CT or magnetic resonance imaging. These detailed 3-dimensional images are used within the software preoperatively to identify bone resection depth, preoperative and target postoperative alignment, optimal component size and alignment, leg length and offset restoration, volumetric bone removal, deformity correction, and the boundaries of hard tissue removal. Having preoperative images and a preoperative plan to approve allows the surgeon to devise the entire surgical resection plan, implant sizing, implant positioning, and alignment before even entering the operating room. This preoperative imaging is then correlated to the patient's anatomy during the procedure after exposure of the joint before initiating bone resection, generally using computer navigation registration of easy to locate and important landmarks. The robot then executes based on the surgeon's preapproved preoperative plan. Potential disadvantages of image-based systems include the increased cost of the imaging study, patient inconvenience and additional travel to obtain the study, and risk of radiation exposure during the CT scan [1,27].

Imageless systems rely on registration of the patient anatomy after surgical exposure in the operating room to create a virtual model and surgical plan that is then executed during the procedure. This registration relies solely on the surgeon's accuracy of inputting data points at the time of surgery. Without a preoperative image and plan, implant size, position, and alignment are determined intraoperatively after patient registration. Advantages to imageless systems include decreased cost of the procedure, increased convenience to the patient, and no preoperative radiation exposure. Potential disadvantages include lack of true preoperative planning and inability to verify the anatomic registration points at the time of surgery against a more detailed 3-dimensional imaging set.

Closed vs Open Platforms

Robotic systems may have “closed” or “open” platforms, which may limit the surgeon's ability to choose which implant systems and what manufacturer's implants may be used based on compatibility. Some systems have closed implant platforms allowing only one specific manufacturer's implant(s) to be used during the procedure. Open implant platforms can allow different implant companies and designs to be used per the surgeon's preference or patient's demand. Surgeons may not be comfortable utilizing a different implant for the sake of performing a robotic assisted procedure or may prefer 1 implant design rationale over the one available on the robotic system in their hospital. As outcomes related to robotics become more understood, surgeons will individually need to decide whether and when the benefits of robotics outweigh the benefits they believe exist in the implant system they currently use if a closed system is preferable. In the case of open systems, some specificity and functionality is generally lost to satisfy the need for an open system, and therefore on the other hand, a surgeon may need to decide if the benefits of the open implant options outweigh the loss of certain functionality in open platform systems. As an example, many open systems have 3D data on a number of implant types but lack the depth of design specificity and biomechanical rationale data to optimally predict kinematics for implant positioning. If coupled with an imageless system that uses certain registration landmarks and lacks the ability to include individual anatomic variation, some believe that some specificity and predictive value is lost [1]. The clinical significance of these differences remains debated.

Soft Tissue vs Hard Tissue

Much of the initial field of robotics has focused on advancing laparoscopic surgical techniques. In 2000, the Food and Drug Administration (FDA) approved the first robotic surgical system—the da Vinci Surgical System. This is considered a sophisticated robotic platform designed to expand a surgeon's capabilities and offer a state-of-the-art minimally invasive option for major surgery. Physicians have used the da Vinci System successfully worldwide in approximately 1.5 million various surgical procedures to date in multiple surgical fields including cardiac, colorectal, general surgery, gynecology, head and neck, thoracic, and urology [28]. The da Vinci System is a passive, remote, telemanipulator system that allows the surgeon to sit at the da Vinci console and view a magnified, high-resolution 3D image of the patient's anatomy. A surgeon is actively dissecting, cutting, cauterizing, and suturing in real time, while the latest robotic and computer technologies scale, filter, and translate the surgeon's hand movements into precise micromovements of the da Vinci instruments. A surgeon must learn the system controls, adjust to the magnified view, and ultimately make surgical decisions throughout the case that are permanent and irreversible. There is, therefore, a long learning curve and a recognized need to appropriately credential and mentor new surgeons to this technology. The system has no haptic boundaries per se, and the potential improved safety is due to the robot being a better “tool” than traditional dissecting instruments by helping scale and filter surgeon movements.

In contrast to the da Vinci's model on soft tissue, the field of orthopedics has focused on hard tissue models in the advancing robotic field. Knee and hip arthroplasty surgeries require a very high degree of precision when preparing and placing the implants. Since bone does not meaningfully deform during procedures, using bony landmarks allows for reliable and precise anatomic positioning of bone removal via cutting or burring during surgery. The arrival of

Mako robotic arm–assisted surgery, after receiving FDA clearance in 2008, gave orthopedic surgeons an improved ability to obtain precision in partial knee arthroplasties [29]. The Mako system allows the surgeon to use a preoperative CT scan to better visualize the joint, alignment, and deformity before surgery. A 3D view before and during surgery allows the implant position to be customized to the patient's anatomy and the knee ligaments to be balanced virtually. In contrast to the da Vinci system, the Mako system virtually generates the final outcome which is modified as desired and approved by the surgeon, before an incision is even made. Unlike soft tissue robotic surgery systems, image-based, and some imageless, orthopedic systems allow for the cognitive portion of the surgery to be edited, if needed, without patient consequence before the start of the surgery. The surgeon creates and analyzes the final outcome in 3D before surgery and bone resection even begins. This is a very important distinction in understanding differences between orthopedic and nonorthopedic robotic platform strategies.

Robotics in Orthopedics

CASPAR

CASPAR (URS Ortho, Rastatt, Germany) was another early autonomous system. The CASPAR system (Ortho-Maquet/URS, Schwerin, Germany) was an image-guided active robot used for THA and TKA similar to Robodoc [43]. Initial results focused on improving and decreasing the variability in the mechanical axis of the leg. Many studies have demonstrated the importance of the mechanical axis in TKA function, outcomes, and longevity [44,45]. A study performed by Siebert et al, using CASPAR for TKA, noted improved tibiofemoral alignment [46]. However, despite improving tibiofemoral alignment, the CASPAR system was somewhat restrictive. Femoral and tibial bicortical bone screws had to be placed preoperatively (as an initial first surgery) as fiducial markers for registration of the preoperative CT scan allowing for intraoperative robotic function. Operating time for these first 70 cases averaged 135 minutes, but toward the end of the study, did achieve a steady state of approximately 90 minutes, which was approximately equal to the control group. No major adverse events related to the CASPAR system were found.

CASPAR for THA has been shown to increase the accuracy of femoral preparation and position of the cementless prosthesis in the femoral cavity [47]. As defined in the study and when compared with manual THA, the CASPAR group demonstrated better average percentage of bone implant contact (by 33%), improved bone implant gap percentage and decreased maximum gap width [47]. Conversely, CASPAR has been shown to have a low accuracy of postoperative anteversion angles of the femoral stem compared with the preoperative plan [48]. A prospective trial compared the clinical outcome of both conventional (35 hips) and robotic milling (36 hips) procedures using the CASPAR system showing the CASPAR system to have surgeries lasting about 50 minutes longer, patients showing increased blood loss as evidenced by 1.2 mg/dL less hemoglobin, and having significantly lower hip abductor function, and an increased incidence of Trendelenburg's sign [49]. Although improvement in the Harris Hip Score also was comparable in both groups, the incidence of complications was higher in the CASPAR group [49]. The authors recommended critical consideration of possible complications before initiating robotic-assisted THA [49]. These early attempts at robotics, with less advanced systems, clearly showed that robotics can have the potential to portend risks greater than their benefits. The CASPAR robotic system is no longer available for clinical use, and the company is no longer in business.

Acrobot

Acrobot is an acronym for active-constraint robot and was developed largely at the Imperial College of London. The Acrobot used a CT-based software to accurately plan the procedure preoperatively. Intraoperatively, the surgeon guided a small, special-purpose robot, called Acrobot, which was mounted on a gross positioning device. The Acrobot used active-constraint control, which constrains the motion to a predefined region, and thus allowed the surgeon to safely cut the knee bones to fit a TKA prosthesis with high precision. A noninvasive anatomic registration method was used, and this was a predicate to more modern haptic systems such as Mako. The company was acquired by Stanmore Implants Worldwide in 2010 and subsequently agreed to withdraw from robotics and Mako Surgical acquired the assets as part of a confidential patent infringement settlement in 2013.

Contemporary Systems

Robotic systems coupled with navigation were initially developed in orthopedics to improve clinical outcomes and allow consistent reproducibility of more accurate results. Most robotic systems consist of similar components. The steps to a robotically assisted surgery typically involve (a) creating a patient-specific model and interventional plan, (b) intraoperatively registering the model and plan to the patient's anatomy, and (c) using robotic assistance to make bone cuts and carry out the preoperative plan on the patient. Many robotic systems have been developed and prototyped, but only a handful has been successfully used in a clinical setting. More recent and commonly used systems include the Navio PFS (Blue Belt Technologies, Plymouth, MN), the iBlock robotic cutting guide (OMNIlife Science, East Taunton, MA), and the MAKO Robotic Arm Interactive Orthopedic System (Rio; Mako Surgical Corporation, Fort Lauderdale, FL; Tables 1 and 2). Recent advancements have led to further development in software and technology used for THA, TKA, ACL reconstruction, and high tibial osteotomy procedures.

Robodoc/TSolution One Surgical System

In the early 1990s, Howard A. Paul, DVM, and William L. Bargar, MD, teamed up to develop a system to prepare the femoral side of a THA to facilitate the use of cementless stems and improve bony ingrowth [30]. In 1992, the Robodoc system (initially by Curexo Technology, Fremont, CA) designed by Drs Paul and Bargar made history by being the first robot used clinically in orthopedic surgery. This system, initially called Robodoc (Curexo Technology, Fremont, CA), was one of the first to be used for joint arthroplasty [30]. Robodoc was an image-based, active autonomous, milling robotic system. Once the system is positioned and fixed to the patient, markers in the surgical field (fiducials) are then used as a reference

Table 1
Contemporary Robotic Platforms.

Name	Applications	Control	Resection Type	Platform	Preop Image
Robodoc	TKA, THA (femur)	Autonomous	Mill	Open	CT scan
Mako	UKA, THA, TKA	Semiautonomous haptic	Burr, reamer, saw	Closed	CT scan
Navio PFS	UKA	Semiautonomous	Burr	Open	None
iBlock	TKA (femur)	Autonomous	Manual saw	Closed	None

TKA, total knee arthroplasty; THA, total hip arthroplasty; UKA, unicompartmental knee arthroplasty; CT, computed tomography.

Table 2
Outcomes of Robotic-Assisted Arthroplasty.

Author (y); Platform	Brief Outcomes Summary	Ref.
Total knee arthroplasty (TKA)		
Borner et al (2004); Robodoc	Postoperative knee alignment was restored to the planned ideal mechanical axis (00) in 97% of cases. Remaining cases were restored within 10 of ideal mechanical axis.	[37]
Song et al (2011); Robodoc	Significantly less radiographic outliers postoperatively with robotic TKA. No significant difference in patient-reported outcomes.	[38]
Song et al (2013); Robodoc	No differences in postoperative range of motion, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores, and Hospital for Special Surgery (HSS) scores. Improved accuracy of flexion/extension gap balance with robotic-assisted TKA.	[39]
Koulalis et al (2011); iBlock	Improved accuracy and efficiency of final bone resections in all planes vs conventional computer-assisted navigation techniques.	[56]
Suero et al (2012); iBlock	Significant reduction in postoperative mechanical alignment variability and tourniquet time compared with conventional navigated instrumentation.	[57]
Koenig et al (2012); iBlock	Bone resections within 30 of neutral in 98% of cases.	[59]
Ponder et al (2013); iBlock	Significantly more accurate and repeatable bone resections than conventional instrumentation.	[58]
Unicompartmental knee arthroplasty (UKA)		
Gregori et al (2014); Navio PFS	Postsurgical mechanical axis alignment within 10 of the plan in 91% of cases. Improved Oxford Knee Scores from preoperative to 6 weeks postoperative.	[52]
Wallace et al (2014); Navio PFS	Rapid learning curve of an average of 8 (5-11) procedures with the average time over the first 4 cases (tracker placement to trial acceptance) of 64.9 (27-102) min.	[53]
Simons et al (2014); Navio PFS	Narrowed learning curve of the Navio system from an initial case duration of 85-48 min after 5 surgeries.	[54]
Lonner et al (2015); Navio PFS	Medial UKA achieved accurate implementation of the surgical plan with small errors in implant placement.	[51]
Lonner (2009); Mako	Robotic arm—assisted UKA demonstrated increased accuracy in recreating the posterior tibial slope and coronal tibial alignment.	[65]
Coon (2009); Mako	Robotic UKA demonstrated short learning curve and excellent radiographic outcomes (2.5 times improvement in tibial alignment, lower SD).	[66]
Jinnah et al (2009); Mako	Learning curve of robotic-assisted UKA procedures averaged 13 cases. The learning cases did not present an increased risk to the patient.	[67]
Lonner et al (2010); Mako	Tibial component alignment was found to be more accurate and less variable for Mako robotic arm—assisted surgeries compared to those with manual instrumentation.	[68]
Pearle et al (2010); MAKO	The planned and intraoperative tibiofemoral angle was within 1 degree. The postoperative long leg axis radiographs were within 1.6 degrees.	[63]
Citak et al (2013); Mako	UKA was more precise using a semiactive robotic system with femoral and tibial component position compared to the manual technique.	[69]
Jones et al (2013); Mako	Robotic arm—assisted UKA resulted in significantly lower postoperative pain and greater functionality as measured by American Knee Scores compared with manual UKA.	[29]
Coon et al (2014); MAKO	Mako UKA had a cumulative revision rate of 1.2% and high patient satisfaction at an average of 29.6 months follow-up.	[72]
Coon et al (2015); MAKO	At 2-year follow-up, 92% of patients indicated that they were either very satisfied or satisfied with their robotic arm-assisted UKA procedure.	[74]
Bicompartmental arthroplasty		
Tamam et al (2015); Mako	Patients who received patellofemoral arthroplasty in combination with medial or lateral UKA demonstrated 83% good to excellent results.	[70]
Conditt et al (2016); Mako	Robotic-assisted bicompartmental arthroplasty shows good survivorship and functional outcomes at 2-year follow-up with 1/48 procedures requiring revision to TKA.	[71]
Total hip arthroplasty (THA)		
Bargar et al (1998); Robodoc	Robotic THA showed statistically improved fit, fill, and alignment when using ROBODOC to perform cementless primary THA when compared with manual THA	[30]
Bach et al (2002); Robodoc	Robotic THA showed equivalent kinematic gait analysis, pelvic, and hip motion when compared with the conventional THA group	[35]
Haigo et al (2003); Robodoc	Robodoc femoral milling has shown decreased intraoperative embolic events compared with standard femoral broach preparation.	[36]
Schulz et al (2007); Robodoc	Concerns and limitations with aborted surgeries and increased operating time with clinical reports noting technical complications in almost 10% of cases.	[42]
Nawabi et al (2012); Mako	Mako-assisted THA had 4-6 times greater accuracy with version and inclination vs manual THA.	[79]
Illgren (2013); Mako	Significantly less dislocations at 6 months with robotic-assisted THA compared with manual THA performed with a posterior approach.	[13]
Elson et al (2013); Mako	95% of cup placement after impaction was recorded to be within 50 of the surgical plan.	[78]
Domb et al (2014); Mako	100% (vs 80% manual) of Mako THAs placed within the Lewinnek safe zone for anteversion and inclination and 92% (vs 62% manual) within the Callanan safe zone.	[77]
Jerabek et al (2014); Mako	Improved accuracy in achieving desired leg length and offset using Mako-assisted THA compared with manual THA.	[80]
Bukowksi et al (2014); Mako	Significantly higher modified Harris Hip scores and University of California, Los Angeles activity level with Mako-assisted THA compared with manual THA.	[83]
Suarez-Ahedo et al (2015); Mako	Robotic-assisted THA allowed for the use of smaller acetabular cups in relation to the patient' femoral head size, indicating greater preservation of acetabular stock.	[81]

for image guidance. After anchoring in bone, the robot would automatically mill a cavity in the femur for the stem. Initial pilot studies were performed in dogs and human trials began in 1992 [30]. The European Union approved Robodoc for sale in 1994 with the first system being installed in Germany [31]. The early trials in Germany with an older version of the robot and related software led to multiple lawsuits and significant negative media coverage due to a high rate and severity of complications. This is not a condemnation of the current state of robotics but rather support for the cautious adoption of new technology as it develops. Worldwide, the system has been used for >24,000 joint arthroplasties. More recently, the system has been expanded to focus on TKA using a similar technical approach.

Initial clinical trials began in 1994 and were approved by the FDA in 2008 [31-33]. As in the early Robodoc system design, it still remains CT based but is now a computer-aided, robotic milling device that allows cavity preparation for hip arthroplasty and surface preparation for TKA. Preoperatively, the surgeon uses the "ORTHODOC" workstation and transfers data, completes the segmentation, and plans the implant positioning before engaging and operating the robot intraoperatively. Its clinical success and utility has been demonstrated in a series of clinical trials [33,34]. In a study of 72 knees, Park and Lee [34] compared outcomes of robotic assisted with conventional knee arthroplasty at mean follow-up of approximately 4 years. The authors demonstrated significant differences in the coronal femoral component angles (mean, 97.7° vs 95.6°; $P < .01$), sagittal femoral angle (mean, 0.2° vs 4.2°; $P < .01$), and sagittal tibial angles (mean, 85.5° vs 89.7°; $P < .01$) between the robotic-assisted and conventional cohorts. In this particular study, however, no differences in Knee Society Scores were demonstrated. Other authors have proven that overall implant positioning and alignment are consistently within 1° of error in all planes and radiographic improvements in accuracy with robotic assisted arthroplasty compared with conventional techniques [2,38,45]. The company was formerly known as Curexo Technology Corporation and changed its name to Think Surgical Inc in September, 2014.

The strengths of the Robodoc system include an increase in accuracy for dimension and placement, the ability to "see" where the robot is milling, and it achieves a more consistent outcome. The system is an open platform with the capability to utilize numerous implant manufacturers and designs. A randomized multicenter study conducted from 1994 to 1998 showed statistically improved fit, fill, and alignment when using Robodoc to perform cementless primary hip arthroplasty when compared with manual THA [30]. The Robodoc group also had no intraoperative fractures in the series. The Robodoc THA procedure was shown to have equivalent kinematic gait analysis, pelvic, and hip motion when compared with the conventional THA group, begging the question that many ask about whether clinically significant improvements are seen [35]. Preparation of the proximal femur with Robodoc milling has been shown to have a significant decrease in intraoperative embolic events compared with standard femoral broach preparation [36]. The first 100 Robodoc TKA procedures were performed by Professor Martin Börner at the Berufsgenossenschaftliche Unfallklinik in Frankfurt, Germany [37]. In this study, the results showed that the Robodoc system made cuts that were good enough to allow cementless implantation for both the tibia and femur in 76% of the patients. In 97% of the cases, the alignment of the knee was restored to the planned ideal mechanical axis (0° error). In the remaining 3 cases, the knee alignment was restored to within 1° of the ideal mechanical axis. In 2 different prospective studies comparing Robodoc assisted to manual TKA, the robot had more accuracy and less variation in the mechanical axis and had no difference in patient-reported outcome measures [38,39]. In both studies, the Robodoc-assisted TKA procedures averaged 25 minutes longer than the manual procedures but demonstrated less postoperative bleeding.

The Robodoc system is not without weakness. The time needed for planning, registration, and milling is increased compared with traditional surgery and compared with many other robotics platforms. The increase in operative time is a known potential risk factor for prosthetic joint infection [40]. There is also excessive heat generated during milling. If the robot monitoring system detects an error (such as movement of the bone), the robot will stop and the recovery process is a series of steps that must be completed to allow the procedure to safely continue. In addition, surgeons do not have the ability to intervene, and it is difficult to modify the surgical plan intraoperatively. The surgeon has no control of bone preparation after the plan is complete. The robot unit itself is quite large. The current hip application is limited to femoral preparation only; however, it can assist in acetabular positioning by providing the calculated femoral anteversion to provide an appropriate estimate of combined anteversion and decrease component impingement. The application does not allow for live kinematic joint assessment nor final implant position information.

Initial concerns and limitations focused on aborted surgeries and increased operating time after early clinical reports noted technical complications in almost 10% of cases [41,42]. These complications included loosening of the fixed pin system leading to the need to reregister patients, the inability to reregister patients, and errors in workspace recognition. Many surgeries were aborted for various reasons, including when the expected time would exceed 30 minutes to recover from an error, when there were repetitive failures on a step that could not be skipped, or when soft tissue was in danger of being damaged. The most common errors occur after the milling procedure begins, are secondary to interactive factors, and are when the patella tendon was in danger of being damaged [32].

Navio PFS

Navio PFS (Blue Belt Technologies, Plymouth, MN) is a handheld, image-free, open-platform, smart instrument that provides freehand sculpting for unicondylar and patellofemoral knee arthroplasty which was FDA approved in 2012 [50]. Although often referred to as "robotic," the interactive, surgeon-controlled, handheld cutting tool has an end-cutting burr that extends and retracts so that only the planned bone is removed. The lightweight robotic tool combines image-free intraoperative registration, planning, and navigation with bone preparation. As a semiautonomous system, it monitors the surgeon's movements of the burring tool, with safeguards in place to optimize both accuracy and safety via the retraction of the burr tip when the edge of the desired bone removal volume is approached. Navio uses optical-based navigation with an imageless system to provide 3D morphed images and views of the procedure, thus creating a virtual model of the osseous knee. The system continuously tracks the position of the patients' lower limb and the handheld burr, so that the limb position and degree of knee flexion can be changed constantly during the surgical procedure to gain exposure to different parts of the knee during registration and bone preparation.

The Navio system has certain strengths. It is imageless, therefore, eliminating the risk of radiation exposure and associated cost with preoperative imaging. Currently, it uses open implant architecture compatible with multiple implant systems. However, Navio does not rely on "haptic" feedback. Rather, it provides protective control against inadvertent bone removal by modulating the exposure and speed of the motorized burr. Ultimately, this technology strategy alone makes the overall usefulness somewhat limited for larger procedures (eg, TKA) where burring would be onerous and relatively slow. In addition, the safety of the burr retraction is limited to its sensitivity and retraction speed. Users will notice that if the burr is moved quickly, bone outside the planned volume is able to be removed before burr retraction.

Implant accuracy was investigated using a cadaveric study of the medial UKA Navio system and was able to demonstrate implant position within the expected target with low rotational, angular, and translational errors [51]. The first 57 patients undergoing unicompartmental knee arthroplasty (UKA) using the Navio handheld robotic system were evaluated for clinical and functional outcomes, demonstrating postsurgical mechanical axis alignment within 1 degree of the intraoperative Navio plan in 91% of cases [52]. The cutting phase time decreased on average by 32.5 minutes from first to quickest procedure for the 3 surgeons. Improved Oxford Knee Scores were seen from preoperative to 6 weeks postoperative, and the mean mechanical axis deformity was reduced with UKA within the group.

Navio is currently only approved for UKA which does limit its usefulness compared with other available systems, at least at this time. There is a fairly rapid learning curve of an average of 8 procedures (range = 5-11) with the average time over the first 4 cases (tracker placement to trial acceptance) of 64.9 minutes (range = 27-102) [53]. Another study narrowed the learning curve of the Navio system from an initial case duration of 85-48 minutes after 5 surgeries [54]. There is limited complication and outcome data available.

iBlock

The iBlock robotic cutting guide (OMNIlife Science, East Taunton, MA) was previously known as Praxiteles and was FDA approved in 2010 [55]. It is a motorized, bone-mounted cutting guide that positions the saw guide for all femoral resections according to the surgeon's plan, allowing the surgeon to then complete the resections with a standard oscillating saw. Utilized with the NanoBlock, a separate, adjustable, resection block used for tibial resection, the system is an imageless robotic TKA platform. The OmniBiotics computer station uses bone morphing technology to generate a unique 3D digital model of the patient's knee. All anatomic data are acquired intraoperatively with surgeon registration. The system allows for planning of implant positioning and sizing intraoperatively and visualizing planned bone cuts before they are made.

In at least some studies, iBlock's automated cutting guide results in more efficient and more accurate femoral cuts in comparison to the conventional navigation method in a cadaveric model [56]. A cadaveric study compared the automated cutting guide of iBlock to the conventional computer-assisted TKA technique for femoral preparation. The mean femoral preparation time was shorter with the automated cutting guide than the conventional method (5.5 vs 13.8 minutes, $P < .001$). The average deviation in the final bone resections was more accurate with iBlock's automated cutting guide in all planes (frontal/rotational, sagittal, and cut height direction) [56]. The adjustable cutting block was found to provide equal or better component alignment while decreasing postoperative mechanical alignment and tourniquet time compared with conventional navigated instrumentation [57]. The femoral resections using a robotic cutting guide were compared with conventional and +0.5-mm press fit block on sawbones models, and the robotic guide was found to be subdegree and submillimetric, allowing for significantly more accurate and repeatable bone resections than conventional instrumentation [58].

There are very limited clinical data available for this system. A retrospective review of the first 100 cases with the imageless computer-navigated TKA robotic cutting guide at a single institution was performed, allowing 1 surgeon to make bone resections within 3° of neutral in 98% of cases [59]. Radiographic limb alignment was less precise, which is consistent with the known limitations inherent to this measurement technique. An additional 15 minutes during the first 10 cases and 5 additional minutes during the second 10 cases on average, without compromising accuracy, can be expected. The iBlock system is limited by having no haptic feedback, only being available for TKA applications, having a closed platform, and having limited kinematic assessment after implantation of trials and/or implants.

Mako

The Robotic Arm Interactive Orthopedic System (Rio; Mako Stryker, Fort Lauderdale, FL) is a haptic system available in clinical practice for unicompartmental knee arthroplasty, THA, and TKA. As an image-based system, a preoperative CT is used in surgical planning to help determine component sizing, positioning, and bone resection; this is confirmed and adjusted intraoperatively based on the patient's specific kinematics before any surgical resection. During the procedure, the robotic system provides haptic feedback to prevent bone resection outside the executed plan [60]. The MAKO system is currently being used commonly for robotic-assisted UKA and THA procedures, and the total knee platform has been recently FDA approved. The MAKO system has a relatively large and growing body of published literature.

Mako robotic arm–assisted procedures have been shown to overcome technical challenges associated with manual partial and/or multicompartmental knee procedures. A series of feasibility studies demonstrated that, as compared with manual techniques, the robotic system has increased accuracy in recreating the posterior tibial slope and coronal tibial alignment [61-63]. The addition of a robotic system significantly decreases the learning curve seen during the adoption of UKAs with traditional instrumentation [64-66]. The learning curve of robotic-assisted UKA procedures according to 1 study averaged 13 cases, and the learning cases did not present an increased risk to the patient [67]. In a retrospective comparison of patients who underwent Mako-assisted UKA (n = 31 patients) with patients who underwent manual UKA (n = 27 procedures) by a single surgeon, tibial component alignment was found to be more accurate and less variable for Mako-guided surgeries compared to those with manual instrumentation [68]. Similar findings were seen in a study of 12 cadaveric knees; Mako-assisted UKA provided more accurate alignment compared with manual technique [69]. There are also data showing support for improved outcomes with bicompartmental arthroplasty using robotic assistance. In 1 study, a total number of 29 patients (30 knees) with a mean age of 63.6 years were identified who received a patellofemoral resurfacing in combination with medial or lateral compartment resurfacing demonstrated 83% good to excellent results [70]. Other studies have shown similarly improved results with bicompartmental arthroplasty and preservation of the cruciate ligaments [71]. More technically demanding procedures may further drive adoption of robotics.

Clinical outcomes may be positively affected by the use of robotics as well. Mako robotic arm–assisted UKA resulted in significantly lower postoperative pain ($P < .05$) and greater functionality 3 months after surgery as measured by American Knee Society Scores >160 (excellent), compared with manual UKA ($P < .01$) [29]. Office visits to general practitioners and hospitalizations within 3 months of surgery were also lower for Mako-assisted UKA patients (office visits: 30% vs 45%; hospitalizations: 3% vs 8%) [29]. Use of Mako-assisted procedures translated into 54 bed days saved per 100 patients [29]. In a large (n = 797 patients; 909 knees) multicenter study of 6 surgeons, Mako-assisted UKA procedures had a cumulative revision rate of 1.2% and high patient satisfaction at an average of 29.6 months follow-up (range = 22-52) [72]. This revision rate is substantially lower than historically reported rates for manual UKR of 4.5% and 4.8% at a 2-year follow-up (Swedish and Australian national registries, respectively) [73].

Patient satisfaction scores also demonstrate improved patient-reported outcomes and decreased failures for Makoplasty UKA patients. At the 2-year follow-up, nearly all (92%) patients indicated that they were either very satisfied or satisfied with their robotic arm–assisted UKA procedure [74].

The use of manual THA with traditional instruments is associated with complications including dislocation, impingement, and wear, leading to patient discomfort and walking complications. In a recent study evaluating patients undergoing posterior approach THA, individuals receiving manual THA experienced significantly more dislocations at 6 months compared with those undergoing robot-assisted THA ($P < .001$) [13].

Recent studies have revealed that optimal acetabular cup implantation is achieved less frequently than originally believed when considering the Lewinnek safe zones [75]. Malpositioned components can lead to instability due to gross malposition or due to either component–component impingement or anatomic impingement. In cases of a vertical cup, patient may experience dramatic acceleration of linear wear rates. A recent study performed at an academic tertiary referral center revealed that the acetabular cup was positioned in an ideal range only 50% of the time during manually performed procedures without a robot [76]. In a study comparing THA using manual alignment techniques with THA using robotic-assisted alignment, 50 Mako-assisted THAs were matched to historical manual THAs conducted between 2008 and 2012 [77]. Hundred percent of the Mako-assisted THAs were placed within the Lewinnek safe zone for anteversion and inclination (vs only 80% of manual; $P = .001$), and 92% of the Mako-assisted THAs were within the Callanan safe zone (vs only 62% of manual; $P = .001$) [77]. In a multicenter center study of Mako-assisted THA cases, planned cup placement was compared with cup orientation after impaction and immediately postoperatively. In 95% of cases, cup placements were recorded to be within 5° of the surgical plan, demonstrating that Mako robotic assistance provides surgeons with optimal measures to facilitate patient-specific planning [78]. In a cadaveric investigation, 12 acetabular components were implanted into 6 cadaveric pelves: Mako-assisted THA on one side and manual THA on the other side. Hips implanted with the Mako assistance had 4-6 times greater accuracy in version and inclination vs manual THA [79]. Use of Mako-assisted THA has been shown to improve accuracy in achieving desired leg length and offset compared with manual THA based on a cadaveric investigation of 21 hips [80].

Eccentric or excessive acetabular reaming can cause soft tissue impingement, loosening, altered center of rotation, bone-to-bone impingement, intraoperative periprosthetic fracture, early implant failure due to lack of bone ingrowth, and other complications, potentially leading to subsequent revision of THA [81]. In a matched-pair controlled study, the size of the acetabular cup relative to that of the femoral head was used as a surrogate measure of acetabular bone resection. In this study, Mako-guided THA allowed for the use of smaller acetabular cups in relation to the patient's femoral head size compared with conventional THA, indicating greater preservation of acetabular bone stock [82].

Improved component positioning leads to improved range of motion, decreased impingement, and improved stability, potentially improving function and outcome in primary THAs. Data were prospectively collected on primary THAs from a single institution conducted by 1 fellowship-trained surgeon over 3 time periods to compare manual total hip replacements vs Mako-assisted total hip replacement. Mako-assisted THA improved accuracy for both acetabular abduction angles and acetabular anteversion ($P < .0001$) and demonstrated lower dislocation rates at 1 year compared with manual THA ($P < .001$) [13]. The average estimated blood loss was also reduced in the patient group receiving robotic arm–assisted surgery compared with manual THA ($P < .0001$) [13]. At 1-year clinical follow-up, patients who had received Mako-guided THA demonstrated significantly higher modified Harris Hip scores and University of California, Los Angeles (UCLA) activity level compared with manual THA [83].

Mako has received 510(k) market clearance of the Mako total knee application. The total knee application uses the Mako-integrated cutting system. The Mako-integrated cutting system powers a saw blade designed specifically for the Mako platform. This will also be a closed system that uses preoperative 3D imaging and provides a preoperative plan for the surgeon to review, edit, and approve.

Other Systems

In addition to Robodoc, Navio, iBlock, and MAKO, there has been development of miniature bone-mounted robots [25]. For example, PiGalileo (Plus Orthopedics AG, Smith & Nephew, Switzerland) is a passive system that uses a hybrid-navigated robotic device that clamps on to the mediolateral aspects of the distal femoral shaft [25]. The Mini Bone-Attached Robotic System was an active system developed for patellofemoral joint arthroplasty procedures [84]. Plaskos et al presented Praxiteles in 2005, as a passive system that is a miniature bone-mounted robot for TKA [55]. Song et al [85] have developed an active system consisting of a hybrid bone-attached robot for joint arthroplasty that uses hinged prismatic joints to provide a structurally rigid robot for minimally invasive joint arthroplasty. We believe that it will be very important to begin to carefully define the definitions of “robot” and “robotic tools,” as compared with “navigated jigs” and/or “smart instruments.” Surgeons and patients alike deserve clear messaging from companies about how these devices work, how they improve safety and outcomes, and how they add value over time. The marketing teams at many companies seem, too often, to be driving the definition of robotics, only adding confusion of an already poorly defined space.

Cost and Return on Investment

Introducing robots into the orthopedic operating room may improve precision, lower complication rates, and offer higher patient satisfaction scores, but the ultimate acceptance of robotic surgery into common orthopedic practice will also depend on its cost effectiveness, especially in the short term. The initial start-up cost of devices that requires extensive research and development is high and to be commercially viable; these costs must be offset by the average sale price of the device. In the case of Robodoc, the initial price in Europe in the 1990s was $635,000 [31] and in some cases, the end user has paid as much as $1.5 million for the Robodoc device. At least 1 study has shown that when total cost of care is considered and Markov decision analysis is used, that robotic assisted surgery is actually more cost effective than manual surgery when the number of cases exceeds 94 annually, failure rates are less than 1.2% at 2 years, and patient age is considered [86]. As we move into the era of bundled payments and at risk capitation, these more complex means of determining true overall costs are becoming more relevant and more important.

The costs of a robotic system can be offset, however, by saving money on decreased hospital length of stay, and projected savings on a costly revision in the newer payment reform models.

TKA revisions alone have been estimated to cost $49,360 to $93,600 [87,88]. Hospitals must also consider the potential increase in volume of patients attracted to the facility by this new technology. Studies have shown that arthroplasty centers with robotics may shift and grow market share at a rate greater than those centers without such a robot. Third-party payers may also increase the reimbursement to hospitals and surgeons that employ this technology if it can be shown to reduce complications and prevent costly revisions, and given the trajectory of bundled payments models outlined in the CCJR, hospitals and physicians now will have true financial risk for these complications. Based on advances that have already been made, precision and accuracy in performing current procedures will only improve over time, as has been the universal history of robotics in every field.

Discussion

Robotic surgery is beginning to change the landscape of orthopedics. Robots were initially introduced into orthopedic operating rooms to improve precision, accuracy, and patient's overall outcome and satisfaction rates. Robotic-assisted surgery has the potential to achieve these goals by enhancing the surgeon' ability to generate reproducible techniques through an individualized surgical approach. Anatomic restoration with optimized soft tissue balancing, reproducible alignment, and restoration of normal joint kinematics have already demonstrated advantages of robotically assisted total knee surgery, partial knee surgery [89-92], and THA [13,83]. Regardless of what target a surgeon may desire for limb alignment or component position, it is clear that robotics will enable surgeons to carry out more precise and accurate procedures on a more consistent basis with a more patient-specific plan. Much as the greatest pilots who decided not to adapt and learn new instruments and navigation strategies became obsolete when the technology eventually proved that science was safer than art, surgeons need to strongly consider the path of robotics in health care and where on the path they think they will join the journey.

Limitations of Robotics

In addition to the cost associated with robotics in the operating room, there is also a significant amount of education required for surgeons and staff to optimize the safety and usefulness of robotics. The return on investment is never guaranteed, as simply purchasing a robot does not in and of itself improve outcomes. Operative time may be longer, especially during the learning curve, with use of robotic systems, and the preferred robotic system of a surgeon may not be compatible with their preferred implant system. Despite increased accuracy, current robotic systems are designed to execute on a specific plan. These systems still lack the ability to make creative decisions or unilaterally decide how to change the plan during surgery if a new variable becomes present (eg, a fracture requiring cuts for an augment, a ruptured medial collateral ligament requiring cuts for different implant). The systems currently are unable to perform soft tissue balancing, despite the ability of certain systems to provide balancing feedback to the surgeon in very accurate ways. In addition, these systems will make planned cuts regardless of what they may be cutting. Therefore, the surgeon must retract the soft tissues or the tissues in the planned path will be damaged. Future designs will likely include an evolution of failsafe mechanisms and tracking to prevent such inadvertent injury, but currently robots do not differentiate tissue types. Finally, the robot will cut per a plan based on the registration data provided to it. Although image-based systems may provide additional safety by more easily recognizing errors in registration, both image-based and imageless systems are only as good as the data provided to them. Therefore, incorrect registration can lead to the perfect execution of a perfect plan but may do so in completely the incorrect location which could have potentially calamitous results.

Future Robotic Innovations

Current design in the field of robotics has focused on decreasing outliers and improving accuracy in total joint arthroplasty radiographic outcomes. Early data are demonstrating decreased revision rates with unicompartmental arthroplasty and improved functional outcomes with THA. Future innovations will likely continue to improve the planning, setup, and workflow during robotic-assisted arthroplasty. These innovations will be implemented in a way that simplifies the process and minimizes the learning curve. It is difficult to predict the array of technological innovations that will be used to transform robotic-assisted arthroplasty. Critical areas include preoperative analysis, intraoperative sensors, and robotically controlled instrumentation. Preoperative planning with current robotic technology typically involves some type of imaging modality such as CT or radiographs for registration of anatomic landmarks into the robotic-registered space to define boundaries and the operative plan. The next step is to go beyond imaging to appreciate the kinematics of the operative joint before altered by the pathology of arthritis. The preoperative plan will be used to recreate the desired anatomic and kinematic framework. Although prior implant design was limited by the preparation possible with traditional jigs, traditional visualization requirements, and traditional instruments, the future of implant development may look very different. Some companies are already working on implants that will be truly impossible to implant without robotics.

Conclusion

To date, robotics has improved consistency and decreased variability at the cost of increased operative times at the onset with only some emerging evidence supporting improved clinical outcomes. In the future, robotics is moving toward becoming a valuable adjunct to the surgeon in optimizing patient-specific arthroplasty. Although additional research will be required to fully define the costs and benefits of robotics, one thing is clear: robotics appears to be here to stay. Given the universal history of robotic expansion and improved performance over unaided human experts in every industry from manufacturing to aviation to financial services, it may be unclear why we ever questioned that inevitability in the first place.

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