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Review

Robotic Systems and Navigation Techniques in Orthopedics: A Historical Review

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Abstract: Since the da Vinci Surgical System was approved by the Food and Drug Administration (FDA) in 2000, the development and deployment of various robot-assisted minimally invasive surgery (MIS) systems have been largely expedited and boomed. With the rapid advancement of robotic techniques in recent decades, robot-assisted systems have been widely used in various surgeries including orthopedics. These robot-related techniques have been and continue to be transforming the conventional ways to conduct surgical procedures. Robot-assisted orthopedic surgeries have become more and more popular due to their potential benefits of increased accuracy and precision in surgical outcomes, enhanced reproducibility, reduced technical variability, decreased pain, and faster recovery time. In this paper, robotic systems and navigation techniques in typical orthopedic surgeries will be reviewed, especially for arthroplasty. From the perspective of robotics and engineering, the systems and techniques are divided into two main categories, *i.e.*, robotic systems (RS), and computer-aided navigation systems (CANS). The former will be further divided into autonomous RS, hands-on RS, and teleoperated RS. For the latter, three key elements in CANS will be introduced, including 3D modeling, registration, and navigation. Lastly, the potential advantages and disadvantages of the RS and CANS are summarized and discussed. Future perspectives on robotics in orthopedics, as well as the challenges, are presented.

Keywords: robot-assisted surgery; orthopedic surgery; computer-assisted orthopedic surgery; computer-aided navigation system; arthroscopic surgery

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1. Introduction

In 1954, Devol invented the first digitally operated and programmable robot (later known as the Unimate) in the world, which has been viewed as the foundation of the modern robotics industry [1]. Together with Engelberger, they founded the first robotics company in the world named Unimation. The company developed the first Unimate robot based on Devol's patent and sold it to General Motors in 1960 for being used to lift and stack hot pieces of metal [2]. Since then, robots have been continually improved, and spread their applications in the surgical field. In 1985, the first robotic surgical system, Puma 560, was used for neurosurgical biopsies guided by computed tomography (CT) images [2,3]. In the early 1990s, Minerva was introduced as the next-generation neurosurgical robot [4]. In 1988, ROBODOC (Integrated Surgical Systems, Delaware, USA) was introduced in orthopedics [4]. In the same year, PROBOT performed a clinical trial at Imperial College London with the earliest robotic procedure in urology. In 1993, a robotic arm called AESOP (Automated Endoscopic System for Optimal Positioning) (Computer Motion, Inc., Santa Barbara, California, USA) was developed to assist in holding and positioning laparoscopic camera. In 1998, both the ZEUS Robotic Surgical System (Computer Motion, Inc., Santa

Barbara, California, USA) and the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California, USA) were introduced into the market for use in teleoperated surgery [4], while the latter received the Food and Drug Administration (FDA) approval in 2000 for use in general laparoscopic surgery which is considered as a legend in the field of surgical robotics. Thereafter, medical and surgical robotics started to boom in various fields.

Minimally invasive surgery (MIS) allows the surgeon to conduct surgical procedures through much smaller incisions than traditional open surgery, thus has a faster recovery rate and shorter rehabilitation time as well as lower pain for the patient [5]. Robot-assisted MIS involves a robot to improve the quality and precision of surgical procedures. Since the da Vinci Surgical System was approved by the Food and Drug Administration (FDA) in 2000, the development and deployment of various robot-assisted MIS systems have been largely expedited [6,7].

With the rapid advancement of robotic techniques in recent decades, robotic systems have been widely used in various medical fields, such as neurological, laparoscopy, radiosurgery, prosthetics, rehabilitation, orthopedics, ophthalmology, and more beyond [5,8–10]. For example, the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California, USA) and RAVEN II (University of Washington, and University of California, Santa Cruz, USA) for use in teleoperated laparoscopic surgery [8,11,12], the CyberKnife System (Accuray Inc., Sunnyvale, California, USA.) for use in radiosurgery [13], the JHU Steady-Hand Robot for use in retinal microsurgery [14–16]. These robotic systems and techniques are transforming the conventional ways to conduct surgical procedures in a large variety of fields.

Through decades of technique evolvements and clinical evaluations in orthopedic surgeries, plenty of studies have proven that robotic systems and navigation techniques can be beneficial in improving and enhancing surgical outcomes, such as increasing the accuracy and precision of bone cutting and component alignment, reducing operative time, and enhancing patients' satisfaction [17–19].

Numerous review papers on reviewing robots or navigation systems in orthopedics can be found in the literature. Most of them focused on a meta-analysis or reviewing clinical outcomes and user studies [2,19–22], or a specific field like MIS [5], or a specific feature like haptic feedback [23]. Instead of those, this paper will present a historical review of the robotic systems and navigation techniques that exist and have ever existed in the field of orthopedics, especially on those systems still commercially available at present. And the primary focus will be the historical evolvement of the systems as well as the engineering features and techniques from the perspective of engineering. Correspondingly, two main categories will be covered, *i.e.*, robotic systems (RS), and computer-aided navigation systems (CANS). The RS will be further divided into autonomous RS, hands-on RS, and teleoperated RS, while the CANS will be broken down into three key technical elements, including 3D modeling, registration, and navigation.

It is worth noting that in orthopedics, computer-assisted orthopedic surgery (CAOS) divided the surgical systems into three categories, *i.e.*, autonomous (also known as active), semi-autonomous (also known as semi-active), and passive [17,24,25]. Correspondingly, the autonomous systems are equivalent to the autonomous RS used here, and the semi-autonomous systems are equivalent to the hands-on RS used here, while the passive systems indicate the computer-aided navigation systems (CANS) used in this paper. A hierarchical flowchart of these categories and their components are illustrated in Fig. 1.

Common orthopedic surgeries involving RS and/or CANS may include arthroplasty, arthroscopy, and surgical interventions related to tissues in joints. Note that in orthopedics, joint replacement is equivalent to arthroplasty, and similarly total hip replacement (THR) is equivalent to total hip arthroplasty (THA), and total knee replacement (TKR) is equivalent to total knee arthroplasty (TKA). A general flowchart of surgical procedures for orthopedic surgeries is illustrated in Fig. 2. Both RS and CANS play an important role in the procedures, which will be introduced in detail in subsequent sections.

The remaining of this paper is organized as follows. Section 2 presents the robotic systems (RS) in orthopedics including their historical background, applications, main fea-

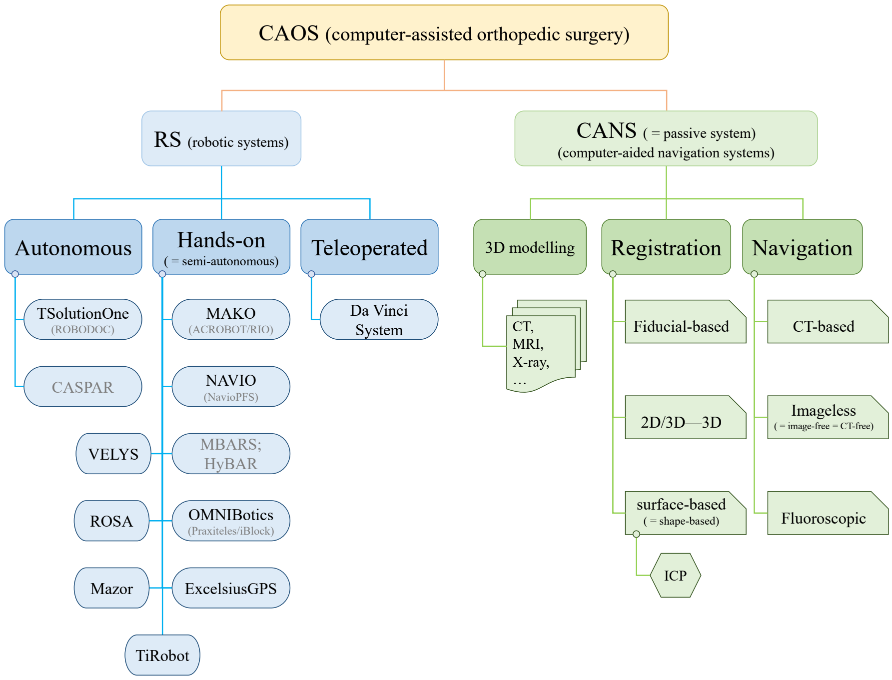

Figure 1. A hierarchical flowchart for the robotic systems and navigation techniques in orthopedics. Note: system names in gray color means either not in use anymore or upgraded with new names; The equal symbol "=" means "equivalent to".

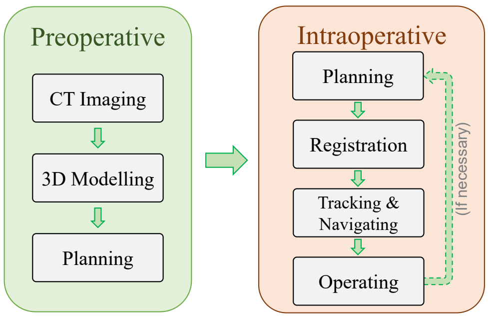

Figure 2. A general flowchart for orthopedic surgeries.

tures, and techniques. Section 3 presents CANS-related techniques including 3D modeling, registration, and navigation. Section 4 provides discussions and future perspectives on the RS and CANS in orthopedics, as well as some novel techniques. Section 5 presents a brief conclusion and future challenges.

2. Robotic Systems (RS)

In this section, the robotic systems (RS) in orthopedics are historically reviewed. For each of the RS, the background of development, the features, applications, techniques, advantages, and disadvantages will be introduced.

Robotic systems (RS) will be divided into three subcategories, *i.e.*, autonomous, hands-on, and teleoperated [23], as illustrated in Fig. 1. The **autonomous RS** indicates that the robot can conduct the surgery completely on its own while the surgeon can only interrupt it by using an emergency stop [26]. The **hands-on RS** is equivalent to semi-autonomous or semi-active robots in the literature of orthopedic surgeries. It indicates that the surgeon and robot cooperatively move the surgical instrument installed on the robot end-effector (EE), which means it requires physical human-robot interaction (*p*HRI) [23]. The **teleoperated RS** indicates a standard leader-follower teleoperation system in which two robots are required.

The leader robot is physically operated by the surgeon, while a follower robot on the remote site (*e.g.*, on the patient side) is controlled by the leader robot via the internet or Ethernet.

2.1. Autonomous RS

2.1.1. **ROBODOC → TSolution One**

ROBODOC Surgical System (Curexo Technology Corporation, Fremont, California, USA) was a fully autonomous robotic system initially designed for total hip arthroplasty (THA) in the 1980s [9,27], and introduced to be used on patients in 1992 [26,28]. It is the first robot that was clinically used in orthopedic surgery [2]. ROBODOC had its first system installed in Germany after being approved for sale by the European Union in 1994 [2,4]. ROBOTDOC was approved by FDA[1] in 2008 for use in THA [19].

The whole system includes ORTHODOC (a 3D preoperative computer modeling and planning workstation) and ROBODOC surgical assistant (a 5-axis SACARA-type surgical robot) [25]. The system conducted its work, *e.g.*, bone milling and preparing for stem implantation, based on preoperative computed tomography (CT) imaging. The workstation will generate a 3D virtual model and produce a customized surgical plan [19]. The system employed fiducials implanted about 5 mm deep in bone for bone motion detection and tracking, thus the tracking accuracy is high and will not be affected by debris and fluids [9]. Since ROBODOC is a fully autonomous system, once it starts to work, the surgeon has only control over emergency stop [19].

The company, Curexo Technology Corporation, changed its name to Think Surgical, Inc. in 2014 [2,29]. Based on ROBODOC technology, its next-generation system named TSolution One (THINK Surgical, Inc., formerly Curexo Technology Corporation, Fremont, California, USA)[2] was developed. Its applications have been expanded to total knee arthroplasty (TKA) [4,19]. The TSolution One was approved by the FDA[3] in 2019 for use in TKA. Currently, the TSolution One system has upgraded to a computer-aided system from the earlier CT-based system [2,4].

2.1.2. **CASPAR**

CASPAR (computer-assisted surgical planning and robotics) (OrthoMaquet/URS, Rastatt, Germany) was another early autonomous 6-degree-of-freedom (DOF) robotic system for THA and TKA [2,9]. It was introduced by OrthoMaquet in 1997, and acquired by Getinge (Gothenburg, Sweden) in 2000, and further acquired and discontinued by Universal Robot Systems (URS, Rastatt, Germany) in 2001 [8]. One example photo of the system is shown in Fig. 3.

Similar to ROBODOC, the CASPAR also has an interactive computer system used for preoperative planning based on CT images [9]. The CASPAR also has similar functions including automatically milling a bone and guiding implant position in THA [19]. Therefore, it was directly competing with the ROBODOC. Although some research studies showed increased accuracy of bone preparation and implant positioning in both TKA and THA with CASPAR [2,30,31], many other studies showed significantly less improvement in Harris Hip Scores, significantly longer procedure times and more blood loss, higher rates of complications, and revision surgeries compared to ROBODOC [2,9,32]. Therefore, CASPAR is no longer in use due to these drawbacks [2].

2.1.3. **CyberKnife**

CyberKnife[4] (Accuray Inc., Sunnyvale, California, USA) is an image-guided robotic system that is specially designed for radiosurgery and radiotherapy [33,34]. CyberKnife

[1] ROBODOC FDA 2008 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K072629
[2] THINK Surgical website (accessed June 2023): https://thinksurgical.com/
[3] TSolution One FDA 2019 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K191369
[4] CyberKnife website (accessed June 2023): https://cyberknife.com/cyberknife-technology/

Figure 3. CASPAR. (Reproduced with permission from *J. Bellemans, Robotics in TKA, 2013, Springer Nature.*)

Figure 4. ACROBOT system. (Reproduced with permission from *F. Rodriguez y Baena and B. Davies, Robotic Surgery: From Autonomous Systems to Intelligent Tools, Robotica, 28(2), 163-170, 2010, Cambridge University Press.*)

system can deliver stereotactic radiosurgery and radiation therapy anywhere in the body including the spine and bone, although it is not a robotic system specially designed for orthopedics. The system autonomously conducts the non-invasive treatment procedures under the surgeons' supervision. Initially conceived in 1992 [35] and fully described in 1997 [36], CyberKnife received FDA approval in 1999[5] for use in intracranial treatment and in 2001[6] for use in extracranial treatment [34]. As of 2020, CyberKnife has delivered treatments to over 400,000 patients worldwide [34]. A technical overview of the CyberKnife system can be found in [34].

2.2. Hands-on RS

Compared with autonomous RS, hands-on RS is much more preferred by surgeons due to the feature of surgeon-in-the-loop and full control by the surgeon. The following ACROBOT, RIO, and MAKO have the same core system but different names at different periods [37].

2.2.1. ACROBOT

ACROBOT system (Acrobot Co Ltd, London, UK) is a semi-autonomous system designed for robot-assisted MIS for unicompartmental knee arthroplasty (UKA) [3,26]. It is the first robot-assisted system used in UKA [37]. One example photo of the ACROBOT system is shown in Fig. 4 [38].

The ACROBOT was named as an acronym for active-constraint robot and was initially designed for knee surgeries [39]. Therefore, it employed active-constraint control, which can constrain the robot's movement within a predefined zone [2,37], thus the surgeon can safely cut the bone with high precision [2]. It provides haptic feedback to the surgeon and is

[5] CyberKnife FDA 1999 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K984563

[6] CyberKnife FDA 2001 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K011024

considered as a prototype of modern haptic systems [37]. ACROBOT is a 6DOF robot that allows only predefined trajectories [40]. It used CT scans for preoperative planning. During the surgery, a small robot called Acrobot was mounted on a gross positioning device and operated on by the surgeon [2]. A non-invasive anatomical registration will be conducted intraoperatively, based on which the drill can be tracked. If the surgical tool is detected to be away from the predefined cutting zone, the system will actively prevent it [37].

Acrobot Co Ltd was acquired by Stanmore Implants Worldwide in 2010, and based on the ACROBOT system the Stanmore Sculptor Robotic Guidance Arm (RGA) System (Stanmore Implants, Elstree, UK) was released [37] and approved by the FDA[7] in 2013 for use in UKA. MAKO Surgical Corp. obtained some confidential patents in 2013 as part of a patent infringement settlement [2,21]. Stryker Corporation acquired MAKO Surgical Corp. in 2013, and acquired Stanmore Implants Worldwide in 2016.

2.2.2. **RIO (← ACROBOT)**

The robotic arm interactive orthopedic system (RIO, previously called the Tactile Guidance System) (MAKO Surgical Corp., Fort Lauderdale, Florida, USA) is the commercialized version of the ACROBOT system [8,23], thus inherited many features from the ACROBOT [26]. It can be used for UKA [26], and TKA [23]. It received FDA approval for use in TKA[8] in 2009 and for use in THA[9] in 2010 [9].

The RIO system features haptic and auditory feedback, force-controlled tip, and surgeon-in-the-loop. The preoperative CT images are used to construct a 3D model of the patient's knee. Then the 3D model is used by the surgeon to do a preoperative plan. The preoperative plan and the 3D model will be used to finalize an intraoperative plan at the beginning of the operation which includes defining an exact cutting zone for the robot. During the operation, the surgeon physically operates the RIO robot to perform bone resection while referencing the 3D bone model on a monitor. The robot will provide haptic and auditory feedback, while constraining the force-controlled tip of the tool (*e.g.*, a rotating burr) to work only within the predefined cutting zone. The robot will automatically stop if the burr is outside of the predefined zone, or the computer has detected more bone being resected than necessary. Therefore, the RIO robot helps to monitor the operation, and provides necessary real-time data for accurate bone cutting and accurate components placement, thus potentially improving the outcomes of the UKA [26]. Therefore, the RIO system heavily relies on the preoperative plan and the surgeon's skill. Besides, it is reported that the RIO system has a short learning curve which is beneficial to surgeons with less experience in operating this system [26,41,42].

2.2.3. **MAKO (← RIO)**

MAKO system (Stryker Corporation, Kalamazoo, Michigan, USA)[10] can be viewed as a new generation of the RIO (MAKO Surgical Corp.) system, which means it is also a semi-autonomous system [10,19]. Founded in 2004, MAKO Surgical Corp., together with its most notable products, RIO (Robotic Arm Interactive Orthopedic System) and MAKOplasty (for partial knee and total hip arthroplasty), was acquired by the Stryker Corporation in 2013. MAKOplasty received FDA approval in 2014 for use in THA[11].

Being further developed and rebranded from the RIO, the MAKO system is an image-based system with haptic and auditory feedback. Preoperative CT images are acquired

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7 RGA FDA 2013 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K121765

8 RIO-MCK FDA 2009 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K090763

9 RIO-THA FDA 2010 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K093425

10 MAKO SmartRobotics website (accessed June 2023): https://www.stryker.com/us/en/joint-replacement/systems/Mako_SmartRobotics_Overview.html

11 MAKOplasty FDA 2014 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K141989

and used to do preoperative planning which will be further confirmed and adjusted intraoperatively based on the patient's true bone anatomy before executing the surgery [2]. A special feature of the MAKO system is a haptic technology named AccuStop that provides auditory beep alert, tactile vibration feedback, and visual feedback with color changes. This haptic technology can assist surgeons in making incisions, saving soft tissues and healthy bones [9]. One drawback of the MAKO system is the high purchasing and surgical costs [9].

Since 2021, the MAKO robots have been enhanced by integrating intraoperative sensor technology. MAKO is integrated with a computer navigation system, and it uses preoperative CT scans to generate a 3D model, then the robot arm will be guided by the 3D model. MAKO is a human-robot collaboration system making use of user input and robotic guidance. Besides the haptic, visual, and audio feedback, it also provides virtual fixture (VF) protection and emergency auto-shutdown for safety strategy. MAKO performed its first THA case in 2010 and received FDA[12] approval in 2017. MAKO has also been used for UKA and TKA [19].

MAKO system is gaining more popularity in clinical practice for UKA, THA, and TKA. In addition to its long history of nearly two decades, there is a large body of research literature about the MAKO system [2]. Many studies have revealed positive outcomes of using the MAKO system than manual techniques. For more clinical case study results on MAKO please refer to [2].

2.2.4. NavioPFS/NAVIO

NavioPFS (Precision Freehand Sculpting) (Blue Belt Technologies, Plymouth, Minnesota, USA) system is a computer-aided orthopedic navigation and surgical burring system, and is also a semi-autonomous, hand-held, and image-free system. It was approved by FDA[13] in 2012 for unicondylar knee arthroplasty (uKA) [2].

The NavioPFS is a handpiece that has a cutting tool (a motorized burr) installed at the robot end-effector, and the burr can extend and retract. A related safety strategy is that by modulating the retraction (exposure control) and speed of the burr (speed control) [27], inadvertent bone removal can be avoided although there is not haptic feedback in this system. Another big advantage of this system is its imageless feature meaning that preoperative CT imaging is not needed, and all the registration, planning, and navigation will be performed during the surgery. Note that the imageless feature is equivalent to the image-free feature in this paper. NavioPFS employs an optical-based navigation system via a passive infrared (IR) tracking camera and trackers. Intraoperative data from the trackers will be collected and displayed in a graphical format, and together with anatomic landmarks and surface painting techniques, a 3D model of the patient's femur and tibia can be created thus a surgical plan can be made by the surgeon intraoperatively [2,9].

The NavioPFS system has been proven to have reduced implant position errors [43], satisfied mechanical axis alignment accuracy, decreased bone cutting time, and improved Oxford Knee Scores [2]. The learning curve for operating the NavioPFS has been shown to be fairly rapid [44,45].

Blue Belt Technologies Inc., a Carnegie Mellon University spin-off company that was founded in 2003, was acquired by Smith & Nephew plc (London, UK) in 2016 [10]. In 2019, Smith & Nephew acquired the orthopedic unit of Brainlab, after which Smith & Nephew's NAVIO surgical system upgraded its software to Navio 7.0. The software upgrade made a significant reduction in required data point collection and in workflow stages, faster surface modeling, and improved usability [9]. The current Smith & Nephew's NAVIO surgical

[12] MAKO-THA FDA 2017 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K170593

[13] NavioPFS FDA 2012 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K121936

(a) MBARS **(b)** HyBAR

Figure 5. MBARS and HyBAR. (Reproduced with permission from *A. Wolf et al., MBARS: Mini Bone-Attached Robotic System for Joint Arthroplasty, International Journal of Medical Robotics and Computer Assisted Surgery, 1(2): 101-121, 2005, John Wiley and Sons*; and with permission from *S. Song et al., HyBAR: Hybrid Bone-Attached Robot for Joint Arthroplasty, International Journal of Medical Robotics and Computer Assisted Surgery, 5: 223-231, 2009, John Wiley and Sons.*)

system[14] expanded the applications to TKA and UKA, and together with its PFJ software, it can assist the surgeon in making implant plans and help them to prepare the bone for implantation [24].

2.2.5. BRIGIT

BRIGIT (bone resection instrument guidance by intelligent telemanipulator) system [46], was developed by MedTech SA (Montpellier, France). The system was implemented with a compliant control strategy aiming for more compliant and safer human-robot interaction [47]. It was integrated with a computer navigation system, and can be used for TKA to accurately position bone-cutting guides based on the preoperative plan [27,46]. According to the initial design, the system can be operated either in cooperation mode with physical human-robot interaction or in teleoperation mode with haptic feedback [46]. The system was acquired by Zimmer Biomet (Warsaw, Indiana, USA) in 2006, but was not commercialized [46].

2.2.6. MBARS/HyBAR

MBARS (mini bone-attached robotic system) robot, as shown in Fig. 5a, is a semi-autonomous robot developed at Carnegie Mellon University for TKA [48]. This type of system employed a special feature of small and bone-mounted robots, which are considered to be more efficient and cost-effective than large robotic systems [26,48].

The MBARS involves attached high-speed orthopedic tools, thus the major design issues are considered to be structural rigidity and clamping mechanism [49]. To solve this, a HyBAR (hybrid bone-attached robot), as shown in Fig. 5b, was designed for patellofemoral joint arthroplasty [49]. The HyBAR is an autonomous system with enhanced structural rigidity by using hinged prismatic joints in its novel kinematic configuration, while a new modular clamping system was introduced to enhance the robotic procedure [2,49].

2.2.7. Praxiteles $\rightarrow$ iBlock

Praxiteles (Praxim Ltd, Grenoble, France), presented in 2005, is also a semi-autonomous system and is in the category of MBARS [50]. The Praxiteles, as shown in Fig. 6, was designed to guide the saw blade or to use a passive bone milling process, and the risk of soft tissue damage can be expected to be reduced by less-invasive exposures [27].

The OMNINAV iBlock robotic cutting guide (formerly known as Praxiteles, OMNIlife Science (now owned by Corin Group), East Taunton, MA), is a motorized, bone-mounted

[14] NAVIO Surgical System website (accessed June 2023): https://www.smithnephewlivesurgery.com/navio-surgical-system

Figure 6. Praxiteles. (Reproduced with permission from *C. Plaskos et al., Praxiteles: A Miniature Bone-Mounted Robot for Minimal Access Total Knee Arthroplasty, International Journal of Medical Robotics and Computer Assisted Surgery, 1(4): 67-79, 2005, John Wiley and Sons.*)

cutting guide for all femoral resections [51], and approved by FDA[15] in 2010 for use in TKA applications [2,27]. Similar to the NAVIO system, the iBlock is also imageless. Its OmniBiotics computer station can generate a 3D digital model of the patient's knee by using patented bone morphing technology and intraoperative anatomic data [27]. Based on the 3D model, the surgeon can make the implant plan intraoperatively and see the planned bone cuts before they are executed.

Although there are limited clinical data available for this system, some studies have shown the iBlock system can obtain more efficient, accurate, and repeatable bone resections, as well as shorter bone preparation time [2,52]. The limitations of the iBlock system include no haptic feedback, only for TKA applications, a closed platform, and limited kinematic assessment after implantation [2].

2.2.8. **OMNIBotics (← iBlock)**

OMNIBotics knee system[16] (OMNIlife Science Inc. (acquired by Corin Group in 2019), Raynham, MA, USA), a new version of iBlock, is an image-free miniature bone-mounted robotic system for bone cutting and ligament balancing in TKA [4]. It initially received FDA[17] approval in 2017. The OMNIBotics system includes a bone-mounted robotic cutting guide (iBlock) for guiding bone resections and a robotic ligament tensioning tool (active spacer). The unique feature of integrating an active spacer allows for reproducible tensioning of the soft tissues accurately before and after the bone cuts, and for adjusting the interface fit between the implant and the bone intraoperatively.

The image-free feature does not require preoperative images. Instead, the 3D model of the patient's anatomy is reconstructed via the bone morphing technique intraoperatively, while the accuracy can be within 1 mm in all mapped areas [4]. The bone-mounted robot do not need camera-based tracking during robotic positioning and resection guidance. Once the robot is mounted and calibrated, the surgeon can perform the bone resection in sequence by operating on the robot-attached oscillating saw [4].

2.2.9. **PiGalileo**

PiGalileo (Plus Orthopedics AG, Switzerland, now owned by Smith & Nephew, UK), as shown in Fig. 7, is a miniaturized and bone-mounted robotic cutting jig guided by a computer-aided navigation system for TKA and THA [27,53]. The robot is clamped to the bone before surgery, and a cutting guide is accurately positioned with the help of

[15] iBlock FDA 2010 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K090953
[16] OMNIBotics website (accessed June 2023): https://www.coringroup.com/healthcare-professionals/solutions/omnibotics/
[17] OMNIBotics knee system FDA 2017 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K163338

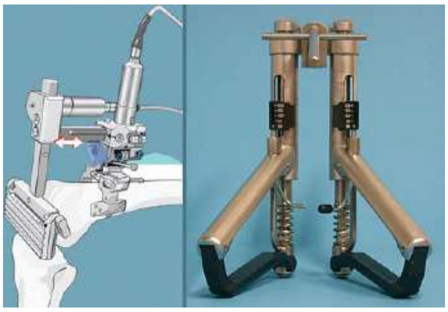


Figure 7. PiGalileo System and ligament balancer. The ligament balancer with force and distance scale is used to measure the ligament tension and gap size. (Reproduced with permission from *P. Ritschl et al., Modern Navigated Ligament Balancing in Total Knee Arthroplasty with the PiGalileo System, 2007, Springer Nature.*)

the navigation system [27]. Once the position is confirmed, the surgeon can conduct the operation.

Its two computer-aided navigation systems for TKA[18] and THA[19] are approved by FDA in 2006 and in 2007, respectively [54]. The PiGalileo's imageless navigation systems can assist the surgeon in bone cutting and implant positioning during joint replacement by collecting intraoperative data and tracking surgical tools and bone positions via stereotaxic technology and infrared (IR) markers.

The PiGalileo has been demonstrated with good surgical outcomes including high accuracy of implant positioning, improved bone cutting precision, and shorter surgical times [27].

2.2.10. ROSA

ROSA (robotic surgical assistant) (Zimmer Biomet Robotics, formerly MedTech SA, Montpellier, France) is a robotic system for TKA and THA [17]. The FDA approved its ROSA hip system[20] in 2021, and ROSA knee system[21] in 2022.

According to the FDA documents, the ROSA hip system[22] (as shown in Fig. 8a) is a CT-free, fluoroscopic-guided system that can be used to assist surgeons in accurately positioning and implanting hip components, while the robotic arm is used to assist in the guidance of the surgical tools. Fluoroscopic images, intraoperatively acquired by a C-arm, will be used to determine the surgical tools' orientation in relation to the patient's anatomy and as a guide for bone component orientation. The system provides pre-, intra-, and post-operative measurements relative to patient anatomy. The robotic arm is maintained stationary to keep the instruments in a fixed orientation during bone component implanting.

ROSA knee system[23] (as shown in Fig. 8b) can assist surgeons in bone resection and assessing the state of the soft tissues to facilitate implant positioning intraoperatively. This system can be either image-based or imageless. For the image-based option, a preoperative 3D virtual bone model needs to be generated preoperatively which can be used by the surgeon to make a preoperative surgical plan. For the imageless option, the landmarks

[18] PiGalileo-TKR FDA 2006 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K061362
[19] PiGalileo-THR FDA 2007 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K070731
[20] ROSA Hip System FDA 2021 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K210998
[21] ROSA Knee System FDA 2022 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K213708
[22] ROSA Hip System website (accessed June 2023): https://www.zimmerbiomet.com/en/products-and-solutions/zb-edge/robotics/rosa-hip-system.html
[23] ROSA Knee System website (accessed June 2023): https://www.zimmerbiomet.com/en/products-and-solutions/specialties/knee/rosa--knee-system.html

(a) ROSA Hip System **(b)** ROSA Knee System **(c)** ROSA ONE System

Figure 8. ROSA systems. (Reproduced with permission from © Zimmer Biomet, Warsaw, Indiana, USA.)

data on the patient's bony anatomy will be collected intraoperatively and used to create an intraoperative surgical plan. The accuracy of resections, knee state evaluation, and soft tissue assessment will be the same between the two options since both of them are always based on intraoperative landmarks. The robotic arm can assist in precisely positioning the component relative to the implantation plan.

ROSA Spine was developed for minimally invasive spine procedures around 2015 [55,56] and approved by FDA[24] in 2016. The system includes a patient-side cart bearing for a 6DOF robotic arm and a workstation, and an optical camera serving for navigation purposes. In addition to pedicle screw placement, it is also promising to be used for spinal fusion, percutaneous endoscopic lumbar discectomy, intracorporeal implant positioning, and radiofrequency ablation [55–57]. By coupling with intraoperative flat-panel CT guidance, the system can perform accurate pedicle screw placement [55]. Registration can be performed automatically by using a fiducial box (held by the robotic arm) and a percutaneous reference pin. The robot can monitor and follow the patient's body movements in real-time by tracking the movement of the vertebrae, thus real-time robotized navigation guidance can be provided by the system. Preoperative and postoperative 3D CT scans can be acquired by an O'arm device and transferred to the workstation. Then, by co-registration, the difference between the initial 3D planning and the actual screw positions can be measured [55]. Accurate screw placement can be achieved due to the robot's ability of real-time movement tracking on the vertebrae [55]. Later, the ROSA Spine System is integrated into the ROSA ONE System[25] (as shown in Fig. 8c) and approved by FDA in 2019 [57].

2.2.11. VELYS

VELYS robotic-assisted solution (VRAS)[26] (DePuy Synthes, now owned by Johnson & Johnson, Warsaw, Indiana, USA), as shown in Fig. 9 [58], is a new system designed from proprietary technology developed by Orthotaxy. It performed its first TKA case in Auckland, New Zealand in 2020 [59], and was approved by FDA[27] in 2021.

VELYS employed a novel patient-specific TKA technique that can intraoperatively collect accurate data on both the bony anatomy and the soft tissue envelope of the knee [59]. This technique allows the surgeon to make intraoperative plan while preserving the soft tissues during the TKA surgery. The robot-assisted saw can assist in conducting the

[24] ROSA Spine FDA 2016 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K151511

[25] ROSA ONE Spine website (accessed June 2023): https://www.zimmerbiomet.eu/en/products-and-solutions/zb-edge/robotics/rosa-spine.html

[26] VELYS Robotic-Assisted Solution website (accessed June 2023): https://www.jnjmedtech.com/en-US/patient/velys/robotic-assisted-solution

[27] VELYS FDA 2021 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K202769

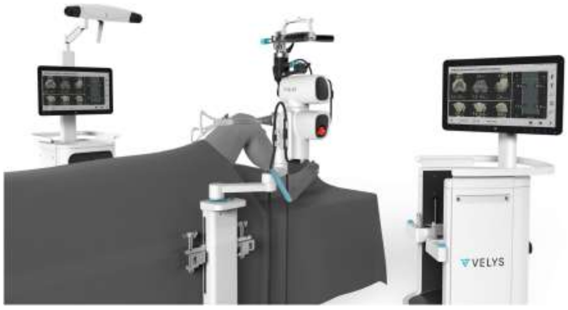


Figure 9. VELYS Robotic-Assisted Solution. (Reproduced from *G.W. Doan et al., Image-Free Robotic-Assisted Total Knee Arthroplasty Improves Implant Alignment Accuracy: A Cadaveric Study, The Journal of Arthroplasty, 37(4): 795-801, 2022, Elsevier.*)

implantation plan precisely, accurately, and efficiently [59]. Early outcome results and limited data indicate favorable outcome scores and high patient satisfaction [59].

2.2.12. Mazor

Spine Assist (Mazor Robotics, Caesarea, Israel) is the first robotic system used in spine surgery and was approved by FDA[28] in 2004 [57]. The Spine Assist system evolved into the Renaissance system which was approved by FDA[29] in 2011, and then Mazor X which was approved by FDA[30] in 2017, and then Mazor X Stealth (Medtronic, Dublin, Ireland) which was approved by FDA[31] in 2018. The example products of Mazor systems are shown in Fig. 10. Note that Mazor Robotics[32] was acquired by Medtronic in 2018. A detailed comparison between these four versions of the Mazor systems can be found in [57]. Nowadays the robotic system is just called Mazor. A systematic review on robotics in spine surgery can be found in [60,61].

The Spine Assist robotic system can be used for pedicle screw placement in spine surgery, but the accuracy of the screw placement is relatively low [55,57]. The updated version, the Renaissance system, preserves a similar operational workflow but significant software changes [57]. Finally, the latest version of the Mazor system, Mazor X Stealth, has an accuracy of around 99%-100% for the screw placement. Both Spine Assist and Renaissance require preoperative CT scans, based on which preoperative planning (*e.g.*, optimal implant size and trajectory) will be conducted. Nowadays, Mazor system can be used in conjunction with the imaging system O-arm for 3D images, besides the use of a CT scan (Scan & Plan workflow). Before the spine surgery, the robot will be mounted to the patient's spine. During the surgery, intraoperative fluoroscopic images of the anatomy will be acquired and matched with the preoperative CT scans in real-time, and this procedure is called CT-to-Fluoro workflow. Alternatively, the Scan & Plan workflow can be used. In both workflows, the robotic arm will provide guidance according to the preplanned trajectory [57].

As mentioned earlier, the upgraded versions of Mazor[33] do not require preoperative CT scans anymore while a feature of instrument tracking is also added [57,62]. Although preoperative CT is not mandatory, Mazor can accept preoperative or intraoperative CT

[28] Mazor SpineAssist FDA 2004 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K033413

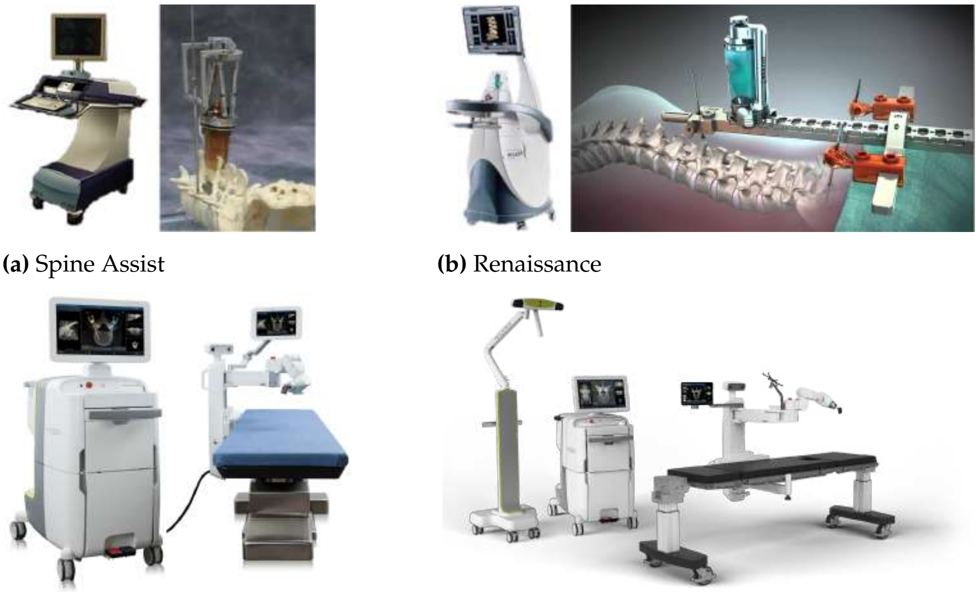
[29] Mazor Renaissance FDA 2011 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K110911

[30] Mazor X FDA 2017 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K163221

[31] Mazor X Stealth FDA 2018 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K182077

[32] Mazor Spine Robotics website (accessed June 2023): https://www.medtronic.com/ca-en/healthcare-professionals/therapies-procedures/spinal-orthopaedic/spine-robotics.html

[33] Mazor X Stealth website (accessed June 2023): https://www.medtronic.com/ca-en/healthcare-professionals/products/spinal-orthopaedic/spine-robotics/mazor-x-stealth-edition.html



(a) Spine Assist **(b)** Renaissance

(c) Mazor X **(d)** Mazor X Stealth Edition

Figure 10. Mazor systems for spine surgery. (Reproduced with permission from © Medtronic, Dublin, Ireland.)

for screw planning. Before the spine surgery, the robot will be attached to a table and then mounted to the patient's spine. During the surgery, 3D images are acquired and then the intraoperative anatomy is matched with the CT scan via fluoroscopic images for intraoperative guiding purposes. The robot arm will perform procedures according to the preplanned trajectory while a 3D camera offers real-time instrument tracking [57]. The latest version of Mazor is integrated with Medtronic's Stealth navigation system which can further improve navigation accuracy.

2.2.13. ExcelsiusGPS

ExcelsiusGPS[34] (Globus Medical, Audubon, PA, USA), as shown in Fig. 11, is a robotic system with real-time image guidance for spine surgery and was approved by FDA[35] in 2017 [57]. The robotic arm is mounted on the floor rather than the patient's bone. Preoperative CT scans are not mandatory but optional for screw trajectory planning. Optionally, intraoperative CT or radiographs can also be used for the planning. The ExcelsiusGPS system employed a shock-absorbing dynamic reference base and a separate surveillance marker and associated surveillance software to improve the system navigation integrity [57,63]. Also, the ExcelsiusGPS system employed an extremely rigid arm for its robotic guidance system, which can achieve an accuracy of less than 1 mm of tool deflection under a lateral disturbance force of 200 N. Additionally, the system will alert the surgeon if any tool deflection is detected by the surveillance software during the surgery [57,63].

2.2.14. TiRobot

TiRobot[36] (TINAVI Medical Technologies, Beijing, China) is a robotic system developed in China for use in spine surgery and received China FDA approval in 2016 [64]. The TiRobot platform consists of three components including a workstation, an optical tracking camera, and one 6-DOF floor-mounted robotic arm as shown in Fig. 12 [64]. The fluoroscopic-image-based registration employs a cross-referencing approach by using a

[34] ExcelsiusGPS website (accessed June 2023): https://www.globusmedical.com/musculoskeletal-solutions/excelsiustechnology/excelsiusgps/

[35] ExcelsiusGPS FDA 2017 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K171651

[36] TiRobot website (accessed June 2023): https://en.tinavi.com/index.php?c=article&a=type&tid=1

Figure 11. Globus ExcelsiusGPS for spine surgery. (Reproduced with permission from © Globus Medical, Inc., Audubon, PA, USA.)

Figure 12. TINAVI TiRobot for spine surgery. (Reproduced from *H. Lan et al., Intramedullary Nail Fixation Assisted by Orthopaedic Robot Navigation for Intertrochanteric Fractures in Elderly Patients, Orthopaedic Surgery, 11: 255-262, 2019, John Wiley and Sons.*)

dynamic reference base on the patient's body and another dynamic reference base on the robotic arm [60]. The TiRobot system can achieve real-time 3D navigation by tracking the relative positions of the patient and the robotic arm [60]. The workstation houses the interface for screw planning and visual feedback [64]. The robotic arm can help surgeons accurately position the surgical tools and implants. TiRobot can also be used for other surgeries like intramedullary nail fixation for intertrochanteric fractures [65].

2.3. Teleoperated RS

2.3.1. Da Vinci Surgical System

The da Vinci surgical system[37] (Intuitive Surgical, Sunnyvale, CA, USA), as shown in Fig. 13, is the most successful teleoperated robotic system for MIS (minimally invasive surgery) in the market. Initially, the system is designed for microvascular surgery [66], and conducted a robot-assisted heart bypass procedure in 1998 in Germany and a robot-assisted radical prostatectomy procedure in 2000 in Paris, France [4]. It received FDA[38] approval in July 2000 for laparoscopic surgery, and since then, the system expanded its applications into various surgical fields and procedures [66]. Lots of surgeries in a wide variety of fields have been successfully conducted by this system, such as prostatectomies, cardiac valve repair, and gynecologic surgical procedures [9]. The da Vinci surgical system further received FDA approval in 2001 for use in prostate surgery, in 2002 for mitral valve repair surgery, in 2005 for gynecological surgery [4].

The da Vinci system is a teleoperated system, and it consists of two patient side manipulators (PSMs), one endoscopic camera manipulator (ECM), and two master tool manipulators (MTMs). The surgeon will remotely control the PSMs by physically operating on the MTMs while the remote scene on the PSM site will be presented to the surgeon via a console by using the ECM. The da Vinci system can translate the surgeon's hands

[37] Da Vinci website (accessed June 2023): https://www.intuitive.com/en-us/products-and-services/da-vinci
[38] Da Vinci FDA 2000 file (accessed June 2023): https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfpmn/pmn.cfm?ID=K990144

Figure 13. Da Vinci Surgical System. (© 2023 Intuitive Surgical Operations, Inc.)

manipulation movements from MTMs to PSMs via the console in real-time, such as bending, rotating, grasping, palpating, and cutting, while providing haptic feedback to the surgeon for an immersive experience.

In orthopedics, the applications of the da Vinci surgical system can be largely limited due to the fact that the system is designed more suitable for manipulating soft tissues (*e.g.*, suturing, ablation, needle insertion) than rigid bones (*e.g.*, cutting, burring). Some surgeries regarding soft tissues or nerves in orthopedics have been conducted using the da Vinci system. For example, da Vinci system was successfully used for ulnar nerve decompression at the elbow [67] and supraclavicular brachial plexus dissection and nerve root grafting at the shoulder [68]. Some cases of anterior lumbar interbody fusion (ALIF) in spine surgery are also reported to be successful by using the da Vinci surgical system [69,70].

2.4. RS Remarks

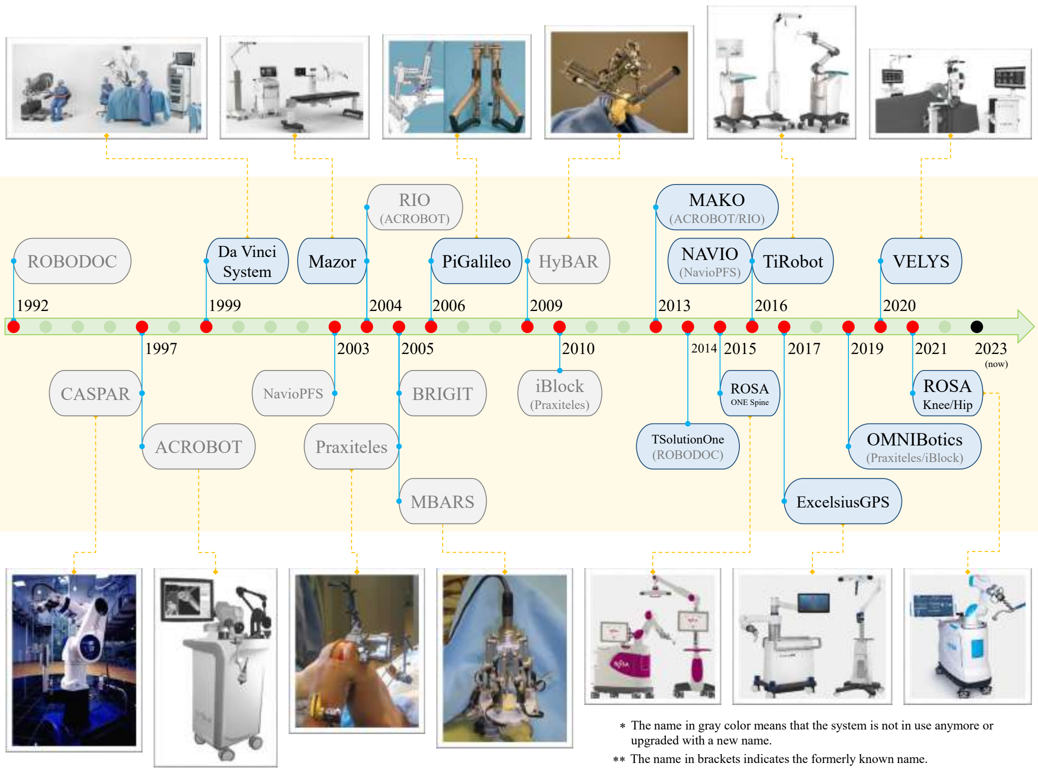


Figure 14. Robotic systems (RS) in the timeline.

The RS systems in the timeline are illustrated in Fig. 14. Currently, the time-honored robotic systems including TSolution One (formerly ROBODOC; THINK Surgical, Fremont, California, USA), MAKO (formerly ACROBOT/RIO; Stryker Corporation, Kalamazoo, Michigan, USA), NAVIO (Smith & Nephew plc, London, UK), and Mazor (Mazor Robotics, Caesarea, Israel) are still available and continue to improve and thrive in the market. Compared to their relatively large robot body, on the other hand, MBAR represents an emerging trend of mini bone-attached robots with potentially more efficiency and lower cost. ROSA and VELYS are newly developed products in the market. Da Vinci Surgical System represents a more versatile robot that has a large potential to be used in a large variety of surgeries for the teleoperated systems used in MIS. In general, by overlooking the robotic systems developed for orthopedics in the past decades, their functions are mainly focusing on bone cutting, positioning, and alignment, while the precision has been increasing whereas the variability has been decreasing [2].

For autonomous RS, it is still cautious about using it in orthopedic surgery due to ethical issues and safety concerns on autonomous operation [26]. Typical issues and concerns include potential muscle/nerve damage and technical complications. For example, when a procedure stop occurred during the bone cutting, re-registration is required while sometimes frequent registration failures may cause the surgery to abort [25].

Compared to autonomous RS, hands-on RS may be more acceptable by surgeons due to the feature of human-in-the-loop [25]. When operating a hands-on RS, the surgeons have full control of the robot and can stop the surgical operations (*e.g.*, bone cutting) at any time they want. This can ensure the safety of the patient at the maximum.

For teleoperated RS, their applications in orthopedics are limited. The main reason is that orthopedic surgeries are more related to manipulation with rigid bone cutting and implant alignments which are not suitable for teleoperated RS. However, for those orthopedic surgeries regarding soft tissues, nerves, and vascular, the teleoperated RS could still be applicable and useful.

3. Computer-Aided Navigation Systems (CANS)

Computer-aided navigation systems (CANS) can be taken as a parallel category to RS. The CANS focuses on navigation with the help of computers. It can be either integrated with an RS or independent from an RS. When integrated together, all the coordinates of the CANS (*e.g.*, CT image frame, and external camera frame) will be registered into the coordinates of the RS, then for navigation. When independent from an RS, *i.e.*, no robots appear in surgery, all the coordinates will be registered into the digital patient's model/image or the camera frame, then for navigation.

In the category of computer-aided navigation systems (CANS), three basic elements are included, *i.e.*, **3D modeling**, **registration**, and **navigation**. Strictly, the CANS are computer-assisted systems rather than robot-assisted systems. However, a robot-assisted system (here equivalent to RS) usually includes a CANS system implicitly or explicitly. Implicitly means that an RS itself can be viewed as a special navigation system since any point in the robot workspace can be tracked based on robot kinematics [17]. Explicitly means that a CANS can be integrated with a robotic system to enhance the system's ability (*e.g.*, tracking and visualization). Therefore, a CANS can be used either independently or integrated with an RS, which means a CANS can be an essential part of assisting surgeons in surgery, no matter whether a robot is involved or not. This also means that the CANS has more wide and more general applications than RS in orthopedics and beyond.

In CAOS tripartite categories, the term of passive systems is equivalent to the CANS here [17,25]. The CANS does not perform any actions on patients thus no relevant safety concerns. Instead, the CANS only collects intraoperative data and provides visualized information and guidance to the surgeons thus helping them to better achieve their surgical objectives accurately and precisely.

A large amount of case studies have shown that the CANS can offer more accurate surgical outcomes, such as placement of the components in UKA, alignment of the femoral and tibial components, tibial slope, and the mechanical axis [17,25].

Table 1. Rotobic systems (RS) in orthopedics.

RS	System	Usage	Features	Pros/Cons (⊕/⊖)
Autonomous	TSolutionOne (ROBODOC)	TKA; THA.	⊙ IBM,1980s; ⊙ first patient in 1992; ⊙ pre-CT based; ⊙ 3D preoperative planning workstation ORTHODOC; ⊙ 5-axis robot; ⊙ bone milling; bone preparing.	⊖ surgeon cannot intervene but stop the robot; ⊖ recovery process is complex if robot stopped during surgery.
	CASPAR	TKA; THA.	⊙ pre-CT based; ⊙ bone milling & preparation; ⊙ position guiding.	⊖ problematic in many studies; ⊖ thus not in use already.
Hands-on (=semi-autonomous)	ACROBOT	TKA; UKA.	⊙ pre-CT based preop. plan; ⊙ 6DOF robot; ⊙ haptic feedback; ⊙ bone cutting; ⊙ active-constrained control.	⊕ system actively prevents the drill from deviating the predefined cutting zone.
	RIO	TKA; THA; UKA.	⊙ inherited from ACROBOT; ⊙ pre-CT based; ⊙ haptic & audio feedback; ⊙ bone cutting; ⊙ force-controlled tip.	⊕ system actively prevents the tool from deviating the predefined cutting zone; ⊕ short learning curve.
	MAKO	TKA; THA; UKA.	⊙ inherited from RIO; ⊙ pre-CT based; ⊙ bone cutting; ⊙ emergency auto shutdown; ⊙ a computer navigation system.	⊕ emergency auto shutdown; ⊕ haptic & audio feedback; ⊕ VF (virtual fixture).
	NAVIO (NavioPFS)	TKA; UKA; uKA.	⊙ image-free system; ⊙ tool tip extend/retract; ⊙ IR optical-based navigation system; ⊙ safety strategy of modulating burr retraction and speed.	⊕ imageless, thus no pre-CT needed. ⊖ no haptic feedback.
	BRIGIT	TKA.	⊙ teleoperated mode available; ⊙ compliant control strategy.	⊕ collaborative or teleoperated mode.
	MBARS; HyBAR	TKA.	⊙ small & bone-mounted robot; ⊙ can be autonomous.	⊕ more efficient; ⊕ cost-effective.
	iBlock (Praxiteles)	TKA.	⊙ imageless system; ⊙ bone morphing technique; ⊙ computer station OmniBiotics; ⊙ intraop. anatomic data; ⊙ intraop. planning.	⊕ can see the planned bone cut before execute. ⊖ no haptic feedback; ⊖ limited kinematic assessment after implantation.
	OMNIBotics	TKA.	⊙ upgraded from iBlock; ⊙ image-free system; ⊙ bone morphing technique; ⊙ small & bone-mounted robot; ⊙ robotic tensioning tool (active spacer).	⊕ active spacer can help to improve surgical outcomes.
	ROSA	TKA; THA; Spine.	⊙ either imageless or image-based; ⊙ bone resection; bone positioning; ⊙ soft tissue assessment.	⊕ intraop. landmarks data.
	VELYS	TKA.	⊙ imageless; ⊙ patient-specific TKA technique.	⊕ intraop. data on both anatomy and soft tissue; ⊕ allow intraop. planning.
	Mazor	Spine.	⊙ SpineAssist is the 1st robot for spine; ⊙ four evolved system versions.	⊕ accept preop. or intraop. CT for planning; ⊕ real-time tool tracking.
	ExcelsiusGPS	Spine.	⊙ surveillance marker; ⊙ shock-absorbing.	⊕ accept preop. or intraop. CT, or radiographs for planning; ⊕ real-time image guidance.
	TiRobot	Spine.	⊙ real-time 3D navigation.	⊕ cross-referencing registration.
Teleop.	da Vinci	MIS.	⊙ applied to various MIS surgeries.	⊕ versatile for various MIS surgeries. ⊖ suitable for manipulating soft tissue but not rigid bones.

Note: **UKA** (unicompartmental knee arthroplasty); **uKA** (unicondylar knee arthroplasty); **TKA** (total knee arthroplasty); **THA** (total hip arthroplasty). **pre-CT**, preoperative CT image; **preop.**, preoperative; **intraop.**, intraoperative; **Teleop.**, teleoperated; **IR**, infrared; **MIS**, minimally invasive surgery; **DOF**, degree of freedom. System names in gray color mean either not in use anymore or upgraded with new names.

3.1. Three basic elements

A complete set of CANS techniques in orthopedics includes three basic elements, *i.e.*, 3D modeling, registration, and navigation [10].

3.1.1. 3D modeling

3D modeling is about reconstructing a 3D digital model of the patient's bone, and then the model can be further used to make preoperative planning by the surgeon. Typically, the 3D model is reconstructed from preoperative images (*e.g.*, CT, X-ray, MRI). For example, most of the previously introduced RSs do the 3D modeling based on preoperative CT scans. Some other systems (*e.g.*, NAVIO) generated the 3D model by using bone morphing techniques and intraoperative tracking data, then visualizing the 3D model in a graphical format.

3.1.2. Registration

Registration is a core and compulsory procedure for any CANS system or RS system being used in orthopedic surgeries. The quality of registration fundamentally and directly determines the accuracy and precision of the surgical outcomes [17]. It is worth mentioning that both RS and CANS are heavily relying on registration, while RS is more so than an independent CANS due to the fact that the surgical work is conducted by the robotic-attached tool in RS rather than the surgeon alone [17].

Before the surgery in the operating room, registrations between the patient's true bone, the corresponding 3D model, the robotic system (if applicable), and the surgical tool need to be conducted first. Some methods may be needed to ensure accurate registration. There are three typical registration methods including **fiducial-based paired-point matching**, **surface-based**, and **2D/3D–3D registration** [25]. ROBODOC initially used fiducial-based registration and changed to surface-based registration in 1999, while studies have proved that the surface-based registration is as accurate as the fiducial-based registration [25].

Fiducial-based paired-point matching method is a modified version of the paired-point matching method [25]. To get a high-accuracy and reproducible registration, fiducials need to be placed into the target bone before the preoperative CT scanning such that these fiducials will appear in the CT images. These fiducials will be used for registration by using the paired-point matching method. During the surgery, these fiducials will be used as the reference points for the patient's bone, and relate it to the preoperative plan. However, the fiducial-based registration requires an additional minor operation of placing the fiducials into the bone before the preoperative CT scanning which brings fiducial site pain or inflammation to the patients [25].

Surface-based (also known as shape-based) registration does not need fiducials. It employed a widely-used iterative closest point (ICP) algorithm and the least-squares method to match the points on the 3D model surface with those on the patient's bone surface [71,72]. To avoid local minima, the paired-point method will be used first to do a baseline registration, then a certain number of points will be used to do a refinement surface-based registration [25]. An advantage of surface-based registration is that it can be conducted and updated intraoperatively and in real-time, which makes it more robust than other registration methods.

The 2D-3D or 3D-3D registration method makes use of intraoperative fluoroscopic images [25]. Although this method has been shown to be accurate for use in robot-assisted THA in a lab setting, it has not yet been widely accepted by clinical robotic surgeries [25].

3.1.3. Navigation

Navigation is the kernel element and function of a navigation system. Given an accurate 3D model and an accurate registration, the surgical tools and the patient's bone landmarks can be precisely tracked either by a set of tracking devices or by the robot coordinate system. A sensor-based navigation system usually uses optical sensors or magnetic sensors to track the 3D positions of the target bones, the surgical tools, and any other objects (*e.g.*, implants) needing to be tracked [25]. An optical IR-based system can track objects with high accuracy by using infrared (IR) light tracking cameras and infrared light reflecting markers [25]. However, the optical-sensor-based tracking system can be easily affected by light-sight blocking. The magnetic sensor does not have this problem, but it may be affected by metallic objects within its workspace [25]. A novel approach for active optical navigation has been proposed recently, where the optical tracking system (OTS) is installed on a robot that can actively adjust the pose of the OTS [73].

Based on the working principles, CANS includes three typical types of navigation systems being used in orthopedic surgeries, *i.e.*, **CT-based**, **imageless**, and **fluoroscopic** [25]. In 1994, two years after the ROBODOC was first used on humans, the first CT-based navigation system was developed and used in THA in Pittsburgh [17,74]. CT-based navigation is prevail among most of the previously introduced robotic systems. Although CT-based navigation has the highest accuracy, a big disadvantage is that acquiring preoperative CT images and making preoperative plans based on them are time-consuming which may bring more cost and radiation exposure to patients [25].

Imageless navigation, also known as "surgeon-defined anatomy" technology, employs some other techniques such as infrared (IR)-based tracking, stereotaxic technology, and bone morphing technology. Note that here the imageless or image-free means that no preoperative CT images are required but may still need camera-based intraoperative tracking for navigation. Together with the intraoperatively collected patient's anatomic data, an abstract of the patient's anatomy can be generated [17]. This kind of imageless technique is adopted by some robotic systems, such as the NAVIO system and Praxiteles. The accuracy of imageless navigation will depend on the techniques adopted.

Fluoroscopic navigation has a similar principle to imageless navigation but uses fluoroscopic images. The fluoroscopic navigation is good for use in trauma and spine surgeries but is limited in other orthopedic surgeries due to its cumbersome registration procedures [25].

3.2. Typical Systems

3.2.1. Stryker Navigation system

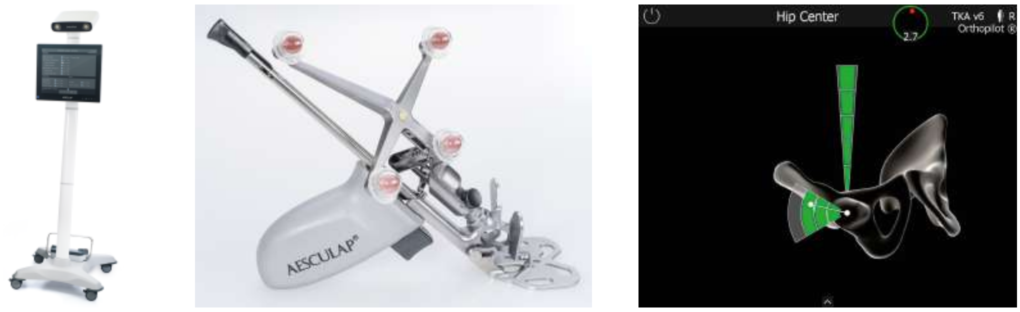
Stryker Navigation system II Cart[39] (Stryker, Kalamazoo, MI, USA), is an optical-based navigation system with an optical localizer accuracy of about 0.07 mm [75]. The navigation system can reconstruct the 3D bone model by using the original CT data. Dynamic reference trackers will be placed on the patient's bone for later registration with considerations of avoiding nerve injuries and interrupting navigation pointer operations [75]. A study on validating the registration accuracy of a Stryker navigation system (Stryker II cart Navigation system) for elbow arthroscopic debridement showed that the registration accuracy can achieve to be within 1 mm [75].

3.2.2. OrthoPilot

OrthoPilot[40] (Aesculap/BBraun, Germany), as shown in Fig. 15, is a pure navigation system that conducted its first surgery in 1997 [18]. It is an imageless navigation system, and it works based on intraoperative data acquired by an optical tracking system [18]. The tracking system consists of an infrared (IR) tracking camera and IR Spectra localizer (Northern Digital Inc.). Currently, the OrthoPilot has been used in TKA, revision TKA, and THA. A detailed introduction to using OrthoPilot over two decades can be found in [18].

[39] Stryker NAV3i website (accessed June 2023): https://www.stryker.com/us/en/navigation/products/nav3i.html

[40] OrthoPilot website (accessed June 2023): https://www.bbraun.com/en/products-and-solutions/therapies/orthopaedic-surgery/orthopilot.html



(a) Hardware **(b)** Multitool **(c)** Software display

Figure 15. OrthoPilot navigation system. (Reproduced with permission from © Aesculap AG, Tuttlingen, Germany.)

Figure 16. Brainlab Knee3. (Reproduced with permission from © Brainlab AG, Munich, Germany.)

3.2.3. Brainlab Knee3

Brainlab Knee3[41] (Brainlab AG, Munich, Germany), as shown in Fig. 16, is a new imageless navigation system for use in TKA [59]. It is featured with real-time assessment of the knee as a complete kinematic structure and predicting final joint stability at each surgical step. It can display X-rays and templated plans during navigation. It can also predict and visualize the virtual interaction between 3D kinematics, joint stability, and implant alignment [76].

3.3. CANS Remarks

The three basic elements of CANS, *i.e.*, 3D modeling, registration, and navigation are critical conditions to each other. 3D modeling is the necessary prerequisite for registration, while registration is the necessary prerequisite for navigation. The accuracy of 3D modeling directly affects the accuracy of registration, and the latter will further determine the accuracy of the navigation.

The CANS is an independent technique that can be either used together with the RS or used alone during surgical procedures. The applications of CANS are much wider and more general than RS since a robot may be not demanded or applicable in some surgeries while navigation can be always helpful. From another perspective, the existing RS mainly focuses on hip/knee arthroplasty while the CANS has a relatively wider variety of applications, such as shoulder [22], elbow [77], and ankle. A systematic review of CT-based intraoperative navigation techniques used in total shoulder arthroplasty (TSA) can be found in [22].

4. Discussions and Future Perspectives

Both CANS and RS have been playing an increasingly critical role in modern orthopedic surgeries. According to a review study [17,78], the ratio of patents to publications related to CANS and RS in knee arthroplasty increased from around 1:10 in 2004 to around 1:3 in 2014. The benefits brought by RS and CANS include but are not limited to augmenting the surgical procedures, fine-tuning surgical plans to personalized patient profiles, and

[41] Brainlab Knee3 website (accessed June 2023): https://knee3.brainlab.com/#/main-menu

proving intraoperative data and real-time visualization to the surgeons for a more accurate and precise surgical outcome [17].

With decades of evolution, RS and CANS themselves have gone through critical improvement and upgrading. Without a doubt, RS and CANS will continue to thrive and play an indispensable role in orthopedics.

A critical unique feature of RS in orthopedics is that they must be capable of dealing with high forces and stiffness due to the rigid nature of their target object of bones, while the da Vinci surgical system is more suitable for soft-tissue-related procedures. The main advantages of RS applied in orthopedics include increased accuracy and precision of implant positioning, enhanced reproducibility, improved implant stability, and less resulting pain. On the other hand, the main disadvantages of RS include potential safety concerns, high economic costs, and potentially longer operative time.

CANS will continue to develop along two parallel paths. One is to integrate with robotic systems, another is to be used alone without involving RS. For the latter, CANS is capable of being used in more versatile surgeries where robots are not needed or not yet available. In that case, with the help of CANS, surgeons can perform conventional surgeries with potentially better and more accurate surgical outcomes.

4.1. RS and CANS for Various Orthopedic Surgeries

From Table 1, it can be found that most of the robotic systems are applied for hip/knee surgeries, some are for spine surgeries, and no specific robotic system is exclusively for elbow/shoulder surgeries. For example, ROSA has robot-assisted systems for the hip, knee, and spine, respectively, but only has a computer-aided system for assisting in planning and navigation for the shoulder. The RSs have been abundantly developed and frequently used in hip/knee surgeries but not in elbow/shoulder/foot/ankle surgeries, while the latter seems more favorable on CANSs [79]. The possible reason could be that there are much more cases and demand for knee/hip surgery than elbow/shoulder surgery. The knee is the largest hinge joint in the body while the hip is a large ball-and-socket joint. Both the knee and hip joints take a lot of wear, tear, and stress from daily activities (*e.g.*, walking, running, jumping) while supporting the body weight in horizontal and vertical directions, and they are more vulnerable to injury and osteoarthritis than elbow/shoulder or any other joints.

Technically, all joint replacement/arthroplasty surgeries are open surgeries since a significant incision needs to be made in order to expose the bone for bone cutting or implant positioning. It is worth noting that in joint replacement/arthroplasty, minimally invasive approach/procedure has different definitions, such as shorter incision length, non-dissection of quadriceps tendon, non-eversion of the patella, or non-dislocation of the tibiofemoral joint [80]. Therefore, strictly speaking, all joint replacement/arthroplasty are open surgeries rather than MIS which in the latter only several trocars need to be made in order to insert the surgical instruments for performing the surgery. In this sense, arthroscopic surgeries belong to the category of MIS. For arthroscopic surgeries, several portals are made to insert an arthroscope and surgical tools, and the surgical tools will be used to perform the surgery with the help of the arthroscope. Arthroscopic surgeries can be used for a large variety of indications. For example, elbow arthroscopy can be used for the management of stiffness related to degenerative arthritis, loose bodies, lateral epicondylitis, synovitis, osteochondritis dissecans, symptomatic plica, infection, contracture, instability, and fracture management [81].

Arthroscopic surgeries (*e.g.*, arthroscopic debridement) is an active field that is being transformed by techniques of RS and CANS, although there is yet no specific robotic system specially designed for them. One possible reason is that there is high demand for accuracy and precision for surgeries of joint replacement/arthroplasty but not for arthroscopic surgeries. Also, for those arthroscopic surgeries related to soft tissue manipulation rather than rigid bone cutting, laparoscopic-type robotic systems like the da Vinci surgical system can be employed [67,68]. A robotic system can be helpful in arthroscopic surgeries, such as holding with the arthroscope as a robotic assistance. On the other hand, a navigation system can also bring benefits, such as tracking and visualizing the real-time location of the tool tip. Accompanying the wide usage of arthroscopic surgeries with the benefits of MIS, RS and CANS are getting deeply involved in arthroscopic surgeries [82].

4.2. Novel Robotic Designs

In addition to traditional rigid robots, novel types of robots, instruments, and approaches are developed for use in orthopedic surgeries [83]. A curved-drilling approach has been developed by integrating curved-drilling tools with a continuum dexterous manipulator (CDM) for use in core decompression of the femoral head osteonecrosis [84]. The curved-drilling technique and bendable medical screws have been examined on cadaveric specimens for minimally invasive interventions in orthopedic surgery [85]. A redundant robotic system consisting of a rigid-link robot and a CDM has been proposed for the treatment of pelvic osteolysis and for autonomous debridement of osteolytic bone lesions in confined spaces [86,87]. A miniaturized tendon-driven articulated surgical drill was designed for bone drilling which can be used in minimally invasive spine fusion [88]. Hand-held robotic systems have also been developed for minimally invasive orthopedic surgeries [89,90]. Recently, a concentric-tube steerable drilling robot is developed for spinal fixation procedures and implanting flexible pedicle screws [91,92]. Although these novel designs have not yet been applied in the clinical setting, their benefits in orthopedic surgeries can be expected in the near future.

4.3. Surgical Simulators

In parallel to robotic systems, another promising robotic technique is surgical simulators for training novices, *e.g.*, virtual reality (VR) arthroscopy trainer, VirtaMed ArthroS Hip/Knee/Shoulder/Ankle (VirtaMed AG, Zurich, Switzerland), and insightArthroVR (GMV, Madrid, Spain) [93,94]. By using surgical simulators, the surgical skills of the novice can be improved before they start to conduct surgeries on human patients. This can largely enhance the novice's confidence and reduce the risk of surgical mistakes in patients caused by lacking practical experience and unfamiliar operations on surgical robotic systems.

4.4. Artificial Intelligence (AI)

As a prominent topic in recent years, artificial intelligence (AI) is getting extraordinarily popular especially after the breakthrough made by ChatGPT (OpenAI, San Francisco, California, USA), although AI itself is not a novel concept [95]. Some AI-based features have already been applied in robot-assisted surgeries, for example, AI algorithms presented in [95–97]. Benefiting from the huge amount of patient data available in literature and hospitals, a series of reliable AI-based techniques can be expected, such as AI-based diagnosis, AI-based pre- and intra-operative planning, AI-based intraoperative navigation, AI-based decision-making, and AI-based control of robotic systems [95]. By appropriately incorporating these AI features, the capability of the robot and navigation systems can be further improved and enhanced. On the other hand, this is also an opportunity for developing fully autonomous robotic systems and pushing them a step forward. One can imagine that AI-powered fully automated robotic systems can be developed and accepted by the public in the future.

The future of CANS and RS in orthopedics is promising with the rapidly advancing and evolving new technologies, such as image-guided techniques, virtual reality (VR), augmented reality (AR), mixed reality (MR) [98,99], advanced robotic control strategies, AI, and even novel biodegradable materials [100,101].

5. Conclusion and Future Challenges

As a brief conclusion, it is an unstoppable trend for the RS and CANS to be introduced into more variety of surgical scenarios besides hip/knee surgeries, and it is rapidly happening. Robotics and navigation techniques have been playing increasingly important roles in elbow/shoulder, foot/ankle, spine surgeries, arthroscopic surgeries, and far beyond [22,77,79,82,102,103]. With the newly emerging techniques, such as AI, VR, and soft/flexible robotics, robots and navigation systems in orthopedics will become more intelligent, more reliable, and more economical in the future.

Accompanying the increasingly thriving potential of the RS and CANS in orthopedics and beyond, many challenges may emerge. First of all, fully autonomous robotic systems may still face big challenges in being accepted. Safety is always of the utmost concern both for surgeons and patients. To ensure safe surgery, surgeon-in-the-loop is usually a preferable solution for robot-assisted surgery than fully autonomous robotic systems. In return, this will slow down the development of autonomous systems. In this situation, how to find a way to improve the quality and stability of autonomous systems could be challenging. Artificial intelligence (AI) is increasingly popular nowadays. Another challenge could be how should the developers incorporate AI features into the existing robotic and navigation systems in order to enhance the capabilities of the system while ensuring system stability and safety. Economic costs can be also a challenge in making robotic systems widely accepted both by patients and hospitals. Without a doubt, to make robot-assisted surgery affordable to patients, more efforts and collaborations need to be made by manufacturers, hospitals, developers, and surgeons. Last but not least, surgeons with traditional surgical skills may face a challenging situation for operating robot-assisted surgeries. Novel training approaches and strategies need to be established in order to help surgeons to acquire robot-assisted surgical skills based on their own traditional surgical skills.

(– END –)

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Abbreviations

The following abbreviations are used in this manuscript:

RS	robotic system
CANS	computer-aided navigation system
CAOS	computer-assisted orthopedic surgery
FDA	Food and Drug Administration
CT	computed tomography
MIS	minimally invasive surgery
VF	virtual fixture
VR	virtual reality
MR	mixed reality
AR	augmented reality
AI	artificial intelligence
uKA	unicondylar knee arthroplasty
UKA	unicompartmental knee arthroplasty
UKR	unicompartmental knee replacement (=UKA)
TKA	total knee arthroplasty
TKR	total knee replacement (=TKA)
THA	total hip arthroplasty
THR	total hip replacement (=THA)
TSA	total shoulder arthroplasty
pre-CT	preoperative CT image
preop.	preoperative
intraop.	intraoperative
IR	infrared
ICP	iterative closest point
DOF	degree of freedom
CDM	continuum dexterous manipulator
pHRI	physical human-robot interaction
MTM	master tool manipulator
PSM	patient side manipulator
ECM	endoscopic camera manipulator
OTS	optical tracking system

References

1. Devol, G.C. Programmed article transfer. *USA Patent* **1961**, *2*, 237.
2. Jacofsky, D.J.; Allen, M. Robotics in arthroplasty: a comprehensive review. *The Journal of arthroplasty* **2016**, *31*, 2353–2363.
3. Davies, B. A review of robotics in surgery. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* **2000**, *214*, 129–140.
4. Lonner, J.H. *Robotics in knee and hip arthroplasty: Current concepts, techniques and emerging uses*; Springer, 2019.
5. Vitiello, V.; Lee, S.L.; Cundy, T.P.; Yang, G.Z. Emerging robotic platforms for minimally invasive surgery. *IEEE reviews in biomedical engineering* **2012**, *6*, 111–126.
6. Garcia Jr, J.C.; de Souza Montero, E.F. Endoscopic robotic decompression of the ulnar nerve at the elbow. *Arthroscopy Techniques* **2014**, *3*, e383–e387.
7. D'Ettorre, C.; Mariani, A.; et al. Accelerating surgical robotics research: Reviewing 10 years of research with the dVRK. *arXiv preprint arXiv:2104.09869* **2021**.
8. Beasley, R.A. Medical robots: current systems and research directions. *Journal of Robotics* **2012**, *2012*.
9. Ginoya, T.; Maddahi, Y.; Zareinia, K. A historical review of medical robotic platforms. *Journal of Robotics* **2021**, *2021*, 1–13.
10. Abdelaal, A.E.; Mathur, P.; Salcudean, S.E. Robotics in vivo: A perspective on human–robot interaction in surgical robotics. *Annual Review of Control, Robotics, and Autonomous Systems* **2020**, *3*, 221–242.
11. Pugin, F.; Bucher, P.; Morel, P. History of robotic surgery: from AESOP® and ZEUS® to da Vinci®. *Journal of visceral surgery* **2011**, *148*, e3–e8.
12. Hannaford, B.; Rosen, J.; Friedman, D.W.; King, H.; Roan, P.; Cheng, L.; Glozman, D.; Ma, J.; Kosari, S.N.; White, L. Raven-II: an open platform for surgical robotics research. *IEEE Transactions on Biomedical Engineering* **2012**, *60*, 954–959.
13. Kilby, W.; Naylor, M.; Dooley, J.R.; Maurer Jr, C.R.; Sayeh, S. A technical overview of the CyberKnife system. *Handbook of robotic and image-guided surgery* **2020**, pp. 15–38.
14. Taylor, R.; Jensen, P.; Whitcomb, L.; Barnes, A.; Kumar, R.; Stoianovici, D.; Gupta, P.; Wang, Z.; Dejuan, E.; Kavoussi, L. A steady-hand robotic system for microsurgical augmentation. *The International Journal of Robotics Research* **1999**, *18*, 1201–1210.
15. Mitchell, B.; Koo, J.; Iordachita, I.; Kazanzides, P.; Kapoor, A.; Handa, J.; Hager, G.; Taylor, R. Development and application of a new steady-hand manipulator for retinal surgery. In Proceedings of the Proceedings 2007 IEEE International Conference on Robotics and Automation. IEEE, 2007, pp. 623–629.
16. Ahronovich, E.Z.; Simaan, N.; Joos, K.M. A review of robotic and OCT-aided systems for vitreoretinal surgery. *Advances in therapy* **2021**, *38*, 2114–2129.
17. Picard, F.; Deakin, A.H.; Riches, P.E.; Deep, K.; Baines, J. Computer assisted orthopaedic surgery: past, present and future. *Medical engineering & physics* **2019**, *72*, 55–65.
18. Saragaglia, D. More Than 20 Years Navigation of Knee Surgery With the Orthopilot Device. In *Handbook of Robotic and Image-Guided Surgery*; Elsevier, 2020; pp. 425–441.
19. Perets, I.; Mu, B.H.; Mont, M.A.; Rivkin, G.; Kandel, L.; Domb, B.G. Current topics in robotic-assisted total hip arthroplasty: a review. *Hip International* **2020**, *30*, 118–124.
20. Shatrov, J.; Parker, D. Computer and robotic–assisted total knee arthroplasty: a review of outcomes. *Journal of Experimental Orthopaedics* **2020**, *7*, 1–15.
21. St Mart, J.P.; Goh, E.L.; Shah, Z. Robotics in total hip arthroplasty: a review of the evolution, application and evidence base. *EFORT Open Reviews* **2020**, *5*, 866.
22. Eng, K.; Eyre-Brook, A.; Shields, D.W. A Systematic Review of the Utility of Intraoperative Navigation During Total Shoulder Arthroplasty. *Cureus* **2022**, *14*.
23. Enayati, N.; De Momi, E.; Ferrigno, G. Haptics in robot-assisted surgery: Challenges and benefits. *IEEE reviews in biomedical engineering* **2016**, *9*, 49–65.
24. Battenberg, A.K.; Netravali, N.A.; Lonner, J.H. A novel handheld robotic-assisted system for unicompartmental knee arthroplasty: surgical technique and early survivorship. *Journal of Robotic Surgery* **2020**, *14*, 55–60.
25. Sugano, N. Computer-assisted orthopaedic surgery and robotic surgery in total hip arthroplasty. *Clinics in orthopedic surgery* **2013**, *5*, 1–9.
26. Lang, J.; Mannava, S.; Floyd, A.; Goddard, M.; Smith, B.; Mofidi, A.; M. Seyler, T.; Jinnah, R. Robotic systems in orthopaedic surgery. *The Journal of bone and joint surgery. British volume* **2011**, *93*, 1296–1299.
27. Koenig, J.H.; Hepinstall, M.S. Available robotic platforms in partial and total knee arthroplasty. *Operative Techniques in Orthopaedics* **2015**, *25*, 85–94.
28. Davies, B.; Rodriguez y Baena, F.; Barrett, A.; Gomes, M.; Harris, S.; Jakopec, M.; Cobb, J. Robotic control in knee joint replacement surgery. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* **2007**, *221*, 71–80.
29. Jinnah, A.H.; Luo, T.D.; Plate, J.F.; Jinnah, R.H., General Concepts in Robotics in Orthopedics. In *Robotics in Knee and Hip Arthroplasty: Current Concepts, Techniques and Emerging Uses*; Lonner, J.H., Ed.; Springer International Publishing: Cham, 2019; pp. 27–35. https://doi.org/10.1007/978-3-030-16593-2_3.
30. Decking, J.; Gerber, A.; Kränzlein, J.; Meurer, A.; Böhm, B.; Plitz, W. The primary stability between manual and robot assisted implantation of hip prostheses: A biomechanical study on synthetic femurs. *Zeitschrift fur Orthopadie und Ihre Grenzgebiete* **2004**, *142*, 309–313.

31. Wu, L.d.; Hahne, H.; Hassenpflug, J. The dimensional accuracy of preparation of femoral cavity in cementless total hip arthroplasty. *Journal of Zhejiang University-SCIENCE A* **2004**, *5*, 1270–1278.
32. Siebel, T.; Käfer, W. Clinical outcome following robotic assisted versus conventional total hip arthroplasty: a controlled and prospective study of seventy-one patients. *Zeitschrift fur Orthopadie und ihre Grenzgebiete* **2005**, *143*, 391–398.
33. Kilby, W.; Dooley, J.; Kuduvalli, G.; Sayeh, S.; Maurer Jr, C. The CyberKnife® robotic radiosurgery system in 2010. *Technology in cancer research & treatment* **2010**, *9*, 433–452.
34. Kilby, W.; Naylor, M.; Dooley, J.R.; Maurer Jr, C.R.; Sayeh, S. A technical overview of the CyberKnife system. *Handbook of robotic and image-guided surgery* **2020**, pp. 15–38.
35. Guthrie, B.; Adler Jr, J. Computer-assisted preoperative planning, interactive surgery, and frameless stereotaxy. *Clinical neurosurgery* **1992**, *38*, 112–131.
36. Adler Jr, J.R.; Chang, S.D.; Murphy, M.J.; Doty, J.; Geis, P.; Hancock, S.L. The Cyberknife: a frameless robotic system for radiosurgery. *Stereotactic and functional neurosurgery* **1997**, *69*, 124–128.
37. Liu, P.; Lu, F.f.; Liu, G.j.; Mu, X.h.; Sun, Y.q.; Zhang, Q.d.; Wang, W.g.; Guo, W.s. Robotic-assisted unicompartmental knee arthroplasty: a review. *Arthroplasty* **2021**, *3*, 1–10.
38. y Baena, F.R.; Davies, B. Robotic surgery: from autonomous systems to intelligent tools. *Robotica* **2010**, *28*, 163–170.
39. Davies, B.; Harris, S.; Lin, W.; Hibberd, R.; Middleton, R.; Cobb, J. Active compliance in robotic surgery—the use of force control as a dynamic constraint. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* **1997**, *211*, 285–292.
40. Bargar, W.L. Robots in orthopaedic surgery: past, present, and future. *Clinical Orthopaedics and Related Research®* **2007**, *463*, 31–36.
41. Pearle, A.D.; O'Loughlin, P.F.; Kendoff, D.O. Robot-assisted unicompartmental knee arthroplasty. *The Journal of arthroplasty* **2010**, *25*, 230–237.
42. Rees, J.; Price, A.; Beard, D.; Dodd, C.; Murray, D. Minimally invasive Oxford unicompartmental knee arthroplasty: functional results at 1 year and the effect of surgical inexperience. *The Knee* **2004**, *11*, 363–367.
43. Lonner, J.H.; Smith, J.R.; Picard, F.; Hamlin, B.; Rowe, P.J.; Riches, P.E. High degree of accuracy of a novel image-free handheld robot for unicondylar knee arthroplasty in a cadaveric study. *Clinical Orthopaedics and Related Research®* **2015**, *473*, 206–212.
44. Wallace, D.; Gregori, A.; Picard, F.; Bellemans, J.; Lonner, J.; Marquez, R.; Smith, J.; Simone, A.; Jaramaz, B. The learning curve of a novel handheld robotic system for unicondylar knee arthroplasty. In Proceedings of the Orthopaedic proceedings. Bone & Joint, 2014, Vol. 96, pp. 13–13.
45. Simons, M.; Riches, P. The learning curve of robotically-assisted unicondylar knee arthroplasty. In Proceedings of the Orthopaedic Proceedings. Bone & Joint, 2014, Vol. 96, pp. 152–152.
46. Maillet, P.; Nahum, B.; Blondel, L.; Poignet, P.; Dombre, E. BRIGIT, a robotized tool guide for orthopedic surgery. In Proceedings of the Proceedings of the 2005 IEEE International Conference on Robotics and Automation. IEEE, 2005, pp. 211–216.
47. Kuang, S.; Tang, Y.; Lin, A.; Yu, S.; Sun, L. Intelligent control for human-robot cooperation in orthopedics surgery. *Intelligent Orthopaedics: Artificial intelligence and smart image-guided technology for orthopaedics* **2018**, pp. 245–262.
48. Wolf, A.; Jaramaz, B.; Lisien, B.; DiGioia, A. MBARS: mini bone-attached robotic system for joint arthroplasty. *The International Journal of Medical Robotics and Computer Assisted Surgery* **2005**, *1*, 101–121.
49. Song, S.; Mor, A.; Jaramaz, B. HyBAR: hybrid bone-attached robot for joint arthroplasty. *The International Journal of Medical Robotics and Computer Assisted Surgery* **2009**, *5*, 223–231.
50. Plaskos, C.; Cinquin, P.; Lavallée, S.; Hodgson, A. Praxiteles: a miniature bone-mounted robot for minimal access total knee arthroplasty. *The International Journal of Medical Robotics and Computer Assisted Surgery* **2005**, *1*, 67–79.
51. Allen, M.W.; Jacofsky, D.J., Evolution of Robotics in Arthroplasty. In *Robotics in Knee and Hip Arthroplasty: Current Concepts, Techniques and Emerging Uses*; Lonner, J.H., Ed.; Springer International Publishing: Cham, 2019; pp. 13–25. https://doi.org/10.1007/978-3-030-16593-2_2.
52. Koulalis, D.; O'Loughlin, P.F.; Plaskos, C.; Kendoff, D.; Cross, M.B.; Pearle, A.D. Sequential versus automated cutting guides in computer-assisted total knee arthroplasty. *The Knee* **2011**, *18*, 436–442.
53. Ritschl, P.; Machacek, F.; Fuiko, R., Modern Navigated Ligament Balancing in Total Knee Arthroplasty with the PiGalileo System. In *Navigation and MIS in Orthopedic Surgery*; Stiehl, J.B.; Konermann, W.H.; Haaker, R.G.; DiGioia, A.M., Eds.; Springer Berlin Heidelberg: Berlin, Heidelberg, 2007; pp. 135–140. https://doi.org/10.1007/978-3-540-36691-1_17.
54. Netravali, N.A.; Shen, F.; Park, Y.; Bargar, W.L. A perspective on robotic assistance for knee arthroplasty. *Advances in orthopedics* **2013**, *2013*.
55. Lefranc, M.; Peltier, J. Accuracy of thoracolumbar transpedicular and vertebral body percutaneous screw placement: coupling the Rosa® Spine robot with intraoperative flat-panel CT guidance—a cadaver study. *Journal of robotic surgery* **2015**, *9*, 331–338.
56. Lefranc, M.; Peltier, J. Evaluation of the ROSA™ Spine robot for minimally invasive surgical procedures. *Expert review of medical devices* **2016**, *13*, 899–906.
57. Jiang, B.; Azad, T.D.; Cottrill, E.; Zygourakis, C.C.; Zhu, A.M.; Crawford, N.; Theodore, N. New spinal robotic technologies. *Frontiers of Medicine* **2019**, *13*, 723–729.
58. Doan, G.W.; Courtis, R.P.; Wyss, J.G.; Green, E.W.; Clary, C.W. Image-free robotic-assisted total knee arthroplasty improves implant alignment accuracy: a cadaveric study. *The Journal of Arthroplasty* **2022**, *37*, 795–801.

59. Clatworthy, M.; SURGEON, O.K.; BONE, A.; AUCKLAND, N.Z. Patient-Specific TKA with the VELYS™ Robotic-Assisted Solution. *Surgical Technology International* **2022**, *40*.
60. Perfetti, D.C.; Kisinde, S.; Rogers-LaVanne, M.P.; Satin, A.M.; Lieberman, I.H. Robotic spine surgery: Past, present, and future. *Spine* **2022**, *47*, 909–921.
61. Zhang, Q.; Han, X.G.; Fan, M.X.; Zhao, J.W.; Lang, Z.; Jiang, J.L.; He, D.; Liu, B.; Tian, W. Robotic navigation during spine surgery: an update of literature. *Expert Review of Medical Devices* **2023**, pp. 1–6.
62. Gosrisirikul, C.; Don Chang, K.; Raheem, A.A.; Rha, K.H. New era of robotic surgical systems. *Asian journal of endoscopic surgery* **2018**, *11*, 291–299.
63. Crawford, N.; Johnson, N.; Theodore, N. Ensuring navigation integrity using robotics in spine surgery. *Journal of robotic surgery* **2020**, *14*, 177–183.
64. Huang, M.; Tetreault, T.A.; Vaishnav, A.; York, P.J.; Staub, B.N. The current state of navigation in robotic spine surgery. *Annals of Translational Medicine* **2021**, *9*.
65. Lan, H.; Tan, Z.; Li, K.n.; Gao, J.h.; Liu, T.h. Intramedullary nail fixation assisted by orthopaedic robot navigation for intertrochanteric fractures in elderly patients. *Orthopaedic Surgery* **2019**, *11*, 255–262.
66. Conditt, M., History of Robots in Orthopedics. In *Surgical Robotics: Systems Applications and Visions*; Rosen, J.; Hannaford, B.; Satava, R.M., Eds.; Springer US: Boston, MA, 2010; pp. 661–677.
67. Garcia Jr, J.C.; de Souza Montero, E.F. Endoscopic robotic decompression of the ulnar nerve at the elbow. *Arthroscopy Techniques* **2014**, *3*, e383–e387.
68. Facca, S.; Hendriks, S.; Mantovani, G.; Selber, J.C.; Liverneaux, P. Robot-assisted surgery of the shoulder girdle and brachial plexus. In Proceedings of the Seminars in plastic surgery. Thieme Medical Publishers, 2014, Vol. 28, pp. 039–044.
69. Beutler, W.J.; Peppelman Jr, W.C.; DiMarco, L.A. The da Vinci robotic surgical assisted anterior lumbar interbody fusion: technical development and case report. *Spine* **2013**, *38*, 356–363.
70. Lee, Z.; Lee, J.; Welch, W.; Eun, D. Technique and surgical outcomes of robot-assisted anterior lumbar interbody fusion. *Journal of robotic surgery* **2013**, *7*, 177–185.
71. Besl, P.J.; McKay, N.D. Method for registration of 3-D shapes. In Proceedings of the Sensor fusion IV: control paradigms and data structures. Spie, 1992, Vol. 1611, pp. 586–606.
72. Shigi, A.; Oka, K.; Tanaka, H.; Abe, S.; Miyamura, S.; Takao, M.; Mae, T.; Yoshikawa, H.; Murase, T. Validation of the registration accuracy of navigation-assisted arthroscopic debridement for elbow osteoarthritis. *Journal of Shoulder and Elbow Surgery* **2019**, *28*, 2400–2408.
73. Qin, Y.; Geng, P.; You, Y.; Ma, M.; Wang, H.; Han, J. Collaborative Preoperative Planning for Operation-Navigation Dual-Robot Orthopedic Surgery System. *IEEE Transactions on Automation Science and Engineering* **2023**.
74. Digioia, A.M.; Simon, D.; Jaramaz, B.; Blackwell, M.; Morgan, F.; O'Toole, R.V.; Colgan, B.; Kischell, E. HipNav: pre-operative planning and intra-operative navigational guidance for acetabular implant placement in total hip replacement surgery. In Proceedings of the Computer Assisted Orthopaedic Surgery Symposium, 1995, Vol. 30.
75. Shigi, A.; Oka, K.; Tanaka, H.; Abe, S.; Miyamura, S.; Takao, M.; Mae, T.; Yoshikawa, H.; Murase, T. Validation of the registration accuracy of navigation-assisted arthroscopic debridement for elbow osteoarthritis. *Journal of Shoulder and Elbow Surgery* **2019**, *28*, 2400–2408.
76. Pan, Y.; Jiang, B.; Li, Y.; Yu, Y.; Chen, Y. Alignment analysis of Brainlab knee 3 navigation-guided total knee arthroplasty using the adjusted mechanical method. *Frontiers in Surgery* **2022**, *9*.
77. McDonald, C.P.; Johnson, J.A.; Peters, T.M.; King, G.J. Image-based navigation improves the positioning of the humeral component in total elbow arthroplasty. *Journal of shoulder and elbow surgery* **2010**, *19*, 533–543.
78. Dalton, D.M.; Burke, T.P.; Kelly, E.G.; Curtin, P.D. Quantitative analysis of technological innovation in knee arthroplasty: using patent and publication metrics to identify developments and trends. *The Journal of arthroplasty* **2016**, *31*, 1366–1372.
79. Chen, A.F.; Kazarian, G.S.; Jessop, G.W.; Makhdom, A. Robotic technology in orthopaedic surgery. *JBJS* **2018**, *100*, 1984–1992.
80. Leopold, S.S. Minimally invasive total knee arthroplasty for osteoarthritis. *New England Journal of Medicine* **2009**, *360*, 1749–1758.
81. Athwal, G.S. *PART IV, Elbow and Forearm. Chapter 26, Elbow Arthroscopy*; Elsevier Inc., 2017.
82. Hahn, B.S.; Park, J.Y. Incorporating new technologies to overcome the limitations of endoscopic spine surgery: navigation, robotics, and visualization. *World Neurosurgery* **2021**, *145*, 712–721.
83. Sendrowicz, A.; Scali, M.; Culmone, C.; Breedveld, P. Surgical drilling of curved holes in bone–a patent review. *Expert Review of Medical Devices* **2019**, *16*, 287–298.
84. Alambeigi, F.; Wang, Y.; Sefati, S.; Gao, C.; Murphy, R.J.; Iordachita, I.; Taylor, R.H.; Khanuja, H.; Armand, M. A curved-drilling approach in core decompression of the femoral head osteonecrosis using a continuum manipulator. *IEEE Robotics and Automation Letters* **2017**, *2*, 1480–1487.
85. Alambeigi, F.; Bakhtiarinejad, M.; Sefati, S.; Hegeman, R.; Iordachita, I.; Khanuja, H.; Armand, M. On the use of a continuum manipulator and a bendable medical screw for minimally invasive interventions in orthopedic surgery. *IEEE transactions on medical robotics and bionics* **2019**, *1*, 14–21.
86. Sefati, S.; Hegeman, R.; Alambeigi, F.; Iordachita, I.; Kazanzides, P.; Khanuja, H.; Taylor, R.H.; Armand, M. A surgical robotic system for treatment of pelvic osteolysis using an FBG-equipped continuum manipulator and flexible instruments. *IEEE/ASME Transactions on Mechatronics* **2020**, *26*, 369–380.

87. Sefati, S.; Hegeman, R.; Iordachita, I.; Taylor, R.H.; Armand, M. A dexterous robotic system for autonomous debridement of osteolytic bone lesions in confined spaces: Human cadaver studies. *IEEE Transactions on Robotics* **2021**, *38*, 1213–1229.
88. Wang, Y.; Yip, H.W.; Zheng, H.; Lin, H.; Taylor, R.H.; Au, K.W.S. Design and experimental validation of a miniaturized robotic tendon-driven articulated surgical drill for enhancing distal dexterity in minimally invasive spine fusion. *IEEE/ASME Transactions on Mechatronics* **2021**, *26*, 1858–1866.
89. Ma, J.H.; Sefati, S.; Taylor, R.H.; Armand, M. An active steering hand-held robotic system for minimally invasive orthopaedic surgery using a continuum manipulator. *IEEE robotics and automation letters* **2021**, *6*, 1622–1629.
90. Wang, Y.; Zheng, H.; Taylor, R.H.; Au, K.W.S. A Handheld Steerable Surgical Drill With a Novel Miniaturized Articulated Joint Module for Dexterous Confined-Space Bone Work. *IEEE Transactions on Biomedical Engineering* **2022**, *69*, 2926–2934.
91. Sharma, S.; Sun, Y.; Go, S.; Amadio, J.P.; Khadem, M.; Eskandari, A.H.; Alambeigi, F. Towards Biomechanics-Aware Design of a Steerable Drilling Robot for Spinal Fixation Procedures with Flexible Pedicle Screws. In Proceedings of the 2023 International Symposium on Medical Robotics (ISMR). IEEE, 2023, pp. 1–6.
92. Sharma, S.; Mohanraj, T.G.; Amadio, J.P.; Khadem, M.; Alambeigi, F. A Concentric Tube Steerable Drilling Robot for Minimally Invasive Spinal Fixation of Osteoporotic Vertebrae. *IEEE Transactions on Biomedical Engineering* **2023**, pp. 1–11.
93. Wang, M.; Li, D.; Shang, X.; Wang, J. A review of computer-assisted orthopaedic surgery systems. *The International Journal of Medical Robotics and Computer Assisted Surgery* **2020**, *16*, 1–28.
94. Putzer, D.; Dammerer, D.; Baldauf, M.; Lenze, F.; Liebensteiner, M.C.; Nogler, M. A Prospective Assessment of Knee Arthroscopy Skills Between Medical Students and Residents—Simulator Exercises for Partial Meniscectomy and Analysis of Learning Curves. *Surgical Innovation* **2022**, *29*, 398–405.
95. Nallamothu, P.T.; Bharadiya, J.P. Artificial intelligence in orthopedics: A concise review. *Asian Journal of Orthopaedic Research* **2023**, *9*, 17–27.
96. El-Galaly, A.; Grazal, C.; Kappel, A.; Nielsen, P.T.; Jensen, S.L.; Forsberg, J.A. Can machine-learning algorithms predict early revision TKA in the Danish knee arthroplasty registry? *Clinical Orthopaedics and Related Research* **2020**, *478*, 2088.
97. Kurmis, A.P.; Ianunzio, J.R. Artificial intelligence in orthopedic surgery: evolution, current state and future directions. *Arthroplasty* **2022**, *4*, 1–10.
98. Lohre, R.; Warner, J.J.; Athwal, G.S.; Goel, D.P. The evolution of virtual reality in shoulder and elbow surgery. *JSES international* **2020**, *4*, 215–223.
99. van der Putten, K.; Anderson, M.B.; van Geenen, R.C. Looking through the Lens: The Reality of Telesurgical Support with Interactive Technology Using Microsoft's HoloLens 2. *Case Reports in Orthopedics* **2022**, *2022*.
100. Hussain, M.; Khan, S.M.; Al-Khaled, K.; Ayadi, M.; Abbas, N.; Chammam, W. Performance analysis of biodegradable materials for orthopedic applications. *Materials Today Communications* **2022**, p. 103167.
101. Hussain, M.; Ullah, S.; Raza, M.R.; Abbas, N.; Ali, A. Recent Developments in Zn-Based Biodegradable Materials for Biomedical Applications. *Journal of Functional Biomaterials* **2022**, *14*, 1.
102. Karthik, K.; Colegate-Stone, T.; Dasgupta, P.; Tavakkolizadeh, A.; Sinha, J. Robotic surgery in trauma and orthopaedics: a systematic review. *The bone & joint journal* **2015**, *97*, 292–299.
103. Stauffer, T.P.; Kim, B.I.; Grant, C.; Adams, S.B.; Anastasio, A.T. Robotic Technology in Foot and Ankle Surgery: A Comprehensive Review. *Sensors* **2023**, *23*, 686.