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Orthopedic Surgical Robotic Systems: Comprehensive Review

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Abstract:

Orthopedic surgery is one of the earliest surgical specialties to adopt robotic technology in clinical practice. Over the years, it has become a fascinating field with remarkable achievements. Surgical robots improve alignment accuracy and restore normal kinematics by enabling precise bone preparation, particularly in total joint replacement surgeries. There are various robotic systems available on the market, each tailored to specific types of surgeries with features designed to meet different requirements and operating methods. This paper provides a review of orthopedic robotic systems based on different fracture types, covering robotic systems related to hip and knee, spine, and fracture reduction surgeries. Regardless of the system type, the primary goal of robotic systems is to improve the accuracy and precision of surgical procedures. Although the history of surgical robots is relatively short, they have already demonstrated clinical efficacy when compared to traditional orthopedic surgeries. When considering which robotic system to use, surgeons must carefully assess the advantages and disadvantages of each system to choose the one best suited to their surgical needs.

Keywords: Orthopedical surgery, robotic system, fracture reduction.

1. Introduction

In 1985, surgical robots were firstly applied in Memorial Medical Center, Long Beach, CA, USA. The industrial robot arm (Unimation PUMA 200), which was adjusted, can perform a stereotactic biopsy of the brain guided by CT at an accuracy of 0.05mm [1,2]. After that, in 1992, robodoc was firstly invented in Fremont, California, United States as the first robotic systems for orthopedic surgeries, which was developed by Integrated Surgical Systems (ISS) in Sacramento, California, USA [3,4]. At the first step, it is an active, autonomous, image-based robotic system that allowed surgeons to plan components on the femur side to implant and assist cementless total hip arthroplasty (THA) surgery [5].

The main areas of the robot-assisted orthopaedical surgery are in hip, knee, spine and fracture reduction surgery [6,7].

Orthopedic surgery is one of the earliest surgical fields to apply robot technology in clinical practice, and it has become an attention in the last 30 years [8].

During surgery, robotic support can be used to prepare the bone precisely, to improve the ability of the patients to reproduce alignment and restore normal kinematic function, in order to facilitate total joint replacement [9,10].

There are various kinds of robotic systems on the market, and each was tailored for a specific type of surgery and had a range of features for different requirements and operation. Robotic surgery for joint replacement surgery has been in development for nearly three decades. The first joint replacement system was an active robotic system. In order to perform surgery using these systems, surgeons need to make plans, surgical paths, and Settings in advance. After that, the autonomous system has the ability to perform the operation without the surgeon operating the robotic arm. Robodoc's implant alignment and positioning errors have been shown to be small, however, one of the system's biggest limitations is that it does not allow surgeons to make adjustments to improve ligament balance during surgery. Today, robotic assistance systems for joint replacement are typically semi-active or passive robotic systems, based on robotic devices that assist the surgeon during surgery. Due to the enhanced flexibility of contemporary surgical systems, the later robotic technology enables more precise soft-tissue calibration.

In recent years, the papers on robot-assisted orthopedic surgery have increased significantly. During 2015 and 2020, the amount of the papers has raised from 2500 to 6500 [8].

In this review, through reading the papers about the orthopedic surgical robot in web of science, google scholar, wanfang data, discuss the orthopedic surgical robot system, from the perspective of dealing with different human orthopedic surgery, it is divided into 3 different kinds, including hip and knee, spine and fracture reduction. Fig. 1 shows different kinds of orthopedic surgical robots.

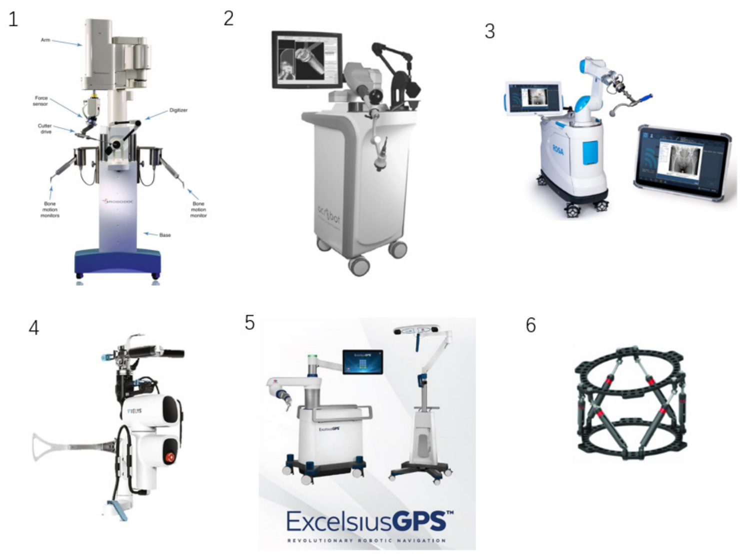

Fig. 1 Different kinds of orthopedic surgical robots. (1) The ROBODOC System; (2) ACROBOT system. (Robotic Surgery: From Autonomous Systems to Intelligent Tools, Robotica, 28(2), 163–170, 2010); (3) ROSA system; (4) VELYS; (5) Globus Excelsius GPS platform; (6) Hexapod external fixator

2. System in Different Kinds of Orthopedical Surgeries

2.1 Hip and Knee

Total hip arthroplasty (THA) is an effective treatment for advanced osteoarthritic hip pain and it is considered as one of the most successful surgeries in modern medical history [11]. However, total hip replacement still carries the risk of failure, with dislocation and mechanical loosening being common problems [12].

At the same time, total knee arthroplasty (TKA) is also used to treat advanced osteoarthritic knee pain to improve the function and reduce the pain. The total knee arthroplasty procedure has been successfully performed since it was first proposed by John Insall in 1974. Joint replacement surgery may be considered for patients with persistent joint symptoms and the pain that do not release through initial treatment.

In the early days, robot-assisted total hip replacement used an active robotic system that imported ct data in advance,

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implanted components according to pre-determined programming, and it could perform the surgery automatically without the surgeon's control. In recent years, more semi-active robots have been used. The semi-active type requires the participation of the surgeons and has a haptic feedback system to achieve real-time communication with the surgeon by providing haptic feedback to facilitate the implementation of preoperative planning in the operating room. In general, the active robot is suitable for placement of the femur side prosthesis, while the semi-active robot is suitable for placement of the acetabular side prosthesis [13]. There are currently four major robotic hip surgery systems: Robodoc, Casper, Acrobot, and Mako, of which only Robodoc and Mako are widely used clinically [12].

Robodoc was invented in the 1980s, which is the first robotic system for orthopedic surgery, and it is also an active system. It can assist the surgeon in planning the type of implant on the femur side before surgery and milling the femur to achieve the optimal size to fit the prosthesis. Before surgery, Robodoc needs "marker points" on the patient to map out anatomical coordinates, which are sent to a computer and then fed back to the robotic arm, combining a five-axis robotic arm with a high-speed milling device [8]. Initially, these "marker points" were titanium screws inserted into the greater trochanter and femoral condyles under local anesthesia before CT scans. This procedure carries risks like fractures, knee pain, nerve damage, and screw breakage. Due to these issues, Robodoc later introduced surface marking technology. Although marking the bone surface during surgery takes extra time, it is safe and effective. Studies show that Robodoc's milling can effectively promote proximal load transfer and reduce bone loss in uncemented stems. Additionally, Robodoc is also considered useful for joint revision surgeries, especially for removing distal cement plugs [14].

Casper is another active robotic system, similar to Robodoc, requiring preloaded CT data and surgical planning. Researchers pointed out several common issues with this system, like long surgery times, significant blood loss, and poor post-op function, so it's not in use anymore [15].

Acrobot is a semi-active robotic system designed to help surgeons. It also needs preloaded CT data, and during surgery, it identifies the patient's anatomy using surface marking. The drill at the robotic arm's tip is moved by the surgeon's hand, guided by haptic feedback. It won't stray beyond the defined milling path based on 3D pre-op planning. Parts of its tech were later acquired by Mako [16].

Rosa is an orthopedic surgical robot specifically for total knee arthroplasty, approved by the FDA in 2019. It does not require advanced preoperative imaging, such as CT scans. Instead, it uses preoperative X-rays of the lower limbs, converting 2D X-ray images into 3D skeletal models through computer software. This allows for virtual planning of implant positioning and ligament balancing before surgery, enabling image-free cases. It is a semi-active surgical system that positions the bone-cutting guide to the distal femoral cut and proximal tibial cut through tactile feedback, and it determines the femoral rotation guide. It can be observed that the system in question is not connected to a saw blade. The objective of this collaborative robotic system is to augment the precision and dependability of bone resection and ligament balancing procedures, while maintaining the existing surgical workflow [17].

Velys is a robot-assisted solution (Depuy Synthes) approved in January 2021. It features a tabletop hardware design that can be integrated into any operating room. It is a semi-autonomous system with a saw arm, utilizing tactile technology to define boundary mechanisms, helping surgeons accurately cut bone during total knee arthroplasty (TKA) to align and position implants relative to soft tissue. It does not require or support preoperative imaging, aiming to improve surgical accuracy in bone cutting and soft tissue balancing, thus enhancing functional outcomes after TKA and reducing outliers [17,18].

2.2 Spine

The first surgical robot which was designed for spinal cord surgery is SpineAssist (Mazor Surgical Technologies, Caesarea, Israel). It occurs at the beginning of 2000, promoted as a solution to the poor alignment rates of screws and the increased exposure to radiation associated with minimally invasive instrumentation of the spinal column. There are experiments showed that screw accuracy has improved and radiation exposure has decreased, comparing to traditional fluoroscopy-guided manual techniques.

Rosa spinal robot was launched in Europe in 2011 and received FDA approval in the United States in 2016 for use in spinal surgeries. The apparatus is equipped with a comprehensive robotic arm, comprising six degrees of freedom, which is situated on a ground-mounted base station. This base station is also furnished with an integrated CAN interface. A distinct optical camera is employed for the purpose of real-time tracking. A detachable reference array is connected to the robotic arm for the calibration process. The standard posterior superior iliac spine or DRB (Dynamic Reference Base) is mounted on the spinous process, serving as the primary anatomical reference point. Preoperative or intraoperative images are then acquired and registered to both the patient and the robot. And a base station is constructed and a robotic arm is deployed onto it. The end effector enables the performance of drilling operations, as well as the implementation of non-navigated drilling techniques and subsequent guidewire placement. Then, a connectable tracker array can be used for pedicle screw tapping and screw insertion via navigated instruments. Pedicle screw tapping and subsequent screw placement can be performed using optional CAN assistance from the tracker array mounted on the instruments. The ROSA spine robot optically tracks patient movement in real-time, compensating for movements caused by breathing and surgical operations. The optical camera is designed to continuously monitor the position of the target patient's DRB in relation to the reference array, which is situated in close proximity to the robotic arm on the base station [17,19,20].

Mazor X spinal robot was firstly launched for commercial in October 2016, and it is an advanced version from Mazor Robotics. The system is semi-active, relying on preoperative Computed Tomography (CT) scans introducing a serial robotic arm and optical navigation system. The robotic arm has been enhanced with fully automated capabilities, eliminating the necessity for a track to be installed on the patient. This enables the robot to move in conjunction with the patient and the bed during the process of breathing and surgery, while maintaining the target trajectory. The proposed methodology does not require the use of optical tracking arrays, which are susceptible to interference from obstructions or unintentional DRB movement. The Mazor X system interacts directly with the patient, attaching to the operating table frame via a rail adapter and to the patient via a bone bridge connection from the robotic arm to pins placed in the PSIS or spinous process. The arm is equipped with three cameras, which first detect and define the surgical area in 3D to prevent collisions with the patient. Reference markers are temporarily fixed on the arm and registration is done using preoperative CT scans through the utilization of AP and oblique fluoroscopic images, or alternatively, intraoperative O-arm cone-beam CT scans. Subsequently, the robot performs the procedure of pedicle cannulation and Kirschner wire insertion, while pedicle tapping and screw placement are done manually under fluoroscopic guidance for depth [17,21].

Excelsius GPS was launched in late 2017 as a robotic spine surgery. Furthermore, the system incorporates a comprehensive navigation platform with real-time instrument tracking, thereby enabling the placement of pedicle screws without the necessity for Kirschner wires. The system is mounted on a ground-based station that provides support for a CAN interface and the robotic arm itself. Instead of larger standard reflective marker balls, the robot's end effector uses small wireless-powered LED markers, and the instruments that traverse and are grasped by the end effector are equipped with their own distinct tracking arrays. Additionally, a standard DRB is affixed to the patient's PSIS, or spinous process. A separate monitoring DRB is also mounted on the bone. To address unintended DRB displacement, which can be overlooked and lead to screw misalignment, an additional optical array, comprising a single reflective marker ball, is positioned in the contralateral PSIS. This monitoring marker continuously updates in real-time and detects deviations greater than 1.0 mm from the DRB, automatically triggering an alert. Optical cameras are used for registration and tracking. While the robot can use preoperative CT scans for fluoroscopic registration, intraoperative CT is the preferred imaging method for registration to streamline workflow. In the event that a 3D CAN configuration is required, the system may alternatively be utilized in the absence of the robotic arm. [22,23].

2.3 Fracture Reduction

With the development of the innovation of the computer, navigation and robot, robot-assisted orthopedical surgery (RAOS) have been applied in many kinds of orthopedical surgeries. However, robot-assisted fracture reduction (RAFR) is still in its early stage. In minimally invasive fracture reduction surgery, the surgeon manually manipulates the fractured bones under continuous intraoperative fluoroscopic monitoring. Limited by the C-arm's observational capabilities, the success of fracture reduction largely depends on the surgeon's skill and experience. Misalignment or poor rotation of the fracture often leads to postoperative complications like malunion and nonunion. As a key part of current robotic systems, external fixators are used in fracture reduction, including unilateral fixators and Ilizarov-type circular fixators. To achieve goals like improved accuracy, sufficient workspace, and force output, various types of robots have been developed over the past few decades, including serial, parallel, and hybrid robotic mechanisms. During the development of RAFR, external fixators were initially developed as robotic prototypes [24-27].

Unilateral external fixators are typically employed to stabilize fractures in long bones or correct deformities resulting from fractures. However, surgical outcomes can be compromised by inaccurate preoperative planning. To address this issue, Kim et al. developed a prototype robotic unilateral external fixator using the Dynafix® system (EBI Medical, USA) to correct bone deformities. While robotic unilateral fixators offer advantages such as low cost and simple structure, their serial configuration often leads to reduced precision [28].

In response to the need for improved fracture reduction

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accuracy, circular fixators were introduced. Majidifakhr et al. designed an external fixator to minimize intraoperative fracture reduction errors. Building on this concept, Tang et al. developed a computer-assisted motorized hexapod fracture reduction system, integrating navigation technology. This system boasts automatic, high-precision fracture reduction, compact size, and lightweight design, making it well-suited for use in operating rooms. However, its application is limited to long bone fractures, and the system's load capacity is restricted by motor power. Furthermore, the continuous current dynamo occupies significant space, introduce potential interference, and limit the surgeon's operational field [29].

Serial robots are designed based on open-chain serial kinematics, offering the advantages of better mobility, dexterity, and a larger workspace. However, this type of motion chain places a burden on each joint from the subsequent joints, hardware, and the target object, leading to drawbacks like lower stiffness, reduced precision, and a decreased payload-to-weight ratio [30,31].

This system was initially designed for industrial applications, where a larger workspace could potentially result in collisions, thereby raising safety concerns in the operating room. Originally, some robots utilized mechanical arms adapted from industrial robots to accommodate various types of fractures. These serial robotic arms can directly manipulate medical instruments and provide a wider range of motion. In order to gain deeper insight into the potential advantages of robot-assisted fracture reduction and to gather data for future investigation, Westphal et al. introduced a surgical remote manipulator system for the reduction of fractures in long bones. However, this system proved to be accurate only for simple fractures and might not provide precise reduction for complex fractures where there is no direct connection between fragments. To address this limitation, Westphal et al. integrated three-dimensional navigation and automated preoperative planning into their system. The aforementioned robots assist in treating long bone or femoral fractures, but for pelvic fractures, Wu et al. employed a six-degree-of-freedom serial manipulator, in conjunction with a robot-assisted traction device, enables the implementation of flexible operational procedures. Meanwhile, Shi, Zhao, and Ge utilized commercially available six-degree-of-freedom robotic manipulators mounted on mobile platforms. Some surgical robotic systems also combine handheld robotic technologies with remote or autonomous operations, allowing surgeons to intervene during robotic surgeries to safely and accurately guide the robot. In order to facilitate such interventions, Kim et al. proposed a system that incorporates two force/torque sensors at the end of the robotic arm. This system uses a customized robotic manipulator with six degrees of freedom and force feedback to improve the precision of long bone fracture reductions [32,33].

Parallel robots, comprising six variable-length struts connecting two platforms, eliminates the cumulative errors that are inherent to serial robots due to the nature of their serial links. As a result, they offer higher stiffness and precision, as the mass each strut carries and actuator positioning errors are averaged rather than accumulated like in their serial counterparts. At the same time, the output force is greatly increased. However, the closed structure of parallel robots limits the workspace, especially the rotational space, though this drawback can be improved by modifying the robot's structure, size, and use. To achieve both high precision and sufficient workspace, and to meet specific clinical requirements (such as joint fractures with multiple major fragments), serial mechanisms are combined with parallel ones [34,35].

Compared to long bone or diaphyseal fracture reductions, joint and pelvic fracture reductions require much smaller translational and rotational workspaces. Nevertheless, the demand for more precise repositioning of fracture fragments is considerable. In responding to these challenges, Raabe et al. employed a hybrid serial-parallel robot to facilitate the reduction of intra-articular fractures. In subsequent research, Dagnino et al. developed a hybrid robot comprising a parallel robot with a UR10 arm and position control methods. The objective was to achieve precise and repeatable manipulation of fragments during minimally invasive joint fracture surgeries. In 2006, Dagnino and colleagues undertook a redesign of the robot configuration, replacing the UR10 with a carrier platform (CP). For two-part joint fractures, Dagnino et al. proceeded to enhance their initial prototype, facilitating the capacity for simultaneous manipulation. Bignardi et al. took a different approach for pelvic fractures, utilizing a hexapod placed vertically under the operating table to handle these complex fractures [34,36,37,38].

3 Conclusion

Surgical robots have been making waves in the field of orthopedic surgeries. Initially they are introduced to improve accuracy and precision, increase patient satisfaction, reduce revision rates, and achieve better surgical outcomes, and now these robots help surgeons produce reliable and repeatable results through personalized approaches. In orthopedics, their advantages include restoring normal joint movement, precise surgical procedures, and optimized soft tissue balancing. Additionally, surgeries performed with robotic assistance are repeatable regardless of the surgeon or patient, making them ideal for younger or less experienced surgeons who need precision and accuracy typically gained from years of practice.

Though orthopedic surgical robots have many advantages, there are still limitations, such as limited application scenarios and venues, potential compounded errors pre-, during, or post-op, possible complications, and longer surgery times. Despite these drawbacks, robotic technology is becoming the most advanced in orthopedics. While some issues persist, the benefits are obvious. Over time, it can be seen that robotic devices will become routine in orthopedic surgery in the near future.

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