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General Concepts in Robotics in Orthopedics

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The history of robotic hardware in the operating room is a relatively short one, with the first robotic system introduced into the medical field in 1985 [1, 2]. This system, the PUMA 560, was designed for increased accuracy for needle placement in a computerized tomography (CT)-guided brain biopsy. Surgical use of robotics has continued to expand and evolve, being embraced by several surgical specialties, including urology, gastroenterology, oncology, and gynecology [2, 3]. Orthopedic surgery joined this technological surge in the mid-1980s with the development and introduction of the ROBODOC (Curexo Technology Corporation, Fremont, CA, originally by Integrated Surgical Systems), led by Hap Paul and William Bargar [4]. This new technology was introduced with the intent of improving the accuracy of femoral bone preparation and anatomic placement of the femoral component in a cementless primary total hip arthroplasty (THA) by using a CT-based, computer-aided robotic milling device [5]. This technology was first used in human subjects in 1992 and was soon adapted for use in primary total knee arthroplasty (TKA) and revision THA procedures [5]. Despite some promising outcomes [6], the usage of the ROBODOC was limited due to early-generation technical complications related to the device [7].

Following the introduction of the ROBODOC, several passive and semiautonomous systems began to emerge [3]. Semiautonomous systems require surgeon involvement; however, they will not deviate from the planned operative procedure. Initially, these systems used three-dimensional (3D) CT scans and preoperative planning to provide real-time feedback intraoperatively in order to enhance the surgeon's control, thus increasing operative safety [8]. The active constraint robot (ACROBOT) (Imperial College, London, UK) was the first semiautonomous system to become available. Initial trials of this device performed by Justin Cobb and colleagues [9] showed consistent and accurate placement of implants in unicondylar knee arthroplasty (UKA) that were superior to the conventional manual technique. Following the promising results seen with the ACROBOT, the MAKO robotic arm (Stryker, Mahwah, NJ, USA) received approval for use by the US Food and Drug Administration (FDA) in 2008. Encouraging results with these semiautonomous systems in UKA have been demonstrated due in part to the greater precision in bone resection and more consistent soft tissue balancing [10, 11]. The success of these systems has led to fur-

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ther interest and expansion of these systems to also include image-free techniques (NAVIO, Smith and Nephew Memphis, TN; OMNIBotics, OMNIlife Science, Inc.; Raynham, MA). Passive systems have also been developed, which involve assisting in preoperative planning, simulation, and intraoperative guidance. These systems are also known as “navigation” systems, and the main distinction, when compared to semiautonomous and active systems, is that the surgeon has complete control of the entire procedure with the computer-aided navigation providing guidance [3]. These systems create 3D visualization of the patient’s anatomy in order to allow detailed preoperative planning. The goal of this chapter is to provide an updated and comprehensive comparison of current robotic systems available within the orthopedic armamentarium.

Technology Platform Types

Image-Guided Versus Image-Free Surgical Planning

Current robotic systems require the creation of a three-dimensional plan derived from a process of mapping the anatomy of the joint surfaces, with or without a preoperative CT scan. In image-guided systems, a preoperative CT scan (or MRI in some navigation systems) of the involved joint and limb is obtained. In knee arthroplasty cases, the protocol involves a scan of the patient’s hip, knee, and ankle to gather the patient-specific data on limb alignment (mechanical axis) and anatomic features of the knee. The software converts the CT scan data into segmented slices, which creates the three-dimensional patient-specific bone model for surgeon templating prior to surgery. It then allows manipulation and coordination of the collected bone surface data to model the limb and accurately plan the implant size, alignment, and corresponding volume and orientation of bone resection. In the case of THA, the software utilizes the virtual 3D images to plan bone resection depth, optimal component size and alignment, leg length and offset restoration, and volumetric bone removal. The preoperative plan is then correlated to the patient’s anatomy which is registered intraoperatively by surface mapping after arthrotomy [8]. The virtual plan is then carried out by surgical manipulation of the robotic tool. Despite the benefits of being able to virtually plan the surgery preoperatively, the downsides of a preoperative CT scan include the increased (and often unreimbursed) cost of the imaging study, patient inconvenience to obtain the study at certified centers, and risk of radiation exposure [8, 12–14].

Alternatively, imageless systems rely entirely on intraoperative registration of the anatomical surfaces and kinematics after arthrotomy to create a 3D virtual model, develop a surgical plan, and define boundaries beyond which the bone cutting tools should not remove surface tissue. Specialized CT or MRI scans are unnecessary. Thus, while imageless systems address the disadvantages presented by the image-based system because no preoperative imaging is used, this then creates potential disadvantages. A true preoperative plan that allows the determination of implant size, position, and alignment cannot be performed. Furthermore, the intraoperative registration relies on the surgeon’s accuracy of inputting the correct data points, which is subject to human error [8]. Despite these potential disadvantages, cadaveric and early clinical studies discussed above demonstrate that the imageless system results in comparably accurate prosthesis placement [15, 16].

Autonomous, Semiautonomous, and Passive Robotic Systems

There are three broad categories of robotic systems used in orthopedic surgery, including autonomous, semiautonomous, and passive systems. Passive systems provide a virtual road map for surgery but do not provide constraints against inadvertent bone and hard surface preparation. Both autonomous and semiautonomous systems incorporate safeguards against removal of bone beyond the 3D plan; they differ in the method and extent of surgeon direction and control in the process of bone removal.

Autonomous Systems

Autonomous robotic systems have the capability of completing an operation without surgeon input, other than establishing and determining the plan of resection, positioning, and sizing. The surgeon performs the initial dissection and approach to set up the robotic system [17, 18]. The robot then performs the remaining operation independently with surgeon oversight; however, the surgeon controls an emergency switch in case of a desire to pause the procedure or to adjust the plan or if there is an impending or actual mishap. Autonomous robots had fallen out of favor due to concerns over nerve and other soft tissue injury, among other complications, although currently there is a resurgence in enthusiasm for autonomous robotics and redoubled efforts to refine techniques and protocols [17, 18]. Examples of autonomous robotic systems include ROBODOC [now TSolution One] (Curexo Technology Corporation, Fremont, CA) (Fig. 3.1) and CASPAR (Ortho-Maquet/URS, Schwerin, Germany), both of which rely on CT imaging for preoperative planning. Initial studies on anthropomorphic phantoms demonstrated high geometric accuracy of both the ROBODOC and CASPAR systems [8, 19–30]. These systems have a predictable learning curve, as evident in the longer operative time and greater blood loss [21, 26–28], but each had greater precision with mechanical axis alignment compared to conventional techniques [27–29]. Disadvantages and limitations of the autonomous systems included additional time for preoperative planning and registration, aborted procedures contributing to longer duration of surgery, lack of surgeon input and intraoperative adjustment, and technical complications [7, 8, 26, 30].

Fig. 3.1 ROBODOC. (Courtesy of Curexo Technology Corporation, THINK Surgical, Inc., Fremont, CA, USA)

Passive Systems

Unlike autonomous systems, passive systems do not independently perform the operations. They are also known as computer-assisted or navigation systems, which use patient- and instrument-centered reference points to provide the surgeon with perioperative recommendations and guide positioning of the surgical tools [29]. The navigation system is composed of a dynamic reference base attached to the instrument or anatomical landmark that emits or reflects an optical-based medium to the tracker [31]. Passive systems further provide guidance on precise placement of the prostheses [17] and have revolutionized minimally invasive techniques in orthopedic surgery.

Navigation-assisted surgery have been used for performing UKA and TKA to address historical shortcomings associated with component malposition. And while several studies have demonstrated the superior accuracy of navigation for achieving femorotibial mechanical axis and component alignment on postoperative radiographs compared to conventional techniques and reducing outliers compared to jig-based techniques, most studies have shown equivalent functional outcomes and comparable survivorship [32–44]. The use of navigation has further extended to

THA, where it has been applied primarily for acetabular component planning, with mixed outcomes in terms of positioning within the targeted "safe zone" [45–51].

Semiautonomous Systems

Semiautonomous robotic systems combine the benefits seen with the passive navigation and the autonomous robotic systems. This is done by using the skills of the surgeon needed for passive navigation and combining these with the control of the robot seen in autonomous systems [17]. Semiautonomous robots, on the one hand, are controlled and manipulated by the surgeon, but the surgeon's control is modulated by the robotic system to limit bone preparation to within a defined volumetric boundary. A feedback loop is established within the system either by haptically constraining the cutting tool or positioning of the cutting blocks or by modulating the exposure or speed of the robotic tool. These safeguards not only optimize precision and reduce error, but they also simplify the surgical procedure. Semiautonomous systems prevent surgeons from deviating from the preoperatively planned bony excision, which has led to an increased accuracy and reduced errors in component placement [8, 15, 52]. Currently, three such systems are in use in the United States for joint arthroplasty. The MAKO robotic arm (Stryker, Mahwah, NJ, USA) (Fig. 3.2) uses a preoperative CT scan to form the predetermined cutting areas for bone preparation and thus is known as an "image-guided" system. The other semiautonomous systems in use are the Navio PFS (Smith & Nephew, Memphis, TN, USA) freehand sculpting robot (Fig. 3.3) and OMNIBOT (OMNIlife Science, Inc.; Raynham, MA) (Fig. 3.4) robotic guide positioner which are "imageless," in that they do not require specialized preoperative imaging for planning or registration [15].

The advantage of semiautonomous robotic systems is that the tools are directly manipulated by the surgeon, which minimizes the learning curve and the potential for inadvertent tissue injury while at the same time facilitating accurate bone preparation even during the early stages of technology adoption [15, 16, 52–63].

Fig. 3.2 MAKO robotic arm. (Courtesy of Stryker, Mahwah, NJ, USA)

Methods of Robotic Restraint

As discussed, the advantage of robotic bone removal is the precision with which surface preparation is accomplished. With current systems, there are essentially two primary methods by which the robotic tools maintain a high level of precision as well as safeguard against inadvertent tissue removal – either by restricting the cutting

Fig. 3.3 Navio (Courtesy of Smith & Nephew, Memphis TN, USA). (Courtesy of Smith & Nephew, Andover, MA, Memphis TN, USA)

tool or positioning of the cutting blocks by haptic constraint to within a defined region or by modulating the exposure or speed of the robotic tool to within a predetermined 3D surface volume. These safeguards not only optimize precision and reduce error, but they also simplify the surgical procedure. With the MAKO robotic arm and TSolution One (ROBODOC) systems, bone resection is determined initially with a preoperative CT scan and then adjusted intraoperatively if needed [17, 21]. During the procedure, tactile haptic feedback is provided to prevent the robotic arm from moving the high speed burr or saw blade outside the predetermined cutting zone [4, 5, 7, 8, 11, 17, 21, 29, 30, 54–65]. In the case of OMNIBOT, control comes in the haptic positioning of cutting blocks through which the surgeon uses a conventional saw to prepare the bone. This approach restricts the resection guides but provides no additional safety mechanism to the cutting tool to prevent errant bone preparation. Nonetheless, emerging data shows success with this mechanism of precision in TKA.

Using an alternative method of restraint, the Navio system controls exposure or speed of the robotic burr. In "Exposure Control" setting, the burr continuously rotates, but it is only exposed when it is within the predefined volume of bone to be prepared and retracted within a protective guard when the instrument tip is outside the desired cutting zone [66]. In "Speed Control" setting, the burr will only spin when within the desired cutting zone. The rotating burr is at full power until it approaches the margin of bone being prepared, at which time its speed linearly decreases to zero [66]. Theoretically, the burr speed/exposure control methods will allow more control and minimize errors seen in bony cuts; however, results to date have shown comparable precision to the haptic system [15].

Soft Tissue Balancing

Finally, soft tissue balancing has been shown to play an important role in knee arthroplasty, to maintain normal knee kinematics and proprioception, and to prevent subsequent wear and instability [67–70]. UKA and TKA outcomes are influenced by lower leg alignment and component rotation, size, and position [71], and intuitively, it makes sense that the use of robotics could help in controlling these multiple variables. However, in both UKA and TKA, precise soft tissue balancing is considered equally, if not more important to successful function and durability. Several current robotic systems incorporate soft tissue balancing algorithms in their planning and procedures, and studies have demonstrated the accuracy of soft tissue balancing associated with robotics in UKA [11] and TKA [28].

Fig. 3.4 OMNIBotics. (Courtesy of OMNIlife Science, Inc., Raynham, MA, USA)

Limitations of Navigation and Robotic-Assisted Surgery

The use of robotic systems has been shown to increase operative time. They require the placement of optical arrays for registration of bony landmarks. Imageless systems then require tracing of selected anatomic areas to create a 3D image of the operative field. Robotic-assisted systems that are based on preoperative CT scan also require the registration of bony landmarks and surfaces in a similar fashion. In a study comparing robotic and manual UKA systems, the mean operative time with robotic system was increased by 20 minutes, which led to an increase cost of approximately $2466 to $9220 [72]. An unobstructed path between optical arrays and the system's tracker is necessary at all times, and optical instruments need to be held in a certain way to be registered. While this can be cumbersome initially, the learning curve is not steep [16, 63]. The use of robotics is associated with a significant financial investment which may be prohibitive to lower volume surgical centers. Without clear clinical advantages, the cost for these systems may not be justified.

Conclusion

The use of navigation and robotic assistance in orthopedic surgery continues to increase, and their application is expanding. Current applications include UKA, PFA, TKA, THA, and spine surgery, but future development of navigation and robotic-assisted systems may include revision total knee and hip arthroplasty as well as other surgical procedures. There is little doubt that robotic technology is here to stay, and the orthopedic community is beginning to embrace it. Trends are now moving toward miniaturization, and once enough progress is made in this direction, it will become a routine part of our armamentarium. However, long-term clinical outcomes of contemporary robotic systems for UKA and TKA are not available. The survivorship of robotic-assisted UKA using the

MAKO robotic arm was 98.9% in 620 patients at 2-year follow-up [73]. The 3-year revision rate for UKAs to TKA using the MAKO robotic system was reported as 5.8% and found to be comparable to conventional UKAs in national registries [74]. Further long-term results are needed to validate the relationship between improved accuracy of component placement and survivorship.

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