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Educational Corner

On Robotic Surgery in Knee Arthroplasty: Beginning of a New Era

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Abstract

During the past two decades, the use of robotic arms in knee arthroplasty has changed from a concept to a reality. These systems promise precision and accuracy while shortening the required learning curve. Although still largely in the early stages, there are currently several commercially available platforms with varying degrees of flexibility. The available models can be classified into several categories based on their mode of operation (whether the system requires imaging input) and degree of autonomy. The present study aimed to review the existing body of literature and provide an outlook of the current landscape. The strengths and weaknesses of the implementation of such systems in knee arthroplasty are also discussed.

Keywords: Robotic Surgery; Arthroplasty; Knee Replacement

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Background

Deemed unlikely just a few decades ago, the use of robotic arms in surgery continues to increase in different fields of practice (1). The robots' inherent ability to perform repetitive tasks with minimal error, coupled with their proficiency in minute and exact movements, makes them ideal machines in the operating room. Especially since the widespread adoption of minimally invasive, keyhole surgeries in recent years, the tendency towards the use of robotic systems has increased greatly. While such operations pose a real challenge for the surgeon as they significantly limit both their field of vision and the ability to maneuver, both obstacles are relatively easy to overcome for a properly designed robotic arm (1).

Robots were first used in orthopedics nearly three decades ago (2). Since then, as with all other branches of surgery, their use in operating rooms has increased significantly to the point that most prominent manufacturers of orthopedic surgery equipment have introduced their own versions of such surgical assistants (3). Robots can perform a wide variety of tasks in the operation and range from simple tool holders and navigation assistants to elaborate machines that allow the surgeon to operate remotely. Overall, the goal of robotic surgery is not to eliminate the surgeon but to augment their ability and improve safety and proficiency. Different robotic systems, along with their capabilities and examples of commercially available products will be discussed in the remainder of this paper.

Robotic-Assisted Knee Arthroplasty

Knee arthroplasty and in particular total knee arthroplasty (TKA) is considered a complex surgery comprising many different steps. Such an operation warrants the need for copious amounts of practice before one can claim to have mastered it. Furthermore, a relatively small operation field surrounded with essential elements (e.g., collateral ligaments and popliteal artery) that must be preserved further complicate the matter. Khlopas et al. conducted a review in which the outcomes of using robotic arms in TKA were assessed in five major categories from precision and accuracy to the learning curve and soft tissue protection. At least in the short term, the overall results pointed to higher scores in all five categories when compared with conventional TKA (4).

Several studies have shown the advantages of implementing robotic arms in TKA by investigating operation results from different angles and with varying details. Perhaps one of the most important aspects of a satisfactory TKA outcome (and arguably one of the most challenging to achieve) is proper limb alignment and soft tissue balancing; a number of studies have shown better results in this regard when robots were used (5, 6) while the robots also improved implant size selection and matching (5) and decreased blood loss (6). Additionally, robotic-assisted surgery has been found to have a significantly shorter learning curve and to be associated with lower surgical team fatigue (4, 7).

Types and Classification

Overall, the robotic platforms used in TKA can be classified both in terms of their bone mapping and virtual model creation and also based on the level of autonomy they have in the operation (8, 9). These classifications are further discussed below. A third classification can also be applied in which the systems can either be open (i.e., compatible with different brands of implants) or closed (i.e., only compatible with a single proprietary brand of implant, usually that of the platform's own manufacturer) (10).

Image-Dependent versus Image-Independent

A cornerstone of the robotic arm's function is the three-dimensional (3D) model of the bone created individually for each patient that enables the machine to recognize different tissue landmarks and operate within predefined windows that ultimately leads to their improved accuracy. This model is obtained via two different mechanisms, some of the platforms are namely image-dependent in that they require preoperative imagery [the most commonly used modality is a computed tomography (CT) scan] to create the 3D model. This allows the surgeon to have adequate time to plan the operation, define the cuts, and modify the model if necessary. Next, in the operating room, the patient's limb is registered via the robot through a series of bone landmarks. This allows the machine to identify different parts of the actual structures with the pre-defined model and be able to apply the designed operation plan to the tissue (8, 9). While possibly allowing more precise planning, these systems are more time-consuming and may require additional imaging to be done preoperatively.

The so-called image-independent platforms do not require preoperative imaging and use particular bony landmarks at the beginning of the operation to modify and tailor an existing generic 3D model of the knee to the patient's measurements and structural specifications. This mechanism alleviates the need for additional imaging and saves time but may produce less accurate models and can potentially affect the end result (8, 9).

Active, Passive, and Semi-Active Platforms

Based on the robot's level of autonomy, they can be classified into active, passive, and semi-active platforms. Active systems operate independently while under the direct supervision of the surgeon.

The limb is usually fixed in the desired position after the landmarks are registered by the computer and then the arm is allowed to make the cuts within predefined windows. Machines are usually programmed to move relatively slowly which allows the surgeon to press emergency switch-off buttons anytime should the robotic arm stray from the plan. While active platforms are considered to be the "most advanced", their sophistication leads to very high initial costs of purchase and installation that have ultimately limited their use.

As for the passive systems, they require the surgeon to fully position and maneuver the arm and make the cuts, and therefore, mainly function as navigation tools. The semi-active platforms, as the name applies, lie in between the two and are the most prevalent of the used systems. They require an active role of the surgeon but complement it with visual, auditory, and tactile feedback and in many cases, limit the cutting window to predefined areas in order to minimize the risk of damage (5, 8, 9).

Examples of Currently Available Products

Solution One: Functioning as an open, active, image-dependent platform, TSolution One (THINK Surgical Inc., Freemont, CA) requires a preoperative CT scan using 1.25 mm slices as the desired thickness to construct the 3D model of the patient's knee. All the operation planning takes place prior to the actual surgery and is applied to this model. After proper exposure and positioning, the bone surfaces of the limb are registered with the robotic arm through a series of predefined landmarks, and afterward, the cutting is done autonomously via the robot's milling tool. Successful and precise identification and registration of the landmarks is an important part of the learning curve and safety features are installed to prevent the operation from commencing if this step is not fully and properly completed. Optical sensors observe the entire cutting procedure in order to detect and compensate for possible limb movements. The surgical team is also supervising the operation (5, 11).

Implementation of TSolution-One was shown to improve the accuracy of mechanical axis restoration while maintaining the same operation time as the conventional approach (12). Another study found that the final result had only minimal deviation from the planned implant positions (13).

OMNIBotics (iBlock): Previously called Praxiteles, OMNIBotics (OMNIlife Science, Raynham, MA, USA) is a semi-active, image-independent, cutting guide system approved by the Food and Drug Administration (FDA) in 2010 which can assist the surgeon in making bone cuts based on pre-defined plans. The system is image-independent; thus, it requires no preoperative imaging, and the construction of the 3D model is done intraoperatively via landmark registration. iBlock is considered a closed platform, and therefore, can only operate with a single brand of implant. The system also does not provide gap-balancing capabilities (5, 10).

A number of studies have assessed the outcome of iBlock's implementation in arthroplasty; a cadaveric study by Koulalis et al. concluded that the use of robotically placed cutting guides significantly reduced the femoral preparation time (14). Another study on 94 cases found that the use of the system improved mechanical alignment while reducing the tourniquet time required for the operation (15).

Navio: Another semi-active, image-independent system, Navio (Blue Belt Technologies, currently distributed by Smith & Nephew, Watford, UK) is a surgeon-operated handheld reamer and saw approved by the FDA in 2012 for unicondylar knee arthroplasty (UKA) and in 2017 for TKA (10). The system is capable of registering the bone surfaces intraoperatively and afterward follows the movements of the reamer, controlling its rotation speed and sleeve movement, and stopping the tool completely if a deviation from the cutting window is detected. It is an open platform and capable of operating with different implant brands (5, 9).

Though the number of studies assessing the outcome of the Navio system is limited, a study by Bollars et al. concluded that operations using the device had fewer outliers concerning the post-operative mechanical axis when compared with conventional surgical methods (16).

Mako: This image-dependent, semi-active, closed robotic platform from Stryker Orthopedics (Mahwah, NJ, USA) was approved by the FDA in 2016. It uses a preoperative CT scan to construct a model of the bone and determine the operation plan. The system is also capable of modifying the surgical plan and implant positioning based on gap balancing and limb alignment intraoperatively if the need arises. The computer monitors the saw movement during the operation, stopping it should the blade deviate from the defined cutting path (5, 9, 10).

As one of the most studied knee arthroplasty robotic systems, a number of studies have shown the use of Mako in UKA to be associated with improved tibial alignment and also a shorter learning curve (17, 18). As for TKA, Sires et al. found that 94.29% of all the cuts done using Mako were within 1 mm of the preoperative plan (19). Another study reported better limb alignment and implant position without an increase in complication rates (20).

Table 1. A comparison of the commercially available robotic systems along with their strengths and weaknesses

Name	Autonomy	Image dependency	Open vs. closed	Strengths	Weaknesses
TSolution One	Active	Dependent	Open	-Active autonomous platform -In case of any error, the system stops automatically to prevent damage to the tissue	-Increased time for preoperative planning -High initial cost of purchase and setup
iBlock	Semi-active	Independent	Closed	-Only the intended bone segment is removed -No preoperative imaging required	-No gap balancing -No haptic feedback
Navio	Semi-active	Independent	Open	-Only the intended bone segment is removed via the control of reamer function -Gap balancing	-A reamer takes longer to cut and struggles in making truly flat surfaces
Mako	Semi-active	Dependent	Closed	-Controlled saw action to ensure precise cut -Gap balancing -Extremely stiff saw blade prevents blade buckling	-Closed and image-dependent platform
Rosa	Semi-active	Independent	Closed	-While operating as image-independent, preoperative imaging can be supplied for further precision -Real-time intraoperative ligament balancing	-An anatomy outside the normal range significantly reduces precision

Rosa: Designed and developed by Zimmer-Biomet (Warsaw, IN, USA) in partnership with MedTech (Montpellier, France), Rosa knee robotic platform is one of the newest systems commercially available. It was approved by the FDA in 2019. The system is an image-independent, semi-active, closed robotic arm that using the intraoperative plans and navigational data, assists the surgeon in the positioning of cutting guides. As the system is image-independent, it does not require preoperative imaging, but imaging data [usually two-dimensional (2D) X-rays] can be used to further complement and optimize the created model. The system allows for real-time intraoperative ligament balancing (5, 9, 21).

Rosa is considered the newest commercially available robotic system approved for knee arthroplasty, and therefore, the amount of published data regarding the system's outcome is limited. A cadaveric study by Parratte et al. reported that Rosa enabled the surgeon to achieve highly accurate cuts in order to attain the planned positions (22).

A detailed comparison of the available robotic systems along with their strengths and weaknesses is available in table 1. Moreover, a timeline is shown in figure 1 depicting all the reviewed models and the year they became publicly available.

Strengths and Weaknesses of Robotic Surgery

The implementation of robotic systems in knee arthroplasty has been shown to increase the precision by which the operation is performed which is hypothesized to result in better outcomes (7).

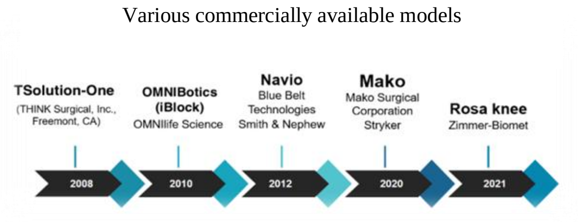

Figure 1. A timeline depicting the reviewed models and the year they became available

With our understanding of the complex knee mechanics constantly evolving, such an improved precision may in fact be a significant factor in achieving better results; however, studies comparing the long-term outcomes of conventional versus robotic-assisted surgery are still lacking. On the other hand, implementation of these systems was feared to significantly increase the operation time, leading to higher chances of infection (23, 24), while also creating a longer and more steep learning curve for the training surgeons. Both concerns have been relatively addressed by the studies that have demonstrated that with a training course comparable (and sometimes shorter) in length to the one needed for conventional surgery, physicians are able to achieve similar operation times when using robotic assistants (25-28).

Conclusion

While the use of robotic assistants in TKA seems to improve operation results both directly and also by reducing surgeon fatigue, long-term studies are still needed to assess the outcome and patient satisfaction over time. Presently available surgical robots already perform a wide variety of tasks in different stages of the operation, yet new and more advanced systems capable of performing the entire operation without the physical presence of a surgeon are not that far behind, and advancements in artificial intelligence promise greatly improved instruments both more precise and more responsive and intuitive in near future.

Conflict of Interest

The authors declare no conflict of interest in this study.

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