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KNEE ARTHROPLASTY

Robotics in orthopaedic surgery: why, what and how?

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Abstract

Introduction Robotics applied to orthopedics has become an interesting topic both from the surgical point of view and the engineering one. The main goal of those systems is the enhancement of joint arthroplasty surgery, providing the robotic support to precisely and accurately prepare the bone, restore the limb alignment and the physiological kinematics of the joint. Various robotic systems are currently available on the market, each addressing specific kind of surgeries and characterized by a series of specific features that may involve different requirements and/or modus operandi.
Material and methods An overview of these devices was performed, addressing the different categories in which robots are subdivided in terms of: operations performed, requirements and level of interaction of the surgeon. The main models currently available on the market were addressed and relative studies in the literature were reported and compared, to highlight the benefits and drawbacks of the different technologies.
Results The different robotic systems were subdivided in: open/closed platform, image-based/imageless and active/passive/semi-active. Regardless of the typology of robotic system, the main aim is to improve precision and accuracy of the operation. It is to be noted that, regardless of the typology of robotic system, the surgeon is still in charge of the planning and approval of the operation: only the precise and consistent execution of his directives is entrusted to the robot. The positive factors have however to be weighed against the fact that robotic systems involve an important initial investment and most of the times require the surgeons and the staff to learn how to operate them (with a learning curve differing from system to system).
Conclusions Each surgeon, when considering if and which robotic system to adopt, has to properly evaluate the different benefits and drawbacks involved to find the surgical robot that fits his needs the best.

Keywords Robotic surgery · TKA · THA · UKA · Robotic systems

Rationale, application and diffusion of robotics in orthopedics

Robotics applied to orthopedics has become an interesting topic both from the surgical and engineering point of view: introduced over three decades ago [1], this application's main goal is the enhancement of joint arthroplasty surgeries, providing the robotic support to precisely and accurately prepare the bone, restoring the alignment of the limb and the physiological kinematics of the joint.

It is indeed true that the surgeon has the skills and knowledge required to address the different tasks and eventual complications involved in a surgical operation, but it is also real that the implementation of such ideal and flawless operations is often depending on the accuracy and repeatability of the tools used, together with the human factor that can influence the outcomes; to address this complicate situation, surgical robots were designed. It is to be noted that this typology of robots, even if sharing common roots with industrial ones, do not share the same rationale: if the industrial ones aim to "replace" the human being with automations, in the clinical field the robots' purpose is to provide an advanced tool to the surgeons rather than substitute them in the surgical room, as the knowledge and the experience of the surgeon plays a fundamental role in operating these devices.

In the last years, robotic surgery has indeed gained a prominent role thanks to it widespread application, that

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led the main orthopedics companies to introduce these devices to their portfolio by developing their own systems or by acquiring/incorporating third party companies. Consequently, this increase of applications led to a significant increment of the quantity of available literature: as shown in Fig. 1, the number of annual publications on the topic 'robotics in orthopaedic' has rose from 2500 to 6500 in the last 5 years [2].

The main fields of orthopedic operation for this kind of devices are hip and knee joints, together with spine surgeries [3, 4]; in this paper, the operations addressed for robotic application are Knee and Hip Arthroplasty, as these alone cover more than the 90% of the whole prosthetic implant market [5, 6].

The main factors leading to a successful surgery are to be found in the implant positioning (thus related to the bone preparation) and its dimensioning, with all the consequences on the surrounding soft tissues and on overall joint stability; the improved precision in the cuts execution provided by a robotic system, therefore, represented a great opportunity for the implants of prosthesis theoretically ideal to restore the physiologic configuration, but highly susceptible to failure in case of malpositioning issues [7].

As the aim of this paper is to provide a general overview of the different features that characterize different surgical robots used in orthopedic (and not to compare their clinical benefits or drawbacks), the author decided to perform a narrative review rather than a systematic review of surgical robotics systems. For instance, the information collected was obtained from surgical robot manufacturers brochures or related material together with data from scientific papers. To provide a clearer overview on the variety of available robotic systems, this narrative review was performed addressing the different categories in which they are subdivided. In the following paragraph, the features of the different robots (in terms of typology of operations performed, requirements and level of interaction of the surgeon) will be listed and compared, providing examples among the main models currently available on the market and the relative studies in the literature; these literature and market researches and comparison, together, will provide an important insight aimed to highlight the benefits and drawbacks of the different technologies and thus helping the surgeon to understand which would be the best option to adopt according to his preferences.

Introduction to the different approaches

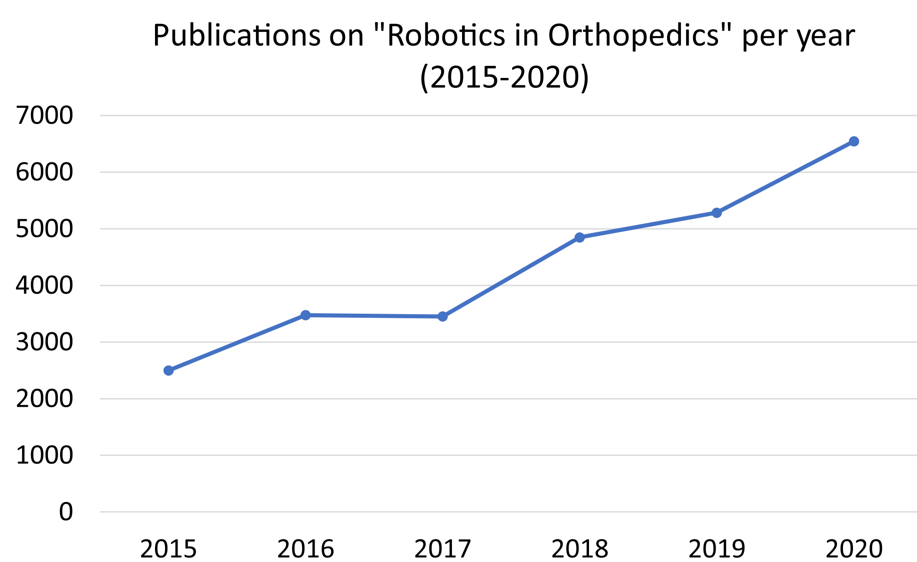
If the finality of providing improved accuracy and precision is shared as a fundamental concept by all the available surgical robots, many different approaches can be followed to pursue this common aim: currently, the market provides indeed different models and options, that can differ among each other in terms of the different pre- and intra-operative approaches (to which the surgeon should comply prior and during the operation) [8–10].

Here follows a brief description of these main approaches.

Closed platforms/open platforms

One of the first features to verify when dealing with a robotic system is the catalog of implant designs (models) that are compatible and that can thus be implanted with the robot assistance: the system can indeed be "closed platform", meaning that only the implants produced by the surgical robot provider (and sometimes not even all of them) are compatible, or "open platform" that allows a broader list

Fig. 1 Number of annual publications on the topic 'robotics in orthopedics' in the year 2015–2020



of possible prosthetic implants. This factor indeed heavily influences the surgeon's freedom in the decision making, since it may limit the choice in terms of prosthesis implant.

Some of the models available on the market, as an example the *TSolution One Surgical System* (formerly called *Robodoc*) (THINK Surgical, Freemont, CA), do not limit the pool of prosthesis models that can be implemented in the operation; on the other hand, some robotic systems have been acquired and are currently provided by the main orthopedic companies which are also prosthesis manufacturers, and for this reason these robots are set to allow only one specific manufacturer's implant design to be implemented during the procedure. Examples of this category are the *ROSA Knee System* (Zimmer-Biomet, Warsaw, IN), the *Mako SmartRobotics* (Stryker, Kalamazoo, MI), the *Navio* (Smith + Nephew, London, UK) and the *OMNIBotics* (Corin, Cirencester, UK).

The 'open/closed platform' feature is of paramount importance, as this constraint may drive the surgeon's choice regardless of his eventual preference or patient's demand; the design rationale could therefore be overshadowed by the availability of models compatible with the robotic system used. On the other hand, open systems may present less specificity, precision and even less functionalities when compared to closed ones [8, 10], as they need to provide a higher level of generalization to be compatible with a broad range of implants: the available models database may indeed be broader than the one provided by closed platforms, but this consequently leads to lower design specificity and the lack of biomechanical-rationale data may undermine the correct prediction of the kinematics deriving from the implant positioning. This downside, coupled with the fact that some open systems rely on landmarks and not actual patient images (and thus are not able to consider individual anatomic variations), may indeed imply that some specificity and this predictive value is lost [3].

Surgeons have then to evaluate if the benefits correlated to the use of a closed robotic system are worth the sacrifice of freedom in prosthesis model choice (and thus personalization) or, on the other hand, if the benefits of the open platform options are enough to balance the loss of specificity and certain functionalities [11].

Image-based/imageless

As mentioned above, another dichotomous approach concerns the way patient information is provided to the robotic system; all these systems require patients' anatomy to be acquired and reported as mapping points or landmarks on the bone (this is usually done during the registration process, done to calibrate the robot to recognize where its cutting tools are in space in relation to the patient and thus to provide the references for the resection), but the way these locations are provided can be "image-based" or "imageless".

In 'image-based' systems, this registration process is performed relying on the preoperative data from full or partial CT or MRI imaging of the patients; in this way, the patients' actual geometries are taken as reference to identify the sought optimal component size and alignment, the bone resection depth, the volumetric bone removal, the preoperative and target postoperative alignments, the leg length and offset restoration, the deformity correction and the boundaries of hard tissue removal. These systems are thus strictly depending on the pre-planning, as in these cases the surgical resection plan, implant sizing, implant positioning and alignment are all defined in advance, before even entering the surgical room. All these landmarks and surgeon's choices are then correlated to the patient during surgery via the use of computer navigation registration: this procedure happens between the exposure of the joint and the actual bone resection, and provides to the robotic system the information required to perform the surgery; this latter is consequently performed according to the preplanning. This approach represents an accurate way to address the patient anatomy and eventual deformities, allowing the surgeon to establish the operating plan in advance, evaluating also the eventual outcomes; these systems, however, bring the main disadvantages of increasing the cost of the operation together with all the complications related to the imaging process, i.e., patients managing and the radiation exposure involved in the CT scan procedure [3, 12]. Examples of robotic systems following this approach are the TSolution One, the ROSA and the Mako Systems.

On the other hand, imageless systems are based on the detection and registration of the required landmarks and surfaces directly on the patient bones, after exposure and thus during the operation itself. The patient's geometries and therefore the surgical plan to follow are then defined and executed on the spot, relying only on the surgeon's accuracy for what concerns the input of the data required: no preoperative imaging or planning are involved, thus implant size, position and alignment are defined intra-operatively based on those data. The geometries are thus generated through a morphing procedure, and this implies that approximation is to be taken into consideration in case of bone and joint deformities that were not accessible during the registration operation. Direct advantages of this approach are related to the fact that no imaging is involved, thus reducing the preoperative cost and the patient managing issues, furthermore avoiding the radiations exposure involved in CT scan sessions; these advantages anyway come with all the drawbacks of not having preoperative info, thus comporting the absence of preoperative planning and outcome evaluations, together with the impossibility to verify the landmarks registration performed by the surgeon during the operation. Some examples of robotic systems following this approach are the Navio and the OMNIBotics.

It is furthermore to be highlighted that robotic systems allowing the surgeons to decide whether to follow the image-based or the imageless approach are available on the market: some systems, as an example the ROSA system, are equipped with a software that the surgeon can use to perform the preplanning to evaluate size and position of the implant, but the imageless option is also available to achieve the same goal as the image-based one.

The main approaches of interaction with the surgeon

After having discussed all the possible approaches involved in the robotic surgical operation planning and setting, it is now time to address the main categories in which the orthopedic robotic systems are subdivided, according to the interaction required from the surgeon during the resection.

Three categories exist, namely the Active Systems, the Passive Systems and the Semi-Active Systems [13, 14].

Active approach

Active Systems are intended to be programmed by the surgeon, but after the registration the level of human interaction is the lowest as the robot performs the resection by itself.

Historically, one of the first surgical robot implementing such strategy is the Robodoc (Initially by Curexo Technology, Fremont, CA); firstly intended for THA only and later adapted also for TKA: this image-based, active and thus autonomous five-axis robotic system was equipped with a tool (mill) that would automatically prepare the cavity for the femoral stem in the patient's bone, after having established the preplanning with the ORTHODOC workstation (in terms of size and positioning of the implant), fixation to the patient and registration of landmarks by the surgeon. This robot, considered to be the first to be ever used for joint arthroplasty [15], was approved by the European Union and firstly installed in Germany in 1994 [16]; its initial lack of refinement in software, nonetheless, brought to a quite high rate of complications during the operations and therefore led the surgeons to wonder if, in case of problems, the best choice would have been to try and fix the robotic issues or to abort the operation and continue with the standard approach [17]. It is then to be highlighted that, concerning THA, active systems are mainly focused on the femoral preparation for stem implant, as the acetabular reaming is still addressed with the traditional approach or with the semi-active one. After these initial applications, Robodoc was then extended also to TKA as a tool to perform the surface preparation, always following the image-based preplanning and positioning protocol [18–20]. All these features were maintained after the acquisition from Think Surgery in 2014, leading to the introduction of the TSolution One.

Another robotic system with similar approach was the CASPAR, "Computer Assisted Surgical Planning and Robotics" (Ortho-Maquet/URS, Schwerin, Germany) [21]. This surgical robot, compatible for both TKA and THA, adopted similar operation protocols and provided improved accuracy in femoral preparation and positioning for THA [22], improving TKA in terms of alignment and axis restoration [23, 24]. However, one of the main flaws of the CASPAR was the longer operation times (up to 100 min, against the 51 of the conventional operation) then leading to further complications [25]: the system is thus no longer on the market.

Similar fate occurred to the Acrobot, Active Constraint Robot (Acrobot Company Ltd, UK): this image-based active system device was aimed solely to the knee joint, with particular focus on the Unicondylar Knee Arthroplasty [26], and could boast a non-invasive landmarks registration approach, which has indeed been acquired and improved for its implementation in the MAKO System (refer to later paragraph).

Passive approach

As direct alternative of active robots, Passive Systems are intended to be used as a guide for the surgeon, who remains the main actor for the entire resection: after pre-planning (in case of image-based systems), the registration is performed and the robot provides the positioning for the cutting tool, which is nonetheless operated by the surgeon as in a traditional operation but under direct supervision of the robotic system, which is providing the guides for the resections.

An example of such approach can be found in the OMNIBotics, which relies on the combination of different devices that were developed by companies then acquired by Corin (as Omnilife Science, Praxim, iBlock) and assembled in a coherent ecosystem. This closed imageless system, focused on total knee joint arthroplasty, requires registration of different landmarks and, after the intraoperative planning for implant size and positioning, provides the navigation system to apply the adjustable cutting guide for tibial resection; ligament balancing is then taken into consideration thanks to a dedicated tool, which provides the information to perform the planning for the femoral resections and thus to position the multi-cut femoral guide.

ROSA Knee System is instead a robotic system that was originally intended as a robotic platform to assist surgeons in planning and performing complex neurosurgical procedures in a minimally invasive manner; after the purchase of Medtech SA (Montpellier, France) by Zimmer-Biomet, the focus of this system switched on orthopedics and it has been modified into a closed (but only in terms of manufacturer, as it is compatible with different models manufactured by the owner) surgical robot, which can be used both as image-based and imageless system. After the application the reference frames and the registration, the system requires the surgeon to define the planning and then supervise the positioning of conventional cutting guides, that the surgeon will then use when performing the resection. Further possibility offered by this system is the measurement of the soft tissue tension during the operation itself, allowing then for a verification of the performed cuts [27].

Semi-active approach

Semi-Active systems are then following a mixed approach: after the process of registration and the establishment of the planning to follow, the robot is operated by the surgeon (who is then involved in the resection, contrary to the Active approach) as an actual tool (as a burr or a saw) to perform the resection, but with an overall automatic control to guarantee the achievement of the decided planning. This control is most of the times provided in the form of a feedback, being tactile, auditory or visual, and thus these systems are also referred to as "haptic". Together with the feedback for the surgeons, these systems also provide safety measures in order not to diverge from the defined resection planning: the resection instrument is handled by the surgeon indeed, but the control is still regulated by the robot that is able to deactivate it, decrease the speed or in some models to even retract the cutting tool in case the area of operation differs from the one previously decided.

Examples of this approach can be found in the MAKO, a closed image-based system used to perform arthroplasties of hip and knee joint (in detail, enabling to perform THA, TKA, UKA and, recently, also PFA implants) [28, 29]. This haptic robot implemented the registration technique of his predecessor Acrobot but shifted from an active approach to a semi-active one, providing real-time referencing to the surgeon to guide the resection, performed with a compatible tool chosen by the surgeon, according to the predetermined plan; a saw can then be used in case of TKA and the burr represents the best option to sculpt the bone for an UKA implant, but both of them are subjected to the safety haptic control. It is to be noted that the plan, defined through the image-based preplanning, can be adjusted intraoperatively to face the eventual inconveniences that may occur.

The Navio system, mainly focused on UKA and TKA, adopts instead an imageless closed approach. A model of the patient's bones is generated with a dedicated palpatory tool after the exposition of the joint, and checks of the soft ligaments involved are performed; in this way the system provides to the surgeon all the main information he may need to then plan the implant size and position. The operation then differs in case a TKA or an UKA is to be implanted: indeed, for what concerns TKA implants, the Navio system proceeds with a semi-active burr resection on the bone, finalized though to the positioning of cutting guides which are then used as in the Passive Systems. The UKA operation, on the other hand, is a more traditional semi-active one as the burr is used to sculpt the bone precisely to fit the implant [30, 31]. It is to be noted that recent studies started to use this system also to perform patello-femoral arthroplasty, but studies concerning the topic are still low in numbers [32]. Peculiarity of this system is the safety mechanism adopted, as the burr does not only stop in case the area of action is trespassed, but a retractile mechanism is also activated to completely remove the cutting surfaces from the table. The new robotic system developed by Smith + Nephew, the CORI, follows the same approaches as the Navio system.

For an overview of the main models available on the market and their main features described in the paper, see Table 1.

Discussions

Robotic surgery has begun to enter the orthopedic field as a way to improve precision and accuracy of the operation, aimed thus at better outcomes and lower revision rates for the patients.

It is to be noted that, to direct the surgical procedure, all the orthopedic robotic systems require the definition of a plan to be followed: this means that the surgeon is ultimately in charge of defining and approving the end result before the bone resections, or even before the surgical operation as a whole. This point is indeed a difference from surgical robots adopted in other fields than orthopedics, representing an advantage for the surgeons in terms of preplanning if compared to the robots which are simply controlled in real time by the surgeon during the operation.

Relying on the surgeon's expertise in the decision-making and planning, the capability of a robotic system to reproduce exactly and in a consistent way the tasks established represents the best option for the surgeon to actually implement what he defined to be the optimal implant. Individual patient-specific anatomy is then respected and the possibility to take in account the soft tissues balancing further improves the restoration of optimal kinematics, showing thus some undeniable advantages of robotically assisted surgery applied to knee joint (both unicondylar and total implants) [33–36] and hip joint [37, 38].

All these factors have however to be weighed against less positive ones: robotic systems are indeed expensive [39] and involve an important initial investment and most of the times require the surgeons and the staff to learn how to operate them, before their actual use (with a learning curve varying from system to system), in addition to the fact that

Table 1 Overview of the main models available on the market and their main features

Model	Implant compatibility		Data requirements		Level of interaction			Compatible surgeries			
	Open platform	Closed platform	Image-based	Imageless	Active	Passive	Semi-active	THA	TKA	UKA	PatelloFemoral Arthroplasty
TSolution One (Robodoc)	X		X		X			X	X		
CASPAR	X		X		X			X	X		
Acrobot	X		X		X				X	X	
ROSA		X	X	X		X			X		
MAKO		X	X				X	X	X	X	X
Navio		X		X		X	X		X	X	X*
CORI		X		X		X	X		X	X	X*
Omnibotics		X		X		X			X		

*Limited amount of literature available

they need to be calibrated in the surgical theater after their implementation; for this reason, operative times may be way longer than the standard approach during the first parts of the learning curve and still be slightly longer after experience is acquired [40, 41]. It is also to be highlighted that the implant model to be implanted and the robotic system have to be compatible to perform the surgery, and this particular narrows significantly the range of choice of the surgeon.

Furthermore, the robot represents simply an actuator for a human-decided plan that is then followed slavishly: this implies that the outcomes are strongly related to the quality of the input provided (both in terms of planning and, very importantly, in terms of the landmarks registration and of the images provided) and that the system has no actual autonomous way to face eventual complications during the surgery (as fractures of the bone during the resection or soft tissues damages, maybe caused by the robot itself as it is not able to recognize the material being cut but only its position).

Considering all these elements, it is then a logical conclusion that, before considering the implementation of surgical robots, surgeons should take in consideration all the aspects in terms of open/closed systems and options for implant selection, of the type of cutting tool provided by each different robot, of the eventual necessities in case imaging is required for preplanning and, overall, in terms of the level of surgeon-robot interaction that the user feels as more suitable.

The other main point to address is then if and when the robotic assistance would be an improvement for the surgery or an help to the surgeon: reports showed improved precision of implant positioning in THA, TKA, and UKA for robotic-assisted surgery compared with conventional techniques, but few clinical studies confirming substantially decreased revision rates and improved implant survivorship for robotic THA and TKA are available in the literature; robotic-assisted TKA, in detail, was associated with shorter length of stay, reduced utilization of services, and reduced 90-day payer costs compared with the conventional surgery [42]. On the other hand, when referring to UKA implants, evidence for improved clinical outcomes of robotic-assisted operation over conventional ones are growing: the implementation of a robotic system significantly decreases the learning curve related to UKA surgery performed with traditional instrumentation [8, 43–45] and furthermore proved itself to be cost-effective compared with traditional UKA over a 5-year period [46], but this still strictly depends on case volumes (more than 94 cases per year being the threshold to actually represent a significant alternative [47]). It is finally to highlight that nearly all studies comparing robotic THA, TKA, and UKA to conventional techniques involve financially conflicted authors, hence results may suffer from bias; further studies without COI may provide unbiased results [48].

In conclusion, the robotic surgery appears to be the optimal choice in case of implants requiring high level of positioning precision to perform correctly (as the UKA or PFA) and involving resections difficult to be performed manually, while for other typologies of applications clear agreement on which approach leads to the best results is still missing.

Although only short or mid-term studies are currently available, over the next years the even wider implementation of robotic surgery will provide further data as surgeons become more familiar with this method and further steps in technology will eventually allow to dampen the costs related to the implementation of these devices, providing to the surgeons a powerful and reliable tool to address even the most difficult operations guaranteeing the optimal outcomes.

Conclusions

This study, aimed to provide a general overview of the different features of current robotic systems, was able to demonstrate how it is currently possible to find in the market several devices characterized by different features and thus different benefits and drawbacks. Therefore each surgeon, when dealing with the questions "why, what and how" to adopt a surgical orthopedic robotic system, has to properly evaluate both sides of the medal to find the surgical robot that fits his needs the best or eventually to decide to continue treating their patients without robotic assistance.

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Declarations

Conflict of interest The authors declare that the submitted work was carried out in the absence of any personal, professional or financial relationships that could potentially be construed as a conflict of interest. The authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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