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Computer navigation and robotic surgery during total knee arthroplasty

I. M. Zazirnyi

Clinical Hospital «Feofaniya», Kyiv. Ukraine

Total knee arthroplasty (TKA) is a successful treatment for knee osteoarthritis. The emphasis on optimal sizing and alignment of the components has led to an increase in the use of tools that allow for preoperative planning and verification of intraoperative steps. Computer navigation and robotic surgery have emerged as valuable tools for planning and performing surgery with greater precision and consistency. Objective. The aim of this paper is to organise information on the use of robotic systems in total knee arthroplasty based on own personal experience and analysis of contemporary literature sources. Methods. This study analysed professional articles that discussed the advantages and disadvantages of using robotic systems during knee arthroplasty. The information was obtained from electronic databases including PubMed, Scopus, Web of Science and Google Scholar, with a search span of over 20 years. Computerised or navigation devices allow the surgeon to enter anatomical data via an interface and receive feedback on the alignment of the implant and the knee as a whole, but cannot be programmed to perform additional tasks. Currently, several patented systems are available, and rapid technological advances in computer processing power have allowed for the rapid development of robotic surgical systems. Robotic systems usually provide feedback similar to navigation systems, but they can also be programmed to assist in specific surgical tasks. It is expected that these systems will become more reliable and accurate in the future, potentially leading to a reduced role for physicians in certain aspects of the surgical process, limiting their involvement to supervision, and thus improving the workflow of the operating room. The integration of new technologies, such as mixed reality, which overlays simulated images on real-life images, is expected to further expand the range of capabilities of these devices. But for now, it is crucial to establish the long-term outcomes of robotic-assisted total knee arthroplasty as a process to determine the viability of widespread adoption of these devices.

Тотальне ендопротезування колінного суглоба (ТЕКС) є успішним методом лікування його артрозу. Акцент на оптимальному розмірі та вирівнюванні компонентів привів до збільшення використання інструментів, які дозволяють складати передопераційні плани та перевіряти інтраопераційні етапи. Комп'ютерна навігація та роботизована хірургія з'явилися як інструменти, які допомагають планувати та виконувати хірургічне втручання з більшою точністю та послідовністю. Мета. На підставі власного досвіду й аналі1зу сучасних джерел літератури систематизувати інформацію зі застосування роботизованої системи під час тотального ендопротезування колінного суглоба. Методи. Матеріали дослідження складалися з фахових статей, які містять відомості щодо плюсів і недоліків використання роботизованих систем під час ендопротезування колінного суглоба. Інформаційний пошук здійснено в електронних базах PubMed, Scopus, Web of Science, Google Scholar із глибиною пошуку понад 20 років. Комп'ютерний або навігаційний пристрій відноситься до пристрою, який має інтерфейс та дозволяє вводити анатомічні дані, а потім надає відгук хірургу щодо вирівнювання імплантатів і загального вирівнювання коліна, але не може бути запрограмований для виконання завдань. Нині існує кілька запатентованих систем, а швидкий технологічний прогрес комп'ютерної обчислювальної потужності стимулював розвиток роботизованих хірургічних систем. Роботизовані системи зазвичай забезпечують зворотний зв'язок, подібний до комп'ютерних систем, але також можуть бути запрограмовані для допомоги у виконанні певних хірургічних завдань. Таким чином, із часом очікується, що РА-ТЕКС стануть усе більш надійними та точними, що потенційно приведе до зменшення ролі лікарів у певних аспектах хірургічного процесу, причому їхня участь буде обмежена наглядом за роботою і, отже, покращенням робочого процесу операційного блока. Проте очікується, що інтеграція нових технологій, таких як змішана реальність, яка накладає змодельовані зображення на зображення реального життя, ще більше розширить діапазон можливостей цих роботів. Але наразі вкрай важливо встановити довгострокові результати тотального ендопротезування колінного суглоба за допомогою роботів як процесу для визначення життєздатності широкого впровадження цих пристроїв. Ключові слова. Колінний суглоб, комп'ютерна навігація, роботизована хірургія.

Keywords. Knee joint, computer navigation, robotic surgery

Introduction

Primary total knee arthroplasty (TKA) is one of the most common surgical interventions in orthopedics worldwide today. Considering the demographic shift towards the aging of the population, the number of such operations is expected to increase in the future. TKA is a powerful method for pain relief and functional recovery in patients with advanced arthrosis, when all conservative options have been exhausted, the patient satisfaction rate ranges from 85 to 90 % [13]. However, many studies report that 15–25 % of patients remain dissatisfied with the results of the procedure [13]. However, according to a recent systematic review, the percentage of adverse outcomes is rapidly decreasing and is about 10 [14]. It is difficult to single out a single cause of dissatisfaction, but misalignment of the components is clearly one of the most likely factors, as this can affect the proper alignment of the axis of support and the balance of the soft tissues. In addition to the rapid increase in the need for TKA in recent years, the number of robotic total knee arthroplasties has increased significantly.

The first surgical specialty that used robots was neurosurgery (1988), later urology (1991). Since then, the use of robotics in surgery has progressed significantly. Experts report increased excellence and reduced rates of iatrogenic complications with robotic surgery. Today, the use of robots in various surgical specialties is very widespread, because a number of advantages have been recorded, namely a smaller surgical incision, more qualitative and accurate processing of soft tissues, faster postoperative recovery, as well as a reduction in the length of stay in the hospital [5] .

Currently, a robotic system has been created in the field of endoprosthetics, which helps to place instruments and implants in the most effective position [22]. Robotic surgery has been shown to help improve the accuracy of implant placement [22]. The creation of computer-assisted TKA (CA-TKA) and robot-assisted TKA (RA-TKA) is promising. These technologies use the ability of computers to process large data sets to achieve a reproducible result, thereby reducing the risk of errors that can lead to incorrect positioning of components, assist in the placement of guide resection templates, and simulate the final result before surgery. Robotic assistants are a tool that doctors can use to perform surgical procedures, minimizing the human factor and maximizing the precision of operations. According to data from the Australian National Arthroplasty Registry, one in three knee arthroplasty is performed using computer navigation or a robot assistant [1].

New reports on the use of this technology in single-unit knee replacement (UKR) show improved results and survival after 2 years (2.8 % of revisions vs. 4.6) compared to traditional methods [1, 2]. Short-term results are similar for both computer-assisted and robot-assisted knee arthroplasty [3].

In orthopedics, RA-TKA is designed to reduce errors associated with bone cuts and endoprosthesis positioning and limb alignment. RA-TKA enables better surgical results for patients than conventional TKA [6].

Purpose: on the basis of own experience and assessment of modern sources of literature to systematize information on the use of a robotic system during total knee arthroplasty.

Material and methods

Research materials consisted of professional articles comrising information on the pros and cons of using robotic systems during knee arthroplasty. The information search was carried out in electronic databases PubMed, Scopus, Web of Science, Google Scholar with a search depth of more than 20 years.

Results and their discussion

Computer-assisted TKA. The first navigational TKA (CA-TKA) was performed in Grenoble in 1997 using an image-free navigation system [5] that used a kinematic model to determine the mechanical position of the limb. Later systems added anatomical landmarks from the knee to the ankle to improve accuracy.

Most systems now work with cameras that allow input of anatomical data via an infrared signal and are then used to analyze the anatomical morphology, alignment, movement and position of the surgical instrument (Figure 1).

For the most part, the system offers the surgeon an operation design in advance, which can be canceled at any time. Most systems can be used to check and measure the incisions to finalize any deviations from the surgical plan, but this step is optional as it allows for significant deviations from the planned incisions without measurement.

CA-TKA has developed into 2 main categories: with and without images. Early systems were based on either fluoroscopic images or non-image navigation, which required intraoperative registration of the center of the femur and the supracalcaneal joint, the joint surface, and other landmarks around the knee joint to create a virtual coordinate system with which to guide the resection according to the desired alignment. Later, image-based systems were developed using preoperative CT and MRI to provide joint surface registration and overall alignment. In some cases, they had additional customized cutting devices or "special guides" created for use with CA-TKA. Recently, hand-held accelerometer-based navigation systems have been developed to estimate instrument alignment and position without the need for large console monitors or computer platforms [15, 16]. Image-based systems gained popularity with the advent of RA-TKA.

Robot-assisted TKA. Robotic TKA (RA-TKA) involves the use of an intelligent tool to perform surgical incisions. The intelligence of the tool lies in its ability to collect data, interpret it and provide accurate results, such as the position of the bone slices required for the procedure. Robots used in surgery can be classified according to the degree of their efficiency during the procedure. The classification includes active, semi-active and passive robotic devices [17].

An active robotic device can perform surgical incisions independently, without the need for direct intervention by the surgeon.

A semi-active robotic device requires the active participation of the surgeon who operates the instrument through a robot control system. The robot provides real-time tactile feedback to the surgeon to facilitate accurate incisions according to the preoperative plan, which allows the physician to experience the tactile sensation of cutting bone during surgery (Fig. 1). This sensory information can help the surgeon adjust his movements and apply the appropriate force, which ensures the desired precision during surgery.

Fig. 1. The robot guides the surgeon to perform a distal section of the femur (semi-active robot). Guide templates are not used for bone cuts

In contrast, a passive robotic device is more like computerized TKA (CA-TKA) in which the robot only helps determine the correct position of the guiding instrument used by the surgeon.

Robotic devices can also be classified according to whether they rely on preoperative imaging of the patient to be integrated during surgery (image-based) or exclusive intraoperative data collection via bony landmark registration (image-free) [18]. The main goal is to create a three-dimensional model that simulates the patient's anatomy to assess ligament balance before implant placement. This will ensure proper balance of flexion and extension, maintain joint stability, optimize range of motion, and maintain limb alignment (Fig. 2).

However, although robotic systems are mostly used as a surgical tool to perform bone incisions, most of them function as closed platforms that limit the surgeon to the choice of implant design depending on the robot manufacturer, regardless of the specific requirements of the patient.

Compared to conventional TKA, RA-TKA demonstrates a higher accuracy of implant positioning, as evidenced by a reduction in the number of cases that exceed 3° from the preoperative plan and an average positioning within 1° of the planned position in all three planes [7]. In addition, RA-TKA provides improved restoration of the native joint line, Insalla-Salvati ratio and offset of the posterior femoral condyle, and improves axis alignment. Despite improvements in objective measures, evidence is still needed to determine whether increased accuracy is associated with actual improvements in functional outcomes and implant survival rates [17].

In the short term, the results are positive. The use of RA-TKA involves a lower level of manipulation of soft tissues, which leads to the minimization of damage and subsequent inflammatory reaction in the surrounding tissues. As a result, the degree of postoperative pain and swelling, perioperative analgesia, and a shorter period of physical therapy are reduced compared to conventional TKA. The requirements for hospital stay and postoperative care also change in the case of using RA-TKA [8]. This is accompanied by a short-term improvement in functional results, as evidenced by indicators on the KSS, WOMAC scales within 1.5 years after total knee joint endoprosthesis [22]; soft tissue protection compared to manual methods [22] reported in various studies [9]. In addition, the limitation of bone cuts by the robot within preoperative defined limits is associated with a decrease in the frequency of posterior cruciate ligament injuries, tibial subluxation, and patellar eversion, compared to classical TKA. However, there are few qualitative studies evaluating the medium- or long-term impact of RA-TKA. The increased accuracy of implant positioning and improvement in postoperative functional evaluations achieved with RA-TKA should be compared with conventional TKA in the long term, as should the life expectancy of the implant within 10 years [19, 20].

Disadvantages of using RA-TKA. One of their main disadvantages is the high cost of installing and maintaining the equipment. Not only by purchasing a robotic device (which costs between $600,000 and $1.5 million), but also for additional preoperative imaging, surgical team training, and computer software upgrades, not to mention that each the robotic device is only compatible with a limited number of implant designs. These costs can be partially compensated, since the use of RA-TKA leads to a reduction of a number of factors: the length of stay in the hospital, the need for analgesia, indicators of re-hospitalization, and the need for physical therapy. However, according to the latest systematic review, the costs of RA-TKA and TKA do not differ (4 studies; 366,410 patients) [21]. The number of annual cases required for RA-TKA to be theoretically cost-effective is 1,000 per year, which places some limitations on the use of these devices. Their use, mainly by surgeons with extensive experience and a significant number of operations, distorts the analysis of potential outcomes. The increased cost is due to the preoperative time delay for the remote planning team to template the optimal size and position the implant, as well as the longer intraoperative time during the initial training phase. Although the learning curve for operative duration and confidence levels of the surgical team is approximately seven to twenty cases, there are no data on the effect of the learning curve for achieving the planned femoral and tibial implant placement. And only after that, the intraoperative time with RA-TKA can be compared with conventional TKA [11, 12]. It should be remembered that RA-TKA requires additional incisions to insert all the optical sensors needed to track movement.

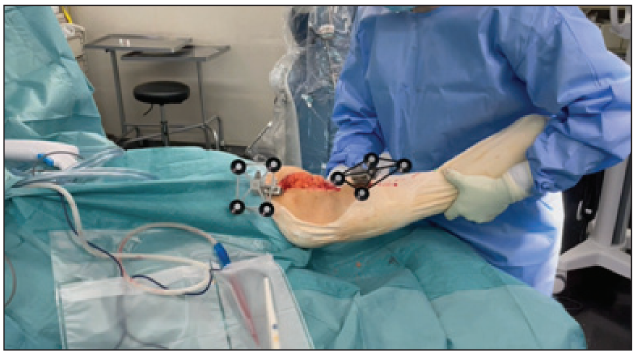

Fig. 2. Ultrasonic sensors (trackers) installed in the tibia and femur allow the operator to create a 3D-model for planning bone cuts

Future prospects. There is sufficient evidence to suggest that robotic assistance improves implant positioning and limb alignment.

However, it is clear that this technology is still in its early stages and there is still a long way to go to establish and validate the potential benefits that are beginning to emerge. This paradigm shift in the TKA procedure provokes the emergence of new unresolved issues. As the costs of these robots come down and open platforms begin to gain traction, we will likely see an overwhelming amount of evidence of RA-TKA effectiveness as more healthcare providers become able to afford the technology. Most of these devices use machine learning algorithms that improve their performance with each successive case, as information gathered from previous procedures is used to fine tune new interventions.

Conclusions

Thus, over time, RA-TKA are expected to become increasingly reliable and accurate, potentially reducing the role of physicians in certain aspects of the surgical process, with their involvement limited to overseeing work and thus improving operating room workflow. However, it is expected that the integration of new technologies such as mixed reality, which superimposes simulated images on real-life images, will further expand the range of capabilities of these robots. But it is now imperative to establish the long-term outcomes of robotic total knee arthroplasty as a procedure to determine the viability of widespread adoption of these devices.

This article was inspired by the experience and knowledge gained during an internship using the Smith & Nephew Cori robotic system for total knee arthroplasty at the IASO Hospital in Larissa (Greece) in October 2023.

Conflict of interest. The author is a paid consultant to Smith & Nephew.

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COMPUTER NAVIGATION AND ROBOTIC SURGERY DURING TOTAL KNEE ARTHROPLASTY

I. M. Zazirnyi

Clinical Hospital «Feofaniya», Kyiv. Ukraine

✉ Ihor Zazirnyi, MD, DSci in Orthopaedics and Traumatology: zazirny@ukr.net