Chapter 3
Robotic Total Knee Arthroplasty

Eun-Kyoo Song and Jong-Keun Seon

Abstract Various robotic systems have been developed to improve the accuracy of implant selection, its positioning and alignment, and bone resection. These systems are currently used worldwide for total knee arthroplasty. Many studies have clearly demonstrated that robotic systems can accurately and reliably control variables such as lower leg alignment, joint-line maintenance, soft tissue balance, and component positioning. In addition, they are more accurate and reliable than those used for conventional total knee arthroplasty. To date, however, few studies have assessed the survivorship and functional outcomes of robot-assisted surgery, and we found no sufficiently powered studies that compared these two parameters between robot-assisted and conventional knee arthroplasty. Although larger survivorship studies are necessary for these comparisons, robotics will continue to progress toward becoming a valuable tool for decreasing the revision rate and improving functional outcomes.

Keywords Total knee arthroplasty · Robotic-assisted · Implant position · Mechanical axis · Outcomes

3.1 Introduction

Total knee arthroplasty (TKA) is a reliable treatment for alleviating pain and achieving functional recovery of the knee joint in end-stage arthritic knees, providing satisfactory outcomes in more than 90% of patients [1–3]. Mechanical alignment, implant position, and soft tissue balance play important roles in treatment success and implant longevity [4–6]. Despite carefully performed procedures and improved instruments, however, various studies have described significant axial or rotational malalignment and unsatisfactory implant positioning [7, 8]. None of the contemporary improvements in implant design, instrumentation, or surgical techniques have resolved these problems completely.

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Robotic surgery has been increasingly chosen as an option to address these problems. The use of robots has proved that human errors made when placing and moving surgical tools could be reduced. Robotic systems are referred to as "active" systems that aid with preoperative imaging, planning, registration, and cutting. Orthopedic surgeons first performed total hip arthroplasty (THA) using a robotic system (ROBODOC) in 1992 [9] (Fig. 3.1a), and the first robot-assisted TKA was performed with the computer-assisted surgical planning and robotics (CASPAR) system in 2000 [10] (Fig. 3.1b). Thus, robot-assisted orthopedic surgery has been available clinically in some form for more than two decades. It is claimed that it has improved the results of total joint arthroplasty by enhancing the surgeon's ability to reproduce the correct alignment and therefore restore normal kinematics [11].

Robotic systems serve as an offline, computerized tool for planning a surgical procedure prior to surgery [12]. Some robotic platforms have been introduced to increase the accuracy and precision of component positioning during total joint arthroplasty. Improved alignment might lead to longer implant survival and less need for revision surgery.

3.2 Contemporary Systems

Many robotic systems have been developed and prototyped, but only a handful have been used successfully in a clinical setting. More recent and commonly used systems include the following: ROBODOC/TSolution One Surgical System (Curexo Technology, Fremont, CA), Navio PFS (Blue Belt Technologies, Plymouth, MN), iBlock robotic cutting guide (OMNIlife Science, East Taunton, MA), and RIO Robotic Arm Interactive Orthopedic System (Mako Surgical Corporation, Fort Lauderdale, FL) (Table 3.1).

3.2.1 ROBODOC/TSolution One Surgical System

The ROBODOC/TSolution One Surgical System, initially called the ROBODOC system (Curexo Technology, Fremont, CA), was one of the first to be used for joint replacement (Fig. 3.1b). The ROBODOC is an image-based, active robotic milling system [11]. Once the system is placed and fixed to the patient, dynamic reference markers (e.g., for navigation) are not needed to track the patient. The robotic arm controls the milling device within a rigid frame according to the preoperative planning based on computed tomography (CT) images after registration. A bone motion sensor is placed on the target bone to detect unacceptable movement of the bone within the frame. Initial clinical trials for use during THA

a

b

c

Fig. 3.1 Robotics in arthroplasty. (**a**) ROBODOC. (**b**) CASPAR system. (**c**) MAKO

Table 3.1 Contemporary robotic platforms

Name	Company	FDA approval	Applications	Control	Resection type	Planning image
ROBODOC	Curexo Technology, Fremont, CA	2008	TKA, THA (femur)	Autonomous	Mill	CT scan
Mako	Stryker, Fort Lauderdale, FL	2006	UKA, THA, TKA	Semiautonomous haptic	Burr, reamer, saw	CT scan
Navio PFS	Blue Belt Technology, Plymouth, MN	2012	UKA	Semiautonomous	Burr	None
iBlock	OMNIlife Science, East Taunton, MA	2010	TKA (femur)	Autonomous	Manual saw	None

TKA total knee arthroplasty, *THA* total hip arthroplasty, *UKA* unicondylar knee arthroplasty, *CT* computed tomography

began in 1994 and were approved by the US Food and Drug Administration (FDA) in 2008 [13, 14].

Preoperatively, the surgeon starts planning the surgery on the ORTHODOC workstation (part of the ROBODOC system) based on CT images. Planning includes outlining the segmentation of the femur and tibia, defining the femoral and tibia coordinates to evaluate implant alignment, and determining the implant size and positioning before engaging and operating the robot intraoperatively. Its clinical success and usefulness have been reported in a series of clinical trials. The advantages of using the ROBODOC system include improved alignment and positioning accuracy as well as its ability to track where the robot is milling. It also achieves a consistent radiological outcome. Its disadvantage is that the planning, registration, and milling take a longer time than when performed with the other contemporary robotic systems [11].

3.2.2 Navio PFS

Navio PFS—a handheld, image-free, open-platform instrument that provides free-hand sculpting for unicondylar and patellofemoral knee arthroplasty—was approved for clinical use by the FDA in 2012 [15]. This lightweight robotic tool combines image-free intraoperative registration, planning, and navigation for bone preparation. The Navio system has certain benefits. It is imageless, thereby reducing the risk of radiation exposure and the cost of preoperative imaging. The safety of the burr retraction, however, is limited because of its sensitivity and retraction speed. Thus, bone outside the planned volume could be removed inadvertently before burr retraction if the burr is moved too quickly.

3.2.3   iBlock

The iBlock robotic cutting guide was previously known as Praxiteles and gained FDA approval in 2010 [16]. It is a motorized, bone-mounted cutting guide that positions the saw guide for all femoral resections according to the surgeon's plan, allowing the surgeon to complete the resection with a standard oscillating saw. Intraoperatively, all anatomical data are acquired with digitization. The system allows planning the implant's size and positioning. It allows visualization of the planned bone cuts. The iBlock system does have some limitations. It provides no tactile feedback, is available only for TKA applications, has a closed platform, and allows only limited kinematic assessment after implantation for evaluating the implant's behavior.

3.2.4   Mako

The RIO Robotic Arm Interactive Orthopedic System is a tactile system used in such clinical procedures as unicondylar knee arthroplasty (UKA), THA, and TKA (Fig. 3.1c). Preoperative CT images are used in this system to determine the component's size and positioning and the amount of bone resection required. This information is then confirmed—with accommodations made as necessary—intraoperatively based on the patient's specific kinematics prior to the surgical procedure. During the operation, the robotic system provides tactile feedback to prevent excessive bone resection [17]. Currently, the RIO system is ordinarily used for robot-assisted UKA and THA. Recently, the FDA approved it for TKA.

3.3   Surgical Technique

Robot-assisted TKA consists of four steps: CT scanning, preoperative planning, registration, and surgery. The surgical process described herein is based on the ROBODOC system.

3.3.1   Preoperative Planning

CT images of the femoral head, distal femur, proximal tibia, and ankle are obtained preoperatively and transferred to the ORTHODOC workstation. The ORTHODOC combines the CT data and displays three-dimensional cross sections of bone on a high-resolution screen. The first planning step is to identify the centers of the hip, knee, and ankle for determining the femoral and tibial mechanical axes. Virtual implantation is carried out by fitting computer-assisted design files of implants to

the bone. Then, the size, position, and alignment of the implant is fine-tuned for the corresponding bone (Fig. 3.2a). After verifying the correct position during virtual surgery, the data for the robotic milling path are created and uploaded to the control unit of the surgical robot.

3.3.2 Registration

A standard incision, with medial parapatellar arthrotomy and lateral eversion of the patella, is performed. The patient's leg (placed in a leg holder) is flexed and rigidly connected to the robot by two transverse Steinmann pins inserted percutaneously through the proximal tibia and distal femur (Fig. 3.2b). These two pins are connected to a frame, which is linked to the robot. Surface-based registration of the femur and tibia is then performed by digitizing a predetermined area of bone surface with a ball-tipped probe, and the accuracy of registration is verified by measuring the discrepancy between the probe tip touching several bone surface points and the bone surface models reconstructed from the CT data (Fig. 3.2c, d).
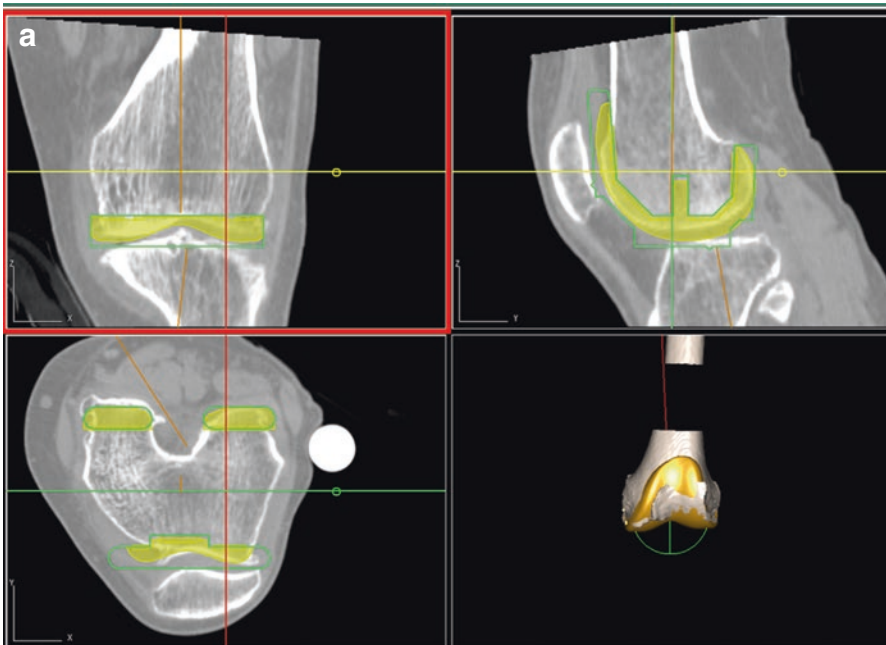

Fig. 3.2 Surgical process of ROBODOC system. (**a**) Planning, (**b**) arthrotomy and fixation, (**c**) registration, (**d**) verification, (**e**) milling, (**f**) cutting surface, (**g**) implantation
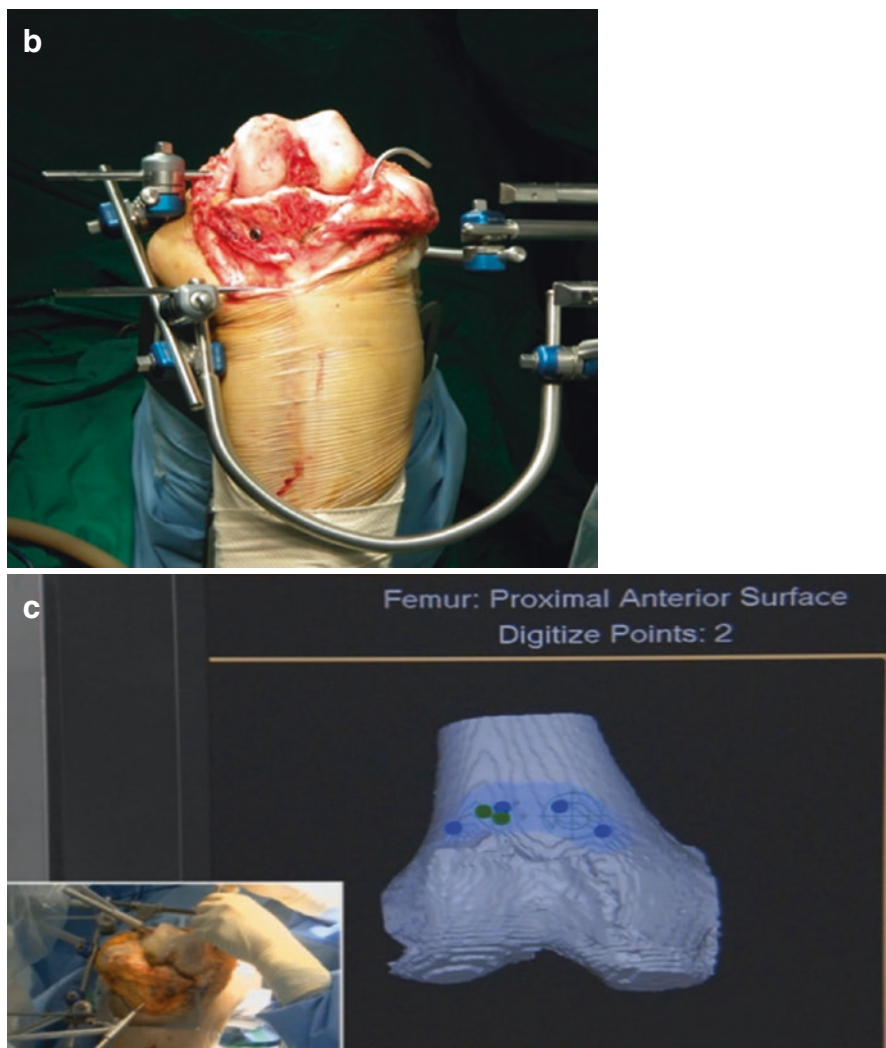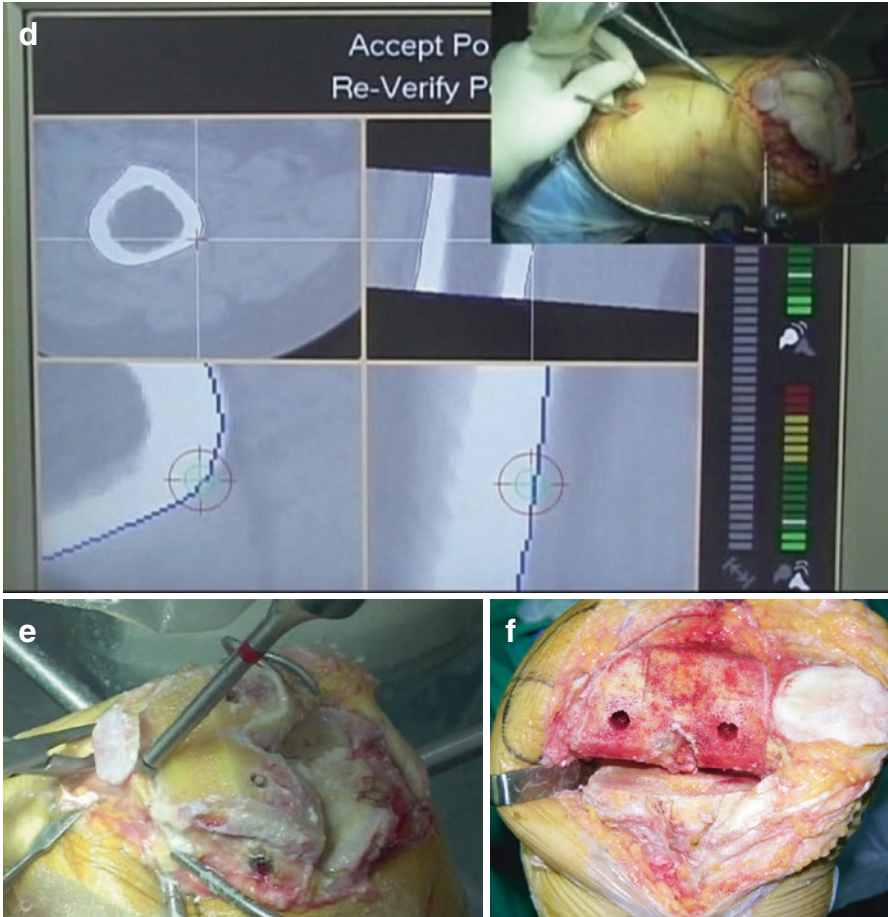
Fig. 3.2 (continued)
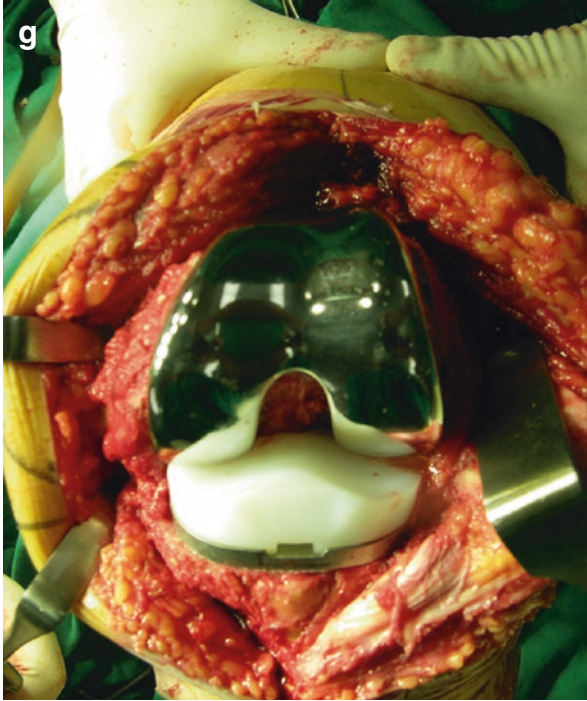
Fig. 3.2 (continued)

Fig. 3.2   (continued)

3.3.3   *Cutting, Soft Tissue Balancing, and Implantation*

After successful registration, the ROBODOC carries out intraoperative precise bone cutting for the implant according to the preoperative plan. This step is accomplished using a milling cutter, with constant normal saline irrigation for cooling and debris removal (Fig. 3.2e). After the bone cuts, the ROBODOC is disconnected and removed (Fig. 3.2f).

Soft tissue balancing is performed in a stepwise manner by releasing only what is required to achieve balance. The order of release for medial soft tissues is as follows: deep medial collateral ligament, posterior medial capsule, and superficial medial collateral ligament. Femoral and tibial implants are manually fixed with cement (Fig. 3.2g).

3.4   Current Outcomes

3.4.1   Radiologic Results

Although robot-assisted TKA is accurate, it is necessary to compare these systems with the gold standard, conventional TKA. Published studies in which robot-assisted systems were used for TKA are summarized in Table 3.2.

Siebert et al. [10] assessed mechanical axis accuracy and mechanical outliers following robot-assisted TKA surgery using the CASPAR system versus conventional TKA. They reported that the difference between preoperative and postoperative mechanical alignment was 0.8° for robot-assisted TKA and 2.6° for conventional TKA. Moreover, they showed that one patient (1.4%) in the robot-assisted group and 18 patients in the conventional group (35.0%) had mechanical alignment of >3° from the neutral mechanical axis.

Liow et al. [18] performed a prospective randomized study and reported that there were no outliers >3° from the neutral mechanical axis in the robot-assisted group, whereas 19.4% of the patients in the conventional group had mechanical axis outliers. They also assessed the joint-line outliers in both groups and found that 3.2% of patients had joint-line outliers of >5 mm in the robot-assisted group compared with 20.6% in the conventional group. Kim et al. [19] assessed the implant accuracy achieved with robot-assisted surgery using the ROBODOC system versus

Table 3.2 Overview of studies that compared clinical and radiologic outcomes between robotic-assisted and conventional TKA

Author	Journal (year)	Mean F/U (years)	Number of patients		Clinical result	Mechanical axis[a]		P
			Robotic	Conventional		Robotic	Conventional	
Liow et al. [18]	JOA (2014)	0.5	31	29	No significant difference	1.3 ± 0.9	1.8 ± 0.2	0.095
Song et al. [12]	KSSTA (2011)	2.0	30	30		0.2 ± 1.6	1.2 ± 2.1	0.035
Kim et al. [19]	Orthopedics (2012)	3.9	32	30		0.2 ± 1.1	−0.5 ± 2.8	0.611
Song et al. [20]	CORR (2013)	5.5	50	50		0.5 ± 1.4	1.2 ± 2.9	0.06
Siebert et al. [10]	Knee (2002)	1	70	52		0.8 ± 1.0	2.6 ± 2.2	0.01

N.S, nonspecific

[a]±, "+" means varus alignment, and "−" means valgus alignment

conventional surgery. They found that robot-assisted TKA had higher implant accuracy and fewer outliers than were seen following the conventional technique.

Finally, Song et al. [12, 20] performed two randomized clinical trials in which they compared mechanical axis alignment, component positioning, soft tissue balancing, and patient preference between conventional TKA surgery and robot-assisted surgery using the ROBODOC system. In the first study [12], they simultaneously performed robot-assisted surgery on one leg and conventional TKA surgery on the other leg. They found that the robot-assisted surgery resulted in fewer outliers regarding the mechanical axis and component positioning. They also found that flexion–extension balance was achieved in 92% of patients treated with robot-assisted TKA surgery but in only 77% of patients treated with conventional TKA surgery. In the other study [20], the authors found that more patients treated with robot-assisted surgery had a <2 mm flexion–extension gap and more satisfactory posterior cruciate ligament tension when compared with those who underwent conventional surgery (Fig. 3.3).

3.4.2 *Clinical Results and Survivorship*

Despite the better radiological outcomes, no significant differences were detected in functional outcomes between the robot-assisted and conventional techniques. The studies comparing functional outcomes following robot-assisted TKA and conventional TKA, however, were frequently underpowered because of their small sample sizes [12]. Furthermore, we found no studies that compared the survivorship of robot-assisted TKA with that of conventional TKA. A few studies, however, reported that robot-assisted TKA has lower rates of mechanical complications and revisions than conventional TKA. Hence, the superior mechanical alignment may result in better long-term outcomes and increased survival rate of implant.

3.5 Limitations of Robotics

Robotic surgery does have some limitations. First, the operative time might be longer, especially during the learning curve, than that for conventional surgery. Second, in addition to the cost associated with the robotic apparatus in the operating room, significant education is required for surgeons and staff to optimize the safety and effectiveness of the surgery. Third, a robotic system cuts according to the bone-cutting path established during the preoperative planning—regardless of what it may actually be cutting. Therefore, the surgeon must be alert to retracting the soft tissues (e.g., patellar tendon, capsule) in the planned path to avoid unnecessary damage.
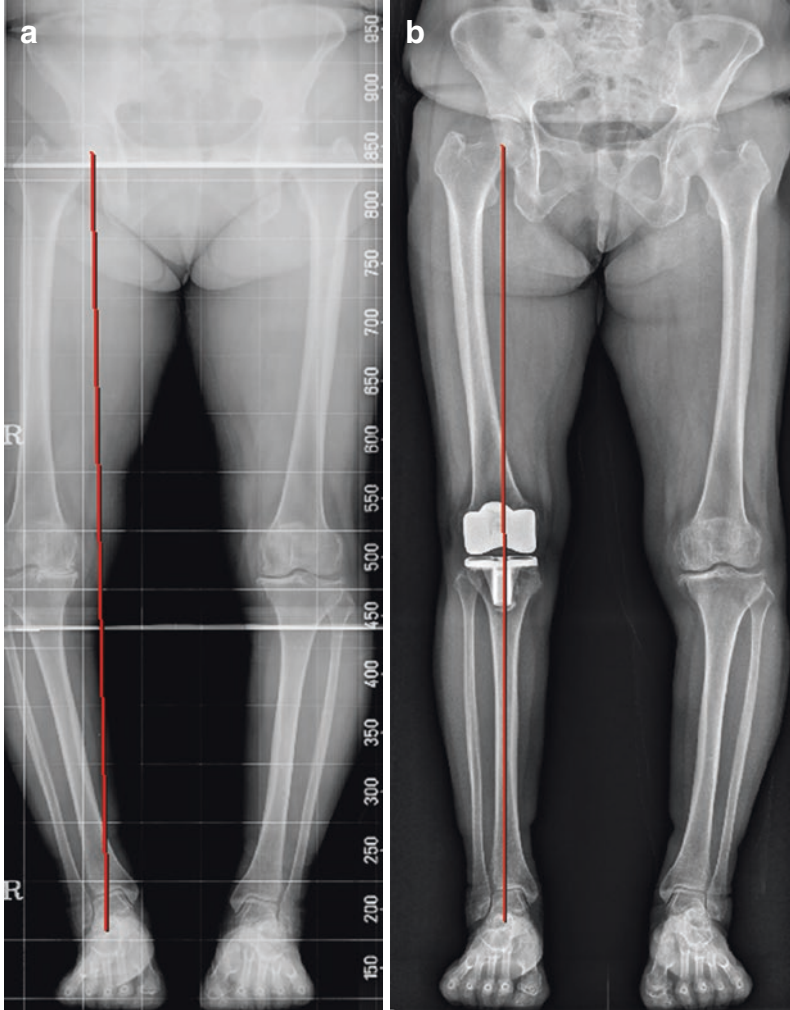
Fig. 3.3 Preoperative (**a**) and 3-year postoperative (**b**) plain radiographs of a 72-year-old woman who underwent total knee arthroplasty with ROBODOC system, showing postoperative neutral alignment

3.6 Future of Robotics

Robot-assisted TKA already safely and effectively enhances the accuracy of the implant's position and decreases the number of outliers of knee arthroplasty by avoiding major adverse events. Future innovations will continue to improve the planning, registration, and cutting methods during robot-assisted arthroplasty. Such developments will be implemented in a way that simplifies the process and minimizes the learning curve. Preoperative planning will be used to create the desired

anatomical and kinematic framework. Whereas earlier implant designs were limited by the preparation possible with traditional jigs/instruments and traditional visualization abilities, the future of implant development appears very different. The combination of robotic technology with navigation systems for real-time monitoring of soft tissue balance achieves the principles of knee arthroplasty, such as accurate bone cutting and precise gap balancing.

3.7   Conclusion

Robotic assistance can clearly improve the accuracy of implant positioning and mechanical alignment during TKA. These benefits may lead to a decrease in complications such as loosening and instability, thereby improving survivorship and functional outcomes. Although few studies have yet identified improved survivorship or better functional outcomes of robot-assisted knee arthroplasty over conventional knee arthroplasty, future well-designed long-term comparative studies will prove the improved survivorship and functional outcomes of robot-assisted knee arthroplasty. Innovation to simplify the process and minimize the learning curve will lead to robotic assistance becoming an invaluable adjunct to the surgeon. The development of this technology will certainly provide better outcomes than we can presently achieve.

References

1. Laskin RS. The Genesis total knee prosthesis: a 10-year followup study. Clin Orthop Relat Res. 2001;388:95–102.
2. Rodriguez JA, Bhende H, Ranawat CS. Total condylar knee replacement: a 20-year followup study. Clin Orthop Relat Res. 2001;388:10–7.
3. Scott WN, Rubinstein M, Scuderi G. Results after knee replacement with a posterior cruciate-substituting prosthesis. J Bone Joint Surg Am. 1988;70:1163–73.
4. Griffin FM, Insall JN, Scuderi GR. Accuracy of soft tissue balancing in total knee arthroplasty. J Arthroplast. 2000;15:970–3.
5. Ritter MA, Faris PM, Keating EM, et al. Postoperative alignment of total knee replacement. Its effect on survival. Clin Orthop Relat Res. 1994;299:153–6.
6. Takahashi T, Wada Y, Yamamoto H. Soft-tissue balancing with pressure distribution during total knee arthroplasty. J Bone Joint Surg Br. 1997;79B:235–9.
7. Aglietti P, Buzzi R, Gaudenzi A. Patellofemoral functional results and complications with the posterior stabilized total condylar knee prosthesis. J Arthroplast. 1988;3:17.
8. Jeffery RS, Morris RW, Denham RA. Coronal alignment after total knee replacement. J Bone Joint Surg Br. 1991;73:709.
9. Börner M, Bauer A, Lahmer A. Rechnerunterstützter Robotereinsatz in der Hüftendoprothetik. Orthopade. 1997;26:251.
10. Siebert W, Mai S, Kober R, et al. Technique and first clinical results of robot-assisted total knee replacement. Knee. 2002;9(3):173–80.
11. Jacofsky D, Allen M. Robotics in arthroplasty: a comprehensive review. J Arthroplast. 2016;31:2353–63.

12. Song EK, Seon JK, Park SJ, et al. Simultaneous bilateral total knee arthroplasty with robotic and conventional technique: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc. 2011;19:1069–76.
13. Bargar WL. Robots in orthopedic surgery. Clin Orthop Relat Res. 2007;463:31.
14. Chun YS, Kim KI, Cho YJ, et al. Causes and patterns of aborting a robot-assisted arthroplasty. J Arthroplast. 2011;26:621.
15. NavioPFS   FDA.   http://www.accessdata.fda.gov/cdrh_docs/pdf12/K121936.pdf.   2006. Accessed 05 Jan 2006.
16. Plaskos C, Cinquin P, Lavallee S, et al. Praxiteles: a miniature bone-mounted robot for minimal access total knee arthroplasty. Int J Med Robot. 2005;1(4):67.
17. Lang JE, Mannava S, Floyd AJ, et al. Robotic systems in orthopaedic surgery. J Bone Joint Surg Br. 2011;93:1296.
18. Liow MH, Xia Z, Wong MK, et al. Robot-assisted total knee arthroplasty accurately restores the joint line and mechanical axis. A prospective randomized study. J Arthroplast. 2014;29(12):2373–7.
19. Kim SM, Park YS, Ha CW, et al. Robot-assisted implantation improves the precision of component position in minimally invasive TKA. Orthopedics. 2012;35(9):e1334–9.
20. Song EK, Seon JK, Yim JH, et al. Robotic-assisted TKA reduces postoperative alignment outliers and improves gap balance compared to conventional TKA. Clin Orthop Relat Res. 2013;471(1):118–26.