Follow us @BoneJointRes

Freely available online OPEN ACCESS

BJR

■ KNEE

Robotic total knee arthroplasty

CLINICAL OUTCOMES AND DIRECTIONS FOR FUTURE RESEARCH

B. Kayani,
F. S. Haddad

University College London Hospitals NHS Foundation Trust, London, United Kingdom

The term ‘robot’ originates from the Czech word ‘robota’, which means forced labour or activity. Karel Capek first used the term in his 1921 play *Rossum’s Universal Robots*, in which robots were a series of factory-manufactured artificial people made from synthetic material that undertook mundane tasks for their human masters. The robots eventually became frustrated with their roles and masterminded a robotic rebellion, leading to the extinction of the human race. Since then, robotics has evolved to describe an array of computer machines that perform preprogrammed, precise, and repetitive procedures. These computer machines have now become integrated into the routine workforce of several industries, including aviation, military, healthcare, finance, construction, and engineering.[1,2] Robotic technology has helped each of these sectors to achieve and sustain levels of precision, productivity, and efficiency that were not possible with humans alone. Within each of these sectors that have integrated robotic technology into the workforce, the use of this technology has never diminished or exited from the industry.[2]

The first robotic surgical procedure was performed by Kwoh et al[3] in 1988 using the PUMA 560 robotic system (Westinghouse Electric, Pittsburgh, Pennsylvania) to undertake neurosurgical biopsies with improved precision. The same robotic platform was used by Davies et al[4] in 1991 to undertake transurethral resections of the prostate with greater accuracy and reduced iatrogenic soft-tissue injury. Over the following two decades, several other surgical robotic devices were developed, including the Zeus (Computer Motion, Inc., Goleta, California) and Da Vinci (Intuitive Surgical, Sunnyvale, California) robotic platforms, which enabled a variety of surgical procedures to be performed remotely using robotically controlled arms and a 3D camera to improve the visual field.[5,6] These robotic devices have been used to perform cholecystectomy, hysterectomy, lobectomy, mitral valve replacement, coronary artery bypass grafting, and prostatectomy. Compared with conventional open surgery or laparoscopic surgery, robotic surgery with these devices is associated with smaller skin incisions, improved precision of soft-tissue dissection, better visualization of the surgical field, and more comprehensive data capture for surgical training.[6,7] Clinically, this has translated to robotic surgery enabling faster postoperative rehabilitation and decreased length of hospital stay compared with conventional and laparoscopic surgery for these procedures.[5-8]

Total knee arthroplasty (TKA) is an effective and cost-efficient procedure that is performed in over 90 000 patients per year in the United Kingdom.[9] Implant survivorship, assessed with revision as the primary endpoint, is greater than 90% at ten years’ follow-up.[10,11] However, patient satisfaction and functional outcomes remain inferior to total hip arthroplasty, with up to 20% of patients remaining dissatisfied following TKA.[12,13] Accurate implant positioning, balanced flexion-extension gaps, proper ligament tensioning, and preservation of the periarticular soft-tissue envelope are important surgeon-controlled variables that affect functional outcomes, implant stability, and long-term implant survivorship.[14-16] Conventional jig-based TKA uses preoperative radiographic films, intraoperative anatomical landmarks, and manually positioned alignment jigs to guide bone resection and implant positioning. However, these handheld techniques are associated with poor reproducibility of alignment-guide positioning, inadvertent sawblade injury to the periarticular soft-tissue envelope, and limited intraoperative data on gap measurements or ligamentous tensioning to

Correspondence should be sent to B. Kayani; email: babar.kayani@gmail.com

doi: 10.1302/2046-3758.810.BJR-2019-0175

Bone Joint Res 2019;8:438–442.

fine-tune implant positioning.[17-19] Suboptimal implant positioning or gap balancing may lead to poor functional recovery, reduced clinical outcomes, increased instability, and reduced implant survivorship.[14-16]

Robotic TKA uses computer software to convert anatomical information into a virtual patient-specific 3D reconstruction of the knee joint. The anatomical information may be obtained using preoperative CT (image-based) or a combination of preoperative radiographs and intraoperative osseous mapping (imageless). The surgeon uses this virtual model to plan optimal bone resection, implant positioning, bone coverage, and limb alignment based on the patient's unique anatomy. An intraoperative robotic device helps to execute this preoperative patient-specific plan with a high level of accuracy.[20-26] The action of the sawblade is confined to the preoperative surgical plan for femoral and tibial resection, which limits iatrogenic periarticular soft-tissue injury and bone trauma.[27,28] Although the first robotic TKA was performed in 1988 using the ACROBOT robotic system (Imperial College, London, United Kingdom), there has been a surge in robotic TKA over the last decade.[29] This has been attributed to recent developments in computer software and technology, and the ease with which modifications can be made to existing technology such as computer navigation.[1,2] Computer-navigated TKA provides patient-specific anatomical data with recommendations for bone resection and optimal component positioning. Robotic TKA takes this one step further by actively controlling and/or restraining the surgeon's motor function to improve the accuracy of achieving the planned bone resection and implant positioning.

There are a variety of robotic TKA devices, some of which actively perform all parts of femoral and tibial bone resections (fully active), while others enable the surgeon to undertake the procedure while providing live intraoperative feedback to help control bone resection to the confines of the preoperative surgical plan (semi-active). ROBODOC (THINK Surgical Inc., Fremont, California) is an example of a fully active robotic TKA application system.[30] The surgeon performs the surgical approach, positions retractors to protect the periarticular soft tissues, and then secures the limb into a fixed device. The robotic device then independently executes the planned bone resections. The Mako Robotic Arm Interactive Orthopaedic System (Stryker Ltd, Kalamazoo, Michigan) is an example of an image-guided semi-active robotic system for robotic TKA.[31] The robotic arm has visual, tactile, and audio feedback that help the surgeon to control the force and direction of saw blade action within the confines of the femoral and tibial bone resection windows. The Navio Surgical system (Smith & Nephew, Andover, Texas) is an imageless semi-active robotic system that uses a handheld platform to intraoperatively map osseous anatomy and guide bone resection.[32] The Rosa Knee System (Zimmer Biomet, Warsaw, Indiana) offers a computer software program to convert 2D knee radiographs into a 3D patient-specific bone model, and a robotic device to help position the cutting blocks and execute the planned bone resections with greater accuracy.[33] Omnibotic (OMNIlife Science Inc., East Taunton, Massachusetts) is a robotic device that uses patented intraoperative Bone Morphin technology to create a 3D model of the osseous anatomy using plain radiographs.[34] This may be combined with the BalanceBot Ligament Balancer (OMNIlife Science Inc.), which uses an intraoperative robotic device to balance the soft tissues. Together, these technologies may help surgeons place implants anatomically while minimizing the need for soft-tissue releases.[34]

Robotic TKA is associated with improved accuracy of achieving the planned femoral and tibial implant positioning, joint line restoration, limb alignment, and posterior tibial slope compared with conventional jig-based TKA.[20,24] This has been attributed to the stereotactic boundaries that confine the action of the sawblade to the preplanned haptic femoral and tibial windows. Song et al[20,21] performed a prospective randomized study on 100 patients undergoing primary TKA, and found that robotic TKA was associated with improved accuracy and reduced outliers in achieving the planned alignment compared with conventional manual TKA. Bellemans et al[22] reviewed outcomes in 25 patients undergoing robotic TKA and reported femoral and tibial implant positioning within 1° of the planned positions in all three planes. Hampp et al[23] performed a study on six cadaveric specimens and found that robotic TKA was associated with improved accuracy of femoral and tibial implant positioning in the coronal, sagittal, and axial planes compared with conventional manual TKA. Improved accuracy in achieving these radiological outcomes has been previously correlated to increased patient satisfaction, greater stability, and improved kinematics through the arc of motion following TKA.[1,25,26] Furthermore, robotic TKA is associated with a learning curve of six to 20 cases for operative times, but there is no learning curve for achieving the planned femoral or tibial implant positioning.[35,36] This is important for the safe implementation of this technology into routine arthroplasty practice and offers an avenue for low-volume arthroplasty surgeons to achieve high levels of accuracy in implant positioning.

Balanced flexion-extension gaps and proper mediolateral ligamentous tensioning are important technical objectives in TKA for optimizing knee kinematics, stability, and long-term implant survivorship.[14-16] Conventional jig-based TKA techniques often utilize controlled soft-tissue releases to achieve balanced flexion-extension gaps and mediolateral soft-tissue tension. Assessing intraoperative gap measurements and periarticular soft-tissue laxity is challenging, and is often dependent on the skill and expertise of the operating surgeon.[36-38] Robotic TKA uses optical motion capture technology to assess intraoperative alignment, component positioning, range of movement, flexion-extension gaps, and mediolateral laxity. This real-time intraoperative data can then be used to fine-tune bone resection and guide implant positioning, in order to achieve the desired knee kinematics and limit the need for additional soft-tissue releases.[27,28] Kayani et al[28] conducted a prospective cohort study comparing bone trauma and periarticular soft tissue injury in 30 patients undergoing conventional jig-based TKA *versus* 30 patients receiving robotic TKA. The study found that robotic TKA enabled better preservation of the periarticular soft-tissue envelope in both correctible and non-correctible coronal plane deformities, and robotic TKA was associated with less trauma to the residual femoral and tibial bone resection surfaces. Khlopas et al[27] conducted a cadaveric study in which six blinded observers reported soft-tissue trauma following bone resection in cruciate-retaining TKAs, and found that robotic TKA was associated with reduced posterior cruciate ligament injury, decreased tibial subluxation, and reduced patella eversion compared with conventional jig-based TKA.

Improved preservation of the periarticular soft envelope secondary to reduced iatrogenic periarticular soft-tissue injury in robotic TKA may help to limit the local inflammatory response, decrease pain, and reduce postoperative swelling compared with conventional jig-based TKA. Siebert et al[39] conducted a retrospective study on 70 patients undergoing robotic TKA *versus* a matched historic cohort of 50 conventional jig-based TKAs, and observed reduced postoperative soft-tissue swelling in the robotic group. Kayani et al[40] conducted a prospective cohort study comparing early functional outcomes in 40 conventional manual UKAs followed by 40 robotic TKAs. The authors found that robotic TKA was associated with reduced postoperative pain, decreased analgesia requirements, shorter time to straight leg raise, increased knee flexion at discharge, and reduced need for inpatient physiotherapy compared with conventional jig-based TKA. Median time to hospital discharge in robotic-arm assisted TKA was 77 hours (interquartile range (IQR) 74 to 81) compared with 105 hours (IQR 98 to 126) in conventional jig-based TKA ($p < 0.001$). Marchand et al[41] compared outcomes in 28 robotic TKAs matched with 20 conventional jig-based TKAs and showed that pain, patient satisfaction, and physical function scores, as measured using Western Ontario and McMaster Universities Arthritis Index (WOMAC), were better in the robotic group compared with the conventional group at six months after surgery.

Improved accuracy of implant positioning and enhanced postoperative rehabilitation in robotic TKA have not translated to any differences in middle- to long-term functional outcomes compared with conventional jig-based TKA. Song et al[20,21] reported no difference in Hospital for Special Surgery (HSS) or WOMAC scores between 50 conventional jig-based TKAs and 50 robotic TKAs at two years' follow-up. Liow et al[42] conducted a prospective randomized trial in 29 conventional jig-based TKAs *versus* 31 robotic TKAs, and found that there was no difference between the two treatment groups with respect to the Oxford Knee Score (OKS) and KSS at two years' follow-up. Yang et al[43] conducted a prospective cohort study on 71 robotic TKAs *versus* 42 conventional jig-based TKAs, and found no difference in HSS and WOMAC scores at a minimum of ten years' follow-up. As with all new technology in medicine and surgery, there is a paucity of prospective randomized controlled trials reporting on longer-term outcomes.

Fixed femoral and tibial arrays provide novel intraoperative data on fixed flexion deformity, range of movement, limb alignment, flexion-extension gaps, and mediolateral ligamentous laxity, which may be used for research and development purposes. For example, existing studies assessing functional alignment in TKA have used patient-specific implants or alignment guides to achieve the preplanned alignment. Robotic technology offers an opportunity to accurately execute the planned bone resection and implant positioning to achieve functional alignment, and fixed intraoperative femoral and tibial arrays enable the surgeon to confirm that this alignment has been achieved. Similarly, changes in gap measurements and alignment following specific ligamentous resection may provide data on ligament biomechanics and kinematics. In anterior and posterior cruciate ligament reconstructions, robotic technology potentially offers an avenue to improve accuracy and reduce outliers in correct femoral and tibial tunnel positioning. Robotic technology may minimize human error and provide objective, real-time data for scientists, clinicians, and engineers to accurately record changes in knee kinematics and function. Intraoperative data on the various stages of robotic TKA may also be used for teaching purposes to improve surgical proficiency.

Robotic technology is associated with several limitations that must be acknowledged when understanding the current role and future potential of this technology in TKA. The robotic device is expensive to install and separate applications may need to be required for total hip arthroplasty, TKA, and unicompartmental knee arthroplasty. The robotic device is only compatible with a limited number of implants from the manufacturer of the robotic device, and additional costs are incurred for preoperative imaging, increased operating times during the learning phase, training the surgical team, updating of computer software and servicing contracts, and consumables. Image-guided robotic TKA requires preoperative CT scans that require extra time and radiation exposure. Additional time is also required for remote preoperative planning and segmentation using the patient-specific virtual models, and a robotic product specialist is required in the operating room to capture data and facilitate the operative procedure. Fully active robotic TKA systems have also been reported to cause periarticular soft-tissue injury, and technical issues with robotic device have required intraoperative conversion to conventional jig-based TKA.[1,17]

Overall, robotic technology enables TKA to be undertaken with improved accuracy of implant positioning and reduced periarticular soft-tissue injury compared with conventional jig-based TKA. This has translated to improved inpatient functional rehabilitation and earlier time to hospital discharge compared with conventional jig-based TKA. Robotic technology offers potential for further research by providing objective data on gap measurements and knee kinematics following specific ligamentous releases, and provides an avenue for executing preplanned implant positioning and alignment with greater precision and reproducibility for study purposes. These advantages must be acknowledged while respecting the limitations of robotic TKA, which include additional costs for installation and maintenance of the robotic machine, additional radiation exposure, and paucity of long-term data showing any functional benefit over conventional jig-based TKA. The results of further high-quality studies with longer term follow-up on functional outcomes, implant survivorship, complications, and cost-effectiveness are awaited.

References

1. **Haddad FS.** Evolving techniques: the need for better technology. *Bone Joint J* 2017;99-B:145-146.
2. **Bohn RE.** From art to science in manufacturing: the evolution of technological knowledge. *Foundations and Trends in Technology, Information and Operations Management* 2005;1:1-82.
3. **Kwoh YS, Hou J, Jonckheere EA, Hayati S.** A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. *IEEE Trans Biomed Eng* 1988;35:153-160.
4. **Davies BL, Hibberd RD, Ng WS, Timoney AG, Wickham JE.** The development of a surgeon robot for prostatectomies. *Proc Inst Mech Eng H* 1991;205:35-38.
5. **Loulmet D, Carpentier A, d'Attellis N, et al.** Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. *J Thorac Cardiovasc Surg* 1999;118:4-10.
6. **Linsky P, Wei B.** Robotic lobectomy. *J Vis Surg* 2017;3:132.
7. **Soto E, Lo Y, Friedman K, et al.** Total laparoscopic hysterectomy versus da Vinci robotic hysterectomy: is using the robot beneficial? *J Gynecol Oncol* 2011;22: 253-259.
8. **El-Hakim A, Tewari A.** Robotic prostatectomy - a review. *MedGenMed* 2004;6:20.
9. **No authors listed.** 15th Annual Report. National Joint Registry for England, Wales, Northern Ireland and the Isle of Man. 2018. https://reports.njrcentre.org.uk/Portals/0/PDFdownloads/NJR%2015th%20Annual%20Report%202018.pdf (date last accessed 17th July 2019).
10. **Argenson JN, Boisgard S, Parratte S, et al.** Survival analysis of total knee arthroplasty at a minimum 10 years' follow-up: a multicenter French nationwide study including 846 cases. *Orthop Traumatol Surg Res* 2013;99:385-390.
11. **Ahmed I, Salmon LJ, Waller A, et al.** Total knee arthroplasty with an oxidised zirconium femoral component: ten-year survivorship analysis. *Bone Joint J* 2016;98-B:58-64.
12. **Lee GC.** Patient-specific cutting blocks: of unproven value. *Bone Joint J* 2016;98-B(Suppl A):78-80.
13. **Chen JY, Lo NN, Chong HC, et al.** The influence of body mass index on functional outcome and quality of life after total knee arthroplasty. *Bone Joint J* 2016;98-B:780-785.
14. **Petrie JR, Haidukewych GJ.** Instability in total knee arthroplasty : assessment and solutions. *Bone Joint J* 2016;98-B(Suppl A):116-119.
15. **Allen MM, Pagnano MW.** Neutral mechanical alignment: is it necessary? *Bone Joint J* 2016;98-B(Suppl A):81-83.
16. **Huang T, Long Y, George D, Wang W.** Meta-analysis of gap balancing versus measured resection techniques in total knee arthroplasty. *Bone Joint J* 2017;99-B:151-158.
17. **Khan M, Osman K, Green G, Haddad FS.** The epidemiology of failure in total knee arthroplasty: avoiding your next revision. *Bone Joint J* 2016;98-B(Suppl A):105-112.
18. **Basselot F, Gicquel T, Common H, et al.** Are ligament-tensioning devices interchangeable? A study of femoral rotation. *Orthop Traumatol Surg Res* 2016; 102(Suppl):S213-S219.
19. **Teter KE, Bregman D, Colwell CW Jr.** Accuracy of intramedullary versus extramedullary tibial alignment cutting systems in total knee arthroplasty. *Clin Orthop Relat Res* 1995;321:106-110.
20. **Song EK, Seon JK, Yim JH, Netravali NA, Bargar WL.** Robotic-assisted TKA reduces postoperative alignment outliers and improves gap balance compared to conventional TKA. *Clin Orthop Relat Res* 2013;471:118-126.
21. **Song EK, Seon JK, Park SJ, et al.** Simultaneous bilateral total knee arthroplasty with robotic and conventional techniques: a prospective, randomized study. *Knee Surg Sports Traumatol Arthrosc* 2011;19:1069-1076.
22. **Bellemans J, Vandenneucker H, Vanlauwe J.** Robot-assisted total knee arthroplasty. *Clin Orthop Relat Res* 2007;464:111-116.
23. **Hampp EL, Chughtai M, Scholl LY, et al.** Robotic-arm assisted total knee arthroplasty demonstrated greater accuracy and precision to plan compared with manual techniques. *J Knee Surg* 2019;32:239-250.
24. **Moon YW, Ha CW, Do KH, et al.** Comparison of robot-assisted and conventional total knee arthroplasty: a controlled cadaver study using multiparameter quantitative three-dimensional CT assessment of alignment. *Comput Aided Surg* 2012;17:86-95.
25. **Abdel MP, Ledford CK, Kobic A, Taunton MJ, Hanssen AD.** Contemporary failure aetiologies of the primary, posterior-stabilised total knee arthroplasty. *Bone Joint J* 2017;99-B:647-652.
26. **Kutzner I, Bender A, Dymke J, et al.** Mediolateral force distribution at the knee joint shifts across activities and is driven by tibiofemoral alignment. *Bone Joint J* 2017;99-B:779-787.
27. **Khlopas A, Chughtai M, Hampp EL, et al.** Robotic-arm assisted total knee arthroplasty demonstrated soft tissue protection. *Surg Technol Int* 2017;30: 441-446.
28. **Kayani B, Konan S, Pietrzak JRT, Haddad FS.** Iatrogenic bone and soft tissue trauma in robotic-arm assisted total knee arthroplasty compared with conventional jig-based total knee arthroplasty: a prospective cohort study and validation of a new classification system. *J Arthroplasty* 2018;33:2496-2501.
29. **Jakopec M, Harris SJ, Rodriguez y Baena F, et al.** The first clinical application of a "hands-on" robotic knee surgery system. *Comput Aided Surg* 2001;6:329-339.
30. **No authors listed.** THINK Surgical Inc. https://thinksurgical.com (date last accessed 23 September 2019).
31. **No authors listed.** Mako Robotic-Arm Assisted Surgery. Stryker. https://www.stryker.com/us/en/portfolios/orthopaedics/joint-replacement/mako-robotic-arm-assisted-surgery.html (date last accessed 23 September 2019).
32. **No authors listed.** NAVIO. Smith & Nephew. http://www.smith-nephew.com/professional/microsites/navio (date last accessed 23 September 2019).
33. **No authors listed.** ROSA Knee System. Zimmer Biomet. https://www.zimmerbiomet.com/medical-professionals/knee/product/rosa-knee.html (date last accessed 23 September 2019).
34. **No authors listed.** OMNIBotics Robotic Assisted Knee Replacement. OMNI. https://www.omnils.com/patients/omnibotic_surgery (date last accessed 23 September 2019).
35. **Kayani B, Konan S, Huq SS, Tahmassebi J, Haddad FS.** Robotic-arm assisted total knee arthroplasty has a learning curve of seven cases for integration into the surgical workflow but no learning curve effect for accuracy of implant positioning. *Knee Surg Sports Traumatol Arthrosc* 2019;27:1132-1141.
36. **Sodhi N, Khlopas A, Piuzzi NS, et al.** The learning curve associated with robotic total knee arthroplasty. *J Knee Surg* 2018;31:17-21.
37. **Jones GG, Kotti M, Wiik AV, et al.** Gait comparison of unicompartmental and total knee arthroplasties with healthy controls. *Bone Joint J* 2016;98-B(Suppl B): 16-21.
38. **Huijbregts HJ, Khan RJ, Fick DP, et al.** Component alignment and clinical outcome following total knee arthroplasty: a randomised controlled trial comparing

an intramedullary alignment system with patient-specific instrumentation. *Bone Joint J* 2016;98-B:1043-1049.

39. **Siebert W, Mai S, Kober R, Heeckt PF.** Technique and first clinical results of robot-assisted total knee replacement. *Knee* 2002;9:173-180.
40. **Kayani B, Konan S, Tahmassebi J, Rowan FE, Haddad FS.** An assessment of early functional rehabilitation and hospital discharge in conventional versus robotic-arm assisted unicompartmental knee arthroplasty: a prospective cohort study. *Bone Joint J* 2019;101-B:24-33.
41. **Marchand RC, Sodhi N, Khlopas A, et al.** Patient satisfaction outcomes after robotic arm-assisted total knee arthroplasty: a short-term evaluation. *J Knee Surg* 2017;30:849-853.
42. **Liow MHL, Goh GS, Wong MK, et al.** Robotic-assisted total knee arthroplasty may lead to improvement in quality-of-life measures: a 2-year follow-up of a prospective randomized trial. *Knee Surg Sports Traumatol Arthrosc* 2017;25:2942-2951.
43. **Yang HY, Seon JK, Shin YJ, Lim HA, Song EK.** Robotic total knee arthroplasty with a cruciate-retaining implant: a 10-year follow-up study. *Clin Orthop Surg* 2017;9:169-176.

Author information

- B. Kayani, MRCS, MBBS, BSc(Hons), Trauma and Orthopaedic Specialist Registrar, Department of Trauma and Orthopaedics, University College London Hospitals NHS Foundation Trust, The Princess Grace Hospital, London, UK.
- F. S. Haddad, BSc, MD(Res), FRCS(Tr&Orth), Professor of Orthopaedic Surgery, University College London Hospitals NHS Foundation Trust, The Princess Grace Hospital, and the NIHR Biomedical Research Centre at UCLH, London, UK.