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# Robotic technology in total knee arthroplasty: a systematic review

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- Robotic total knee arthroplasty (TKA) improves the accuracy of implant positioning and reduces outliers in achieving the planned limb alignment compared to conventional jig-based TKA.
- Robotic TKA does not have a learning curve effect for achieving the planned implant positioning. The learning curve for achieving operative times comparable to conventional jig-based TKA is 7–20 robotic TKA cases.
- Cadaveric studies have shown robotic TKA is associated with reduced iatrogenic injury to the periarticular soft tissue envelope compared to conventional jig-based TKA.
- Robotic TKA is associated with decreased postoperative pain, enhanced early functional rehabilitation, and decreased time to hospital discharge compared to conventional jig-based TKA. However, there are no differences in medium- to long-term functional outcomes between conventional jig-based TKA and robotic TKA.
- Limitations of robotic TKA include high installation costs, additional radiation exposure, learning curves for gaining surgical proficiency, and compatibility of the robotic technology with a limited number of implant designs.
- Further higher quality studies are required to compare differences in conventional TKA versus robotic TKA in relation to long-term functional outcomes, implant survivorship, time to revision surgery, and cost-effectiveness.

**Keywords:** functional outcomes; robotic; total knee arthroplasty

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## Introduction

Total knee arthroplasty (TKA) is an established and highly effective treatment for patients with symptomatic end-stage knee osteoarthritis.[1,2] The procedure is performed in over 90,000 patients per year in the United Kingdom.[3] Pooled registry data has shown that implant survivorship, assessed with revision as the primary endpoint, is approximately 82% at 25 years follow-up.[4,5] However, patient satisfaction and functional outcomes remain inferior to those for total hip arthroplasty.[3] Despite advances in implant design, implant material, enhanced recovery programmes, thromboembolic prophylaxis, antibiotic prophylaxis, patient-specific implants, and computer navigation, recent studies have shown that up to 20% of patients remain dissatisfied following TKA.[2,6–11] 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.[12–19] Conceptually, technology that enables these technical objectives to be delivered with greater accuracy and reproducibility may help to further improve outcomes in TKA.

Robotic technology has been used to improve the accuracy of soft tissue dissection and enhance postoperative rehabilitation in general surgery, cardiology, obstetrics and gynaecology, and ophthalmology.[16] Over the last decade, robotic TKA has gathered momentum as an avenue for improving the accuracy of implant positioning and reducing outliers in limb alignment compared to conventional jig-based TKA.[20–26] However, many clinicians remain sceptical about robotic TKA owing to the substantive set-up costs and limited long-term evidence comparing clinical and functional outcomes to conventional manual TKA.

This article discusses the current role of robotic technology in TKA, explores the benefits of this technology on accuracy of implant positioning and periarticular soft tissue preservation, and highlights the limitations of robotic TKA compared to conventional jig-based TKA.

## Limitations of conventional jig-based TKA

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 techniques are poorly reproducible and accuracy of achieving the planned implant position is dependent on the skill and expertise of the operating surgeon.[27–31] Achieving balanced flexion-extension gaps and proper mediolateral ligamentous tensioning is dependent on subjective intraoperative gap assessments with limited capacity for fine-tuning bone resection and implant positioning. Intraoperative tensioning devices may help to guide soft tissue releases but there is often inter-surgeon heterogeneity with their positioning in the joint and overall distraction forces applied.[32–34] Conventional jig-based TKA also uses a manually controlled sawblade to perform bone resection and handheld instruments to protect the periarticular soft tissue envelope. This manual technique for bone resection may lead to inadvertent injury to the supporting ligamentous structures, which may compromise postoperative clinical and functional recovery, reduce stability, and decrease implant survivorship.[35–38] Conventional jig-based TKA does not provide real-time feedback on the thickness or orientation of the bone cuts. The use of intramedullary referencing guides for bone resection during conventional jig-based TKA may also increase the risk of thromboembolic events and cardiorespiratory complications.[39–40]

## Computer-navigated versus robotic TKA

Computer-navigated TKA involves the use of computer systems that provide live on-screen information on patient anatomy and knee kinematics during surgery. This osseous anatomical map of the patient’s knee joint may be obtained using preoperative computerized tomography (CT) scans (imaged-based navigation) or intraoperative mapping of bony anatomical landmarks on a generic model of the knee joint (non-image-based navigation). Computer navigation provides patient-specific anatomical data with recommendations for bone resection and optimal implant positioning, but the computer system does not actively control or restrain the motor function of the operating surgeon. Robotic TKA uses computer software to convert anatomical information into a virtual patient-specific three-dimensional (3D) reconstruction of the knee joint, which the operating surgeon uses to calculate optimal bone resection and implant positioning. An intraoperative robotic device helps to execute this preoperative patient-specific plan with a high level of accuracy.[20–26] Depending on the degree of control that the robotic device provides the operating surgeon, robotic assistants are classified as either fully active or semi-active systems.

## Fully active versus semi-active robotic TKA systems

Fully active robotic systems work autonomously to perform the planned femoral and tibial bone resections. The surgeon oversees the bone resection and may activate an emergency deactivation switch if required. ROBODOC (THINK Surgical Inc., Fremont, California, USA) is an example of a fully active robotic TKA application system. 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. There has been limited uptake of fully active robotic TKA systems owing to substantial robotic device installation costs and increased risk of complications during the learning phase of this procedure. Park and Lee reported six of their initial 32 fully active robotic TKA procedures had short-term complications including superficial infection, patellar ligament rupture, patellar dislocation, supracondylar fracture, patellar fracture, and common peroneal injury.[20]

Semi-active robotic systems enable the surgeon to maintain overall control over bone resection and implant positioning but provide live intraoperative feedback to limit deviation from the preoperative surgical plan. The Mako Robotic Arm Interactive Orthopaedic system (Stryker Ltd, Kalamazoo, MI, USA) is an example of an image-guided semi-active robotic system for robotic TKA. 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 patient’s limb is secured within a mobile leg holder boot that can be adjusted during bone resection to improve visualization of the operative field. Rapid or jerking movements deactivate the robotic device to help limit iatrogenic bone and soft tissue injury. The Navio Surgical System (Smith & Nephew, Andover, Texas, USA) is an imageless semi-active robotic system that uses a handheld platform to intraoperatively map osseous anatomy and guide bone resection without the haptic boundaries. More recently, the Rosa Knee System (Zimmer-Biomet, Warsaw, Indiana, USA) has gained FDA approval. This robotic system offers a computer software program to convert two-dimensional knee radiographs into a three-dimensional patient-specific bone model. Virtual plans on implant positioning and ligament balancing are created before execution of the desired patient-specific plan using the robotically positioned cutting blocks.

## Stages of robotic TKA

Robotic TKA uses computerized systems at five distinct stages for accurate execution of the patient-specific surgical plan. First, preoperative plain radiographs or CT scans of the knee joint are used to create a virtual three-dimensional reconstruction of the patient's native knee anatomy. Second, the surgeon uses this patient-specific virtual model to plan optimal implant positioning, alignment, and sizing to achieve the desired bone coverage, component position, and limb alignment. Computer software uses this virtual data to calculate femoral and tibial bone resection windows for accomplishing this surgical plan with a high level of precision. Third, intraoperative bone registration and verification of bony landmarks are used to confirm the patient's osseous knee anatomy prior to bone resection. In CT-free robotic application systems, registration is performed by mapping the patient's osseous anatomy onto a generic virtual model of the knee joint, and planning of implant positioning and bone resection is performed intraoperatively. In CT-based robotic knee systems, a patient-specific model of the knee joint is created and osseous anatomy is mapped intraoperatively to confirm bone geometry. Fourth, the surgeon uses the robotic device to perform the bone resections within the pre-planned boundaries of the femoral and tibial bone windows. Fifth, optical motion capture technology is used to re-assess intraoperative flexion and extension gaps, joint stability, range of movement, and limb alignment. The surgeon is able to perform live on-table modifications to bone resection, adjust implant positioning, and fine-tune soft tissue releases to achieve the desired bone coverage, component positioning, knee kinematics, and limb alignment.

## Accuracy of implant positioning

Robotic TKA is associated with improved accuracy in implant positioning and limb alignment compared to conventional jig-based TKA.[20–26] Sawblade action is limited to the confines of the preoperative surgical plan, which helps to execute the planned femoral and tibial bone resections with a high level of precision. Song et al conducted a prospective randomized study on 50 conventional manual TKA versus 50 robotic TKA, and found robotic TKA improved accuracy of mechanical alignment and reduced outliers of greater than 3° in planned alignment compared to conventional manual TKA.[25,26] Bellemans et al 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.[21] Hampp et al performed a cadaveric study on six specimens undergoing conventional manual TKA on one side and robotic TKA on the contralateral side.[22] The authors found that robotic TKA was associated with improved accuracy of femoral and tibial implant positioning in the coronal, sagittal, and axial planes compared to conventional manual TKA, and there was no learning effect for accuracy of implant positioning in the robotic group. Moon et al also conducted a cadaveric study using CT scans to assess the accuracy of implant positioning and limb alignment in 10 conventional jig-based TKAs versus 10 robotic TKAs.[23] The authors found that robotic TKA was associated with high levels of precision in achieving the planned component positioning and reduced outliers in limb alignment compared to conventional jig-based TKA. Robotic TKA has also been shown to more accurately restore the native joint line, posterior condylar offset ratio, and Insall-Salvati ratio compared to conventional jig-based TKA.[24,41] 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.[14–16]

## Learning curve of robotic TKA

The learning curve of robotic TKA is important for understanding the impact of this procedure on the surgical workflow, scheduling of operative cases and theatre lists, and establishing any additional risks or complications during the acquisition of surgical proficiency. Kayani et al assessed the learning curve of robotic TKA by assessing surrogate operative and radiological markers of the learning curve in 60 consecutive conventional manual TKAs followed by 60 robotic TKAs.[42] Using cumulative summative analysis, the authors reported that the learning curve for operative times and surgical team confidence levels with robotic TKA was seven cases. There was no learning curve effect in robotic TKA for achieving the planned femoral and tibial implant positioning, limb alignment, posterior condylar offset ratio, and native joint restoration. Sodhi et al explored the learning curve of robotic TKA in two different surgeons, and found operative times were increased for an initial 20 robotic TKA cases.[43] Thereafter, operative times in robotic TKA were comparable to those of conventional manual TKA in both surgeons. Proponents of robotic TKA claim that this technology helps to produce a more streamlined procedure than conventional jig-based TKA by reducing the need for instrument trays, alignment guides, and cutting blocks, enabling more rapid computer-guided bone resections, and reducing the need for trialling due to the high accuracy of preoperative surgical planning. However, existing studies show that operative times are increased in the learning phase of robotic TKA, and comparable between the two treatment techniques after the proficiency phase for robotic TKA has been achieved.[42,43]

## Periarticular soft tissue injury

Balanced flexion-extension gaps and proper mediolateral ligamentous tensioning are essential for optimizing knee kinematics, stability, and long-term implant survivorship.[35–38] In conventional jig-based TKA, controlled soft tissue releases are performed in 50–76% of patients to balance mediolateral laxity, with some authors advocating for all non-navigated TKAs to undergo ligamentous releases.[17,20,38–40] Robotic TKA uses optical motion capture technology to assess intraoperative alignment, component positioning, range of motion, flexion-extension gaps, and mediolateral laxity. This real-time intraoperative data can then be used to fine-tune bone resection and guide implant positioning to achieve the desired knee kinematics, and limit the need for additional soft tissue releases.[42,44] Robotic TKA also utilizes haptic boundaries that limit the action of the sawblade to the confines of the preoperative surgical plans for femoral and tibial resections, and therefore limit iatrogenic periarticular soft tissue injury. Khlopas et al conducted a cadaveric study in which six blinded observers reported soft tissue trauma following bone resection in cruciate-retaining TKAs with either conventional jig-based TKA or robotic TKA. The authors found that robotic TKA was associated with reduced posterior cruciate ligament (PCL) injury, tibial subluxation, and patella eversion compared with conventional manual TKA.[44]

## Early functional outcomes and time to hospital discharge

Improved preservation of the periarticular soft envelope secondary to reduced intentional soft tissue releases and decreased iatrogenic periarticular soft tissue injury in robotic TKA may help to limit the local inflammatory response, decrease pain, and reduce postoperative swelling compared to conventional jig-based TKA. Siebert et al 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.[45] Kayani et al conducted a prospective cohort study comparing early functional outcomes in 40 conventional manual TKAs followed by 40 robotic TKAs.[46] 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 to 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 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 the Western Ontario and McMaster Universities Arthritis Index (WOMAC) were better in the robotic group compared with the conventional group at six months after surgery.[47] Khlopas et al conducted a prospective non-randomized multi-centre trial comparing 102 conventional jig-based TKAs with 150 robotic TKAs, and found robotic TKA was associated with greater improvements in walking and standing at 4–6 weeks and three months after surgery compared to conventional manual TKA.[48] Ren et al recently conducted a meta-analysis of five studies with 323 robotic TKAs and 251 conventional jig-based TKAs, and reported improved Knee Society Score (KSS) functional score and WOMAC scores in the robotic group at six months follow-up.[49]

## Medium- to long-term functional outcomes

Improved accuracy of implant positioning and enhanced postoperative rehabilitation in robotic TKA have not translated to any differences in medium- to long-term functional outcomes compared to conventional jig-based TKA. Song et al 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.[25,26] Liow et al conducted a prospective randomized trial in 29 conventional jig-based TKAs versus 31 robotic TKAs, and found there was no difference between the two treatment groups with respect to the Oxford Knee Score (OKS) and KSS at two years follow-up.[50] Yang conducted a prospective cohort study on 71 robotic TKAs versus 42 conventional jig-based TKAs, and found no difference in HSS or WOMAC scores at minimum 10 years follow-up.[51] Cho et al recently reported outcomes in 155 robotic TKAs versus 196 conventional jig-based TKAs, and also found no difference in WOMAC, OKS, KSS, or SF-12 at minimum 10 years follow-up.[52]

## Limitations of robotic TKA

Robotic technology is associated with substantial installation and maintenance costs for the robotic device. Further costs are incurred with additional preoperative imaging, increased operating times during the learning phase, training the surgical team, updating of computer software and servicing contracts, and consumables. Many robotic devices are also only compatible with a limited number of implant designs, and different application systems need to be purchased for total hip arthroplasty, TKA, and unicompartmental knee arthroplasty. The cost of purchasing the robotic device ranges between $600 k to $1.5 million US dollars depending on the specification of the robotic machine, support and upgrade agreements, and category of application systems included. These costs may be partially offset as robotic TKA is associated with reduced opiate analgesia consumption, decreased need for inpatient physiotherapy, earlier time to hospital discharge, reduced readmission rates, and fewer discharges to rehabilitation units or skilled nursing facilities compared to conventional jig-based TKA.[53] Robotic TKA requires additional incisions for insertion of the femoral and tibial registration pins to enable optical motion-capture tracking, and image-guided robotic TKA increases radiation exposure to the patient. There are additional time delays for the remote planning team to template the optimal implant size and positioning on the patient-specific virtual model, which then requires further fine-tuning by the surgeon before surgery. Fully active robotic TKA systems have been reported to cause periarticular soft tissue injury and technical issues with robotic devices have required intraoperative conversion to conventional jig-based TKA.[32] The robotic device, computer screens, and infrared sensors reduce the intraoperative working space, and additional instruments and surgical trays may cause instrument crowding.

## Conclusion

Robotic TKA uses preoperative imaging or intraoperative bone mapping to create a patient-specific virtual reconstruction of the knee joint. The surgeon uses this model to plan optimal bone resection and implant positioning, and an intraoperative robotic device to execute this plan with a high level of accuracy. Intraoperative optical motion capture technology enables accurate assessment of ligamentous laxity, which enables the surgeon to fine-tune bone resection and guide implant positioning whilst limiting the need for soft tissue releases. Haptic boundaries also limit the action of the saw to the confines of the preoperative surgical plan to limit iatrogenic soft tissue injury. There is no learning curve for achieving the planned implant position and operative times are equivalent to those for conventional jig-based TKA after the initial learning phase. However, improved radiological outcomes in robotic TKA have not translated to any differences in long-term functional outcomes compared to conventional jig-based TKA. Limitations of robotic TKA include substantial installation and maintenance costs, additional radiation exposure with image-based platforms, and increased operative times during the learning phase. Further high-quality studies with longer-term follow-up on functional outcomes, implant survivorship, complications, and cost-effectiveness are required before this technique is adopted into mainstream TKA practice.

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### ICMJE CONFLICT OF INTEREST STATEMENT

SK reports consultancy, payment for lectures including service on speakers' bureaus, payment for development of education presentations and travel/accommodations/meeting expenses for Smith and Nephew and AO, all outside the submitted work.
FSH reports board membership of the *Bone and Joint Journal* and *the Annals of the Royal College of Surgeons*; consultancy for Smith & Nephew, Corin, MatOrtho and Stryker; payment for lectures including service on speakers' bureaus for Smith & Nephew and Stryker; royalties paid by Smith & Nephew, MatOrtho, Corin and Stryker, all outside the submitted work.
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### LICENCE

### REFERENCES

1. **Haddad FS.** What is the optimal level of expectation? *Bone Joint J* 2017;99-B:1121–1122.
2. **Scott CEH, Turnbull GS, MacDonald D, Breusch SJ.** Activity levels and return to work following total knee arthroplasty in patients under 65 years of age. *Bone Joint J* 2017;99-B:1037–1046.
3. **National Joint Registry for England and Wales.** 15th Annual Report, 2018. http://www.njrcentre.org.uk (date last accessed 22 March 2019).
4. **Evans JT, Walker RW, Evans JP, Blom AW, Sayers A, Whitehouse MR.** How long does a knee replacement last? A systematic review and meta-analysis of case series and national registry reports with more than 15 years of follow-up. *Lancet* 2019;393:655–663.
5. **Vertullo CJ, Lewis PL, Lorimer M, Graves SE.** The effect on long-term survivorship of surgeon preference for posterior-stabilized or minimally stabilized total knee replacement: an analysis of 63,416 prostheses from the Australian Orthopaedic Association National Joint Replacement Registry. *J Bone Joint Surg Am* 2017;99:1129–1139.

6. **Luna IE, Kehlet H, Peterson B, Wede HR, Hoevsgaard SJ, Aasvang EK.** Early patient-reported outcomes *versus* objective function after total hip and knee arthroplasty: a prospective cohort study. *Bone Joint J* 2017;99-B:1167–1175.

7. **Pinsornsak P, Nangnual S, Boontanapibul K.** Multimodal infiltration of local anaesthetic in total knee arthroplasty; is posterior capsular infiltration worth the risk? A prospective, double-blind, randomised controlled trial. *Bone Joint J* 2017;99-B:483–488.

8. **Ogonda L, Hill J, Doran E, Dennison J, Stevenson M, Beverland D.** Aspirin for thromboprophylaxis after primary lower limb arthroplasty: early thromboembolic events and 90 day mortality in 11,459 patients. *Bone Joint J* 2016;98-B:341–348.

9. **Lee GC.** Patient-specific cutting blocks: of unproven value. *Bone Joint J* 2016;98-B:78–80.

10. **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.

11. **Ahmed I, Salmon LJ, Waller A, Watanabe H, Roe JP, Pinczewski LA.** Total knee arthroplasty with an oxidised zirconium femoral component: ten-year survivorship analysis. *Bone Joint J* 2016;98-B:58–64.

12. **Devers BN, Conditt MA, Jamieson ML, Driscoll MD, Noble PC, Parsley BS.** Does greater knee flexion increase patient function and satisfaction after total knee arthroplasty? *J Arthroplasty* 2011;26:178–186.

13. **Chawla H, Nwachukwu BU, van der List JP, Eggman AA, Pearle AD, Ghomrawi HM.** Cost effectiveness of patellofemoral *versus* total knee arthroplasty in younger patients. *Bone Joint J* 2017;99-B:1028–1036.

14. **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.

15. **Kutzner I, Bender A, Dymke J, Duda G, von Roth P, Bergmann G.** Mediolateral force distribution at the knee joint shifts across activities and is driven by tibiofemoral alignment. *Bone Joint J* 2017;99-B:779–787.

16. **Haddad FS.** Evolving techniques: the need for better technology. *Bone Joint J* 2017;99-B:145–146.

17. **Vince K.** Mid-flexion instability after total knee arthroplasty: woolly thinking or a real concern? *Bone Joint J* 2016;98-B(1):84–88.

18. **Boonen B, Schotanus MG, Kerens B, van der Weegen W, Hoekstra HJ, Kort NP.** No difference in clinical outcome between patient-matched positioning guides and conventional instrumented total knee arthroplasty two years post-operatively: a multicentre, double-blind, randomised controlled trial. *Bone Joint J* 2016;98-B:939–944.

19. **Scott CE, Oliver WM, MacDonald D, Wade FA, Moran M, Breusch SJ.** Predicting dissatisfaction following total knee arthroplasty in patients under 55 years of age. *Bone Joint J* 2016;98-B:1625–1634.

20. **Park SE, Lee CT.** Comparison of robotic-assisted and conventional manual implantation of a primary total knee arthroplasty. *J Arthroplasty* 2007;22:1054–1059.

21. **Bellemans J, Vandenneucker H, Vanlauwe J.** Robot-assisted total knee arthroplasty. *Clin Orthop Relat Res* 2007;464:111–116.

22. **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.

23. **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.

24. **Sultan AA, Samuel LT, Khlopas A, et al.** Robotic-arm assisted total knee arthroplasty more accurately restored the posterior condylar offset ratio and the Insall-Salvati index compared to the manual technique: a cohort-matched study. *Surg Technol Int* 2019;34:409–413.

25. **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.

26. **Song EK, Seon JK, Park SJ, Jung WB, Park HW, Lee GW.** Simultaneous bilateral total knee arthroplasty with robotic and conventional techniques: a prospective, randomized study. *Knee Surg Sports Traumatol Arthrosc* 2011;19:1069–1076.

27. **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:16–21.

28. **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.

29. **Karachalios T, Varitimidis S, Bargiotas K, Hantes M, Roidis N, Malizos KN.** An 11- to 15-year clinical outcome study of the Advance Medial Pivot total knee arthroplasty: pivot knee arthroplasty. *Bone Joint J* 2016;98-B:1050–1055.

30. **van der Woude JA, Wiegant K, van Heerwaarden RJ, et al.** Knee joint distraction compared with total knee arthroplasty: a randomised controlled trial. *Bone Joint J* 2017;99-B:51–58.

31. **Mooney LT, Smith A, Sloan K, Clark GW.** The effect of the native kinematics of the knee on the outcome following total knee arthroplasty. *Bone Joint J* 2016;98-B:1471–1478.

32. **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:105–112.

33. **Basselot F, Gicquel T, Common H, et al.** Are ligament-tensioning devices interchangeable? A study of femoral rotation. *Orthop Traumatol Surg Res* 2016;102:S213–S219.

34. **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.

35. **Tayton ER, Frampton C, Hooper GJ, Young SW.** The impact of patient and surgical factors on the rate of infection after primary total knee arthroplasty: an analysis of 64,566 joints from the New Zealand Joint Registry. *Bone Joint J* 2016;98-B:334–340.

36. **Petrie JR, Haidukewych GJ.** Instability in total knee arthroplasty: assessment and solutions. *Bone Joint J* 2016;98-B:116–119.

37. **Allen MM, Pagnano MW.** Neutral mechanical alignment: is it necessary? *Bone Joint J* 2016;98-B:81–83.

38. **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.

39. **Dalury DF.** Cementless total knee arthroplasty: current concepts review. *Bone Joint J* 2016;98-B:867–873.

40. **Mullaji AB, Shetty GM.** Correcting deformity in total knee arthroplasty: techniques to avoid the release of collateral ligaments in severely deformed knees. *Bone Joint J* 2016;98-B:101–104.

41. **Liow MH, Xia Z, Wong MK, Tay KJ, Yeo SJ, Chin PL.** Robot-assisted total knee arthroplasty accurately restores the joint line and mechanical axis. A prospective randomised study. *J Arthroplasty* 2014;29:2373–2377.

42. **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.

**43. Sodhi N, Khlopas A, Piuzzi NS, et al.** The learning curve associated with robotic total knee arthroplasty. *J Knee Surg* 2018;31:17–21.

**44. 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.

**45. Siebert W, Mai S, Kober R, Heeckt PF.** Technique and first clinical results of robot-assisted total knee replacement. *Knee* 2002;9:173–180.

**46. 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.

**47. 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.

**48. Khlopas A, Sodhi N, Hozack WJ, et al.** Patient-reported functional and satisfaction outcomes after robotic-arm-assisted total knee arthroplasty: early results of a prospective multicenter investigation. *J Knee Surg* 2019. doi:10.1055/s-0039-1684014 [Epub ahead of print].

**49. Ren Y, Cao S, Wu J, et al.** Efficacy and reliability of active robotic assisted total knee arthroplasty compared with conventional total knee arthroplasty: a systematic review and meta-analysis. *Postgrad Med J* 2019;95:125–133.

**50. Liow MHL, Goh GS, Wong MK, Chin PL, Tay DK, Yeo SJ.** 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.

**51. 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.

**52. Cho KJ, Seon JK, Jang WY, et al.** Robotic versus conventional primary total knee arthroplasty: clinical and radiological long-term results with a minimum follow-up of ten years. *Int Orthop* 2019. Jun;43(6):1345-1354.

**53. Cool CL, Jacofsky DJ, Seeger KA, Sodhi N, Mont MA.** A 90-day episode-of-care cost analysis of robotic-arm assisted total knee arthroplasty. *J Comp Eff Res* 2019;8:327–336.