

A NEW AGE OF PRECISION IN SURGICAL INTERVENTIONS: THE ROLE OF ARTIFICIAL INTELLIGENCE AND ROBOTICS IN ENHANCING THE ACCURACY OF TOTAL KNEE REPLACEMENT ARTHROPLASTY: A LITERATURE REVIEW

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Abstract

Background and Objective: While classical Total Knee Arthroplasty (TKA) is effective, clinical problems such as mechanical misalignment, prosthetic failure and dissatisfaction (around 15-20%) still exist. The purpose of this literature review is to evaluate the role of Artificial Intelligence (AI) and robotic surgery in improving surgical accuracy and to examine their impact on clinical outcomes in patients compared to traditional methods.

Discussion: Precision surgery begins in the pre-operative phase with AI automating 3D modelling and predictive templating to prevent size mismatch. In the intra-operative phase, the raTKA system utilises this plan to guide bone cuts and obtain real-time soft-tissue gap balance through haptic feedback. The literature review supports that raTKA significantly reduces the incidence of implant position anomalies (>3 degrees) and promotes early recovery. While no significant differences in long-term Patient-Reported Outcome Measures (PROMs) were observed, likely due to a ceiling effect, raTKA has been shown to decrease the incidence of aseptic loosening and early revision surgeries. The main barriers to adoption are the high capital costs and the initial learning curve for the surgeons.

Conclusion: AI and robotics collaboration enhances biomechanical protection, pushing the boundaries of precision in TKA. This technology will be the gold standard for arthroplasty care in the future with the added benefit of being cost-effective and state-of-the-art integration of Augmented Reality (AR) and kinematic alignment.

Keywords: Total Knee Arthroplasty, Artificial Intelligence, Robotic Surgery, Mechanical Accuracy, Clinical Outcomes, Patient-Reported Outcome Measures.

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Introduction

Total Knee Arthroplasty (TKA) is considered to be one of the most successful orthopaedic surgeries for restoring mobility, but conventional surgical techniques are still challenged by the persistent problem of mechanical malalignment. When traditional hand tools are used, the component is frequently positioned more than 3 degrees off the desired mechanical axis.^(1,2) This anatomic mismatch leads to uneven loading, which biomechanically increases polyethylene degradation and risk of subsequent aseptic loosening.^(3,4) These precision limitations have been consistently demonstrated in the literature for over a decade, with residual pain and post-

operative functional dissatisfaction still occurring in up to 20% of patients undergoing conventional TKA, representing a pressing clinical problem to solve.^(5,6)

Transition to the Era of Precision Surgery

The limitations of manual instruments have given way to integrated robotic surgery and artificial intelligence (AI) as the new standard for absolute anatomical precision. This paradigm shift starts in the pre-operative phase with the use of machine learning and deep learning algorithms. AI is already efficiently used in the automatic 3D segmentation of radiological images of patients (CT scans or radiographs) and in predictive templating. This computational approach has been shown to dramatically decrease the risk of size mismatch between the unique anatomy of the patient and the implant, a process that is traditionally highly prone to the visual estimation bias of the surgeon.^(7,8)

Once this AI-based planning is integrated into the operating room, the Robotic-Assisted Total Knee Arthroplasty (raTKA) system acts as a translator, translating computational precision into physical execution. Current semi-active systems with haptic feedback do not replace the surgeon, but restrict the cutting tools not to deviate from the approved 3D plan. Several recent meta-analyses consistently confirm that raTKA significantly reduces the number of mechanical alignment outliers and improves the accuracy of bone resection angles compared to manual techniques.⁽⁹⁾ The biomechanical advantage of raTKA apart from accuracy in cuts is its ability to evaluate soft tissue gap balancing real time before bone cuts. This has been shown to reduce iatrogenic soft tissue trauma and to allow for a much more rapid early functional recovery. The rational planning and the accurate execution represent the main basis in the effort to reduce the patient dissatisfaction rates in the contemporary orthopaedics.⁽¹⁰⁾

Impact on Clinical Outcomes

The advantage of AI and robotics in achieving radiological precision is no longer debatable, but the real challenge for the contemporary orthopaedic literature is to prove if this mechanical precision is directly proportional to improved patient functional outcomes. There is a lot of short-term clinical evidence for Robotic-Assisted Total Knee Arthroplasty (raTKA). Comparative studies have shown a significant reduction in post-operative pain scores, faster achievement of Range of Motion (ROM) and shorter hospital stay in the raTKA patient group. This early clinical improvement is directly related to the minimal trauma to periarticular structures due to the accuracy of the robot-guided bone resection.⁽¹¹⁾

However, in the medium and long term, the current literature shows a more heterogeneous set of results when evaluating the Patient-Reported Outcome Measures (PROMs). In multiple long-term RCTs, including 10-year follow-ups, there was no statistically significant difference in functional scores (Knee Society Score/KSS or WOMAC) between the raTKA and conventional TKA groups.⁽¹²⁾ This phenomenon leads to the ceiling effect hypothesis, where a certain limit of mechanical accuracy may no longer provide additional functional benefits perceptible by the patient subjectively.

But from the point of view of implant survivorship, the early data from national joint registries are providing positive signals. Recent literature has shown a decrease in early revision rates for instability or aseptic loosening in cohorts of raTKA, as robotics effectively eliminates extreme malalignments (outliers) and ligament imbalances.⁽¹³⁾ Therefore, although the superiority of long-term PROMs remains a subject of debate, the potential of raTKA to extend implant lifespan remains a very strong clinical argument.

Challenges, Limitations, and Economic Evaluation

There is much excitement about the clinical superiority and radiological accuracy of AI and robotics, but the implementation of this technology at scale is still faced with major socio-economic and operational hurdles. The main challenge is the financial cost. The capital cost of buying robotic machine systems is very high, and is followed proportionally by the annual costs of maintenance and disposable instruments per surgery. Cost-effectiveness analyses suggest that the adoption of new robotics can be rationally justified, especially in health care systems with limited resources, if the institution has a high surgical volume (TKA cases). Theoretically, the higher initial costs can be offset in the long term by savings from accelerated patient hospital stays and a significant reduction in revision surgery rates.⁽¹⁴⁾

Besides economic obstacles, the transition from conventional methods to the field of precision surgery has a learning curve that should not be overlooked. The current AI systems have intuitively designed interfaces, but literature suggests that the surgeon requires an average of 15 to 30 initial cases to achieve operative time efficiency equivalent to manual techniques. This phase of adaptation is often associated with an increase in operating time which may increase tourniquet time and thus theoretically increase the risk of perioperative complications if not adequately managed.^(10,15) In addition, many robotic platforms dominating the market today require 3-D Computed Tomography (CT-Scan) imaging during the pre-operative phase. This requirement adds to the basic procedural cost burden and exposes the patients to additional radiation. This limitation is now driving further development towards imageless robotic systems based on direct joint space mapping on the operating table.

Future Directions: Advanced AI Synergy and Augmented Reality

The development of precision surgery in TKA will not end with traditional robotic machines. The actual trend of innovation is going fast to miniaturisation of instruments and imageless navigation systems combined with Augmented Reality (AR) and Mixed Reality (MR) technologies. Smart glasses allow surgeons to overlay AI planning data and 3D bone models, which are holographically projected onto the patient's anatomy. This allows surgeons to maintain visual attention on the surgical field without having to divert their gaze to an external monitor screen thus ergonomically improving intra-operative efficiency.⁽¹⁶⁾ Moreover, the predictive powers of AI are now being used to design 3D-printed custom-made implants. In this way, we can depart from the traditional mechanical alignment principle and move toward a fully personalised kinematic alignment, with the aim of restoring the patient's native joint axis and bringing knee kinematics back to as natural as possible..⁽¹⁷⁾

Conclusion

In conclusion, the advent of artificial intelligence and robotics has indisputably ushered Total Knee Arthroplasty into a new era of data-driven precision surgery. The existing literature consistently demonstrates that this technology can overcome perennial challenges in conventional surgery by abolishing mechanical malalignment outliers and reducing periarticular soft tissue trauma. This precision of execution is directly proportional to accelerated recovery, early range of motion acquisition and decreased patient pain intensity in the short term. The presence or absence of subjective functional superiority (PROMs) is still debated in long-term literature due to the ceiling effect phenomenon. However, the ability of robotics to prevent instability and suppress the early revision surgery rates promises very substantial clinical value.

In the future, with the optimisation of cost-effectiveness in addition to overcoming the adaptive learning curve, artificial intelligence and robotics have a strong trajectory to evolve from merely adjuvant instruments to the gold standard of care in total joint arthroplasty surgeries.

References

1. Mason JB, Fehring TK, Estok R, Banel D, Fahrbach K. Meta-Analysis of Alignment Outcomes in Computer-Assisted Total Knee Arthroplasty Surgery. *J Arthroplasty*. 2007 Dec;22(8):1097-106. doi:10.1016/j.arth.2007.08.001
2. Klement MR, Luzzi AJ, Siddiqi A, Valichka K, Sharkey PF. Intra-articular Corticosteroid Injection Following Total Knee Arthroplasty: Is It Effective? *J Arthroplasty*. 2019 Feb;34(2):303-8. doi:10.1016/j.arth.2018.10.033
3. Ritter MA, Davis KE, Meding JB, Pierson JL, Berend ME, Malinzak RA. The Effect of Alignment and BMI on Failure of Total Knee Replacement. *J Bone Jt Surg*. 2011 Sep 7;93(17):1588-96. doi:10.2106/JBJS.J.00772
4. Netter JD, Hermida JC, Chen PC, Nevelos JE, D'Lima DD. Effect of Microseparation and Third-Body Particles on Dual-Mobility Crosslinked Hip Liner Wear. *J Arthroplasty*. 2014 Sep;29(9):1849-53. doi:10.1016/j.arth.2014.04.010
5. Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KDJ. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? *Clin Orthop*. 2010 Jan;468(1):57-63. doi:10.1007/s11999-009-1119-9 PubMed PMID: 19844772; PubMed Central PMCID: PMC2795819.
6. Gunaratne R, Pratt DN, Banda J, Fick DP, Khan RJK, Robertson BW. Patient Dissatisfaction Following Total Knee Arthroplasty: A Systematic Review of the Literature. *J Arthroplasty*. 2017 Dec;32(12):3854-60. doi:10.1016/j.arth.2017.07.021
7. Ramkumar PN, Karnuta JM, Navarro SM, Haeberle HS, Scuderi GR, Mont MA, et al. Deep Learning Preoperatively Predicts Value Metrics for Primary Total Knee Arthroplasty: Development and Validation of an Artificial Neural Network Model. *J Arthroplasty*. 2019 Oct;34(10):2220-2227.e1. doi:10.1016/j.arth.2019.05.034 PubMed PMID: 31285089.
8. Haeberle HS, Helm JM, Navarro SM, Karnuta JM, Schaffer JL, Callaghan JJ, et al. Artificial Intelligence and Machine Learning in Lower Extremity Arthroplasty: A Review. *J Arthroplasty*. 2019 Oct;34(10):2201-3. doi:10.1016/j.arth.2019.05.055
9. Teng Y, Jiang J, Chen S, Zhao L, Cui Z, Khan MS, et al. Periarticular multimodal drug injection in total knee arthroplasty. *Knee Surg Sports Traumatol Arthrosc Off J ESSKA*. 2014 Aug;22(8):1949-57. doi:10.1007/s00167-013-2566-0 PubMed PMID: 23783531.
10. Kayani B, Konan S, Tahmassebi J, Pietrzak JRT, Haddad FS. Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty: a prospective cohort study. *Bone Jt J*. 2018 Jul;100-B(7):930-7. doi:10.1302/0301-620X.100B7.BJJ-2017-1449.R1 PubMed PMID: 29954217; PubMed Central PMCID: PMC6413767.
11. Stoltz MJ, Smith NS, Abhari S, Whitaker J, Baker JF, Smith LS, et al. Patient-Reported Outcomes in Robotic-Assisted vs Manual Cementless Total Knee Arthroplasty. *Arthroplasty Today*. 2024 Dec;30:101488. doi:10.1016/j.artd.2024.101488 PubMed PMID: 39822912; PubMed Central PMCID: PMC11735922.
12. Kim YH, Yoon SH, Park JW. Does Robotic-assisted TKA Result in Better Outcome Scores or Long-Term Survivorship Than Conventional TKA? A Randomized, Controlled Trial. *Clin Orthop*. 2020 Feb;478(2):266-75. doi:10.1097/CORR.0000000000000916 PubMed PMID: 31389889; PubMed Central PMCID: PMC7438149.
13. Batailler C, White N, Ranaldi FM, Neyret P, Servien E, Lustig S. Improved implant position and lower revision rate with robotic-assisted unicompartmental knee arthroplasty. *Knee*

- Surg Sports Traumatol Arthrosc Off J ESSKA. 2019 Apr;27(4):1232-40. doi:10.1007/s00167-018-5081-5 PubMed PMID: 30066017.
14. Ruangsomboon P, Ruangsomboon O, Isaranuwatthai W, Zywiell MG, Naimark DM. Cost-effectiveness of robotic-assisted versus conventional total knee arthroplasty: an analysis from a middle income country. *Acta Orthop.* 2025 Sep 30;96:716-25. doi:10.2340/17453674.2025.44753 PubMed PMID: 41036565; PubMed Central PMCID: PMC12489808.
 15. Sodhi N, Khlopas A, Piuizzi NS, Sultan AA, Marchand RC, Malkani AL, et al. Erratum to: The Learning Curve Associated with Robotic Total Knee Arthroplasty. *J Knee Surg.* 2018 Apr;31(4):370. doi:10.1055/s-0038-1635082 PubMed PMID: 29514361.
 16. Casari FA, Navab N, Hruby LA, Kriechling P, Nakamura R, Tori R, et al. Augmented Reality in Orthopedic Surgery Is Emerging from Proof of Concept Towards Clinical Studies: a Literature Review Explaining the Technology and Current State of the Art. *Curr Rev Musculoskelet Med.* 2021 Apr;14(2):192-203. doi:10.1007/s12178-021-09699-3 PubMed PMID: 33544367; PubMed Central PMCID: PMC7990993.
 17. Moret CS, Hirschmann MT, Vogel N, Arnold MP. Customised, individually made total knee arthroplasty shows promising 1-year clinical and patient reported outcomes. *Arch Orthop Trauma Surg.* 2021 Dec;141(12):2217-25. doi:10.1007/s00402-021-04045-1 PubMed PMID: 34269890; PubMed Central PMCID: PMC8595176.