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The current state of robotics in total knee arthroplasty

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- Robotic total knee arthroplasty (TKA) has demonstrated improved component positioning and a reduction of alignment outliers with regard to pre-operative planning.
- Early robotic TKA technologies were mainly active systems associated with significant technical and surgical complications.
- Current robotic TKA systems are predominantly semi-active with additional haptic feedback which minimizes iatrogenic soft tissue injury compared to conventional arthroplasty and older systems.
- Semi-active systems demonstrate advantages in terms of early functional recovery and hospital discharge compared to conventional arthroplasty.
- Limitations with current robotic technology include high upfront costs, learning curves and lack of long-term outcomes.
- The short-term gains and greater technical reliability associated with current systems may justify the ongoing investment in robotic technology.
- Further long-term data are required to fully ascertain the cost-effectiveness of newer robotic systems.

Keywords: complications; outcomes; robotic-assisted; total knee arthroplasty

Introduction

Background

Conventional total knee arthroplasty (TKA) is a well-accepted, safe and cost-effective procedure for treating symptomatic end-stage knee osteoarthritis.[1,2] However, patient satisfaction remains an issue, with satisfaction rates ranging between 82% and 89%.[3,4] This can be attributed to poorer function, lower implant survivorship and need for revision surgery, resulting from component malalignment or soft tissue imbalance.[5–10] Robotic-assisted technology is a potential solution to the issues faced by conventional TKA. This review provides an overview of

robotic-assisted technology in primary TKA and discusses the evidence-base surrounding its use.

Image-dependent versus imageless robotic systems

Robotic-assisted TKA uses computer software to generate a virtual three-dimensional (3D) model of the patient-specific bony anatomy. This is used by the surgeon to pre-plan bone cuts, component size and positioning. This surgical plan is subsequently mapped intra-operatively to the patient's bony anatomy using navigational software. For image-dependent systems, this virtual 3D model is derived from pre-operative imaging using computed tomography (CT) or magnetic resonance imaging (MRI). In contrast, imageless systems use a more detailed registration of the bony articulating surfaces and joint kinematics recorded intra-operatively post arthrotomy to create this surgical plan. Image-dependent systems allow sufficient time to pre-operatively plan, including choosing implant size and orientation. However, this benefit should be balanced against the additional costs of pre-operative imaging and additional radiation risk.[11–13] Additionally, the intra-operative registration of bony landmarks required by imageless systems is dependent on the operating surgeon's accuracy of inputting correct data points which is subject to human error.[11]

Passive, semi-active and active robotic systems

Passive robotic systems have had limited use in TKA. These systems are based on either computer-assisted or navigation technology, which provide positional guidance to the surgeon via an overhead monitor.[14] With these systems, the potential for human error remains, due to a lack of safety constraints (haptic feedback) on preparation of bony surfaces and component positioning. Furthermore, the improvement in component alignment associated with the use of these systems has not demonstrated any additional benefit in improving long-term implant survivorship and clinical outcomes.[15] Due to the aforementioned limitations of passive robotic systems, both semi-active and active systems are being increasingly used in TKA.[16] Semi-active systems allow the surgeon to guide the robotic arm to perform both femoral and tibial bony

preparation within the confines of haptic constraint pre-determined by surgical planning. This technology therefore requires constant input by the surgeon in order for the procedure to be completed.[17] By contrast, active systems operate autonomously under surgical supervision without real-time guidance.[18] The robotic software is used to configure the surgical plan offline based on pre-operative CT imaging.[14] The surgeon then performs the initial surgical approach, positions retractors to protect soft tissues and attaches the limb to a fixed holding device.[19] Post final calibration, the robotic arm is initiated and performs the femoral and tibial bony resections independently.[20] Once activated, the surgeon maintains control via an emergency manual override button.[21]

Robotic systems

Historic systems

First-generation robotic systems were introduced in the early 2000s. These were fully active systems such as ROBO-DOC (Curexo Technology Corporation, Fremont, CA, USA) and CASPAR (Ortho-Maquet/URS, Schwerin), both of which relied upon pre-operative CT imaging for surgical planning. Several studies highlighted the better alignment accuracy and implant fit using both systems compared to manual TKA.[9,22] However, this failed to equate to an improvement in clinical outcomes. Subsequent concerns due to potential increased risk of infection relating to longer operative times, technical failures and intra-operative complications led to a cessation of their use.[9,14,22,23]

Mako

The Mako Robotic-Arm Assisted System (Stryker, Mako Surgical Corp., Fort Lauderdale, FL, USA) was officially launched for primary TKA in 2017. This image-dependent semi-active system utilizes pre-operative CT imaging to generate a 3D model that is used to plan both femoral and tibial component size and orientation. The pre-surgical plan is 'mapped' to the patient's anatomy intra-operatively and allows for intra-operative adjustments by the operating surgeon. Haptic field constraints ensure that the robotic arm only allows removal of bone within 0.5 mm of the original surgical plan.[24]

Navio

In 2017 the Navio surgical system (Smith & Nephew, Inc., Memphis, TN, USA) was also launched but, unlike Mako, this semi-active system is imageless. A probe is used to map out the bony anatomy of the distal femur and tibia intra-operatively. The surgeon uses a handheld robotic sculpting tool, which slows down and retracts its burr should the surgeon stray away from the confines of the surgical plan. Whilst the entirety of bone preparation can be performed using the burr, for efficiency most surgeons utilize a hybrid approach for primary TKA. This uses the robotic tool to burr out holes to accommodate standardized cutting jigs and subsequently a bone saw is used freehand to prepare both femur and tibia.[25]

ROSA

Originally introduced in Australia in 2018, the ROSA Knee robotic system (Zimmer Biomet, Warsaw, IN, USA) has recently gained Food and Drug Association (FDA) approval in the United States.[26] Unlike other systems, ROSA provides the option of either image-dependent or imageless pathways. The image-dependent software allows generation of a 3D patient-specific virtual model derived from two-dimensional (2D) radiographs, which is then mapped intra-operatively to the patient using a bony landmark registration process similar to other systems. This can also be done using the imageless software intra-operatively, although this pathway requires a more detailed registration of landmark points along the articular surfaces. Once planning is completed, the robotic arm guides a cutting block onto the femur or tibia based on the surgeon's preference for bone preparation. As the robotic arm holds the cutting jig in place, it is secured to the bone with two pins. A bone saw is then used freehand through the cutting guides to prepare the femur and tibia. Post preparation of the femur and tibia, a validation tool can be placed on either prepared surface to ensure the resection correlates with the surgical plan.[27]

OMNIBotics

OMNIBotics knee system (OMNIlife Science, Inc., Raynham, MA, USA) is an imageless semi-active system. This system incorporates the OMNIBot robotic cutting guide for femoral bone cuts combined with a ligament-balancing tool called the BalanceBot. Navigation software is used to guide the placement and pinning of the tibial guide that is then subsequently used to make the tibial cut freehand using a bone saw. The BalanceBot active spacer can then be used to calculate ligament tension throughout flexion/extension. Femoral component planning can then be modified to optimize gap balancing throughout the range of motion. The femoral cutting guide is driven by a robotic arm directly attached to the femoral tracking pin. This robotic arm sequentially aligns the cutting guide in the sagittal plane for each of the five distal femoral cuts required, enabling them to be completed freehand in a similar fashion to the tibia.[28] Given its function, it has been suggested that this system is best classified as a motorized computer navigation system rather than true robotic technology.[26]

TSolution One

TSolution One (Think Surgical Inc., Fremont, CA, USA) is an image-dependent active robotic system that incorporates

technology originally developed for its predecessor ROBO-DOC (Curexo Technology, Fremont, CA, USA). The TSolution One system allows both femoral and tibial preparation for TKA using an autonomous milling system. Once activated, the robot completes all femoral and tibial bone cuts autonomously, although, for safety, the surgeon does have a manual override button. Soft tissue balancing is then calculated with trials before the definitive implants are inserted.[29]

Open versus closed systems

Implant choice associated with robotic systems is limited by whether or not they utilize an 'open' or 'closed' platform. ROBODOC and CASPAR were open platforms. This meant that they provided combability with different implant companies and designs, allowing the surgeon more freedom regarding implant choice tailored to the patient's anatomy. However, in order to facilitate different configurations for multiple prostheses, implant design specificity and biomechanical data to predict optimal implant positioning was markedly reduced.[11,30] Newer robotic systems are predominantly closed platforms. This includes Mako robotic TKA which currently limits implant choice to cemented or uncemented versions of the Triathlon (Stryker, Kalamazoo, Michigan, USA) TKA. As such, surgeons may face having to use alternative implants compared to their usual practice in order to utilize such robotic technology. As long-term outcomes become clearer, surgeons will need to decide whether the risks and benefits of adopting such technology outweigh those associated with the freedom of implant choice.[31,32]

Clinical and radiological outcomes

Implant survivorship is dependent on several factors including post-operative mechanical alignment of the lower limb, component positioning and soft tissue balancing.[33–35] In particular, a varus or valgus malalignment of more than 3° in the coronal plane leads to an uneven distribution of load through the prosthesis leading to earlier radiographic lysis and subsequent risk of aseptic loosening.[36–38] Robotic systems were therefore developed to increase accuracy in implant sizing, component positioning and bone preparation to further reduce the risk of outliers and hopefully improve clinical outcome and long-term survivorship.[9,22,39,40]

Component positioning and alignment

First-generation robotic systems demonstrated mixed results in terms of improving component positioning and alignment. Siebert et al reported improved post-operative alignment with the CASPAR system compared to the manual approach.[9] However, the evidence associated with ROBODOC is conflicting. Song et al reported improvements in mechanical axis alignment, implant positioning and gap balancing in the ROBODOC group compared to the conventional TKA group, which have been corroborated by subsequent non-comparative studies.[23,41,42] However, two studies found no differences between ROBODOC-assisted and manual TKA in terms of hip–knee–ankle angle (HKA) and mechanical axis.[35,43]

More recently, the accuracy of semi-active systems has been evaluated. Kayani et al observed better implant positioning and limb alignment in Mako TKA compared to conventional TKA, with no additional risk of complications.[44] Additionally, Sires et al noted that 94.29% of bone cuts using Mako were within 1 mm of the surgical plan.[45] However, Naziri et al found no difference in post-operative alignment between Mako robotic and conventional TKA.[46]

Bollars et al noted the post-operative mechanical axis was significantly different between the Navio-assisted robotic TKA group compared to the conventional group, with fewer outliers in the robotic group.[47] However, when compared with the post-operative standing long-leg radiographic alignment measurements, there were six (8%) and 11 (15%) outliers compared to the planned and recorded mechanical alignment readings intraoperatively using the Navio registration software. This study attributed these differences between planned mechanical axis and actual post-operative radiographically mechanical axis measurements to increased forces placed through the knee during weightbearing compared to on-the-table robotic measurements.

One of the few comparative studies noted OMNIBot to be 0.5° closer to the mechanical axis compared to a computer-assisted navigation system. In their series of 173 robotically assisted TKAs, Figueroa et al reported that the final implant femoral coronal, rotational and tibial coronal alignment were highly accurate compared with post-operative CT scans.[48] However, overall coronal limb alignment HKA, femoral and tibial sagittal alignment were less accurate. Clark et al compared 52 OMNIBot-assisted TKAs with 29 computer-assisted navigated TKAs, noting reduced navigation time, decreased final malalignment and reduced hospital stay with robotic-assisted TKAs compared to computer-navigated TKAs.[28]

Given ROSA's recent release, studies are limited. A cadaveric study by Parratte et al highlighted that surgeons utilizing this system could perform highly accurate bone resections to achieve planned component positioning compared to target values from intra-operative planning.[49]

Studies on the second generation of active systems are limited. Recently presented data on TSolution One highlighted minimal deviations in component positioning compared to pre-operative planning.[50]

Soft tissue balancing

Appropriate soft tissue balancing is essential in the restoration of normal kinematics, proprioception and prevention of excessive wear and instability in TKA.[51–54] Currently there are limited data available assessing the accuracy and effect of robotic-assisted TKA on soft tissue balancing. Song et al demonstrated that the utilization of ROBODOC achieved satisfactory flexion and extension gaps in 94% of patients compared to only 80% in their conventional group (p = 0.037). However, this was based on the utilization of an additional commercial tensor device post bony preparation allowing the surgeon to perform further soft tissue releases in both groups in order to achieve optimal gap balancing.[23] More recently, a study based on the newer OMNIBot system demonstrated its high accuracy in predicting post-operative gap profile before femoral bony resections. Additionally, the subsequent use of this robotic-assistance led to mediolateral gap balance within 2 mm throughout the flexion range of movement in 90% of patients.[55] Unlike ROBODOC, this newer system incorporates a gap-tensioning in addition to a component-planning algorithm into its software. Combined with the additional accuracy provided by robotic assistance, this ensures that the majority of soft tissue balancing can be achieved via accurate bony preparation and component positioning. This therefore minimizes the need for additional soft tissue releases post prostheses insertion.[55]

Avoidance of bony and soft tissue injury

Most current systems, including Mako, incorporate similar soft tissue algorithms into their robotically assisted TKA pathways.[21,56] However, this semi-active system additionally provides haptic feedback ensuring bony resections are confined to within 0.5 mm of the original surgical plan.[24] This additional accuracy provides protection against inadvertent bony and soft tissue trauma compared to conventional TKA, potentially impacting on long-term clinical and functional outcomes.[54,57] A cadaveric study by Hamp et al also highlighted the reduction of iatrogenic soft tissue injuries particularly associated with the posterior cruciate ligament (PCL) using Mako robotic assistance compared to conventional TKA.[58] Inadvertent PCL resection should be avoided as it creates gap-balancing mismatch by increasing the flexion gap more than the extension gap.[59] Given the importance of optimal gap balancing in reducing instability and minimizing wear, the soft tissue protection offered by semi-active systems via haptic feedback may therefore improve functional outcomes and survivorship in the long term.

Functional outcomes

Early functional data plays an important role in appraising current robotic systems given the significant upfront costs of the technology.

Kayani et al noted that Mako-assisted TKAs were associated with reduced pain within the first three days, improved early functional recovery and earlier hospital discharge compared to conventional TKA.[60] Furthermore, Naziri et al reported greater range of motion (ROM) and shorter length of stay in the Mako group compared to the conventional group.[46] However, there were no differences in functional outcomes, final ROM and patient-reported outcome measures (PROMs) at three months. By contrast, several studies have suggested greater functional improvements as measured by the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and Knee Society Score (KSS) in the short term.[61–64] There are limited data on use of the Navio system in TKA. A prospective cohort study comparing the clinical, radiographic and PROMs data between Navio-assisted and conventional TKA is currently underway.[65]

Regarding active systems, functional outcome data associated with TSolution One is limited, with only one study noting improvements in objective and functional outcome scores at 12 weeks.[50] The majority of studies regarding active technology have evaluated its direct predecessor, ROBODOC, with equivocal short-, medium- and long-term functional outcomes compared to conventional TKA.[66,67]

Complications

Earlier robotic systems were associated with significant complications. Park et al reported a complication rate of 19%, including superficial infection, patellar tendon rupture and dislocation, supracondylar fracture and peroneal nerve injury.[14] However, these appeared to be restricted to their earlier cases and attributed to a smaller incision used during the learning phase. Once a larger incision was used, these complications were subsequently avoided. Technical complications were also highlighted. Incidence of intra-operative conversion to conventional TKA arthroplasty due to ROBODOC technical failure has been reported in up to 30% of cases.[68,69] Complication rates associated with newer systems appear to be low. In their study of Mako-assisted TKAs, Marchand et al reported no complications or conversions to manual TKA.[70] Similarly, no complications were noted by Naziri et al in their Mako-assisted group of 40 cases.[46] Kayani et al observed similar complication rates for their Mako and conventional TKAs.[60] At the time of writing only one clinical study has been published relating to Navio robotically assisted TKA, which did not divulge any potential complications.[47]

There is a paucity of data regarding the incidence of deep prosthetic joint infection (PJI) in robotic TKA. Two recent systematic reviews suggested that the incidence was higher in robotic TKA at 1.6–1.7% compared to

0.44–1.00% in manual TKA.[19,71] However, these data were based on a limited number of comparative studies using earlier active robotic technology that is now obsolete.[9,14,23,72] Given the small numbers involved, it is questionable whether these figures were a true representation of PJI for each treatment group. More recently, the Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR) data have noted a higher early revision rate for infection when utilizing newer semi-active robotic technology compared to manual arthroplasty.[24]

Survivorship

Survivorship data for robotic TKA remains scarce, although long-term data for earlier systems such as ROBODOC have recently been reported. Three comparative studies evaluating this system demonstrated comparable survivorship rates with conventional TKA of more than 97% after 10 years.[41,66,67]

Survivorship data are currently lacking for robotically assisted TKA utilizing the newer generation of predominantly semi-active systems. These systems have previously been established for uni-compartmental implantation, with early promising survivorship rates noted between 95% and 99% with a mean follow up of 19 to 27 months.[73–75] Recent registry data noted a cumulative revision rate of 2.6% at three years for Mako-assisted UKA compared with 5% for the non-robotically assisted group.[24] Whether this robotic system can produce similar survivorship data when used for TKA implantation remains to be seen. A randomized controlled trial evaluating Mako robotic TKA compared to conventional TKA is currently underway.[76] However, more long-term studies are required to fully appraise and assess this and other newer robotic systems.

Clinical application

Learning curve

The learning curve typically refers to the number of cases needed to achieve a consistent state of outcomes.[77] For robotic TKA, this commonly includes the assessment of reduction in surgical time. Kayani et al suggested this was seven cases for performing Mako robotically assisted TKA. Additionally, there was no learning curve with regards to achieving planned component positioning and limb alignment. This was also more accurate than the comparative conventional TKA group (p < 0.001) without any added risk to the patient.[44] Another study of 132 robotic Mako TKAs suggested a similar learning curve of approximately six cases. Other studies have suggested a longer learning curve of 20 cases based on the number required to achieve operative times comparable with conventional

TKA. Importantly, these studies demonstrated no additional risk of complications during the learning phase associated with this current robotic technology.[46,78] This is significantly different compared to previously reported outcomes of historic systems where high early complication rates were noted during the learning phase associated with increased soft tissue damage. This included patella tendon injuries relating to inadequate surgical exposure.[14,69]

Cost-effectiveness

When assessing cost-effectiveness, the reliability of robotic technology must be considered. With earlier systems, technical failure meant additional costs of utilizing conventional instrumentation had to be factored into up to a third of cases.[69] The failure and abandonment of ROBODOC mid-procedure meant surgical times in theatre were protracted, reducing theatre time utilization and increasing concerns of infection.[69,79,80] These potential extra costs and lack of superior survivorship data combined with the initial upfront and running costs of approximately $545,000 and $1,360 respectively, failed to prove robotic TKA was cost-effective.[81]

With other active systems suffering a similar fate, focus was shifted towards more semi-active systems.[82] These newer systems are still associated with high front-end costs including the base system, operational costs, disposables, pre-operative imaging and implants.[83] These systems have an estimated initial start-up cost of $800,000 and a recurring cost of $1,500 per patient to implement and carry out robotic TKA.[81] Disposables are estimated to cost between $750 to $1,300 depending on system used.[84] For image-based systems, pre-operative imaging costs start from $260. Although the price of prostheses varies between geographical locations based on price negotiations between different manufacturers and hospitals, they still make up a significant proportion of cost. A 2012 report noted TKA implants accounted for 13% to 87% of total procedural costs.[85] The ability to choose from a wider range of prostheses may be a potential area for significant cost savings. Therefore, the use of open systems such as TSolution One may help to offload some of the cost burden associated with the adoption of robotic technology by providing opportunity to utilize reduced implant costs compared to closed systems with more limited choice.[86]

The annual maintenance cost for most robotic systems is between $40,000 and $150,000.[86] This includes software upgrades that can otherwise be an extra financial burden. Chen et al recently analysed the increased cost associated with robotic compared to manual arthroplasty. They noted the use of the Mako system added an extra 12.2% and 6.1% to cost expenditure when performing

100 and 300 arthroplasty cases respectively. Under the equivalent pricing structure, they suggested similar cost increases of 13.9% and 6.6% when using the TSolution One robotic system.[86]

Major cost drivers in the post-operative stage such as revisions and readmission rates should be considered for future cost-analysis of robotically assisted TKA. These data are limited as the majority of the literature is based on older now redundant systems. A recent study however, noted a 5% lower readmission rate with robotically assisted TKA compared to conventional arthroplasty.[84] By extrapolating this data and factoring in the cost of revision, Chen et al noted a 4% decrease in overall cost of primary TKA in their cost-analysis model when utilizing robotic technology compared to conventional arthroplasty.[86] Recently, studies have also shown lower 90-day episode-of-care costs associated with robotically-assisted TKA compared to conventional arthroplasty. Savings were driven by fewer readmission rates, a shorter in-hospital stay and a less costly utilization of nursing services post discharge.[87,88]

Despite these encouraging figures, whether or not robotic technology improves long-term PROMs and implant survivorship must be assessed. These potential incremental cost savings could then be factored into a more accurate evaluation of its cost-effectiveness to justify its ongoing use. Finally, the volume of arthroplasty performed using such technology is a critical part of cost evaluation. A study evaluating the cost per quality-assisted life year using computer-assisted TKA compared to conventional arthroplasty noted that utilizing the former may be cost-effective. This conclusion was despite only considering a marginal improvement of implant survivorship in both 60 and 75 year olds but relied on a high volume of arthroplasty (250 cases) being performed per year.[89]

Discussion

Historic active robotic TKA systems demonstrated improvements in alignment and a reduction in post-operative blood loss compared to conventional methods.[9,14,22,23,82] However, an increased risk of technical failure, increased operative times and complications meant that the significant financial investment required in these earlier systems was not deemed cost-effective.[9,14,68,69,82] Current predominantly semi-active robotic systems demonstrate greater technical reliability compared to their predecessors with no increased risk of complications compared to conventional TKA.[44] Additionally, the haptic feedback provided by these systems confers superior soft tissue protection compared to conventional TKA, which may explain the early functional benefits with these systems.[57,58,62–64,90] In contrast, these early functional gains were lacking in older systems, where a much larger surgical exposure was required to prevent iatrogenic soft tissue injury.[14] Long-term functional outcomes

comparing these newer robotic systems with conventional techniques are still required. Nevertheless, the reported benefits in an early post-operative phase should be taken into account when assessing the cost-effectiveness of persisting with this technology.

Robotic systems optimize component positioning and reduce alignment outliers. Nonetheless, there remains debate regarding the effect of malalignment of greater than 3° on clinical and functional outcomes.[91–93] Therefore, the need to invest in robotic technology to reduce these radiographic outliers is contested.[93] Additionally, several studies have demonstrated comparable if not superior radiographic outcomes with the conventional approach compared to robotic-assisted technology in high-volume surgeons. This highlights the importance of taking into account surgical experience and volume when appraising robotic technology.[46,94] It is plausible that the potential for improvement in functional outcome scores and PROMs data in robotic TKA compared to conventional TKA may be most apparent in lower-volume surgeons although there may be less enthusiasm for such studies of proficiency in this demographic.[93]

The reported incidence of PJI in robotic TKA is low and based on a handful of cases in small comparative studies utilizing redundant systems.[19,71] Despite this, concerns have been raised regarding the potential increased risk posed by additional equipment, increased theatre traffic, surgical robotic techniques and increased operative time.[24,71] These factors have been suggested as likely contributors in a recent registry study highlighting increased early revision for infection in robotically assisted arthroplasty.[24] Although these data were based on the implantation of uni-compartmental knee replacements, the concerns still remain for TKA implanted using similar robotic technology. Further studies are therefore required with greater case numbers to assess the rates of PJI associated with robotic TKA as well as its potential long-term benefits.

Type of platform is an important factor to consider. Open platforms offer compatibility with numerous implant types but lack the depth of more intricate design specificity and biomechanical data, which are essential for optimal component positioning and kinematics. Closed systems limit variation in implant choice and as such, surgeons may have to change from their preferred prostheses. As a result, a learning curve relating to new implant usage may be introduced, independent of the learning curve associated with this technology. Whether the use of different platforms will translate into any meaningful clinical difference is unclear. Further evaluation of this effect will be challenging, as a centre is unlikely to utilize two different robotic systems.

Limitations

There are several limitations to this review. Firstly, the rapid evolution of robotic TKA has led to a shift from fully

active to predominantly semi-active systems. Given the only recent introduction of semi-active technology, the majority of studies available are based on historic active systems that are now redundant. Of the studies into novel systems, only short-term data are available, which suggest early functional gains. However, whether these improvements, as well as better radiographic alignment and soft tissue balancing, equate to improved long-term functional outcome and survivorship remains to be seen. Additionally, the lack of randomized control trials, the heterogeneity of outcome data and lack of standardized data collection makes comparative analysis between these different studies difficult.[71]

Finally, as most robotic technologies currently in use are closed systems, the comparison of individual robotic systems versus manual implantation of TKA using different implants is limited. Furthermore, the evaluation between different robotic systems utilizing the same implant is also largely prevented. Any long-term comparisons between different robotic systems must take into account the impact of individual prosthetic design. However, without cross-compatibility of similar implants between different robotic systems, the impact of implant bias on outcome measures including survivorship data will be difficult to prevent.

Conclusions

Improving patient satisfaction following primary TKA poses an important challenge that may be addressed with robotic-assisted technology. While early robotic systems have failed to confer any meaningful clinical benefit and justify the excess costs, newer robotic systems have demonstrated promise by minimizing soft tissue damage, reducing hospital stay and improving short-term functional outcomes. However, the economic impact of introducing this technology with significant upfront and maintenance costs requires closer examination. This is especially important as conventional TKA is already considered a reasonably successful and already expensive procedure.[86] Thus, while early results from the latest generation of robotic TKA hopefully justify the ongoing investment in such technology, long-term functional outcomes and survivorship should be fully appraised to support its continued use.

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