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MAKO CT-based robotic arm-assisted system is a reliable procedure for total knee arthroplasty: a systematic review

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Abstract

Purpose The aim of this study was to investigate the clinical and radiological results of the MAKO CT-based robotic-assisted system for total knee arthroplasty (TKA).

Methods A PRISMA systematic review was conducted using four databases (MEDLINE, EMBASE, Pubmed, GOOGLE SCHOLAR) to identify all clinical and radiological studies reporting information regarding the use and results of the CT-based robotic-assisted system to perform TKA between 2016 and 2020. The main investigated outcome criteria were postoperative pain, analgesia requirements, clinical scores, knee range of motion, implant positioning and the revision rate. The ROBINS-I tool (Risk Of Bias In Non-randomized Studies of Interventions) was used to evaluate the quality of included studies and the risk of bias.

Results A total of 36 studies were identified, of which 26 met inclusion criteria. Of these 26 studies, 14 were comparative. The follow-up varied from 30 days to 17 months. This CT-based, saw cutting Robotic TKA is associated with a significantly lower postoperative pain score (2.6 versus 4.5) and with significantly reduced time to hospital discharge (77 h versus 105), compared with conventional TKA. The two comparative studies assessing functional outcomes at 1 year reported significantly better functional scores with CT-based robotic TKA compared with conventional TKA (WOMAC score: 6 ± 6 versus 9 ± 8 ($p < 0.05$); KSS function score: 80 versus 73 ($p = 0.005$)). Only three comparative studies assessed implant positioning, and these reported better implant positioning with CT-based robotic-assisted TKA.

Conclusion The CT-based robotic-assisted system for TKA reduced postoperative pain and improved implant positioning with equal or slightly superior improvement of the functional outcomes at one year, compared to conventional TKA.

Level of evidence Systematic review level IV.

Keywords Total knee replacement · Robotic surgical procedure · Computerized tomography · Patient outcomes · Radiological assessment · MAKO

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Introduction

Total knee arthroplasty (TKA) is an effective surgery providing pain relief and improved quality of life. However, patient satisfaction following TKA ranges from just 75 to 89% using different patient-reported clinical outcome measures [2, 7, 38]. Up to 6% of patients who undergo a primary TKA may require a revision within 5 years from the index procedure according to a large meta-analysis from worldwide arthroplasty registries on 689,608 primary surgeries [21]. Different approaches have been considered to improve TKA clinical and radiological outcomes, such as the use of computer-assisted surgery with navigation, image based and image-less robotic system assistance [1, 51], accelerometer or other sensor use [34, 50], and different surgical alignment techniques [12, 26].

The current motivations behind robotic-assisted TKA are improved surgical implant positioning, alignment accuracy, advancing articular surface design that allows for independent intercompartmental resurfacing, optimizing component positioning based on normal soft tissue balancing and tension, and ultimately improving patient clinical and functional outcomes. Several systematic reviews reported the clinical and radiological outcomes of robotic-assisted TKA in general, including different types of robotic-assisted systems [1, 8, 39, 41]. They reported satisfying outcomes, particularly an improvement in implant positioning with robotic-assisted systems compared with a conventional technique. The various robotic-assisted systems are quite different (image-based, image-free, different cut systems, different methods for planning) and therefore, are not equivalent. During this early phase of robotic-assisted surgery development, it is important to distinguish the differences between each system and to assess them independently. The CT-based robotic-assisted system (MAKO system) adapted for TKA has been available since 2016. There is no systematic review summarizing the main results of this specific CT-based robotic arm system, such as implant position, knee alignment accuracy, clinical and functional advantages and disadvantages. CT-based arm-assisted robotic technology might be a valuable tool that can reduce surgical complications and decrease the risk of implant failure. But a focused assessment is necessary to improve individual practice.

The aim of this systematic review was to summarize all the relevant surgical and clinical results of the MAKO CT-based robotic arm-assisted system for TKA.

Materials and methods

Article identification and selection process

A search in August 2020 was performed to identify all available literature that described the results of TKA performed with the image-based robotic-assisted system. The search was performed through PubMed, EMBASE, MEDLINE, GOOGLE SCHOLAR, and the COCHRANE LIBRARY databases from 2016 to 2020 inclusive, using the 2009 Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol (PRISMA).

Inclusion criteria for the search strategy included all English and French language studies reporting information regarding the use and results of the image-based robotic-assisted system to perform TKA. The types of included articles were randomized controlled studies, cohort studies, case-controlled studies, and cadaveric studies. The following terms were used: “total knee arthroplasty” or “total knee replacement”; “MAKO” or “image-based robotic-assisted” or “robotic-arm assisted”. Exclusion criteria consisted of (1) editorial articles, (2) systematic reviews or meta-analyses, (3) case reports, (4) articles on revision unicompartmental knee arthroplasty (UKA), and (5) articles evaluating joints other than the knee. The abstracts from all identified articles were independently reviewed by two investigators. Articles were excluded on the basis of the title and abstract if they did not assess TKA performed by the image-based robotic-assisted system (MAKO system). Full-text articles were obtained for review to allow further assessment of inclusion and exclusion criteria where necessary.

Additionally, all references from the included studies were reviewed and reconciled to verify that no relevant articles were missing from this systematic review that met inclusion criteria.

The main investigated outcome criteria were postoperative pain and analgesia requirements during the hospitalization, the short-term clinical scores and knee range of motion, implant positioning, and the short-term revision and complication rates.

Quality assessment

The ROBINS-I tool (Risk Of Bias In Non-Randomized Studies of Interventions) [48] was used to evaluate the quality of the included studies and their relative risk of bias

Table 1 Summary of quality assessment of included studies

Authors	Confounding	Selection of patients	Classification of interventions	Deviations from intended interventions	Missing data	Measurement of outcomes	Selection of reported results
Marchand et al. [32]	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate
Sodhi et al. [45]	Moderate	Serious	Low	Low	Serious	Serious	Moderate
Kayani et al. [17]	Moderate	Low	Moderate	Low	Low	Moderate	Low
Kayani et al. [18]	Moderate	Moderate	Moderate	Low	Low	Low	Low
Kayani et al. [16]	Moderate	Low	Low	Low	Moderate	Moderate	Low
Khlopas et al. [20]	Moderate	Moderate	Low	Low	Low	Moderate	Moderate
Marchand et al. [30]	Moderate	Moderate	Low	Low	Low	Serious	Moderate
Smith et al. [44]	Moderate	Low	Low	Low	Low	Moderate	Moderate
Naziri et al. [37]	Moderate	Moderate	Low	Low	Low	Moderate	Low
Cool et al. [10]	Moderate	Moderate	Moderate	Low	Serious	Serious	Serious
Sultan et al. [49]	Serious	Moderate	Moderate	Moderate	Serious	Moderate	Serious
Mont et al. [36]	Moderate	Low	Moderate	Low	Serious	Serious	Moderate
Bhimani et al. [5]	Moderate	Moderate	Low	Low	Moderate	Moderate	Low
Cotter et al. [11]	Moderate	Low	Low	Low	Low	Low	Low
Marchand et al. [33]	Moderate	Moderate	Low	Moderate	Serious	Serious	Serious
Marchand et al. [31]	Moderate	Moderate	Moderate	Low	Moderate	Moderate	Moderate
Sires et al. [42]	NA	NA	NA	NA	Low	Moderate	Low
Malkani et al. [28]	NA	NA	NA	NA	Low	Low	Low
Sires et al. [43]	NA	NA	NA	NA	Low	Moderate	Low
Khlopas et al. [19]	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate
Hampp et al. [13]	Moderate	Low	Low	Low	Low	Moderate	Low
Hampp et al. [14]	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate
Manning et al. [29]	Moderate	Low	Low	Low	Low	Moderate	Low

(Table 1). This included bias due to confounding, selection of participants classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selection of reported result. The categories for risk of bias judgements are “Low risk”, “Moderate risk”, “Serious risk” and “Critical risk”. The worst judgement bias assigned within any one domain gives the judgement score of the complete study.

Results

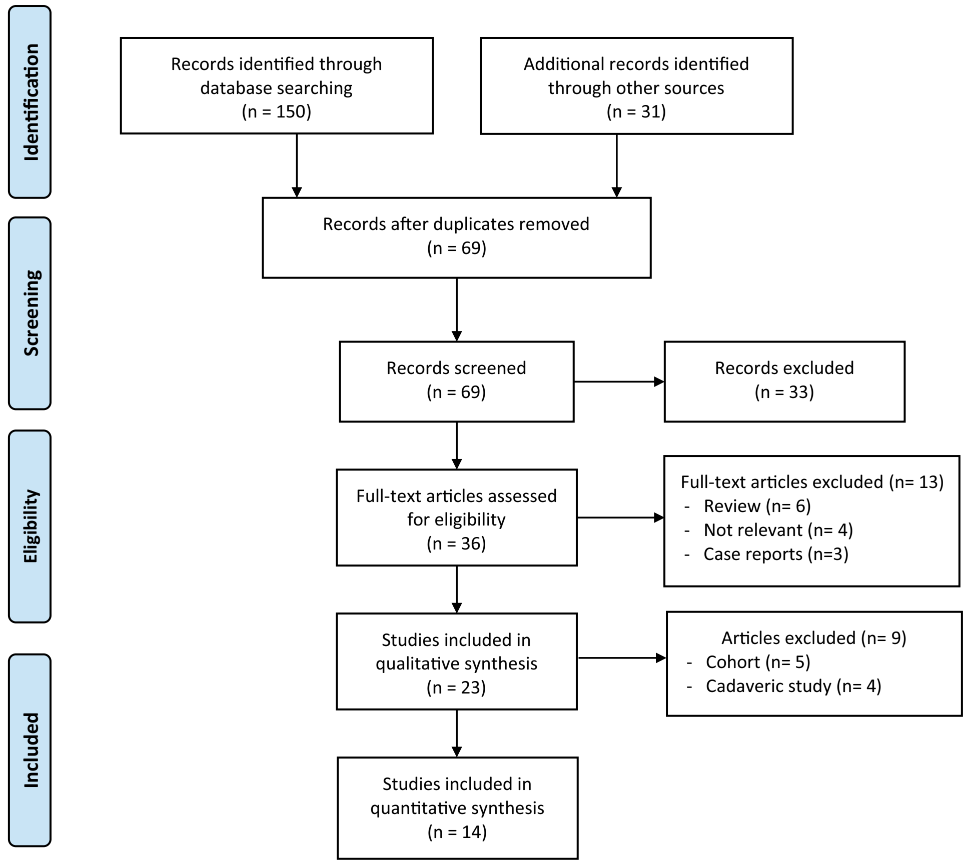
Included articles and study characteristics

The PRISMA flow diagram for study selection is shown in Fig. 1. A total of 36 potential full-text articles were identified by the search strategy. Of the 36 articles, 4 were excluded as not relevant, 6 were excluded, because they were reviews and three were case reports. Of these, 1 study presented a low risk of bias according to the ROBINS-I [48], 17 studies presented a moderate risk (Table 1). The reported follow-up periods ranged from a minimum of 30 days to a maximum of 17 months. Fourteen studies were controlled with a TKA group performed by image-based robotic-assisted system and a TKA group performed by conventional technique (Table 2).

Functional outcomes

The majority of the controlled studies assessed early functional outcomes after TKA performed with the image-based robotic-assisted system (Table 3). Marchand et al., in a comparative study of 20 consecutive robotic arm-assisted TKAs, described a lower mean pain score at 6 months in the robotic group ($p < 0.05$) [32]. This difference in pain score is not significant at 1 year [30]. In a prospective comparative study, robotic arm-assisted TKA was associated with reduced postoperative pain (3.6 in the robotic group versus 6.3), decreased analgesia requirements during initial hospitalization, and also decreased length of stay in hospital (mean 77 h in robotic group versus 105 h in the conventional group) compared with conventional jig-based TKA ($p < 0.001$) [18]. Other studies reported similar short-term results (low pain scores, low opioid usage, shorter length of stay) [5, 37].

Fig. 1 Flowchart from the initial literature search through to data extraction from the final list of included studies



Some authors described better satisfaction after robotic-assisted TKA compared with conventional TKA in the short term [32, 44], whereas other studies did not report a significant difference [20].

Several case-controlled studies assessed the short-term functional postoperative scores, with a maximum follow-up of 17 months, between robotic-assisted and conventional TKA, with inconclusive results [20, 30, 37, 44].

The mean knee flexion at discharge was also higher in the robotic group (104.1°) compared to the conventional group (93.3°) ($p < 0.001$) [18]. The mean knee flexion at 90 post-operative days appears superior in the robotic group, with a better improvement compared to preoperative flexion [37].

Accuracy of implant positioning

Two comparative studies assessed implant positioning. Robotic arm-assisted TKA improved accuracy in achieving the planned implant position compared to conventional jig-based TKA (Table 4) [16, 49]. Kayani et al. demonstrated that the robotic-assisted system improved the accuracy of femoral coronal and sagittal alignment, tibial coronal and sagittal alignment, joint line restoration, tibial slope and limb alignment, compared to a conventional technique [16]. Sires et al. performed postoperative CT scans to assess the accuracy of the CT-based robotic-assisted TKA [43]. They reported that 93% of the reported intraoperative measurements were ≤ 3 degrees of the postoperative CT measurements. The results were also similar for coronal limb alignment.

Complications and implant survivorship

The rate of early complications was not significantly different between robotic-assisted TKA and conventional TKA [11, 18] (Table 5). The main short-term complication reported was manipulation under anesthesia, without a difference between robotic-assisted and conventional TKA [11, 37, 44]. Malkan et al. found less manipulation under anesthesia in the group of robotic-assisted TKA compared than conventional TKA [27]. Kayani et al. reported a minor wound dehiscence over the incision for the proximal tibial registration pins [18]. There were no other specific complications of the image-based robotic-assisted system. Short-term revisions were rare and the majority of the studies did not report revisions after robotic-assisted TKA [11]. Malkani

Table 2 Demographic information for included studies

Authors	Year	Study type	Nb RATKA	Nb Controls	Age (years)	Mean BMI	Sex Male/Female (%)	Mean follow-up
Comparative studies								
Marchand et al. [32]	2017	Retrospective Monocentric Case–control	20	20	69 ± 10	NR	30/70	6 months
Sodhi et al. [45]	2018	Retrospective Monocentric Case–control	240	20	NR	NR	NR	NA
Kayani et al. [17]	2018	Prospective Monocentric Case–control	30	30	68.5 (43–84)	29.15 ± 4.5	47/53	Intraoperative
Kayani et al. [18]	2018	Prospective Monocentric Case–control	40	40	69.7 (53–85)	27.9 (22–37)	45/55	30 days
Kayani et al. [16]	2018	Prospective Monocentric Case–control	60	60	67.6 ± 7.6	27.2 ± 3.6	47/53	30 days
Khlopas et al. [20]	2019	Prospective Multicentric Case–control	150	102	65 (43–83)	30.7 (20–40)	37/63	3 months
Marchand et al. [30]	2019	Retrospective Monocentric Case–control	53	53	65 ± 7	33 ± 7	47/53	1 year
Smith et al. [44]	2019	Retrospective Monocentric Case–control	120	103	68 (40–86)	31.2 (18–47)	40/60	17 months
Naziri et al. [37]	2019	Retrospective Monocentric Case–control	40	40	69.5	29.1	40/60	3 months
Cool et al. [10]	2019	Retrospective Multicentric Case–control	519	2595	NR	NR	NR	3 months
Sultan et al. [49]	2019	Prospective Monocentric Case–control	43	39	67 (46–79)	31 (20–39)	37/63	6 weeks
Mont et al. [36]	2019	Retrospective Multicentric Case–control	519	2,595	NR	NR	42/43	90 days
Bhimani et al. [5]	2020	Retrospective Monocentric Case–control	140	127	65.4	NR	39/61	7.3 weeks
Cotter et al. [11]	2020	Retrospective Monocentric Case–control	147	139	NR	30.6 ± 5.4	48/52	90 days
Cohorts								
Marchand et al. [33]	2018	Retrospective cohort	330	–	NR	NR	NR	NA
Marchand et al. [31]	2018	Prospective cohort	355	–	67 (35–93)	30 (18–40)	NR	NA
Sires et al. [42]	2019	Prospective cohort	37	–	69.4 ± 8.5	NR	27/73	NA
Malkani et al. [28]	2020	Prospective cohort	188	–	NR	NR	NR	2 years
Sires et al. [43]	2020	Retrospective cohort	29	–	72.9 ± 9	NR	28/72	6 months
Cadaveric studies								
Khlopas et al. [19]	2017	Cadaveric Case–control study	6	7	NA	NA	NA	NA
Hampp et al. [13]	2018	Cadaveric Case–control study	6	6	74 (53–93)	25 (17–40)	67/33	NA
Hampp et al. [14]	2019	Cadaveric Case–control study	12	12	81 (68–89)	26 (20–36)	50/50	NA
Manning et al. [29]	2019	Cadaveric Case–control study	6	6	76 (61–85)	24.1 (20–30)	50/50	NA

et al. reported 4 revisions on 188 patients: 2 aseptic revisions (for unexplained pains and tibial fracture) and 2 septic revisions [28]. No study found a higher rate of infection after robotic-assisted TKA compared than conventional TKA.

Soft tissue and bone preservation

In a comparative study, Kayani et al. reported that robotic-assisted TKA was associated with reduced bone and periarticular soft tissue injury compared with conventional TKA,

Table 3 Reporting of functional outcomes following robotic total knee arthroplasty (TKA)

Authors	Functional scores	ROM	LOS	Postop pain score	Patient-reported outcome measures
Comparative studies					
Marchand et al. [32]	WOMAC total: 7 ± 8 (vs 14 ± 8)	NA	NA	WOMAC Pain: 3 ± 3 (vs 5 ± 3)	The robotic-assisted cohort had a significantly lower mean pain score and a significantly lower mean total patient satisfaction score at 6 months
Sodhi et al. [45]	NA	NA	NA	NA	There was a learning curve for the use of robotic-assisted TKA. After the learning curve, the operating time of robotic TKA is similar to the conventional technique
Kayani et al. [17]	NA	NA	NA	NA	Robotic TKA had decreased bone and periarticular soft tissue injury, with reduced medial release compared to conventional TKA
Kayani et al. [18]	NA	NA	77 h (vs 105)	2.6 (vs 4.5)	Robotic TKA is associated with reduced postoperative pain and analgesia requirements, with improved early functional recovery, with reduced time to hospital discharge compared with conventional TKA
Kayani et al. [16]	NA	NA	NA	NA	In the robotic group, the operative time decreased significantly after the initial seven cases
Khlopas et al. [20]	KSS at 3 months: 67.2 (16–100) (vs 65.5 (18–99))	NA	NA	NA	No significant difference in short-term patient satisfaction and functional outcomes at 3 months after TKA between robotic and conventional groups
Marchand et al. [30]	WOMAC total: 6 ± 6 (vs 9 ± 8)	NA	NA	WOMAC Pain: 2 ± 3 (vs 3 ± 4)	One-year postoperative total WOMAC score and physical function WOMAC score were significantly lower in the robotic-assisted cohort ($p < 0.05$) compared with the conventional group
Smith et al. [44]	Satisfied 94% (vs 82%) F-KSS: 80 (vs 73) K-KSS: 85 (vs 82)	119° (vs 116°)	2.1 days (vs 2.6)	NR	Robotic TKA had a better satisfaction rate. KSS function scores were significantly better at 6 weeks and 1 year postoperatively ($p = 0.02$, 0.005), and KSS knee scores were significantly better at 1 year postoperatively ($p = 0.046$)
Naziri et al. [37]	KSS at 60 days: 91.9 (vs 91.7) KSS at 90 days: 88.2 (vs 89.5)	121.3° (+ 3.8) (vs 109.8° (− 8.7°))	1.27 days (vs 1.92)	NA	The mean length of stay was longer for conventional TKA compared to robotic TKA. There was no significant difference in postoperative KSS or complication rate at 30, 60, and 90-day follow-up
Cool et al. [10]	NA	NA	NR	NA	Robotic TKA is associated with lower 90-day EOC costs
Mont et al. [36]	NA	NA	1.8 days (vs 2.5)	NA	Robotic TKA is associated with significantly lower 30, 60, and 90-day postoperative EOC costs. 90-day readmissions were significantly lowered
Bhimani et al. [5]	NA	NA	1.9 days (vs 2.3)	2.6 (vs 3.5) at rest	At 6 weeks postoperatively, robotic TKA had lower average VAS pain score at rest and with activity ($p = 0.03$), lower opioid usage ($p < 0.001$), shorter LOS ($p < 0.001$) compared to conventional group
Cotter et al. [11]	NA	NA	1.2 days (vs 1.6)	NR	Ninety-day EOC costs were $2090 lower for robotic TKA ($p < 0.001$)

Table 3 (continued)

Authors	Functional scores	ROM	LOS	Postop pain score	Patient-reported outcome measures
Cohorts					
Malkani et al. [28]	SF12 (MCS, PCS): 57 (41–69) FJS: 75 (14–100) F-KSS 84 (20–100) K-KSS 92 (40–100)	NR	NR	NR	The patients with robotic TKA had excellent outcomes across multiple PROM metrics at 2 years, and very few early complications
Cadaveric studies					
Khlopas et al. [19]	NA	NA	NA	NA	Robotic TKA has shown better protection of soft tissue around the knee compared with conventional TKA
Hampp et al. [14]	NA	NA	NA	NA	Less damage occurred to the PCL in robotic TKA versus conventional TKA ($p<0.001$). Robotic TKA had non-significantly less damage to the deep medial collateral ligaments ($p=0.149$), iliotibial bands ($p=0.580$), poplitei ($p=0.248$), and patellar ligaments ($p=0.317$)
Manning et al. [29]	NA	NA	NA	NA	Robotic TKA, as opposed to conventional TKA, demonstrated consistent equal load distribution between the medial and lateral compartments through a functional arc of motion (assessed with orthosensors). The change in load imbalance was significantly greater in conventional TKA at flexion of 0–60°. Point of motion was parallel and there was no medial pivot in the robotic group

without assessment of the clinical outcomes [17]. With a new score that classified bone and soft tissue injuries (MASTI classification system), they demonstrated superior accuracy of the robotic-assisted system during knee preparation. In a cadaver study, Hampp et al. then Khlopas et al. showed that less soft-tissue damage occurs utilizing robotic-assisted TKA, particularly regarding the posterior cruciate ligament [14, 19].

The learning curve for robotic TKA

Kayani et al. described an improvement of the operative time of robotic arm-assisted TKA (89.2 vs. 66.8 min, $p=0.01$) and of the surgical team stress levels after seven robotic cases [16]. But there was no learning curve effect of robotic arm-assisted TKA on accuracy of achieving the planned implant position and limb alignment. In a comparative study of 240 robotic-assisted TKAs, a significant difference was found in mean operative times for the first robotic-assisted cohort and the conventional cohort (81 vs. 68 min, $p<0.05$) [45]. However, no significant differences in mean operative times were found between the last robotic-assisted cohort and the conventional cohort (70 vs. 68 min, $p>0.05$).

Cost

Cool et al. showed that robotic-assisted TKA patients had statistically significantly lower 90-day episode-of-care (EOC) costs [10]. A study of Medicare Fee-For-Service (FFS) members, that included 519 CT-based robotic-assisted TKAs, assessed the utilization and payer costs for postoperative services [36]. It reported that the robotic-assisted TKA versus conventional TKA cohort average total episode payment was US $17,768 versus US$19,899 ($p<0.0001$) at 30 days, US$18,174 versus US$20,492 ($p<0.0001$) at 60 days, and US$18,568 versus US$20,960 ($p<0.0001$) at 90 days. There was a trend towards increased operative time in robotic arm-assisted TKA, but overall time to hospital discharge was reduced in the robotic group ($p<0.001$) [18].

Recently, Cotter et al. performed an interesting study associating intraoperative costs and inpatient costs in a comparative study [11]. Total intraoperative costs were higher ($10,295 vs. $9998, respectively, $p<0.001$) and inpatient costs were lower ($3893 vs. $5587, respectively, $p<0.001$) comparing robotic-assisted TKA and conventional TKA. Length of stay was reduced by 25% ($p<0.0001$) and prescribed opioids were reduced by 57% ($p<0.0001$) comparing robotic-assisted TKA and conventional TKA. Ninety-day EOC costs were $2,090 lower for robotic-assisted TKA ($p<0.001$).

Table 4 Results of implant positioning in robotic total knee arthroplasty (TKA)

Authors	Mechanical alignment (°)	Joint Line (mm)	Femoral coronal alignment (°)	Femoral sagittal alignment (°)	Tibial coronal alignment (°)	Tibial sagittal alignment (°)	Implant positioning
Comparative studies							
Kayani et al. [16]	RMSE: 1.5 ± 0.9 (vs 3.2 ± 1.2)	RMSE: 1.0 ± 0.6 (vs 2.9 ± 1.4)	RMSE: 1.0 ± 0.4 (vs 4.1 ± 1.1)	RMSE: 2.1 ± 0.7 (vs 4.2 ± 0.8)	RMSE: 1.0 ± 0.5 (vs 3.6 ± 0.8)	RMSE: 2.0 ± 0.6 (vs 3.9 ± 1.0)	Robotic TKA improved accuracy in achieving the planned implant position compared to conventional TKA, without a learning curve
Sultan et al. [49]	NR	NR	NR	NR	NR	NR	The mean postoperative posterior condylar offset ratio (PCOR) was higher in conventional TKA compared to robotic TKA (0.53 vs. 0.49; $p = 0.024$). The mean difference between preoperative and postoperative PCOR was larger in conventional TKA (0.03 vs.0.004; $p = 0.01$). The number of patients who had postoperative Insall-Salvati Index outside of the normal range was higher in conventional TKA (12 vs. 4)
Cohorts							
Marchand et al. [33]	NR	NR	NR	NR	NR	NR	All knees in varus or valgus knee alignment were corrected in the appropriate direction, within a few degrees of neutral, and no knees were overcorrected
Marchand et al. [31]	NR	NR	NR	NR	NR	NR	A total of 332 patients (99%) achieved a post bone cut flexion gap difference of between 2 and 2 mm (mean, 0 mm)

Table 4 (continued)

Authors	Mechanical alignment (°)	Joint Line (mm)	Femoral coronal alignment (°)	Femoral sagittal alignment (°)	Tibial coronal alignment (°)	Tibial sagittal alignment (°)	Implant positioning
Sires et al. [42]	NR	NR	RMS: 0.46° ± 0.28	RMS: 0.55° ± 0.46	RMS: 0.53° ± 0.56	RMS: 0.59° ± 0.42	26 (81%) knees had a mechanical axis alignment < 3°, 5 (16%) < 3° varus, and 1 (3%) < 3° valgus The maximum deviation from mechanical axis alignment was 5° varus
Sires et al. [43]	1.29 ± 1.25	NR	1.17 ± 1.1	1.8 ± 1.12	1 ± 0.8	1.8 ± 1.2	76 (87%) of the femoral intra-operative measures were < 3° compared with CT measures 54 (93%) of the tibial intra-operative measures were < 3° compared with CT measures 93% of intra-operative measured limb alignment was < 3° compared with postoperative CT measures
Cadaveric studies							
Hampp et al. [13]	NR	NR	0.6 ± 0.3 (vs 3.2 ± 1.4) (p = 0.003)	0.6 ± 0.5 (vs 2.8 ± 2.1) (p = 0.009)	0.9 ± 0.4 (vs 0.9 ± 0.8) (p = 0.022)	1.1 ± 1.6 (vs 1.5 ± 1.3) (p = 0.093)	Robotic TKA has greater accuracy and precision of bone cuts and component placement, based on the preoperative plan, compared with conventional TKA

Table 5 Reporting of complications and revisions following robotic total knee arthroplasty (TKA)

Authors	Complication rate	Complications	Revision rate	Revisions
Comparative studies				
Kayani et al. [16]	1.67% (1/60) (vs 1.67% (1/60))	Wound dehiscence at pin-site (Wound dehiscence)	0% at 30 days (vs 0%)	–
Smith et al. [44]	14.2% (17/120) (vs 12.6% (13/103))	Manipulation under anesthesia ($n=9$ (vs 9)) Pulmonary embolism ($n=2$ (vs 0)) Arthroscopic arthrolysis ($n=6$ (vs 3)) (Hematoma ($n=1$))	0% at 1 year (vs 0%)	–
Naziri et al. [37]	0% (vs 2.5% (1/40))	(Manipulation under anesthesia ($n=1$))	0% at 90 days (vs 0%)	–
Cotter et al. [11]	0.7% (2/147) (vs 3.6% (5/139))	Manipulation under anesthesia ($n=3$ (vs 4)) Infection ($n=0$ (vs 1)) Quadriceps tendon rupture ($n=1$ (vs1))	2.7% at 90 days (vs 3.6%)	NR
Cohorts				
Malkani et al. [28]	1.59% (3/188)	Pulmonary embolism ($n=1$) Manipulation under anesthesia ($n=2$)	2.12% (4/188)	Aseptic revisions ($n=2$) Septic revision ($n=2$)

Discussion

The key findings of this systematic review are:

1. reduction of postoperative pain and decreased analgesia requirements during the hospitalization with the robotic-assisted system;
2. more accurate and reproducible implant positioning with robotic-assisted TKA;
3. similar risk of short-term complications or revision for robotic-assisted TKA and conventional TKA [17];
4. lower 90-day EOC costs with robotic-assisted TKA.

Functional outcomes

Several studies suggested that the implementation of robotic arm-assisted surgery may help to further improve early functional recovery and reduce time to hospital discharge in patients undergoing TKA [18, 30, 44]. However, at 6 months and at 1 year, the functional results are similar for both surgical techniques in several studies [20, 37].

Operative and cadaveric studies assessed the soft tissue injuries in robotic-assisted TKA and in conventional TKA, with less damage in robotic TKA. This system allowed better soft tissue protection around the knee and facilitated knee exposure [14, 17, 19]. It would be interesting to assess the clinical outcomes after TKA according to the soft tissue injury. The learning curve and improvement in surgical time was short (only seven cases to improve the surgical time by 22 min) [16]). Longer surgical times did not negatively impact upon postoperative outcomes, because there was no significant difference in functional outcomes between groups of longer and shorter operating durations. The difference in functional outcomes disappeared over time. Currently, at mid-term, the use of the robotic-assisted system is at least equivalent to the conventional technique for functional outcomes, but not superior. This lack of significant difference at mid-term between robotic-assisted TKA and conventional TKA is also reported with other robotic-assisted systems such as ROBODOC [22, 23], or for other surgeries such as unicompartmental knee arthroplasty (UKA) [3].

Complications and revisions

This review of image-based robotic-assisted TKA did not find any specific complications for the robotic-assisted system. The complication and revision rates were low in both robotic-assisted and in conventional technique cohorts at short-term follow-up. Other studies of the robotic-assisted system for knee replacements found some specific complications of this system, such as infection or fracture at the pin insertion site or pin breakage [25, 52]. In 2014, Hansen et al. [15] and Blyth et al. [6] did not find complications related to the MAKO system in UKA cohorts. In the literature, possible complications indirectly related to the use of a robotic-assisted system, such as stiffness or infection, were comparable between robotic and conventional groups [25, 35]. In contrast to robotic-assisted UKA in the Australian Orthopaedic Association National Joint Arthroplasty Registry, the studies about CT-based robotic-assisted TKA did not find higher rates of infection in the robotic group [47].

To assess revision rates according to the use of a robotic-assisted system, a long-term study is needed. Indeed, most revisions occur in the mid- to long-term, and rarely in the short-term, even for surgical mistakes. The robotic-assisted system for UKA was effective in decreasing revision rates, but UKA is a technically demanding surgery with a higher risk of revision compared with TKA.

Implant positioning

A few studies assessed implant positioning after robotic-assisted TKA with the MAKO system. All these studies demonstrated the efficacy of robotic-assisted TKA in restoring the mechanical axis alignment in fairly common clinical scenarios where mild deformity was successfully corrected. The technique was also more accurate than the conventional method in restoring mechanical alignment and decreasing the number of outliers. No learning curve has been identified for accuracy of implant positioning or limb alignment [16]. An image-based robotic-assisted system allows for good accuracy, even without system experience. This robotic-assisted system is based on a CT scan, with the preoperative planning being very accurate [43]. If the preoperative planning is not appropriate, it is likely due to poor surgical planning. The robotic-assisted system is ultimately a tool to improve surgical accuracy [13, 16, 43, 49]. Other robotic-assisted systems have reported similar results. In one randomized controlled study, the authors found no statistical difference in the absolute mechanical axis, but did obtain significant differences in the rate of outliers between the robotic-assisted group (ROBODOC) (0%) and the conventional group (19.4%) ($p = 0.049$) [22]. Furthermore, Song et al. performed a randomized study of 100 patients and found no outliers in the robotic-assisted group compared with 24% in the conventional group [46].

Several robotic systems have also demonstrated improved accuracy of implant positioning in UKA, such as the Acrobot [9], the Navio [3, 40] and the MAKO systems [4, 24]. These robotic-assisted systems can be more accurate for several reasons: more accurate preoperative planning, particularly for image-based robotic-assisted systems and a robotic arm which improves the precision of the surgeon. It would be interesting to compare implant positioning between different types of robotic-assisted systems to assess the effect on accuracy of the use of image-based and image-free robotic-assisted systems, a robotic arm or burr and a conventional computer navigation system.

Cost

The evaluation of the robotic-assisted system cost must take into account the system cost, the cost of the hospitalization and the cost of complications and surgical revisions. Cool et al. and Mont et al. reported that robotic-assisted TKA patients had statistically significantly lower 90-day EOC costs [10, 36]. Nevertheless, several parameters should also consider the cost of the robotic-assisted system, the cost of the consumable products for each surgery, and the cost of mid-term or long-term complications and revisions. Recently, Cotter et al. performed a comparative study about the intraoperative and inpatient costs for robotic-assisted TKA compared with conventional TKA [11]. They described that 90-day EOC costs were $2,090 lower for robotic-assisted TKA compared with conventional TKA. Nevertheless, some parameters were not considered in this study (for example, the reimbursement system), so it is difficult to make conclusions about the robotic-assisted system's cost.

Our findings should be considered with an understanding of the key limitations of the data set. First, the inclusion criteria, such as English language or the requirement of full text access, may have excluded relevant studies. Second, the methodology score has known limitations with regard to the type of studies included (cohort and cadaveric studies) and the difficulties in assessing the validity of the analyses conducted without having access to the raw data. Third, there was an important variability between the studies with respect to the type of outcome measurement parameters used, the follow-up period, the patient population and cohorts evaluated, and the analyses performed. This heterogeneity limits the possibility of performing a true meta-analysis of the results. Moreover, there are not yet any published randomized controlled trials. These randomized studies are currently in progress. The studies on robotic arm-assisted TKA with the MAKO image-based robotic-assisted system are few in number and mainly have short-term follow-up (< 2 years). Furthermore, the follow-up period for these studies remains short, principally because this system is so new. Future studies with longer term follow-up will be more conclusive in assessing the outcomes and benefits. Furthermore, this systematic review was only about one robotic-assisted system. There are a lot of studies reporting the results of TKA using various robotic-assisted systems with interesting results. Nevertheless, the aim of this study was to target this particular robotic-assisted system. Indeed, all robotic-assisted systems are not equivalent and use different planning data (CT-based, image-free). It is important to assess each specific system.

The main strength of this study, compared to previous systematic reviews, was the assessment of only one image-based robotic-assisted system for TKA. The aim was to assess all knowledge about this specific system to improve our understanding of the positives and negative aspects. There are no studies specifically evaluating each robotic-assisted system. Distinguishing between these different systems remains important, as surgeons use a specific system and need expertise in that particular system.

Conclusion

Robotic-assisted TKA demonstrated satisfying short-term clinical and radiological outcomes. The postoperative outcomes during hospitalization were equal or slightly superior for the robotic-assisted group compared to conventional TKA, without significant differences in clinical and functional results at short and mid-term. Current evidence shows advantages of image-based robotic-assisted TKA in mechanical knee alignment, implant positioning, ligamentous balance and soft tissue protection. However, powerful studies at longer term follow-up are critical to assess the long-term advantages of this robotic system, particularly for TKA survivorship or potential benefits of alternate alignment philosophies.

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Compliance with ethical standards

Conflict of interest CB, AF and JS declare that they have no conflict of interest. ES: consultant for Corin. FH: Royalties from Stryker, Smith & Nephew, MatOrtho, Corin, Springer; Paid presentations from Stryker, Smith & Nephew, MatOrtho, Zimmer; Consultant from Stryker, Smith & Nephew; Research support from Stryker, Smith & Nephew, MatOrtho, Corin, Zimmer; Orthopaedic publications editorial for Bone and Joint Surgery, Annals of Royal College of Surgeons, Hospital Medicine. FC: Consultancy fees, royalties, and fees for participation in review activities from Stryker and consultancy fees from Adler. SL: consultant for Stryker, institutional research support to Corin and Amplitude.

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