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KNEE ARTHROPLASTY

Robotic-assisted knee arthroplasty: an evolution in progress. A concise review of the available systems and the data supporting them

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Abstract

Introduction A review of the data supporting robotic systems currently available is presented focussing on precision and reproducibility, radiological outcomes, clinical outcomes, and survivorship.

Materials and methods Scientific literature published on robotic systems for knee arthroplasty was reviewed using the reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Inclusion criteria were any study involving robotic-assisted UKA or TKA that reported precision of implant positioning or functional outcomes or range of motion or survivorship, including cadaveric or dry bone studies with a minimum of 6-month follow-up.

Results Thirty-nine studies were identified for robotic-assisted unicompartmental knee arthroplasty, and 24 studies for robotic-assisted total knee arthroplasty. Those that reported on radiological outcomes or cadaver studies consistently demonstrated improved precision with the use of robotic systems irrespective of the system. PROMS and survival data demonstrated equivalent short-term results. However, many studies reported outcomes inconsistently and few had long-term clinical follow-up or survivorship data.

Conclusions This review adds to the body of evidence supporting improved precision and reproducibility with robotic assistance in knee arthroplasty. Despite intensive funding of research into robotic knee systems, there remains considerable heterogeneity in exposure and outcome analysis and few quality long-term studies demonstrating translation to better clinical outcomes and implant survivorship.

Keywords Robotic-assisted surgery · Robotic-arm assisted · Total knee arthroplasty · Unicompartmental arthroplasty

Introduction

The expectation is that robotic assistance delivering precision in knee surgery will translate to improved clinical outcomes and long-term implant survivorship. Short-term studies demonstrating evidence of non-inferiority to instrumented techniques [2, 37] is eroding the scepticism about robotic systems. Robots come at significant cost [14] without evidence of long-term improved survivorship. Therefore, it remains prudent to evaluate robotic systems to ascertain that the goal of improving long-term survivorship of implants remains in view.

The current iteration of robotic-assisted knee arthroplasty (RAKA) developed from incremental integration of digital and computerised technologies beginning 3 decades ago, with computer navigation. The evolution of this process has been driven partially by the orthopaedic product market. To fully understand the currently available tools, an overview of a decades' long history of mergers and acquisition of technologies and implants is helpful (Fig. 1). Some technologies have been integrated, while others have been taken off the market. Essentially, robotic systems build on CAS with task execution under instruction from the operating surgeon, but with higher precision, reproducibility, and less physical effort [28]. Depending on system (Table 1), robots offer active constraint in the execution of the operative plan, thus minimising harm to surrounding soft-tissues [29, 39, 41, 79]. Robots are ergonomically nimbler than humans, enabling more complex cuts and unconstrained implant design. Data collected at each decision step, allow accurate correlation with clinical outcome completing evaluation. The power of RAKA systems is leveraged when the data captured and analysed at

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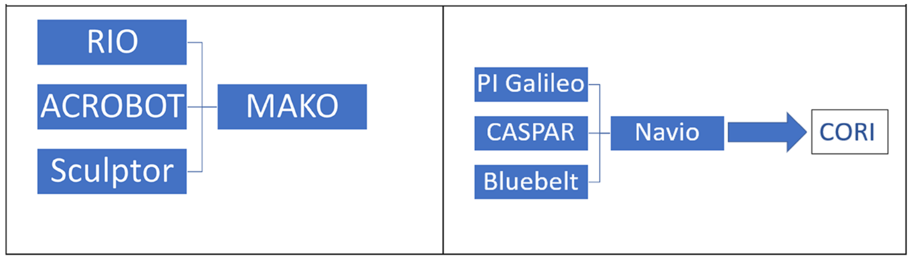

Fig. 1 Stryker Mako was developed after acquisition of RIO, ACROBOT and Sculptor technologies. Smith and Nephew Cori emerged after company acquisition of PI Galileo, CASPAR and Blue-belt technologies

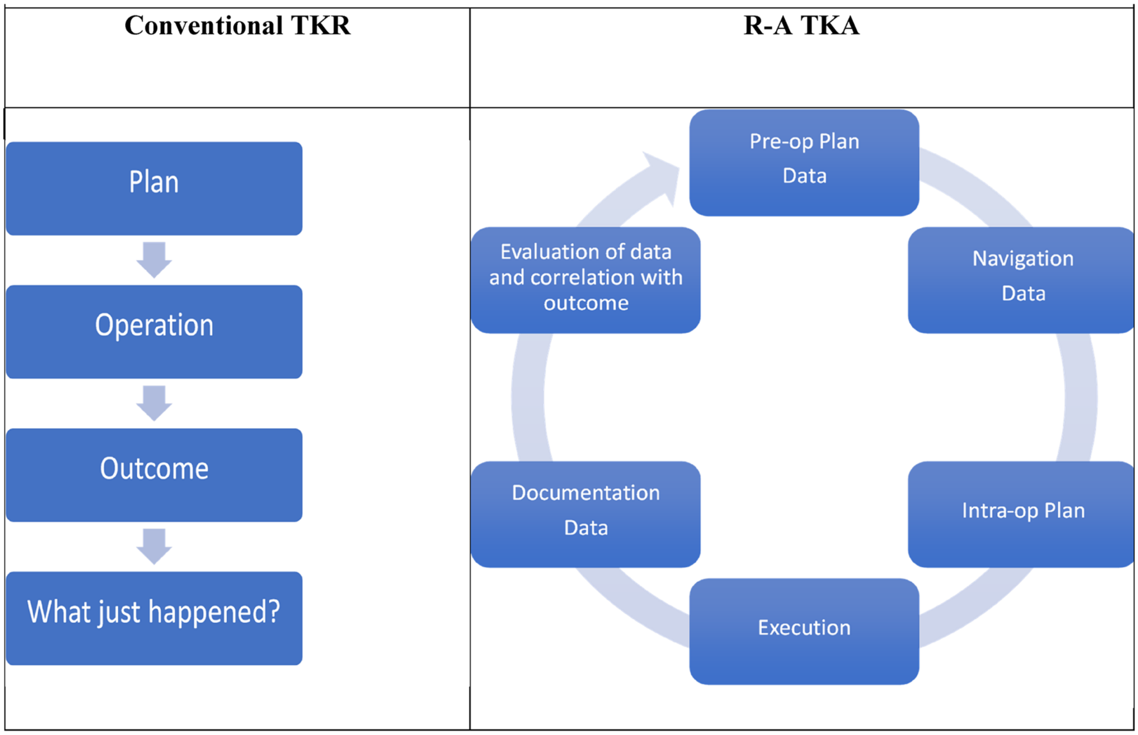

Fig. 2 Process of conventional TKR vs R-A TKA: integration of data-driven feedback in TKA

each step (Fig. 2) enables targeted evaluation of precisely defined variables that may influence the clinical success of knee arthroplasty surgery. Documentation of alignment [10, 23], soft tissue tensioning [87], patella treatment and implant design, increase the granularity of intra-operative decision making and the tools with which knee arthroplasty can be analysed and improved (Fig. 2).

We examined published literature on robotic systems for outcomes of surgical precision and reproducibility, clinical reports of PROMS, and survivorship. Synthesis of the available data is hindered by lack of long-term studies, heterogeneity of features offered by robotic systems and the reporting of outcomes (Fig. 4).

Ultimately, correlation with improved long-term clinical results and survivorship will justify robotic assistance. It may not be that the robot itself improves survivorship, rather it is the tool most capable of performance analysis, enabling the next generation in improved knee arthroplasty design (Table 1).

Materials and methods

We conducted an evaluation of the current literature based on the PRISMA guidelines [], dividing papers into those assessing outcomes of RA-UKA, and those addressing RA-TKA.

Study selection and screening

A search was conducted independently by two authors (JS and JE) on February 1st, 2021, using four databases (MEDLINE, EMBASE, Pubmed, GOOGLE SCHOLAR). Search terms included ["robotics" (MeSH Terms) OR "robotics"

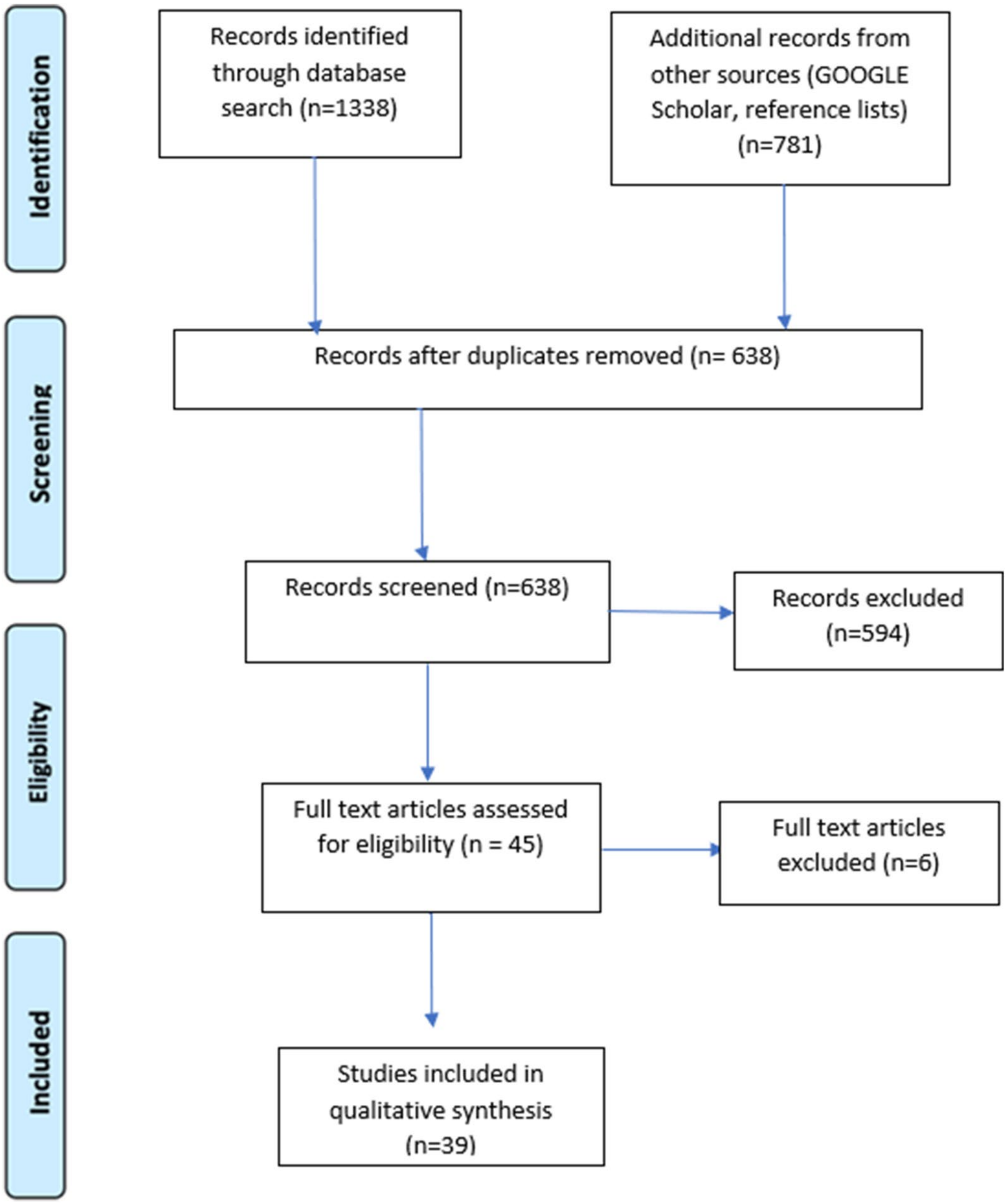

Fig. 3 PRISMA (preferred reporting items for systematic review and meta-analysis) flow diagram outlining the selection process for articles pertaining to robotic-assisted UKA

(All Fields) OR "robotic" (All Fields)] OR ["knee" (All Fields) AND "surgery" (All Fields)] OR ["knee surgery" (All Fields)]. The inclusion criteria were any study involving robotic-assisted UKA or TKA that reported precision or accuracy of implant positioning, functional outcome, range of motion or survivorship, including cadaveric or dry bone studies between 2000 and 2020. Studies were initially screened through titles and abstracts. Bibliographies were searched of all major robotic systematic reviews. Studies were excluded if they were review articles, not published in English, outcome data were not extractable or did not have more than 6-month follow-up. Systems that have been subsumed (ACROBOT, CASPAR and PI Galileo) were excluded from the final analysis. Any discrepancies were resolved through discussion with a third reviewer (BF).

UKA search results

A total of 638 records were identified for screening initially. Of these, 594 were excluded based on listed criteria. A total of 45 full text articles identified for eligibility, after which a further 6 were excluded. Thirty-nine studies

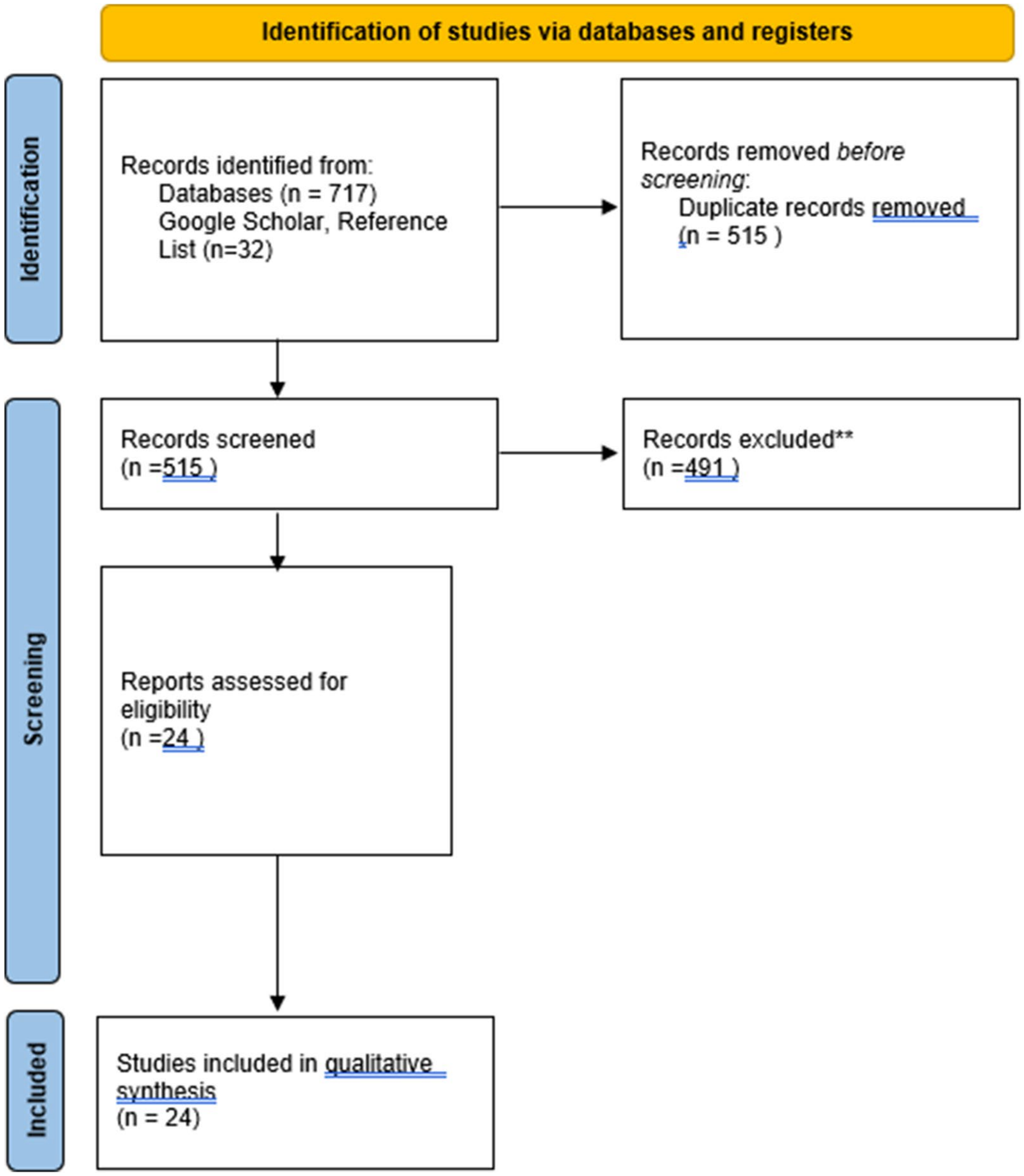

Fig. 4 PRISMA (preferred reporting items for systematic review and meta-analysis) flow diagram outlining the selection process for articles pertaining to robotic-assisted TKA

with minimum 6-month follow-up were included in the final synthesis (Fig. 3).

Results

Precision, radiographic findings, clinical results and survivorship for R-A UKA are limited to the MAKO and NAVIO systems. Most publications report on the MAKO, including survivorship data out to 5 years [9, 44, 84]. Some included studies considered both lateral R-A UKA, and R-A BiKA (medial UKA + patellofemoral arthroplasty) [8, 9, 81].

R-A UKA

Table 2 summarises 39 publications fulfilling inclusion criteria on outcomes for R-A UKA. Studies documenting radiological, clinical and survival data using Acrobot and Caspar [18, 33, 69, 71] systems have been subsumed by MAKO (Stryker) and Cori (Smith and Nephew), respectively (Fig. 1.), and therefore have not been included in this review. With respect to UKA, the only robotic systems with published data are MAKO and NAVIO. Most studies (26) analysed the MAKO robot, followed by the NAVIO (8). Two studies compare the MAKO and NAVIO robotic platforms to each other [49, 67]. Twenty-three studies declared financial

Table 1 Requirements and features of robotic systems currently available

	Steps of Knee Replacement	Information Acquired	Omni	Cori	Mako	Robodoc	Rosa	Velys
Planning	A. Preop Image-based planning	CT 3-D Recon	No	No	Yes	Yes—Plan finalized	"stitched" digital XRs	No
	B. Intra-operative registration	Surface mapping	Surface mapping	Surface mapping	Verification of CT Plan	Verification of CT Plan	Surface mapping	Surface Mapping
	Centre of hip rotation		On table	On table	On table	–	On table	
		Alignment	Yes	Yes	Yes	Yes	Yes	Yes
	Assessment of soft tissues	V-V lig. curves	Yes	Yes	0°–10° and 85°–95°	No	Yes	Yes Accubalance™
		Virtual gap balancing	Balance-bot	Yes	Yes	No	Yes	Yes
	Finalization of Plan	Implant size and position	Limited to Corin Implants	Limited to S&N Implants	Limited to Stryker Implants	"Open"	Limited to fixed-bearing Zimmer implants	Limited to De Puy Attune implants
	C. Workflow Options	Tibia/Femur first	Either	Either	Either	Mech. align	Either	
	Referencing:	Anterior	Yes	Yes	Yes	Yes	Yes	
		Posterior	Yes	Yes	Yes	Yes	Yes	
Execution	Cutting tool with active constraint		No	Yes	Yes—AccuStop® haptic	Yes	No	
	D. Femoral cuts		Positions cutting guide for all cuts	Handheld reamer cuts ± defines rotation	Executes femoral cuts	Execute femoral cuts	Positions femoral cutting guide for single distal cut ± rotation	
	Size specific femoral cutting jig		No longer required	Surgeon decides	No longer required	No longer required	No	Yes
	E. Tibial cuts		Surgeon positions cutting guide	Surgeon positions cutting guide	Executes tibial cuts	Executes tibial cuts	Positions tibial cutting guide	
Evaluation	F. Computer validation of cuts	Accuracy of Robot	Required	Required	Required	Optional	Required	
	G. Computer Documentation	Alignment	Yes	Yes	Yes	No	Yes	
		Range of motion	Yes	Yes	Yes	No	Yes	
	H. Ligament balance	V-V lig. curves	Yes	Yes	No	No	Yes	
		Pressure assessment	Balancebot	No	Verasense*	No	No	
	I. Feedback to surgeon/insurer/prospective patients	Implant usage frequency tables	No	Planned	YES	No	Planned	

* Verasense (trademark) is a single-use device with a microprocessor to quantify the load and contact position of the tibial insert for trial implantation

Table 2 Thirty-nine R-A UKA studies meeting criteria by Robot

References	Design	Robot	Country/Institution	Authors declare industry benefits
Batailler et al. [3]	Retrospective case control	NAVIO	Croix-Rousse Hospital, Lyon, France	Yes
Battenberg et al. [4]	Retrospective cohort	NAVIO	Rothman Institute, Philadelphia, U.S.A	Yes
Bell et al. [5]	Prospective RCT	MAKO	Glasgow Royal Infirmary, Scotland, U.K	Yes
Blyth et al. [5]	RCT	MAKO	Glasgow Royal Infirmary, Scotland, U.K	No
Burger et al. [5]	Retrospective Case Series	MAKO	HSS, New York, U.S.A	Yes
Canetti et al. [11]	Retrospective case control	NAVIO	Croix-Rousse Hospital, Lyon, France	Yes
Citak et al. [16]	Cadaveric study	MAKO	HSS, New York, U.S.A	Yes
Deese et al. [20]	Case control series	MAKO	Southeast Georgia Health System Brunswick, U.S.A	Yes
Dretakis et al. [21]	Retrospective cohort	MAKO	Hygeia Hospital, Athens, Greece	Yes
Dunbar et al. [22]	Retrospective cohort	MAKO	Holy cross Hospital, Florida, U.S.A	No
Gaudiani et al. [25]	Retrospective cohort	MAKO	HSS, New York, U.S.A	No
Gilmour et al. [26]	Retrospective cohort	MAKO	Glasgow Royal Infirmary, Scotland, U.K	Yes
Gladnick et al. [27]	Retrospective cohort	MAKO	HSS, New York, U.S.A	No
Hansen et al. [30]	Retrospective cohort	MAKO	Doctors Hospital Columbus, Ohio, U.S.A	No
Herry et al. [31]	Retrospective cohort	NAVIO	Croix-Rousse Hospital, Lyon, France	No
Jaramaz et al. [34]	Sawbone study	NAVIO	Robotics Institute, Pittsburgh U.S.A	Yes
Klasan et al. [43]	Retrospective cohort	MAKO	North Shore Hospital Auckland, New Zealand	Yes
Khamaisy et al. [40]	Retrospective cohort	MAKO	HSS, New York, U.S.A	No
Kleeblad et al. [46] regional fem + tib radioluc	Retrospective cohort	MAKO	HSS, New York, U.SA	Yes
Kleeblad et al. [45] prediciting feasibility	Retrospective cohort	MAKO	HSS, New York, U.S.A	Yes
Kleeblad et al. [44] midterm	Retrospective cohort	MAKO	HSS, New York, U.S.A	Yes
Leelasestaporn et al. [49]	Comparative prospective cohort	NAVIO vs MAKO	Ramathibodi Hospital, Bangkok, Thailand	No
Lonner et al. [50]	Retrospective cohort	MAKO	Pennsylvania Hospital Philadelphia, U.S.A	Yes
MacCullum et al. [51]	Retrospective registry cohort	MAKO	Columbia University Medical Center, New York, U.S.A	No
Mergenthaler et al. [59]	Retrospective cohort	NAVIO	Croix-Rousse Hospital, Lyon, France	Yes
Mofidi et al. [60]	Retrospective cohort	MAKO	Wake Forest University School of Medicine, Salem U.S.A	Yes
Negrin et al. [63]	Retrospective cohort	NAVIO	Clinica Las Condes, Santiago, Chile	No
Pearle et al. [66]	Retrospective cohort	MAKO	HSS,New York, U.S.A	Yes
Plate et al. [67]	Retrospective case series	MAKO	Wake Forest University School of Medicine, Salem U.S.A	Yes
Porcelli et al. [68]	Comparative prospective cohort	NAVIO vs MAKO	Italian Orthopaedic Research Society	No
St Mart et al. [78]	Registry Cohort	MAKO	AOA Registry, Adelaide, Australia	Yes

Table 2 (continued)

References	Design	Robot	Country/Institution	Authors declare industry benefits
Smith et al. [75]	Sawbone study	NAVIO	University of Strathclyde, Glasgow, U.K	Yes
Suero et al. [79]	Retrospective case series	MAKO	HSS, New York, U.S.A	No
Tamam et al. [83]	Retrospective case series	MAKO	Wake Forest University School of Medicine, Salem U.S.A	Yes
Van der List et al. [84]	Prospective cohort	MAKO	HSS, New York, U.S.A	No
Van der List et al. [85]	Retrospective cohort	MAKO	HSS, New York, U.S.A,	No
Van der List et al. [14]	Retrospective cohort	MAKO	HSS, New York, U.S.A	No
Watanabe et al. [87]	Case series	MAKO	Department of Cartilage Regeneration Tokyo, Japan	Yes
Zuiderbaan et al. [88]	Retrospective cohort	MAKO	HSS, New York, USA	Yes

Table 3 R-A UKA studies publishing precision (range) and accuracy (defined by discrepancy between planned and postoperative implant positioning) by year of publication

References	Robot	Robotic Coronal Outliers (%)	Conventional coronal Outliers (%)	Robotic sagittal Outliers (%)	Conventional sagittal Outliers (%)
Citak et al. [16]	MAKO vs Conventional	Range within 1.9 mm, 3.7°	Range within 5.4 mm and 10.2°	Range within 1.9 mm, 3.7°	Range within 5.4 mm and 10.2°
Jaramaz et al. [34]	NAVIO Sawbone	Joint line range 0.04–0.42 mm	–	< 0.54 mm (SD 0.23 mm), and 1.08°(SD 0.53°)	–
Dunbar et al. [22]	MAKO compared to Cobb Manual Technique	RMSE Femur 1.3 mm (2.6°) RMSE Tibia 1.1 mm (1.5°)	Femur + tibia 2.6 mm (4.1°)	RMSE Femur 1.6 mm (2.3°) RMSE Tibia 1.6 mm (1.9°)	Femur + Tibia 2.4 mm (6.0°)
Smith et al. [74] compared planned to executed implant positioning	NAVIO Sawbone	Rotational error 3.2°, angular error 1.46° Max translational error 1.18 mm	-	Rotational error 3.2°, angular error 1.46° Max translational error 1.18 mm	–
Mofidi et al. [60]	MAKO	Femoral (25–38%)	–	Tibial (16–18%)	–-
Bell et al. Accuracy < 2° target [5]	MAKO vs conventional Oxford UKA	Tibia 42% Femur 30%	Tibia 59% Femur 72%	Tibia 20% Femur 43%	Tibia 59% Femur 74%
MacCallum et al. [51] Tibia only	MAKO vs Zimmer High-Flex, M-G,S&N Journey	2.6° ± 1.5	3.9° ± 2.4	2.4° ± 1.6 (safe zone defined as 3°–9°)	4.9° ± 2.8 (safe zone defined as 3°–9°)
Gaudiani et al. [25]	MAKO	Joint line reproduced MA corrected from 5.43° ± 2.58 to 2.76° ± 2.14, $p < 0.0001$	–	PCOR reproduced PTS lower (4.91°Vs 2.28°)	–
Herry et al. [31]	NAVIO vs Conventional	Mean joint line distalization 1.4 mm (-3 to 6)	Mean joint line distalization 4.7 mm (2–9)	–	–
Kleeblad et al. [45]	MAKO	(13%)	–	–	–
Batailler et al. [3]	NAVIO vs conventional	Tibia (11%)	(35%)	PTS (< 82°) Med UKA (3.5%) Lat UKA (4.3%)	PTS (< 82°) Med UKA (17.5%) Lat UKA (17.4%)
Leelasestaporn et al. [49]	MAKO VS	HKA 179.7° (1.5)	–	Femur 89.7°(0.4) PTS -6.1°(1)	–
	NAVIO	HKA 180.1° (2.2)	–	Femur 90.2°(1) PTS—5.8°(1)	
Negrin et al. [62]	NAVIO vs conventional	Femur (12%) Tibia (19%)	Femur (44%) Tibia (39%)	Tibia (6%) Femur (25%)	Tibia (17%) Femur (72%)

Table 4 R-A UKA studies publishing patient related outcome measures (PROMs) and survivorship

Study	Robot prosthesis (*n*)	Mean age (years)	BMI kg/m^2	PROMS at final follow up	Follow-up	Revision rate
Dunbar et al. [22]	MAKO (20) All-PE tibial inlay UKSystem	71 (49–92)	28 ± 5	KSS Total 163 ± 17 KSKS 88 ± 10 KSFS 75 ± 16	36 months	None reported
Tamam et al. [81]	MAKO (BiKA) (29) Onlay	63.6 (39–82)	34.7 ± 9.49	OKS 36.43 (± 8.56)	27 months	0%
Gladnick et al. [27]	MAKO Inlay (25)	62.8 (45.5–84.1)	29.8 (15.2–40.7)	WOMAC improvement Pain 7.5 Stiffness 2.8 Function 24.8	31 months	10.3%
	Onlay (30)	63.3 (45.3–85.3)	28.9 (19.0–46.5	WOMAC improvement Pain 4.3 Stiffness 2.2 Function 15.0	27 months	2.2%
Plate et al. [66]	MAKO (595) Inlay (151) Onlay	64 ± 11	32.1 ± 6.5	OKS 37 ± 11	34.6 ± 7.8 months	5.8%
MacCallum et al. [51]	MAKO Onlay (87)	Not reported	Not reported	Not Reported	32 months	3.4%
Van der List et al. [65]	(143) M-UKA	65.4 ± 9.4	27.2 ± 4.2	WOMAC 89.8 ± 11.7 FJS 71.2 ± 24.5	29 months	None Reported
	(36) L-UKA	65.0 ± 13.0	28.9 ± 4.7	WOMAC 90.2 ± 12.4 FJS 70.9 ± 28.2		
Zuiderbaan et al. [88]	MAKO Restoris MCK Onlay (104)	65.0 ± 9.2	26.2 (18.3–39.1)	WOMAC Stiffness score improved in patients 65 + years $p = 0.035$	0%	2–3.7 years
Blyth et al. [6] RCT	MAKO Restoris MCK (64) Oxford Phase 3 UKA	Not reported	Not reported	No significant difference between treatment arms at 12 months postop on AKSS, OKS FJS	0%	12 months
Gaudiani et al. [25]	MAKO Onlay (91)	64.9 ± 10.5	28.6 ± 4.51	WOMAC 8 KSKS 97 KSFS 83 KSS Satisfaction score 9 (out of 10)	49 months	3%
Kleeblad et al. 2017 [46]	MAKO Restoris Onlay (101)	63.4 (44.6–85.0)	28.6 (18.6–52.9))	WOMAC 91 (± 8)	5 years	2%
Pearle et al. [65]	MAKO Onlay (909)	69.1 ± 9.5	29.4 ± 4.9	92% satisfied or very satisfied	22 – 52 months	1.2%
Van der List et al. [65]	MAKO Restoris Onlay (166)	64.9 (± 9.2)	29.2 (± 5.3)	WOMAC 89.7 (± 13.6)	32 months	N/A
Van der List et al. [65]	MAKO Restoris (36) Inlay	61.7 ± 10.2	31.3 ± 5.7	WOMAC 82.4 (± 18.7)	61 months	7.7%
	(42) Onlay	64.6 ± 8.7	29.3 (± 6.3)	WOMAC 92.0 (± 10.4)	61 months	3.4%
Canetti et al. [11]	NAVIO HLS Uni evolution, Tornier® Inlay	66.5 ± 6.8	24.2 ± 4.3	KSS–Objective 66.3 ± 8.9 KSFS 84.6 ± 11.3	Mean 37.2 ± 5.3 months	0% R-A Vs 17.6% conventional

Table 4 (continued)

Study	Robot prosthesis (*n*)	Mean age (years)	BMI kg/m^2	PROMS at final follow up	Follow-up	Revision rate
Deese et al. [20]	MAKO Onlay	62 ± 10	31.7 ± 4.8	KOOS: Pain 90.19 ± 15.25 Symptoms 87.83 ± 14.08 ADLs 89.62 ± 14.22 Sport 70.78 ± 27.36 QOL 78.55 ± 21.24	Mean follow-up 54 months	1.2%
Kleedblad et al. [44]	MAKO Restoris Onlay (432)	67.3 years ± 8.9	29.7 ± 4.7	91% satisfied or very satisfied	5–7.7 years	3%
Gilmour et al. [26]	MAKO Onlay	61.8 ± 7.84	Not reported	AKSS 193.5 (IQR 184.0–198.0) OKS 46 (IQR 42.0–48.0)	24 months	0%
Batailler et al. [3]	NAVIO HLS Uni evolution, Tornier® Inlay	69 ± 9.6	26.1 ± 4.1	KSFS—92.6 ± 13 KSKS—90 ± 11 Satisfaction rate 74%	19.7 ± 9 months	5%
Dretakis et al. [21]	MAKO	71.7 ± 9.1	27.2 ± 3.5	80% 'very satisfied' WOMAC Total 47.8 ± 8.2 Pain 1.6 ± 1.3 Function 45.7 ± 8.5	54 months	0%
Battenberg et al. [4]	NAVIO	64.7 ± 9.6	30.3 ± 5.4	None documented	24 months	0.8%
Burger et al. [8]	MAKO (802) M-UKA	63.5 ± 9.5	28.7 ± 5.3	KOOS 84.3 ± 15.9	2–10.8 years	2.2%
	(171) L-UKA	64.4 ± 11.0	26.9 ± 4.8	85.6 ± 14.3		2.3%
	(35) PFA/ BiKA	58.2 ± 11.6	27.0 ± 4.9	78.2 ± 14.2		6.7%
Klasan et al. [43]	MAKO Onlay (94)	64.4 ± 9.3	Not reported	OKS 35.4 ± 7.2 improvement average of 13.2 ($p < 0.001$)	17 months (6–29)	2.1%
Leelasestaporn et al. [49]	NAVIO (14)	70.9 (5.9)	26.0 (3.17)	KSFS 99.9 ± 0.25 KSKS 96.9 ± 5.7	12 months	0%
	MAKO (15)	71.5 ± 6.3	25.8 ± 3.3	KSFS 94.7 ± 1.2 KSKS 99.5 ± 10.1		0%
St Mart et al. [77]	MAKO (2851) Onlay	65.7 ± 9.3	Not reported	Not reported	2.6%	36 months
Mergenthaler et al. [59]	NAVIO HLS Uni evolution, Tornier® Inlay	66.7 ± 9.3	27.0 ± 4.2	KSFS 92.8 ± 13.4 KSKS 91.9 ± 10.6 Satisfaction rate—82%	Minimum 12 months	4%
Negrin et al. [62]	NAVIO Journey UNI (S&N) (18)	66 (56–82)	Not reported	OKS 45 (37–47)	6 months	None reported
	Conventional (16)	65 (41–76)		39 (23–48)		

support from the company that owned the robot in the study. Results are summarised in Tables 3 and 4.

R-A TKA

A total of 515 abstracts addressing R-A TKA were identified for further screening. After first stage screening, a total of 24 full texts were included based on the listed eligibility criteria (Fig. 4). Most studies were on the MAKO with 11 meeting inclusion criteria, followed by the ROBODOC (6), OMNIbot (3), NAVIO (2) and ROSA with (2) (Tables 5, 6 and 7). At the time of writing, no published results are currently available for the Velys™ system (De

Table 5 Twenty-four studies of R-A TKA studies by Robot

References	Design (*n*)	Robot	Follow-up (mean)	Country	Authors Declare Industry Benefits
Bollars et al. [7]	Retrospective case–control (77)	NAVIO vs conventional	N/A	Belgium Netherlands	Yes
Cho et al. [15]	Retrospective case–control (160)	ROBODOC vs conventional	11 years	South Korea	No
Collins et al. [19]	Retrospective Case Series (72)	NAVIO	N/A	Australia	Yes
Figueroa et al.[24]	Case series (173)	OMNIbot	N/A	Chile/Australia	No
Hampp et al. [29]	Cadaveric study (12)	MAKO	N/A	U.S.A	Yes
Jeon et al. [35]	Retrospective series (79)	ROBODOC vs conventional	129.1 months	South Korea	No
Kayani et al. [38]	Prospective cohort (60)	MAKO vs Conventional	30 days	U.K	Yes
Khlopas et al. [41]	Cadaveric study (6)	MAKO	N/A	U.S.A	Yes
Kim et al. [42]	Single surgeon RCT (750)	ROBODOC vs conventional	10 years	South Korea	No
Mahoney et al. [52]	Retrospective cohort (143)	MAKO vs conventional	6 weeks	U.S.A	Yes
Malkani et al. [54]	Retrospective cohort (188)	MAKO	2 years	U.S.A	Not stated
Manning et al. [55]	Cadaveric study (5)	MAKO	N/A	U.K	Yes
Marchand et al. [57]	Retrospective case series (20)	MAKO vs conventional	6 months	U.S.A	No
Marchand et al. [56]	Retrospective case series (53)	MAKO vs conventional	12 months	U.S.A	No
Parratte et al. [64]	Cadaveric (30)	Rosa	N/A	France U.K. U.S.A	Yes
Seidenstein et al. [70]	Cadaveric (14)	Rosa vs conventional	N/A	U.S.A	Yes
Sires et al. [72]	Retrospective cohort (33)	MAKO	N/A	Australia	No
Smith et al. [73]	Case–control (120)	MAKO vs conventional	12 months	U.S.A	Yes
Song et al. [75]	Within patient case control (30)	ROBODOC vs conventional	16 months	South Korea	No
Song et al. [76]	RCT (50)	ROBODOC vs conventional	65 months	South Korea	Yes
Suero et al. [78]	Case series (30)	Omnibot vs conventional	N/A	USA	Yes
Sultan et al. [80]	Retrospective Cohort (43)	MAKO vs conventional	N/A	U.S.A	No
Wakelin et al. [85]	Case series (135)	Omnibot	12 months	USA/Japan	Yes
Yang et al. [86]	Retrospective case control (71)	ROBODOC vs conventional	10 years	South Korea	No

Puy, J&J). The longest clinical follow-up was 15 years, reported for the ROBODOC system [42].

MAKO UKA

a. Precision

Twelve studies report on precision and accuracy with R-A UKA. In 2012, Citak et al. [16] performed a cadaveric study analyzing femoral and tibial implant placement errors by comparing preoperatively planned position with postoperatively achieved results between R-A (MAKO) UKA and conventional groups. The root-mean-square error (RMSE) was used to quantify alignment errors, reporting femoral component placement were within 1.9 mm and 3.7° in all directions of the planned implant position for the robotic group, while RMS errors for the manual group were within 5.4 mm and 10.2°. Average RMS errors for tibial component placement were within 1.4 mm and 5.0° in all directions for the robotic group; while, for the manual group, RMS errors were within 5.7 mm and 19°.

In 2014, Mofidi et al. [60] published accuracy results based on a retrospective radiological analysis of 232 knees, comparing postoperative femoral and tibial sagittal and coronal alignments to the equivalent measurements collected intraoperatively by the Mako robot. They reported average coronal and sagittal plane inaccuracy of respectively 2.2° ± 1.7°, and 3.6° ± 3.3°, concluding that inaccuracy observed may be attributed to cementing technique.

Only two studies [5, 51] had a conventional comparison arm and in both a modest benefit was demonstrated in the robotic group with fewer outliers in both planes. The most scientifically rigorous of these was the randomised controlled trial conducted by Bell et al. [5] directly comparing MAKO R-A UKA with instrumented Oxford UKA. They

Table 6 R-A TKA studies publishing on precision and accuracy (defined by radiographic implant positioning within 3° of arbitrary target) by year of publication

References	Robot	Alignment	HKA outlier	Femur coronal	Tibia coronal	Femur sagittal	Tibia sagittal
Song et al. [76]	ROBODOC	MA	0%	0%	0%	0%	6.7% ($n=2$)
Suero et al. [79]	OMNIbot	MA	9%	Not reported	0%	Not reported	15%
Song et al. [77]	ROBODOC	MA + gap balance	0%	0%	0%	0%	1.9% ($n=1$)
Yang et al. [87]	ROBODOC	MA	8.7%	5.8%	–	–	–
Cho et al. [15]	ROBODOC	MA + gap balance	10.6% ($n=12$)	8.0% ($n=9$)	7.1% ($n=8$)	3.5% ($n=4$)	5.3% ($n=6$)
Marchand et al. [58]	MAKO	MA	18%	–	–	–	–
Figueroa et al. [24]	OMNIbot	KA	17%	2%	1%	0%	7%
Jeon et al. [35]	ROBODOC	MA	10.7% ($n=9$)	8.3% ($n=7$)	11.9% ($n=10$)	3.6% ($n=3$)	20.2% ($n=17$)
Kim et al. [42]	ROBODOC	MA	14%	11%	–	12%	11%
Parratte et al. [65]	Rosa	MA	All angles measured within 1° between planned and achieved resection				
Bollars et al. [7]	NAVIO	MA	6%	14%	86%	0%	17%
Mahoney et al. [52]	MAKO	MA	Improved accuracy for R-A TKA for femoral rotation($p=0.015$) and tibial alignment and slope ($p<0.001$)				
Seidenstein et al. [71]	Rosa	MA	0%	0%	0%	7.1% ($n=1$)	0%
Collins et al. [19]	NAVIO	MA	6.7%	–	–	–	–

found that the R-A UKA system resulted in a significantly greater proportion of components implanted within 2° of the target femoral component sagittal position (57% versus 26%, $p=0.0008$), femoral component coronal position (70% versus 28%, $p=0.0001$), femoral axial position (53% versus 31%, $p=0.0163$) and tibial component sagittal position (80% versus 22%, $p=0.0001$) and tibial axial position (48% versus 19%, $p=0.0009$).

MacCallum et al. [51] in their 2016 retrospective radiological analysis of a registry cohort of 177 patients receiving a conventional UKA and 87 patients receiving a R-A UKA determined that coronal tibial baseplate positioning was more accurate with respect to their arbitrary safe zone for R-A UKA than conventional UKA (2.6° ± 1.5°versus 3.9° ± 2.4° $p<0.0001$), but sagittal plane alignment was not (4.9° ± 2.8°versus 2.4° ± 1.6°$p<0.0001$). Overall precision was delivered by the R-A UKA system, but accuracy of PTS determined by arbitrarily defined "safe zone" of 3°–9° was better with a conventional technique.

Gaudiani et al. [25] performed a radiological assessment of R-A (MAKO) UKA implant positioning reporting on pre- and postoperative reproduction of (sagittal) posterior condylar offset ratio (PCOR), posterior tibial slope (PTS) and (coronal) joint line reproduction and (correction of) mechanical axis (MA). They found precise reproduction of the joint line and PCOR. Both pre-operative PTS and varus were corrected towards neutral. The authors conclude that R-A UKA helps quantify surgical parameters.

In 2018, Kleeblad et al. [45] reported on the feasibility of correcting varus deformity in their series of 200 R-A UKA with a mean pre-operative deformity of 10° (7°–18°). They concluded that 98% of candidates with a preoperative varus deformity between 7 and 18° could be reliably restored to within 7° varus using the MAKO R-A Restoris UKA system.

There were two studies demonstrating comparable precision between NAVIO and MAKO robots [49, 67].

b. PROMS

Eighteen studies reported PROMS with the MAKO R-A UKA (Table 4). All studies with conventional comparison groups reported equivocal or better PROMS, however in no study were they statistically significant at last follow-up. Three studies reported satisfaction rates, 80% [21], 91% [25] and 92% [65]. In their RCT [26] with clinical outcome, Gilmour et al. concluded equivalency between R-A UKA and conventional UKA at 2 years.

c. Survivorship

A total of 27 studies had clinical outcome data on R-A UKA using the MAKO tool. Nineteen studies reported survivorship outcomes on pooled data of 6042 UKA performed using MAKO, the majority of which were medial UKAs, with smaller numbers for lateral compartment or bicompartmental arthroplasty. In their registry study of 2851 MAKO Restoris arthroplasties, St Mart et al. [77] reported comparable short-term (3 year) cumulative percent revision of 2.6% for MAKO R-A UKA, despite increased early infections. Three studies reported 5-year revision rate of 2.2% [8], 3% [44] and 7.7% and 3.4% (for tibial inlay and onlay implants, respectively) [84]. The longest follow-up survival data available for R-A UKA are 5 years.

Table 7 R-A TKA studies publishing PROMs and survival by year of publication

References	Robot implant (*N*)	Follow-up	Outcomes	Revision
Song et al. [75]	ROBODOC Zimmer NexGen PS (24)	12 months	ROM 129° (SD ± 13.8) HSS 95.9 (SD ± 5.2)	Not reported
Song et al. [76]	ROBODOC Cemented Zimmer NexGen PS (50)	5 years (mean 65 months)	HSS 95.7 ± 4.0 WOMAC 28.9 ± 4.4 ROM 128 ± 5.1	
Marchand et al. [57]	MAKO Triathlon CR[b] (20)	6 months	WOMAC Pain—3 (± 3) Physical function score 4 (± 5) Total 7 (0–22)	N/A
Yang et al. [86]	ROBODOC CR Zimmer NexGen (71)	10 years	WOMAC = 80.8 ± 15.4 VAS = 5.5 ± 3.5 ROM = 132.6° ± 10.5° HSS = 65.7 ± 7.7	2 revisions for infection 97.1%
Cho et al. [15]	ROBODOC Zimmer NexGen (154)	10 years	ROM 130.7° (4.4) HSS 88.5 (3.3) KSS pain 45.3 (4.2) KSFS 87.8 (7.3) WOMAC 10.1 (13.7) SF-12 Physical 48.3 (6.8)	98.8% *N* = 2 (1.2%) revised for infection
Jeon et al. [35]	ROBODOC Cemented Zimmer NexGen PS ± patella resurfaced(84)	10 years	KSKS 89.7 ± 12.9 (9 years) KSFS 85.4 ± 13.1 ROM 137.2° ± 11.2 SF-36 P 47.5 ± 8.5 SF-36 M 56.5 ± 10.1	98.8%
Marchand et al. [56]	MAKO Triathlon CR[b] (53)	12 months	WOMAC 6 ± 6 Physical function 4 ± 4 Pain 2 ± 2	Not reported
Smith et al. [73]	MAKO Triathlon patella resurfaced (120)	12 months	KSKS 85 KSFS 80 WOMAC 11 (SD ± 4.5)	100%
Kim et al. [42]	ROBODOC Cemented Duracon PS ± Patellae resurfaced (724)	10 years (mean 13 years)	KSKS—93 ± 5 WOMAC 18 ± 14 (last FU) ROM—125° 6 ± 6° UCLAS activity scores—7	98% implant survival at 15 years 0.6% (4) had superficial infections,
Mahoney et al. [52]	MAKO Triathlon CR[b] (143)	12 months	Veterans RAND 12-item health scale 52.9 vs 505.5 (Con) KSS satisfaction 35.9 vs 35.2 (con) KSS symptoms 20.8 vs 20.3 (con) KSFS 84.6 vs 81.1 (con)	100%
Malkani et al. [54]	MAKO Triathlon (188)	2 years	FJS 75 (14–100) KSFS (20–100) KSKS 92 (40–100)	*N* = 3 97.9% survival (2 infections, 1 tibial fracture)
Wakelin et al. [85]	OMNI-Bot Patellae resurfaced (135)	12 months	KOOS pain score improvement $\Delta = 11.2$, $p = 0.002$) when tibio-femoral balancing achieved[a]	99.26% traumatic MCL injury

KSFS Knee Society Functional Score, *KSKS* Knee Society Knee Score, *OKS* Oxford Knee Score, *WOMAC* Western Ontario and McMaster Universities Osteoarthritis Index, *AKSS* American Knee Society Score, *FJS* Forgotten Joint Score, *KOOS* Knee Injury and Osteoarthritis Outcome Score, *VAS* Visual Analogue Scale, *HSS Score* Hospital for Special Surgery Score, UCLA Activity Score, *ROM* Range of Movement, *KSS* Knee Society Score, *SF-36* Short Form 36 Health Survey

[a]Tibio-femoral balancing defined by at least two targets achieved, with the greatest improvement observed when all three targets were satisfied. Joint gap thresholds of an equally balanced or tighter medial compartment in extension, medial laxity ± 1 mm compared to the final insert thickness in midflexion, and a medio-lateral imbalance of less than 1.5 mm in flexion

[b]Unclear in study text if patella was resurfaced

NAVIO (CORI) UKA

a. Precision

Smith et al. [74] originally validated the accuracy of the NAVIO robotic system for UKA in a saw bone model. The authors reported RMS angular errors were 1.05°–1.52° for the three planes of the femoral implant and 0.66°–1.32° for the three planes of the tibial implant. The mean femoral and tibial cut surface data for all 20 bones showed that there was a slight undercut of 0.14 mm for the femur and 0.21 mm for the tibia, results comparable to those reported for the MAKO system by Citak et al. [16]. The motorized cutting burr used in this platform was originally described in a paper by Jaramaz et al. [34]. The accuracy of the cutting burr was quantified as an average distance from the planned implant position of 0.54 mm (SD 0.23 mm) and an average angular difference of 1.08° (SD 0.53). Herry et al. in 2017 [31] reported improved joint line restitution when utilizing NAVIO robotic assistance with the same implant, although the joint line was distalized in both the conventional and R-A groups.

Two studies compared outlier numbers for NAVIO UKA implants to conventional techniques [59, 62]. In both studies, the conventional technique had over double the outliers in both the coronal and sagittal position of tibial and femoral components.

Batailler et al. [3] in their retrospective case control study compared implant position between conventional and Navio R-A UKA and found a significantly higher rate of outliers in the conventional group with respect to limb alignment, and coronal and sagittal tibial base plate positioning, reporting that up to 35% of conventional tibial base plates as radiographic outliers. In 2021, Negrin et al. [62] published on the radiological accuracy of a group of conventional UKA compared to R-A UKA and based on an arbitrary radiological target. Of the 34 patients admitted to the study, 18 underwent R-A UKA achieving the arbitrary target 87% of the time, compared with 28% in the conventional group.

b. PROMs

A total of eight Canetti et al. [11] studies reported clinical outcome data for R-A UKA using the NAVIO system.

Five studies reported PROMS using the NAVIO robot. All studies reported superior or equivocal results when comparing to a conventional technique, however the differences achieved never reach statistical significance. The longest follow-up was 2 years. Satisfaction was reported in two studies as 74% [3]and 82% [59]. Return to sport was reported by Canetti et al. [11] for lateral R-A UKAs compared with those using conventional instrumentation. Two studies [49, 67] directly compared robotic UKR systems. In both cases the MAKO robots was compared to the NAVIO, neither study finding clinically significant differences in results (KFS and KSS) at 12 [49] or (KOOS) 24 months [67]. Both studies found an increased operating time of about 15 min for the NAVIO compared to the MAKO robot. No differences in complication rates were reported in either study.

c. Survivorship

Four studies reported survivorship results with maximum 2-year follow-up. Two-year revision rate was reported as 0% [11], 5% [3], 0.8% [4] and 4% [59].

MAKO TKA

a. Precision

Sires et al. [72] in 2020 reported in their case series of 33 TKAs that 87.36% of intraoperative measurements of femoral component position came within 3° compared with the findings of the postoperative CT, and a further 71.27% were within 2° compared with post-operative CT measurements. Tibial component placement was recorded within 3° of the postoperative CT findings in 93.11%, and within 2° in 74.14% of measurements. Intra-operatively recorded limb alignment was within 3° of the CT measurement in 93.10% of cases. In series comparing MAKO to conventionally instrumented TKA, Sultan et al. [80] reported improved accuracy and consistent restoration of posterior condylar offset ratio and Insall-Salvati Ratio in a radiographic study with MAKO to conventional TKA and Kayani et al. [7] in a single surgeon series demonstrated improved implant accuracy with the MAKO. Coronal and sagittal alignment for both tibial and femoral components were closer to planned position and the differences between groups were all reported to be statistically significant.

Two cadaveric studies [29, 41] reported that MAKO robotic precision improved PCL protection. Manning et al. [55] demonstrated improved tibiofemoral balancing using the MAKO compared to conventional gap technique TKA. The study did not report the level of training or experience of the surgeon performed the gap-balanced TKAs.

b. PROMs

Most studies reporting PROMs in a TKA population using MAKO did not have data beyond 6-month follow-up and were excluded from the final analysis. Only five studies

[52, 54, 56, 57, 73] reporting PROMs after 6 months on the MAKO TKR were identified. Most reported a small trend to improved outcome with the MAKO. Marchand et al. reported improved pain scores at 6 [57] and 12 months [56] compared to conventional TKA, with the difference at 1 year being less pronounced and not statistically significant. Smith et al. [73] reported improved satisfaction at 12-month follow-up compared to conventional TKA, however Mahoney et al. [52] reported no difference in 12-month PROMS including satisfaction at 12-month follow-up.

c. Survivorship

Two studies report survivorship data for MAKO TKA beyond 6-month follow-up. Malkani et al. [54] reported a year revision rate of 2.1% ($n = 4$) in 188 TKA using the MAKO robot. Smith et al.[73] reported outcomes in 120 MAKO TKA compared with 102 instrumented TKA and has 100% implant survival at 1 year for both groups, although stated some patients had been excluded due to the development of periprosthetic joint infection. Mahoney et al. [52]reported 100% implant retention at 12-month follow-up in 143 RTKA using the MAKO.

ROBODOC TKA

ROBODOC was the first active robotic system developed for orthopaedic surgery and has the longest follow-up data [42].

a. Precision

Six studies compare the accuracy of the ROBODOC to conventional techniques [44–49]. All studies used a mechanical alignment philosophy and consistently showed fewer outliers in overall hip-knee-angle alignment as well as femoral and tibial sagittal and coronal implant placement. Rotational alignment was not addressed. The comparison manual instrumentation groups included the NexGen, Duracon and Triathlon implants and equipment and were the same implants as used in the ROBODOC series.

b. PROMs

Six studies reported PROMS in TKA cohorts using the ROBODOC [15, 35, 42, 75, 76, 86]. Follow-up periods range from 1 to 10 years with heterogeneous PROMS. Whilst most studies demonstrate a small benefit in PROMS, satisfaction and range of motion for robotic TKA compared to conventional TKA, these differences never reach statistical significance nor a minimally relevant clinical threshold.

c. Survivorship

Four studies [15, 35, 42, 86] reported survivorship outcomes using the ROBODOC platform comparing to conventional TKA groups using the same prosthesis. One study [42] used the Duracon prosthesis, with the remainder using NexGen implants. Three of the studies [15, 35, 86] showed modest improvements in implant survival rates for the robotic groups compared to the conventional technique groups. The largest study with the longest follow-up reported 98% implant survival record, with over 700 conventional and robotic TKAs in each group at 15-year follow-up [42].

NAVIO (CORI) R-A TKA

a. Precision

Casper et al. [12] assessed the accuracy of the NAVIO robot for TKA in a cadaveric study, using either cutting guides or the hand-held semi-active burr using three different prosthesis (Journey II, Genesis II and Legion). The authors compared the translational, angular, and rotational differences between the planned and achieved positions of the implants. The mean femoral flexion, varus/valgus, and rotational error was − 2.0°, − 0.1°, and − 0.5°, respectively. The mean tibial posterior slope, and varus/valgus error was − 0.2°, and − 0.2°, respectively. Accuracy as measured by the robot was improved with use of the burr compared to cutting guides. Bollars et al. [7] concluded equivalence in their case–control study comparing NAVIO assisted to conventional TKA with a goal of mechanical alignment.

b. and c. PROMs and survivorship

No studies have published clinical outcomes beyond 6 months for the NAVIO (Cori) robot in TKA to date.

OMNIBOT R-A TKA

a. Precision

Two studies [47, 48] examined the accuracy of OMNIbot compared to navigated TKA in cadaveric testing finding that the Omnibot delivered more consistent implant positioning and bone cuts. Koulalis et al. [48], in 2010 reported improved precision of coronal implant placement (0.24° vs 1.16°, $p = 0.015$) and thickness of bone cuts (0.37 vs 1.41 mm, $p = 0.01$) when using the OMNIbot, also reporting in 2011 [47] improved accuracy of coronal (0.55° versus 1.1°, $p = 0.0041$) and sagittal (0.75° versus 2.0°, $p < 0.0001$) plane bone resection, and cut height (0.56 mm versus 1.6 mm, $p < 0.0001$).

The OMNIbot has been compared to conventional, patient specific cutting (PSC) guides and computer-assisted surgery in accuracy studies. Suero et al. [78] found the OMNIbot to have fewer outliers than a conventional technique for achieving a neutral mechanical alignment. Clark et al. [17] compared the PRAXIM (forerunner to the OMNIbot) precision to a computer-assisted technique. In a retrospective study of 81 matched patients, R-A TKA was 0.5° closer to planned coronal alignment than CAS TKA when comparing the PRAXIM robot to a Stryker navigation system. 37% of the femoral cuts were within a half degree of the planned cut angle, 63% of axial rotations were within a half degree, and 50% of the tibia slope cuts were within a half degree of the planned value. The precision of the OMNIbot has also been compared to patient specific instrumentation (PSI) guides. Nam et al. [61] found 92.7% of OMNIbot-assisted TKAs were aligned within 3° of the intended target compared to only 70.7% of TKAs with PSC ($p = 0.02$).

In their postoperative CT analysis of implant position, Figueroa et al. [24] in 2019 concluded that the OMNIbot provided high precision for rotational, coronal femoral and tibial cuts, less so for hip-knee angle and sagittal cuts.

b. PROMs

Two studies have published PROMS in a TKA cohort utilizing the OMNIbot. Martin-Hernandez et al. [58] examined 198 patients in a multi-centred, multi-surgeon performed cohort of TKA (118 robotic versus 80 conventional). The conventional group had shorter operating time (78 min) compared to OMNIbot TKA (83 min). At final 3-year follow-up the OMNIbot had modestly improved clinical outcome measures except for the KSS in which the conventional group demonstrated higher scores (83.8 vs 79.2). Wakelin et al. [85] showed that integration of the soft tissue balancing component of this system (Balancebot) with defined tibiofemoral gap goals could improve clinical outcomes. They reported a statistically significant improvement in KOOS pain score ($\Delta = 11.2$, $p = 0.002$) when these targets were met.

c. Survivorship

Two studies report on survivorship: Wakelin et al. [85] reported a 99.26% survivorship in 135 consecutive TKA performed using the Omnibot and Martin-Hernandez [58] et al. 100% in 119 robotically assisted TKA using the OMNIbot at 3-year follow-up.

ROSA® R-A TKA (Zimmer Biomet, Warsaw, IN, USA)

a. Accuracy

Two cadaveric studies have assessed the precision of the ROSA for TKA. In their study of 30 cadaveric TKAs Parratte et al. [64] reported over 90% of implant alignment being within 3° of target position and > 90% of bone cuts being within 2 mm of intended target cut thickness. Seidenstein et al. [70] reported similar findings when comparing the ROSA to conventionally performed TKA with 100% versus 75% of cases within 3° target implant position and 93% versus 60% within 2° target. They reported R-A precision of bone resection angles to within 0.6° (standard deviation 0.4°), except for the femur flexion ($1.3° \pm 1.0°$), and within 0.7 mm with standard deviations below 0.7 mm for bone cuts.

b. PROMs and survivorship

Currently there is no published literature on clinical outcomes on the ROSA knee system. Zimmer Biomet is currently in the recruitment phase and aims to enrol 300 participants with early results due in late 2022 or early 2023 aiming to evaluate clinical outcomes.

Discussion

The strength of this study is that it summarises the limited clinical results of R-A KA, across five different robotic systems, confirming potential for robotic assistance to improve surgical precision and patient outcomes. Comparative studies in this review consistently reported statistical equivalence between treatment arms for risk of infection, revision nor manipulation under anaesthesia.

Limitations

Studies documenting robotic assistance are often industry supported and lack in scientific rigour [53].

Studies on R-A UKA were concentrated in North America [4, 9, 16, 20, 22, 25, 27, 30, 40, 44–46, 50, 51, 82–84]. One of the largest series from Burger et al. [8] reported 5-year survivorship in a single surgeon series on a group that included medial, lateral, patellofemoral and bicompartmental (medial and patellofemoral) knee arthroplasty. Despite calls for improved scientific rigour, variables are rarely optimally matched between comparison groups [68].

The most scientifically rigorous studies have been conducted on the ROBODOC. Studies on this open platform vary in implants, with inconsistent patella resurfacing strategies. Studies supporting the ROBODOC system are geographically limited to South Korea [15, 35, 42, 75, 76, 86].

Patient selection bias limits the conclusions that can be drawn about robotic systems. UKA results appear more sensitive to patient and implant selection than robotic platform used. R-A UKA outcomes are negatively influenced by age < 65, BMI > 30 kg/m^2 and inlay tibial prosthesis [68]. These findings were consistent across the series by Burger et al. [8], Pearle et al. [65] and Zuiderbaan et al. [88] and Kleeblad et al. [44]. Blyth et al. [6] noted poorer PROMS in patients with high levels of anxiety and depression pre-operatively. Two studies [66, 88] found no relationship between BMI and revision rate.

Variation in the quantification of precision of implant positioning between studies makes comparison difficult. Accuracy is studies reported here is defined as the difference between planned and executed positioning, without clinical validation [81]. Song et al. [75] in their within-patient randomised case–control study of 30 patients receiving bilateral TKAs determined that despite improved accuracy of surgical results with R-A TKA knees, there was no clinically detectable difference at 12 months. Controversy regarding accuracy is also reflected in the heterogeneity of reports on alignment strategy. Alternative methods for assessing accuracy of implant position include joint line restoration reported by Herry et al. [31], PCOR [25, 80] and femoral component prominence, as reported by Klasan et al. [43] but these were not tabulated here.

Heterogeneity in PROMS reported makes between-study comparison difficult. Furthermore, their validity remains questionable. Adriani et al. [1] in their systematic review concluded that only the Forgotten Joint Score showed acceptable validity. Only two studies [6, 84] used FJS and it is possible that subtle differences are not being captured.

Improvement in objectivity in reporting of outcomes is expected to follow with technological advances. For example the FDA (United States Food and Drug Administration) approval for collaboration between Canary Medical Inc. and Zimmer Biomet to produce implants capable of real-time measurement of activity, range of motion and in-situ pressure[32].

Inconsistent reporting of survivorship between studies is misleading. Gaudiani et al.[25] reported 99% survivorship in their cohort of 91 robotic UKA, despite conversion of 2 UKA in the cohort to TKA and 'one device was removed'. These were not included amongst revisions.

Secondary outcomes of faster procedure times, reduced learning curves[19, 38], reduced hospital stay and sterilization costs, need for fewer theatre personnel, reduced infection risk, and ultimately reduced financial burden per case are often touted in publications, but there is limited evidence to support this and can be a complex calculation dependent on an economy of scale[13, 36]. These outcomes were beyond the scope of this analysis.

There is much published on diminishing learning curves with robotic techniques, but few studies analyse the effect of the institutional and surgeon volume on the quality of surgeries performed. Ultimately, it may be that the precision afforded by robotics is more important for the inexperienced low-volume surgeon than the experienced surgeon.

The association between improved precision and improved long-term clinical outcome remains undetermined. Industry is intimately involved in most studies presented and care must be taken with the interpretation of results. Due to the volume of potential confounding variables in many publications, it will only be with diligent recording and analysis that the benefit afforded by R-A KA can be recognised. Fortunately, data capture and analysis are features of robotic systems.

Conclusion

The most important finding from our review is that in cadaveric, radiographic and clinical studies, robotic platforms confirm improved precision and reproducibility compared with conventional techniques, regardless of the robotic platform. Clinical studies demonstrated reduced morbidity associated with increased precision of a robotic-assisted cutting tool [29, 39, 41, 79]. Comparisons conducted between robotic-assistance models have shown equivalence amongst robotic systems. These findings are limited in external validity due to the heterogeneity of the scientific literature.

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Declarations

Conflict of interest None.

Ethical approval As this review is based on published and publicly reported literature, no specific ethical approval for this review is required.

Informed consent As this is a secondary review study is based on primary research, no new informed consent has been obtained. All included studies had informed consent a priori.

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