

# What are the benefits of robotic-assisted total knee arthroplasty over conventional manual total knee arthroplasty? A systematic review of comparative studies

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## Abstract

Total knee arthroplasty (TKA) is a highly successful operation that improves patients' quality of life and functionality. Yet, up to 20% of TKA patients remain unsatisfied with the functional outcomes. Robotic TKA has gained increased attention and popularity in order to improve patient satisfaction and implant survivorship by increasing accuracy and precision of component implantation. The current systematic review was run in order to compare implant survivorship, complication rates, clinical outcomes, and radiological outcomes between robotic-assisted TKA (RA) and conventional manual TKA (CM). Articles were referenced from the US National Library of Medicine (PubMed/MEDLINE), EMBASE, and the Cochrane Database of Systematic Reviews. Nine comparative studies with 1199 operated knees in 1159 patients were included, 614 underwent active or semi-active robotic-assisted TKA compared to 585 CM-TKA. Improvements in the RA group were reported for early functional outcomes, radiographic outliers (RA 16% vs CM 76%) and radiolucent lines (RA 0% vs CM 35%). No significant differences between the two groups were reported in

overall survivorship (RA 98.3% vs CM 97.3%), complication rate (RA 2.4% vs CM 1.4%) and operative time (RA 88 min vs CM 79 min). Despite higher costs, robotic-assisted TKA offers better short-term clinical outcomes when compared to conventional manual technique with reduction in radiographic outliers and reduced risks of iatrogenic soft tissues injuries (reduced blood loss and postoperative drainage). Further high-quality long-term studies of modern robotic systems are required in order to evaluate how the increased accuracy and reduced outliers affect the long-term survivorship of the implants and the clinical outcomes.

## Introduction

Total Knee Arthroplasty (TKA) has been widely recognized as the gold standard treatment for end-stage knee osteoarthritis.<sup>1,2</sup> This procedure is performed in more than 600.000 patients per year in the United States (US) and the number is projected to grow by 673% in 2030.<sup>3</sup> Despite the great improvements in implant design, materials and patient-specific rehabilitation programs, up to 20% of patients are dissatisfied following TKA.<sup>2,4</sup> Limb alignment and accuracy of implant positioning are widely considered among the most important prognostic factors for long-term implant survivorship, patient satisfaction and clinical outcomes.<sup>1,4-10</sup>

Robotic technology in TKA has been developed in order to increase accuracy in implant positioning and to reduce outliers in limb alignment compared to conventional manual technique.<sup>11-13</sup> However, trust on robotic-TKA is limited by increased costs and longer operative time, associated with a lack of long-term evidence comparing clinical and functional outcomes to conventional manual TKA.<sup>13</sup> The restoration of mechanical axis (0° within ± 3° of standard deviation [SD]) through tibial and femoral perpendicular cuts with respect to their mechanical axis is strongly associated with higher implant survivorship and clinical outcomes.<sup>11,12,14,15</sup>

The first robotic systems introduced in TKA were active robots based on CT images: ROBODOC® (Think Surgical, Fremont, CA, USA, originally by Integrated Surgical Systems) in 1992, and CASPAR System® (U.R.S.-ortho GmbH & Co. KG, Rastatt, DE). The surgeon was responsible of performing the surgical approach and exposition of the distal femur and proximal tibia, secure the limb into a fixed device and let the robot perform the planned bone resections. However, the CASPAR system

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Key words: Robotic surgery, Total knee arthroplasty, Robotic knee surgery, Clinical outcomes, Survivorship.

Contributions: FM, GC, IDM: designing the work. FM, GC, RDF, VDM, GA, DDM, MAM, IDM: acquisition and analysis of the data and drafting the work. IDM, GM, PKS: revised it critically for important intellectual content. IDM: final approval of the version to be published.

Conflict of interests: the authors declare no potential conflict of interests.

Funding: none.

Availability of data and materials: The dataset used and analyzed is available from the corresponding author.

Ethics approval and consent to participate: Not applicable.

Informed consent: Not applicable.

Received for publication: 11 April 2020.

Accepted for publication: 17 June 2020.

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Orthopedic Reviews 2020; 12(s1):8657  
doi:10.4081/or.2020.8657

was somewhat restrictive: femoral and tibial bone screws had to be placed preoperatively (during an initial first surgery) as fiducial markers for registration of the CT-scan in order to allow for intraoperative robotic functions. Autonomous robots had fallen out of favor due to concern over nerve and soft tissue injury and have been progressively replaced by semiautonomous systems.<sup>16,17</sup>

## Classification of robotic systems

There are three types of robotic system: autonomous (active), hands-on (semi-active) and passive, based on the degree of surgeon control over the robot. The passive systems do not perform independently the operation, they are known as computer-assisted or navigation systems based on patient- and

instrument- centered reference points to provide the surgeon with perioperative recommendations and guide positioning of the surgical tool.<sup>18</sup> Active robots hold the cutting tool and autonomously make the tibial and femoral resections. Semi-active robots combine both principles, the surgeon maintains the overall control over the bone resections under the surveillance of the robot that provides a live intraoperative feedback to limit deviation from the preoperative surgical plan.<sup>12,13</sup> A three-dimensional model of the knee is obtained either intraoperatively or from dedicated preoperative images through an integrated surgical planning system that allows to make a plan of bone resections and implant positioning (Table 1).<sup>12,13</sup>

Currently, the semi-active robotic systems are widely used in robotic-assisted TKA. The Mako Robotic Arm Interactive Orthopaedic system (RIO; former MAKO Surgical Corp.®, FL, USA; now Stryker Ltd, Kalamazoo, MI, USA), approved by the Food and Drug Administration (FDA) for TKA in 2015, is an image-guided semi-active robot system that requires a CT scan to generate a 3D model of the patient's bone structure. The plan can be modified intraoperatively with data collected during the operation and applied to the CT model. The Navio Surgical System (former Blue Belt Technologies; now Smith & Nephew, Andover, TX, USA), approved by the FDA for TKA in 2017, is an imageless CT-free semi-active robot system that intraoperatively capture the osseous anatomy during the planning phase and guides bone resection without haptic boundaries. In early 2019 was introduced the Rosa Knee System (Zimmer-Biomet, Warsaw, IN, USA), a stereotaxic instrumentation system. Three-dimensional (3D) model of the knee is obtained from preoperative two-dimensional x-rays or based on MRI planning tools, landmarks are recorded intraoperatively based on the surgical plan. This system enables the surgeon to personalize in real time the surgical plan based on each patient's individual characteristics. The cutting jigs are positioned and hold by the robot

(collaborative robotic system, a.k.a. cobot), while the surgeon performs the bone cuts.<sup>19</sup> Conversely, the Navio Surgical System and the Mako Robotic Arm Interactive Orthopaedic system do not require cutting blocks but creates stereotactic boundaries that assist the surgeon in the tibial and femoral resections.

### Limitations of robotic-assisted systems

Multiple limitations have been addressed to robotic-assisted TKA: installation and maintenance costs for the robotic devices, additional costs as a consequence of the longer surgical time, the long learning curve of the surgeon and surgical team, eventual additional imaging required for the preoperative plan with increased radiation exposure (when considering image-based systems) and femoral and tibial incisions for insertion of the registration pins.<sup>20,21</sup> In addition, it has been reported an increased blood loss and a longer anesthesia due to the longer surgical time with the first generation of robotic systems.<sup>20,21</sup> Implant choice in robotic-assisted procedures is often limited by whether or not a robotic system utilizes an "open" or "closed" platform: closed platforms (MAKO system, Rosa Knee System, Navio system) limit the surgeons to specific, proprietary implant types; open platforms (ROBODOC system), however, permit the surgeon to use multiple implants from different companies depending on the surgeon's preference. Lastly, fully active robotic systems have been associated with and increased soft tissue disruption and technical difficulties when converting to a conventional manual-jig procedure.<sup>20</sup>

In order to obtain a wider vision on the benefits of robotic-assisted TKA over conventional manual TKA, a systematic review of comparative studies was run to establish survivorship of the implant, complication rates, clinical outcomes, and radiographic outcomes.

## Materials and Methods

The systematic search was conducted in accordance with the Preferred Reporting

Items for Systematic Reviews and Meta-Analyses guidelines. The US National Library of Medicine (PubMed/MEDLINE), EMBASE, and the Cochrane Database of Systematic Reviews were queried for publications from January 1990 to December 2019 using various combinations of the search terms "total knee arthroplasty," "robot-assisted total knee arthroplasty," "robotic total knee", "robot total knee replacement" in combination with the Boolean operators (AND, OR, \*).

Only abstracts that compared the clinical outcomes of patients who underwent robotic TKA with conventional manual TKA were reviewed. Inclusion criteria were any original study in which patients 18 years and older received a primary TKA, postoperative complications were reported, clinical outcomes were reported using validated patient-reported scales, radiographic outcomes were reported and implant survivorship free of implant revision was reported. Exclusion criteria were case reports, surgical technique reports, review articles, expert opinions, letters to editors, biomechanical reports, instructional course lectures, studies on animal, cadaver or in vitro investigations, book chapters, abstract from scientific meetings, unpublished reports, studies with less than 20 knees per group, studies with a mean follow-up less than 3 months and studies written in non-english language.

Two independent reviewers (F.M. and G.C.) separately conducted the described search by title and abstract. Both authors compiled a list of studies not excluded after application of the inclusion and exclusion criteria. If the title and abstract of each study contained insufficient information to determine its appropriateness for inclusion, the full manuscript was reviewed. If the articles met inclusion criteria following a title and abstract screen, the full text was obtained and reviewed. A cross-reference research of the selected articles was also performed to obtain other relevant articles for the study. If there was disagreement between the 2 reviewers, the senior author (I.D.M.) was consulted and consensus was reached. During

**Table 1. Robotic Systems and Functional Characteristics.**

System	Corporation	Arthroplasty	Preoperative Planning	Control	Platform	Bone Resection
ROBODOC	THINK Surgical, Freemont, CA, USA	TKA, THA (femur)	CT scan	Autonomous	Open	Mill
iBlock	OMNlife Science, East Taunton, MA, USA	TKA	None	Autonomous	Closed	Saw
CASPAR	U.R.S.-ortho GmbH & Co. KG, Rastatt, DE	TKA, THA	CT scan	Autonomous	Open	Mill
MAKO	Stryker Ltd, Kalamazoo, MI, USA	UKA, PFA, TKA, THA	CT scan	Semiautonomous, haptic	Closed	Burr, saw
Navio PFS	Smith & Nephew, Andover, TX, USA	UKA, PFA, TKA	None	Semiautonomous	Closed	Burr, saw
Rosa knee	Zimmer-Biomet, Warsaw, IN, USA	TKA	None	Semiautonomous	Closed	Saw

TKA, Total Knee Arthroplasty; THA, Total Hip Arthroplasty; UKA, Unicodylar Knee Arthroplasty; PFA, Patellofemoral Arthroplasty.

initial review of the data, the following information were collected for each study: title, first author, year of publication, study design, number of patients, patients dead and lost at follow-up, age of patients, length of follow-up, type of robotic system, type of knee implant, complications, survivorship of the implants, radiographic and patients-reported outcomes.

The level of evidence in the included studies was determined using the Oxford Centre for Evidence-Based Medicine Levels of Evidence. The methodological quality of each study and the different types of detected bias were assessed independently by each reviewer with the use of modified Coleman methodology score.<sup>22</sup>

## Results

### Study Selection

The search resulted in 107 abstracts that were examined (Figure 1). Following elimination of duplicate articles, predetermined inclusion and exclusion criteria were applied. In total, 9 articles<sup>16,18,23-29</sup> met the inclusion criteria and were included in the analysis (Table 2).

### Quality of studies and possible risk of bias

Among the 9 studies, 3 were randomized control trials (RCTs) (out of 9, 33%)<sup>23,24,26</sup>, 3 (33%)<sup>18,25,29</sup> prospective comparative studies and 3 (33%)<sup>16,27,28</sup> retrospective comparative

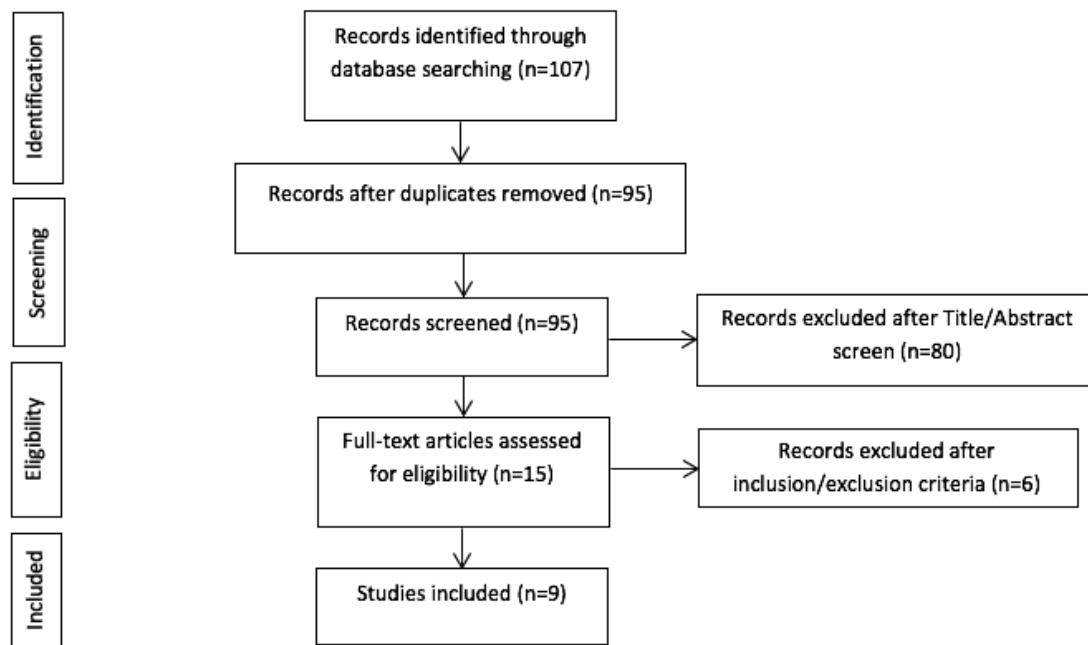
studies. Two studies (22%)<sup>23,26</sup> were classified as level of evidence (LOE) I, 1 study (11%)<sup>24</sup> as LOE II, 1 study (11%)<sup>16</sup> as LOE III and 5 studies (55%)<sup>18,25,27-29</sup> as LOE IV.

The “quality assessment” of the studies for methodological deficiencies was examined using the modified Coleman methodology score.<sup>22</sup>

The total mean modified Coleman score was 58/100 (range, 40/100 to 72/100) assessing for fair overall quality of the studies. Selection, detection and performance biases were found in 6 studies out of 9.<sup>16,18,25,27-29</sup> A meta-analysis was not undertaken due to the general fair quality of the studies (Table 2).

**Table 2. Type of study, level of evidence, mean follow up per study.**

Author	Type of study	Level of evidence	Mean follow up (months)	Modified Coleman score	Type of bias
<i>Khlopas et al. 2019</i>	Prospective case control	IV	3	66	Selection, detection and performance
<i>Cho et al. 2019</i>	Retrospective case control	IV	130	48	Selection, detection and performance
<i>Yang et al. 2017</i>	Retrospective case control	IV	126 (100-138)	45	Selection, detection and performance
<i>Merchand et al. 2017</i>	Prospective case control	IV	6	60	Selection, detection and performance
<i>Liow et al. 2016</i>	Randomized control trial	II	24	67	Detection and performance
<i>Song et al. 2013</i>	Randomized control trial	I	65 (41-81)	72	Detection and performance
<i>Song et al. 2011</i>	Randomized control trial	I	16 (13-19)	57	Detection and performance
<i>Park et al. 2007</i>	Prospective case control	IV	45	63	Selection, detection and performance
<i>Siebert et al. 2002</i>	Retrospective case control	III	6	40	Selection, detection and performance



**Figure 1. PRISMA flow diagram outlining the systematic review process. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.**

## General characteristics

Overall, 1199 TKAs in 1159 patients were included in the systematic review; robotic-assisted (RA) TKA was performed in 614 knees (51%, 608 patients) whereas conventional manual (CM) TKA was performed in 585 knees (49%, 551 patients). Women represented 72% of the patients in the RA-TKA group and 70% in the CM-TKA group. The mean age of the patients in the RA-TKA group was 66 years (range, 63 to 69 years), while in the CM-TKA group was 68 years (range, 65 to 68 years). The mean follow-up was 46 months (range, 3 months to 11 years) (Table 3).

The ROBODOC® System (Think Surgical, Fremont, CA, USA) was used in 6 studies (67%)<sup>18,23,24,26-28</sup>, the MAKO Robotic-Arm (MAKO Surgical Corp, Ft. Lauderdale, FL, USA) in 2 studies (22%)<sup>25,29</sup> and the CASPAR® System (U.R.S.-ortho GmbH & Co. KG, Rastatt, DE) in 1 study (11%)<sup>16</sup>.

In the RA-TKA group the NexGen knee system (NexGen®, Zimmer Inc., Warsaw, IS, USA) was implanted in 374 knees (out of 614, 61% in the RA group), the Triathlon Cruciate Retaining system (Stryker, Mahwah, NJ) in 170 cases (28%) and the LC Search Evolution® knee-system (Aesculap, Tuttlingen, Germany) in 70 cases (11%). In the CM-TKA group the NexGen knee system (NexGen®, Zimmer Inc., Warsaw, IS, USA) was implanted in 463 cases (out of 585, 79%) and the Triathlon Cruciate Retaining system (Stryker, Mahwah, NJ) in 122 cases (out of 585, 21%) (Table 3).

The operating time was reported in 4 studies out of 9 (44%)<sup>16,23,24,26</sup>. Three studies

(11%)<sup>23,24,26</sup> reported mean surgical time of 88 minutes in the RA group (range, 79-95 minutes) and of 79 minutes in the CM group (range, 70-93 minutes). Among the 4 studies, 3 did not achieved statistical significance ( $p$ =not significant). However, Song *et al.*<sup>23</sup> reported that the mean operative time in the RA group was 25 minutes longer when compared with the CM group ( $p$ <0.001), while the postoperative blood drainage was higher in the CM group ( $933 \pm 467$  mL) when compared with the RA group ( $613 \pm 318$  mL,  $p$ <0.001). Song *et al.*<sup>26</sup> reported a lower mean blood loss in the RA group ( $568.6$  mL,  $SD \pm 385$ ) when compared with the CM group ( $816$  mL,  $SD \pm 425$ ,  $p=0.005$ ).

## Survivorship and complication rates

Four studies (44%)<sup>24,26-28</sup> reported revision rates. The overall revision rate was 1.7% in the RA group and 2.7% in the CM group. Yang *et al.*<sup>27</sup> reported an overall survivorship of 98.5% at 5 years in the RA group and 97.6% in the CM group; 97.1%, and 92.3% respectively at 10 years ( $p=0.31$ ). Cho *et al.*<sup>28</sup> reported an overall survivorship of 98.8% in the RA group and 98.5% in the CM ( $p=0.563$ ), with no cases of aseptic loosening in the RA group compared to the two cases in the CM group (1%,  $p=0.48$ ). Song *et al.*<sup>26</sup> reported a survivorship among both groups of 100% at short-term follow up (1.3 years) from infection and aseptic loosening. Liow *et al.*<sup>24</sup> reported an overall survivorship of 93.5% in the RA group and 100% in the CM group at a mean follow-up of 2 years. One of the 2 revision in the RA group was due to persistent lateral-sided pain

secondary to lateral overhang of the tibial component at 20 months, likely related to manual implantation after abortion of robotic procedure (Table 4).

Six studies (66.7%)<sup>16,18,23,24,27,28</sup> reported complications that required reoperation with an overall reoperation rate of 2.4% in the RA group (15 out of 614) and 1.4% in the CM group (8 out of 331) at a mean follow-up of 5.5 years (range, 0.5-10.8 years). However, none of the studies reported statistical significance when comparing the two groups ( $p=0.27$ ,  $p=0.48$ ). Periprosthetic joint infection was the most frequent complication among both groups (RA 1.7%; CA 1%). Complications directly associated to the robotic systems surgical technique were reported in 2.3% of the cases (14 out of 614). Further complications that did not required reoperation are addressed in Table 4.

## Radiographic outcomes

All studies aimed to mechanical alignment. Radiographic outliers were defined with an error greater of  $\pm 3^\circ$  for mechanical axis ( $\theta$ ), coronal ( $\alpha$ ) and sagittal ( $\gamma$ ) femoral inclinations and coronal ( $\beta$ ) and sagittal ( $\delta$ ) tibial inclinations. Five studies (55%)<sup>16,23,26-28</sup> analyzed radiographic outcomes and reported an overall rate of outliers of 16% (64 out of 381) in the RA group and 76% (306 out of 404) in the CM group. Among them, Song *et al.*<sup>23</sup> reported a significant reduction of outliers for mechanical axis in the RA group when compared with the CM group (0% vs 24%;  $p$ <0.001). Siebert *et al.*<sup>16</sup> reported a highly significant difference in tibiofemoral

**Table 3. Number of patients, sex, mean age, type of robot and type of knee implant per study.**

Author	Patients/knees	Sex	Mean age (years)	Type of robot	Type of knee implant
<i>Khlopas et al. 2019</i>	RA: 150/150 CM: 102/102	RA: 95f/55m CM: 59f/43m	RA: 65 CM: 68	MAKO	Triathlon CR
<i>Cho et al. 2019</i>	RA: 155/160 CM: 196/230	RA: 141f/14m CM: 163f/33m	RA: 68 CM: 68	ROBODOC	RA: NexGen CR: 157, PS 3 CM: NexGen CR: 167, PS 63
<i>Yang et al. 2017</i>	RA: 71/71 CM: 42/42	RA: 66f/6m CM: 39f/3m	-	ROBODOC	NexGen CR
<i>Merchand et al. 2017</i>	RA: 20/20 CM: 20/20	RA: 14f/6m CM: 10f/10m	RA: 69 CM: 67	MAKO	Triathlon CR
<i>Liow et al. 2016</i>	RA: 31/31 CM: 29/29	-	-	ROBODOC	NexGen LPS Flex
<i>Song et al. 2013</i>	RA: 50/50 CM: 50/50	RA: 46f/4m CM: 45f/5m	RA: 66 CM: 65	ROBODOC	NexGen
<i>Song et al. 2011</i>	RA: 30/30 CM: 30/30	RA: 30f CM: 30f	-	ROBODOC	NexGen
<i>Park et al. 2007</i>	RA: 32/32 CM: 30/30	-	RA: 63 CM: 68	ROBODOC	NexGen LPS
<i>Siebert et al. 2002</i>	RA: 69/70 CM: 52/52	RA: 48f/21m CM: 40f/12m	RA: 66 CM: 68	CASPAR	RA: LC Search Evolution CM: NexGen

RA, Robot-assisted technique; CM, Conventional-manual technique; -, Not reported.

alignment between the two groups (RA: 1/70, 1.4% [4° deviation from planned angle] vs CM: 18/52, 35% [deviation >3°-7°];  $p<0.0001$ ). Song *et al.*<sup>26</sup> reported a significant improvement in outliers for tibial sagittal inclination ( $\delta$ ) (RA 2/30, 7% vs CM 15/30, 50%;  $p=0.001$ ), for femoral coronal inclination ( $\alpha$ ) (RA 0% vs CM 8/30, 27%;  $p=0.008$ ) and for mechanical axis ( $\theta$ ) (RA 0% vs CM 7/30, 23%;  $p=0.001$ ). Yang *et al.*<sup>27</sup> reported a significant improvement regarding radiographic outliers for mechanical axis ( $\theta$ ) (RA 6/69, 9% vs CM 13/39, 33%;  $p<0.001$ ), coronal femoral inclination ( $\alpha$ ) (RA 4/69, 6% vs CM 12/39, 31%;  $p<0.001$ ), sagittal femoral inclination ( $\gamma$ ) (RA 10/69, 14% vs CM 23/39, 60%;  $p<0.001$ ) and sagittal tibial inclination ( $\delta$ ) (RA 6/69, 9% vs CM 17/39, 44%;  $p<0.001$ ). Finally, Cho *et al.*<sup>28</sup> reported a higher rate of outliers among the CM group (91%, 128 cases) when compared to the RA group (19%, 22 cases;  $p<0.05$ ).

Radiolucent lines (RLLs) were analyzed in only one study (11%); Yang *et al.*<sup>27</sup> reported no cases of radiolucent lines (RLLs) in the RA group and 6 cases (35%) in the CM group (4 on the femoral side and 2 on the tibial side) at a mean of 10.5 years (range, 8.4 - 11.5 years); none of the RLLs

were progressive and 5 of them (83%) were <2mm ( $p<0.001$ ).

### Clinical outcomes

Clinical outcomes were reported in all 9 studies (100%)<sup>16,18,23-29</sup> with significant postoperative improvements compared to the respective mean preoperative values. Six studies (66%)<sup>18,23,24,26-28</sup> reported a mean postoperative range of movement (ROM) in the RA group of 126° (range 118°-133°) and of 128° (range 122°-131°) in the CM group. The Hospital for Special Surgery (HSS) score was used in 4 studies (44%)<sup>23,26-28</sup> reporting a mean postoperative value of 92 points in the RA group (range, 88.5-96.7 points) and 91 points in the CM group (range, 86.7-94.7 points). The Western Ontario and McMaster Universities (WOMAC) score was used in 5 studies,<sup>23,26-29</sup> reporting a mean value of 13 points in the RA group (range, 7-29 points) and 16 points in the CM group (range, 11-30 points) ( $p<0.05$ ). Liow *et al.*<sup>24</sup> reported a better SF-36 general health ( $p=0.04$ ) at 6 months and a better SF-36 vitality ( $p=0.03$ ) and role emotional ( $p=0.02$ ) at 2 years postoperatively in the RA group when compared with the CA group. The postoperative Knee Society Score (KSS) was

used in 3 studies,<sup>18,24,25</sup> reporting a mean value of 80 points in the RA group (range, 66-92 points) and 82 points (range, 67-91 points) in the CA group ( $p<0.001$ ) (Table 5).

## Discussion

Robotic-assisted technique has been associated with increased accuracy and precision in coronal and sagittal alignment, better early functional outcomes and reduced limb malalignment compared with conventional manual-jig technique.<sup>11-13,15</sup>

Based on the current evidence there is no difference in short-to-mid term survivorship, aseptic loosening, periprosthetic joint infection and complication rates between RA-TKA and CM-TKA. In addition, there is no significant difference regarding the operating time between the two techniques suggesting that longer time is not associated with increased complication. The incidence of pin-related fracture as technique-related complication is very low and overall not reported in the literature, however, technique-related complications were reported in 2.3% of the cases in the RA group.

**Table 4. Complications in Robotic-Assisted and Conventional Manual-jig Technique.**

Author	RA Complications	CM Complications
Khlopas <i>et al.</i> 2019	-	-
Cho <i>et al.</i> 2019	2 Deep infections (two-stage revision)	1 Deep infection (two stage revision) 2 Aseptic Loosening (implant revision) 2 Polyethylene wear (implant revision) 1 Knee instability (implant revision) ( $p=0.48$ )
Yang <i>et al.</i> 2017	2 Deep infection (two-stage revision) No cases of radiolucent lines	2 Deep infection (two-stage revision) 1 Knee instability (implant revision) ( $p=0.27$ ) 6 Radiolucent lines, non-progressive ( $p<0.001$ )
Merchand <i>et al.</i> 2017	-	-
Liow <i>et al.</i> 2016	1 Superficial wound infection 1 Early infection (washout and liner exchange) 1 Lateral pain in tibial component due to malposition after aborted procedure (revision tibial component) 1 Deep vein thrombosis 3 Abortion of robot procedure (2 technical error and 1 robot error)	1 Deep vein thrombosis
Song <i>et al.</i> 2013	2 Superficial wound infections 1 Seroma at pin site 2 patellar tendon abrasion 1 Skin rash (conservative treatment)	2 Superficial wound infections 1 Incisional skin sloughing
Song <i>et al.</i> 2011	-	-
Park <i>et al.</i> 2007	1 Superficial wound infection 1 Patellar tendon rupture 1 Patellar dislocation 1 Peroneal injury	-
Siebert <i>et al.</i> 2002	3 Skin irritation at pin site (conservative treatment) 1 Complication due to defective registration marker, full correction achieved by converting to a manual technique	-

RA, Robotic-assisted technique; CM, Conventional manual-jig technique.

Regarding clinical outcomes, patients' satisfaction was increased in RA-TKA group with better early clinical outcomes compared to CM-TKA and no significant differences of ROM were reported between the two groups, in line with what is reported in the current literature.<sup>12,13</sup> Previous studies suggested that postoperative ROM and implant stability are influenced from the posterior inclination of the tibial component.<sup>12,30</sup> In addition, insufficient knee ROM is usually caused by inappropriate component sizing, a tight extension or flexion gap, component malalignment or malrotation, a lack of rehabilitation and swelling of the periarticular soft tissue.<sup>31</sup> Siebert *et al*,<sup>16</sup> reported reduced soft tissue swelling and earlier regain of full ROM in the RA group when compared to the CM group. However, there was no significant difference regarding ROM between the two groups and soft tissue swelling was not properly quantified. Nevertheless, WOMAC and KSS scoring systems showed significantly higher scores in the RA-TKA group ( $p < 0.05$ ). Improved preservation of the periarticular soft tissue in robotic TKA may reduce local postoperative inflammatory response, pain and postoperative soft tissue swelling. According to our results, in the RA group was reported a reduced mean intraoperative blood loss (RA 568 mL, SD  $\pm$  385 vs CM 816mL, SD  $\pm$  425;  $p = 0.005$ ) and reduced postoperative drainage (RA 613  $\pm$  318 mL vs CM 933  $\pm$  467 mL;  $p < 0.001$ ).<sup>23,26</sup> These findings, in line with the current literature,<sup>13</sup> support that increased soft tissue protection is associated with reduced postoperative pain and periarticular swelling, leading to better early clinical outcomes. However, only two

studies included in this systematic review compared blood loss and postoperative drainage between the two groups, more evidences are needed to evaluate the association between intraoperative soft tissue protection and early clinical outcomes.

Regarding the radiological findings, lower incidence of outliers was assessed for mechanical axis ( $\theta$ ), coronal ( $\alpha$ ) and sagittal ( $\gamma$ ) femoral inclinations and coronal ( $\beta$ ) and sagittal ( $\delta$ ) tibial inclinations confirming the higher accuracy and precision of the technique. The high degree of accuracy was demonstrated in the cadaveric study by Parratte *et al*,<sup>19</sup> using the Rosa Knee System (Zimmer-Biomet, Warsaw, Indiana, USA). The author reported no significant difference compared to the preoperative plan in resection angles (except for the femoral flexion angle, mean difference of  $-0.95^\circ$ ); no differences regarding the thickness of the resection (except for the distal medial femoral and medial proximal tibial cuts) and the hip-knee-ankle angle mean difference was  $-0.03^\circ \pm 0.87^\circ$ . However, further *in vivo* studies are necessary to evaluate if the accuracy obtained in a cadaveric study is reproducible in larger cohorts. Given the similar mid-term survivorship between RA-TKA and CM-TKA, the significative higher accuracy and precision in alignment correction and the lower incidence of outliers in both coronal and sagittal planes might represent a strong determinant for implants long-term survivorship, where there are still no studies available.

Surgical time continues to be an issue in robotic-assisted technique; it can lead to a higher risk of infection, blood loss and other postoperative complications,<sup>32</sup> 127 min has been indicated as a critical point leading to

an increased risk of infection.<sup>33</sup> According to Hampp *et al*,<sup>34</sup> following a single cadaver training for a surgeon with no previous robotic experience, it was sufficient a number of 12 RA-TKAs to obtain greater accuracy and precision compared with the conventional manual technique. Siebert *et al*,<sup>16</sup> reported a longer surgical time for the first 70 robotic cases (mean 135 minutes, range 80-220 minutes) followed by an almost normal surgical time (approximately 90 minutes). Song *et al*,<sup>26</sup> reported a mean operative time 25 minutes longer in the robotic-assisted TKA but no increased complication rates in short-term follow-up. Sodhi *et al*<sup>35</sup> analyzed the learning curve of two high-volume surgeons with no previous experience in robotic-assisted TKA in 40 cases and reported a significant decrease in operative time from the first 20 cases to the last 20 cases. In addition, there was no significant difference between the last 20 robotic-assisted cases compared to the conventional manual technique (99 vs 84 vs 81 minutes;  $p < 0.05$ ). Kayani *et al*,<sup>36</sup> reported that robotic-assisted TKA was associated with a learning curve of 7 cases for operative time and surgical team comfort levels but there was no learning curve for accuracy of implant positioning, limb alignment, posterior condylar offset ratio, posterior tibial slope and joint line preservation.

Increased costs are a consistent problem in robotic surgery. According to the current literature, these costs may be partially offset since RA patients had statistically significantly lower 90-day Episode-of-Care costs ( $p < 0.0001$ ), lower facility costs, shorter length-of-stay, and higher chance of being dismissed at home.<sup>37</sup> One potential cost-related concern is the preoperative imaging

**Table 5. Operating Time, ROM, HSS, WOMAC, KSS and KS Function Score.**

Author	Clinical Outcome Scale	Significant Difference between RA-TKA and CM-TKA
Khlopas <i>et al</i> . 2019	KSS <sup>1</sup>	NO <sup>1</sup> RA 65.5-CM 67.2
Cho <i>et al</i> . 2019	ROM <sup>1</sup> , HSS <sup>2</sup> , WOMAC <sup>3</sup> , KSf <sup>4</sup>	NO <sup>1</sup> RA 130.7°-CA 130°; <sup>2</sup> RA 88.5-CM 86.7; <sup>3</sup> RA 10.1-CM 13; <sup>4</sup> RA 87.8-CM 87.4
Yang <i>et al</i> . 2017	ROM <sup>1</sup> , HSS <sup>2</sup> , WOMAC <sup>3</sup>	NO <sup>1</sup> RA 132.6°-CM 131; <sup>2</sup> RA 89-CM 88; <sup>3</sup> RA 7.6-CM 11.5
Merchand <i>et al</i> . 2017	WOMAC	YES RA 7-CM 14 ( $p < 0.05$ )
Liow <i>et al</i> . 2016	ROM <sup>1</sup> , KSS <sup>2</sup> , KSSf <sup>3</sup>	NO <sup>1</sup> RA 118°-CM 125°; <sup>2</sup> RA 82-CM 88; <sup>3</sup> RA 77-CM 74
Song <i>et al</i> . 2013	ROM <sup>1</sup> , HSS <sup>2</sup> , WOMAC <sup>3</sup>	NO <sup>1</sup> RA 128°-CM 129°; <sup>2</sup> RA 96.7-CM 94.7; <sup>3</sup> RA 28.9-CM 30
Song <i>et al</i> . 2011	ROM <sup>1</sup> , HSS <sup>2</sup> , KSS <sup>3</sup>	NO <sup>1</sup> RA 129°-CM 129°; <sup>2</sup> RA 95.2-CM 94.7; <sup>3</sup> RA 11-CM 13
Park <i>et al</i> . 2007	ROM <sup>1</sup> , KSS <sup>2</sup> , KSSf <sup>3</sup>	NO <sup>1</sup> RA 118°-CM 122°; <sup>2</sup> RA 92-CM 91; <sup>3</sup> RA 88 CM 88

ROM, Range of Movement; HSS, Hospital for Special Surgery Score; WOMAC, Western Ontario and McMaster Universities; KSS, Knee Society Score; RA, robotic-assisted technique; CM, conventional-manual technique.

such as CT-scans; however, this enhanced imaging modality did not contribute to net higher overall healthcare costs.<sup>37</sup> Kayani *et al.*<sup>36</sup> reported that reduced bone and periarticular soft tissue injury is a factor in lowering the overall cost by reducing the post-acute care. The soft tissue protection in RA technique has been previously described in a cadaveric study by Khlopas *et al.*<sup>38</sup> assessing that in robotic-assisted technique tibial subluxation and patellar eversion are not required in order to achieve an optimal visualization, reducing ligament and capsular stretching, length of stay, and complication rate. Kayani *et al.*<sup>39</sup> in order to standardize the soft tissue involvement, proposed a Macroscopic Soft Tissue Injury classification (MASTI) based on intraoperative assessment of the soft tissue envelope. The knee was divided in four zones (medial tibial, lateral tibial, anterior and posterior), evaluated for soft tissue iatrogenic injury and graded from stage 1 to 6: uninvolved soft tissue, planned soft tissue release, soft tissue contusion, soft tissue fibrillation or incomplete damage, soft tissue cleavage and complete unintentional soft tissue detachment. The sawblade, active only within the confines of the stereotactic boundaries, may have helped to better protect the periarticular soft tissue envelope compared to the manually controlled sawblade.

Promising results of the robotic-assisted technique have been reported in the unicompartmental total knee arthroplasty using the Robotic Arm Interactive Orthopedic (RIO) System (MAKO Surgical Corp., Ft. Lauderdale, FL, USA) with 2-to-3 years survivorship of 98.8%.<sup>40</sup> Significant improved outcomes have been described by Zhang *et al.*<sup>41</sup> In addition, Batailler *et al.*<sup>42</sup> compared the BlueBelt Navio surgical system (Smith and Nephew®) with the conventional manual technique reporting a better overall alignment and no cases of complications directly related to the robotic technique.

Multiple limitations have been encountered. The majority of the studies involved (7 out of 9, 78%) robotic systems no longer in use since the fully active ROBODOC System® and the CASPAR System® are now outdated and replaced by the newer systems. Functional outcomes were evaluated using various systems, which made it difficult to organize it and give an overall interpretation. The majority of the studies included (5 out of 9) were level of evidence IV with reported selection, detection and performance bias.

## Conclusions

This systematic review of comparative studies supports that robotic-assisted TKA offers benefits in accuracy, precision and alignment correction with lower outliers and reduced errors in coronal and sagittal planes. Patients' satisfaction in RA-TKA is increased in the early postoperative time with better clinical outcomes compared to CM-TKA. Short-to-mid-term survivorship and complication rates did not show significant difference among the two groups. However, further high-quality long-term studies and RCTs comparing modern robotic systems and conventional manual technique are needed to validate the relationship between improved accuracy and implant survivorship, complication rates, functional outcomes and cost-effectiveness.

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