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KNEE ARTHROPLASTY

The evolution of robotic systems for total knee arthroplasty, each system must be assessed for its own value: a systematic review of clinical evidence and meta-analysis

Hannes Vermue[1] · Cécile Batailler[2] · Paul Monk[3,6] · Fares Haddad[4] · Thomas Luyckx[5] · Sébastien Lustig[2]

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Abstract

Introduction Robotic systems have been introduced to improve the precision of total knee arthroplasty. However, different robotic systems are available, each with unique features used to plan and execute the surgery. As such, due to this diversity, the clinical evaluation of each robotic platform should be separated.

Methods An extensive literature search of PubMed, Medline, Embase and Web of Science was conducted with subsequent meta-analysis. Randomised controlled trials, comparative studies, and cohort studies were included regarding robot-assisted total knee arthroplasty. Evaluated outcomes included clinical results, surgical precision, ligament balance, surgical time, learning curve, complications and revision rates. These were split up based on the robot-specific brand: ROBODOC (T-SOLUTION ONE), OMNIBOT, MAKO, NAVIO (CORI) and ROSA.

Results With a follow-up of more than 10 years, no improved clinical outcomes have been noted with the ROBODOC system compared to the conventional technique. If available, other platforms only present short-term clinical outcomes. Radiological outcomes are published for most robotic setups, demonstrating improved surgical precision compared to the conventional technique. Gap balance assessment is performed differently between all systems, leading to heterogeneous outcomes regarding its relationship on clinical outcomes. There is a similar learning curve based on operative time for all robotic platforms. In most studies, robot assistance requires longer operative time compared to the conventional technique. Complications and revision rates are published for ROBODOC and MAKO, without clear differences to conventional total knee arthroplasty.

Conclusion The main finding of this systematic review is that the current evidence regarding each robotic system is diverse in quantity and quality. Each system has its own specificities and must be assessed for its own value. Regarding scientific literature, the generic term of robotic should be banned from the general conclusion.

Level of evidence Systematic review level IV.

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

✉ Hannes Vermue
Hannes_Vermue@hotmail.com

1 Department Orthopaedic Surgery, University Hospital Ghent, Ghent, Belgium

2 Department Orthopaedic Surgery, University Hospital Centre Lyon, Lyon, France

3 Department Orthopaedic Surgery, Auckland City Hospital, Grafton, New Zealand

4 Department of Trauma and Orthopaedics, University College Hospital, London, UK

5 Department Orthopaedic Surgery, AZ Delta, Roeselare, Belgium

6 Auckland Bioengineering Institute, University of Auckland, Grafton, New Zealand

Introduction

The field of total knee arthroplasty (TKA) has been continuously evolving throughout the last decades. While the main idea of resurfacing has remained, multiple technical concepts and innovations have been the target of change [2, 12, 35, 47]. For instance, surgical navigation and patient-specific instruments were introduced to improve surgical precision compared to conventional instruments. However, due to lack of long-term clinical benefit, neither surgical navigation nor patient-specific instruments are systematically used today [2]. Recently, robots have been added to the surgeons' arsenal to improve surgical precision even further. They provide the surgeon a real-time evaluation of the knee joint, while (semi-) actively aiding to perform the required bony cuts during TKA [51, 56, 61]. Although the first robot-assisted (RA) TKA has been performed in 1988 using the ACROBOT system, the current robotic platforms are not identical to what they were during initial development [17]. The introduction of the currently available robotic systems has led to an increase in RATKA. However, similarly to surgical navigation and patient-specific instruments, the question remains whether robotics will be used systematically in all cases in the long run. Of note is the increasing attention to data collection, which could be a thriving factor for using robotics, at least for scientific purposes [16]. The large amount of data collected during surgical workflow allows precise correlation with clinical outcomes.

In the last couple of years, major orthopaedic firms have jumped on the bandwagon and released their own version of a robotic platform to aid the orthopaedic surgeon during total knee surgery [3, 19, 30, 64, 66]. However, each system has a unique set of design characteristics, which cannot be overlooked. First, the reference frame and working volume are either based on an image-less or image-based philosophy. Next, all systems have a different type of motor control to restrict the surgeon in performing bony resections. Third, ligament tension assessment could be performed manually, sensor assisted or standardised during full range of motion. Finally, most robotic systems are dedicated to brand-specific implants, partially limiting the opportunity to compare between the different available robotic platforms.

As a result, the clinical evidence regarding RATKA cannot be grouped indiscriminately. Therefore, these systems should be assessed separately by peer review. This systematic review serves the goal of evaluating present literature for each individual robotic system currently available, related to patient-reported outcome measures, surgical precision, ligament balance, learning curve, complications and revision rates.

Materials and methods

In December 2021, a search was performed in the electronical databases PubMed, Medline, Embase and Web of Science without date restriction. The reviewing process was completed independently by two authors (H.V. and C.B.). In case of disagreement, a third reviewer (S.L.) intervened to achieve consensus. The search strategy consisted the following terms: total knee replacement, total knee arthroplasty, robotics, robotic surgical procedure and robot-assisted. The reviewing process started with removal of all duplicates, after which all articles were evaluated for eligibility by title and abstract. Full-text articles were obtained for review to allow further assessment of inclusion and exclusion criteria. The reference lists of all relevant articles were reviewed to identify additional studies. This work was performed according to the PRISMA guidelines [29].

The inclusion criteria were defined as all English language studies evaluating clinical outcomes (patient-reported outcome measures and functional outcomes), surgical precision, gap balancing, learning curve, surgical time, complications and revision rates after RATKA. Randomised controlled trials, cohort studies and case–control studies were incorporated into the review process. The exclusion criteria were editorials, systematic reviews or meta-analyses, case reports, conference abstracts and the unavailability of full texts.

For both RATKA and conventional TKA, surgical precision was assessed as the difference between the intended implant position and the final position of the implant. The following variables were assessed regarding surgical precision: hip–knee–ankle axis (HKA), coronal femoral implant position, coronal tibial implant position, sagittal femoral implant position and sagittal tibial implant position. The methodology (radiography, computed tomography, intraoperative navigation) used to evaluate implant position was noted.

Data was collected using a predefined datasheet to behold the following study outcomes: clinical outcomes (patient-reported outcome measures and functional outcomes), surgical precision, learning curve, surgical time, complications and revision rates. The evidence was split up based on the robot used in the study: ROBODOC (T-SOLUTION ONE), OMNIBOT, MAKO, NAVIO (CORI) and ROSA (Table 1).

Quality assessment

The quality of the included studies and their relative risk of bias were evaluated with the ROBINS-I tool (Risk Of Bias In Non-Randomised Studies of Interventions) [58] (Table 2). The invested bias domains include bias due to confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes and selection of reported result. These domains were categorised based on the risk on bias being “low”, “moderate”, “serious” and “critical”. The worst judgement bias assigned within any one domain gives the judgement score of the complete study. All studies were screened for research funding or any conflict of interest to the orthopaedic company distributing the robotic system.

A meta-analysis was conducted using Review Manager 5.4 (Cochrane Collaboration, Oxford, UK) based on all studies comparing RATKA with conventional TKA. Heterogeneity among the studies was assessed using the χ^2 test and I^2. A fixed effect model was applied when $I^2 < 50\%$, and a random effects model when $I^2 > 50\%$. A p value < 0.05 was considered statistically significant.

Table 1 An overview of the robots analysed in this systematic review with their unique characteristics

	MAKO	NAVIO/CORI	ROSA	OMNIBOT	TSOLUTION
Release for TKA	2017	2017	2019	2017	2000
Image	Image based	Imageless	Both	Imageless	Image based
Control	Semi-active oscillating saw	Semi-active burr	Guided manual sawblade	Guided manual sawblade	Active burr
Boundary control	Yes	Contour-based	No	No	Yes
Dependent gap analysis	Manual	Manual	Manual	Standardised and integrated	None
Footprint	Standalone–big	Handheld	Standalone–big	Fixed to the patient	Standalone–big
Implant	TKA/UKA brand restricted stryker	TKA/UKA brand restricted smith and nephew	TKA/UKA Brand restricted zimmer-biomet	TKA brand restricted corin	TKA/UKA open access

Results

The PRISMA flow diagram can be seen in Fig. 1. After removal of duplicates, a total of 960 relevant references were found, and after screening, 92 full-text articles were assessed for eligibility. Further exclusion of 46 references and the addition of 2 articles by relevant references resulted in a total of 48 full-length articles [1, 3–9, 11, 13, 15, 18–20, 22, 24–27, 31–33, 36–44, 48, 49, 51, 52, 54–56, 58–67]. According to the ROBINS-I tool, 3, 41 and 4 studies were presented with low, moderate and serious risk of bias, respectively. In Appendix 1, an overview is given of all evidence for each system. In Appendix 2–6, each separate outcome is presented in detail.

ROBODOC/TSolution One

The ROBODOC system is the only system with long-term clinical follow-up. However, there was no short- or long-term (> 10 years) evidence illustrating better outcomes after total knee arthroplasty with ROBODOC compared to the conventional procedure. Of note, these studies were performed based on a principle of mechanical alignment. With respect to the radiological outcomes, there was no to some minor, although significant, improvement of surgical precision to achieve coronal and sagittal component alignment and hip–knee–ankle axis in case a robotic system was used [8, 18, 26, 33, 44, 55, 56, 67]. Based on the conducted meta-analysis, surgical precision was higher for ROBODOC compared to the conventional technique regarding HKA and tibial coronal and sagittal alignment ($p = 0.02$, 0.04 and 0.003 respectively, Fig. 2). Several studies have reported a lower proportion of outliers (> 3° coronal or sagittal malalignment compared to neutral mechanical alignment) in RATKA compared to the conventional procedure, but it was not correlated to improved clinical outcomes [8, 26, 33, 55, 56, 67]. Concerning gap balancing, there was one randomised controlled trial by Song and colleagues demonstrating a lower extent of gap imbalance (defined as a difference of > 2 mm between the extension and flexion gap) in case of RATKA compared to the conventional technique [56]. In this study, gap balance was obtained with a commercially available tensioner [56].

According to Mahure et al. there was a learning curve of 10–12 cases based on the exact operative times [37]. The transition of a learning phase to proficiency phase could be seen after 12–19 cases, based on a CUSUM (cumulative summation) analysis. There was no impact of the learning curve on patient outcomes and operative complications. Overall surgical time, from incision to skin closure, was on average 23 min longer with ROBODOC compared to conventional TKA ($p = 0.02$; Fig. 2, Appendix 6). There was no difference in complications, long-term revision rates or long-term implant survival compared to the conventional technique. In total, 17% (2/12) of the included studies on the ROBODOC system demonstrated industry funding with a potential conflict of interest.

OMNIBOT

One study by Blum et al. compared the Knee Osteoarthritis Outcome Scores (KOOS) of a prospective RATKA cohort with the KOOS of the FORCE-TJR cohort, which is an accessible database of conventional total knee arthroplasty outcomes. No significant differences were seen between the two cohorts [5]. Based on the automated gap evaluation with the BalanceBot, a target for gap balance was defined as a difference of 1.5 mm between either extension/flexion or medial/lateral gap. In a prospective trial by Keggi and colleagues, comparing the OMNIBOT with and without predictive plan by the BalanceBot, the utilisation of predictive balancing led to a significant increase of 37% (88 vs 51%) in the amount of knees classified as balanced. All balanced knees demonstrated improved KOOS for subscore Pain at 3 months postoperatively, subscore Symptoms at all postoperative time points, subscore Activities of Daily Life at

Table 2 Risk of bias analysis according to ROBINS-I tool and a conflict of interest summary

	Authors	Confounding	Selection of patients	Classification of interventions	Deviations from intended interventions	Missing data	Measurement of outcomes	Selection of reported results	Funding/conflict of interest
ROBODOC	Park et al. [44]	Moderate	Low	Low	Low	Low	Low	Low	No
	Song et al. [55]	Low	Low	Low	Low	Low	Low	Low	No
	Song et al. [56]	Low	Low	Low	Low	Moderate	Low	Low	Yes
	Liow et al. [31]	NA	NA	NA	NA	Low	Moderate	Moderate	No
	Liow et al. [33]	Low	Low	Low	Low	Low	Low	Low	No
	Liow et al. [32]	Moderate	Low	Low	Low	Low	Moderate	Moderate	No
	Yang et al. [67]	Moderate	Moderate	Low	Low	Moderate	Low	Low	No
	Cho et al. [8]	Moderate	Moderate	Low	Low	Moderate	Low	Low	No
	Jeon et al. [18]	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate	No
	Kim et al. [26]	Moderate	Low	Low	Low	Low	Low	Low	No
	Mahure et al. [37]	NA	NA	NA	NA	Moderate	Moderate	Moderate	No
	Stulberg et al. [59]	NA	NA	NA	NA	Low	Low	Low	Yes
OMNIBOT	Blum et al. [5]	NA	NA	NA	NA	Low	Moderate	Moderate	Yes
	Suero et al. [60]	Moderate	Moderate	Moderate	Low	Low	Moderate	Low	Yes
	Clark et al. [9]	Moderate	Serious	Low	Low	Moderate	Low	Low	No
	Nam et al. [42]	Moderate	Moderate	Low	Low	Low	Moderate	Low	No
	Figuero et al. [13]	Moderate	Moderate	NA	NA	Low	Low	Low	No
	Wakelin et al. [66]	Moderate	Moderate	NA	NA	Low	Moderate	Moderate	Yes
	Keggi et al. [24]	Moderate	Low	Low	Low	Low	Low	Moderate	Yes
ROSA	Vanlommel et al. [64]	Moderate	Moderate	Low	Low	Moderate	Moderate	Low	Yes

Table 2 (continued)

	Authors	Confounding	Selection of patients	Classification of interventions	Deviations from intended interventions	Missing data	Measurement of outcomes	Selection of reported results	Funding/conflict of interest
MAKO	Marchand et al. [40]	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate	NR
	Sodhi et al. [54]	Moderate	Serious	Low	Low	Serious	Serious	Moderate	No
	Kayani et al. [20]	Moderate	Low	Moderate	Low	Low	Moderate	Low	Yes
	Kayani et al. [22]	Moderate	Moderate	Moderate	Low	Low	Low	Low	Yes
	Kayani et al. [19]	Moderate	Low	Low	Low	Moderate	Moderate	Low	Yes
	Khlopas et al. [25]	Moderate	Moderate	Low	Low	Low	Moderate	Moderate	Yes
	Marchand et al. [39]	Moderate	Moderate	Low	Low	Low	Serious	Moderate	Yes
	Smith et al. [52]	Moderate	Low	Low	Low	Low	Moderate	Moderate	No
	Naziri et al. [43]	Moderate	Moderate	Low	Low	Low	Moderate	Low	No
	Sultan et al. [61]	Serious	Moderate	Moderate	Moderate	Serious	Moderate	Serious	Yes
	Bhimani et al. [4]	Moderate	Moderate	Low	Low	Moderate	Moderate	Low	Yes
	Malkani et al. [38]	NA	NA	NA	NA	Low	Low	Low	No
	Sires et al. [50]	NA	NA	NA	NA	Low	Moderate	Low	No
	Sires et al. [51]	NA	NA	NA	NA	Low	Moderate	Low	No
	Mitchell et al. [41]	Moderate	Moderate	Low	Low	Low	Moderate	Moderate	No
	Mahoney et al. [36]	Moderate	Moderate	Low	Low	Moderate	Low	Low	Yes
	Shaw et al. [49]	Moderate	Moderate	Moderate	Low	Low	Low	Low	No
	Vermue et al. [65]	NA	NA	NA	NA	Moderate	Moderate	Low	No
	Deckey et al. [11]	NA	NA	NA	NA	Low	Low	Low	No
	Chang et al. [7]	Moderate	NA	NA	NA	Low	Low	Moderate	Yes
	Bardou-Jacquet et al. [1]	Serious	NA	NA	NA	Low	Moderate	Moderate	Yes

Table 2 (continued)

	Authors	Confounding	Selection of patients	Classification of interventions	Deviations from intended interventions	Missing data	Measurement of outcomes	Selection of reported results	Funding/conflict of interest
NAVIO	Held et al. [15]	Moderate	Moderate	Moderate	Low	Low	Low	Moderate	Yes
	Bollars et al. [6]	Moderate	Low	Low	Low	Low	Low	Low	No
	Laddha et al. [27]	NA	NA	NA	NA	Low	Moderate	Moderate	No
	Vaidya et al. [62]	NA	NA	NA	NA	Low	Moderate	Low	No
	Savov et al. [48]	Moderate	Low	Low	Low	Low	Moderate	Low	Yes
	Vaidya et al. [63]	Low	Moderate	Low	Moderate	Low	Moderate	Low	Yes
	Bell et al. [3]	NA	NA	NA	NA	Low	Moderate	Moderate	Yes

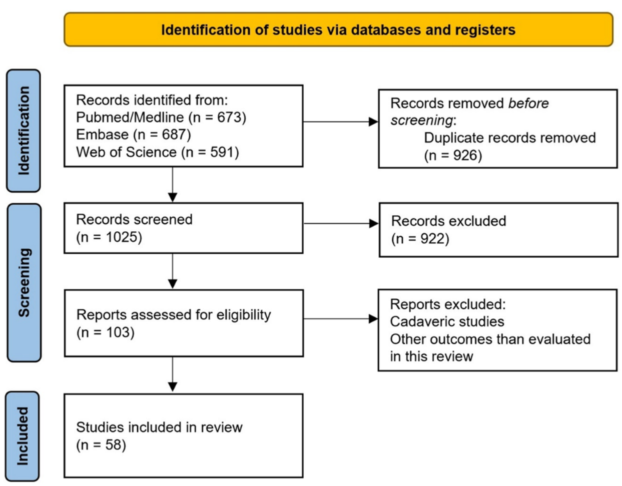

Fig. 1 An overview of the PRISMA-flowchart used in this study

6 months, and subscore Quality of Life at 3 months and 6 months compared to unbalanced knees ($p < 0.05$; without reaching the minimal clinical important difference) [24]. As such, specific targets for ligament balance with the BalanceBot have been published by Wakelin et al. which could improve PROMs: an equally balanced or tighter medial compartment in extension, medial laxity ± 1 mm compared to the final insert thickness in midflexion, and a mediolateral imbalance of less than 1.5 mm in flexion [66]. One study was able to demonstrate minor significant superiority of the OMNIBOT system regarding surgical precision to achieve coronal tibial component position compared to patient-specific instruments, with an average difference of 0.5° between both ($p = 0.02$) [42]. There is no published data on the learning curve, surgical time and complication or revision rates. A conflict of interest or industry funding was found in 57% (4/7) of the included studies on the OMNIBOT system.

MAKO

The MAKO robot system was the most intensively researched out of all robotic systems for total knee surgery. There were some studies advocating improved clinical outcomes up to 1 year postoperatively compared to the conventional technique [22, 39–41, 52]. However, long-term clinical outcomes are still lacking. The surgical precision achieved with the system was higher compared to the conventional technique [19, 61], more specifically for HKA and tibial coronal alignment ($p < 0.001$ and $p = 0.008$ respectively, Fig. 3). Nevertheless, there was no demonstrated correlation between the accuracy of the bone resections and the improvement of clinical outcomes with this robotic system. There were two studies advocating improved ligament balance with sensor technology combined with the MAKO platform [7, 28]. To reach the transition from the learning phase to the proficiency phase, 7–43 cases should be completed [19, 54, 65]. Component alignment and gap balance were not influenced by a surgeon's learning curve. Overall surgical time, from incision to skin closure, was not significantly different between RATKA and the conventional technique ($p = 0.95$, Fig. 3). After completing the learning curve setup time of the robot took 9.2 ± 1.5 min in the study by Kayani et al. [19]. In the included studies, there was no evidence for a difference in complications between robot-assisted and conventional TKA [22, 38, 41, 43, 52]. There

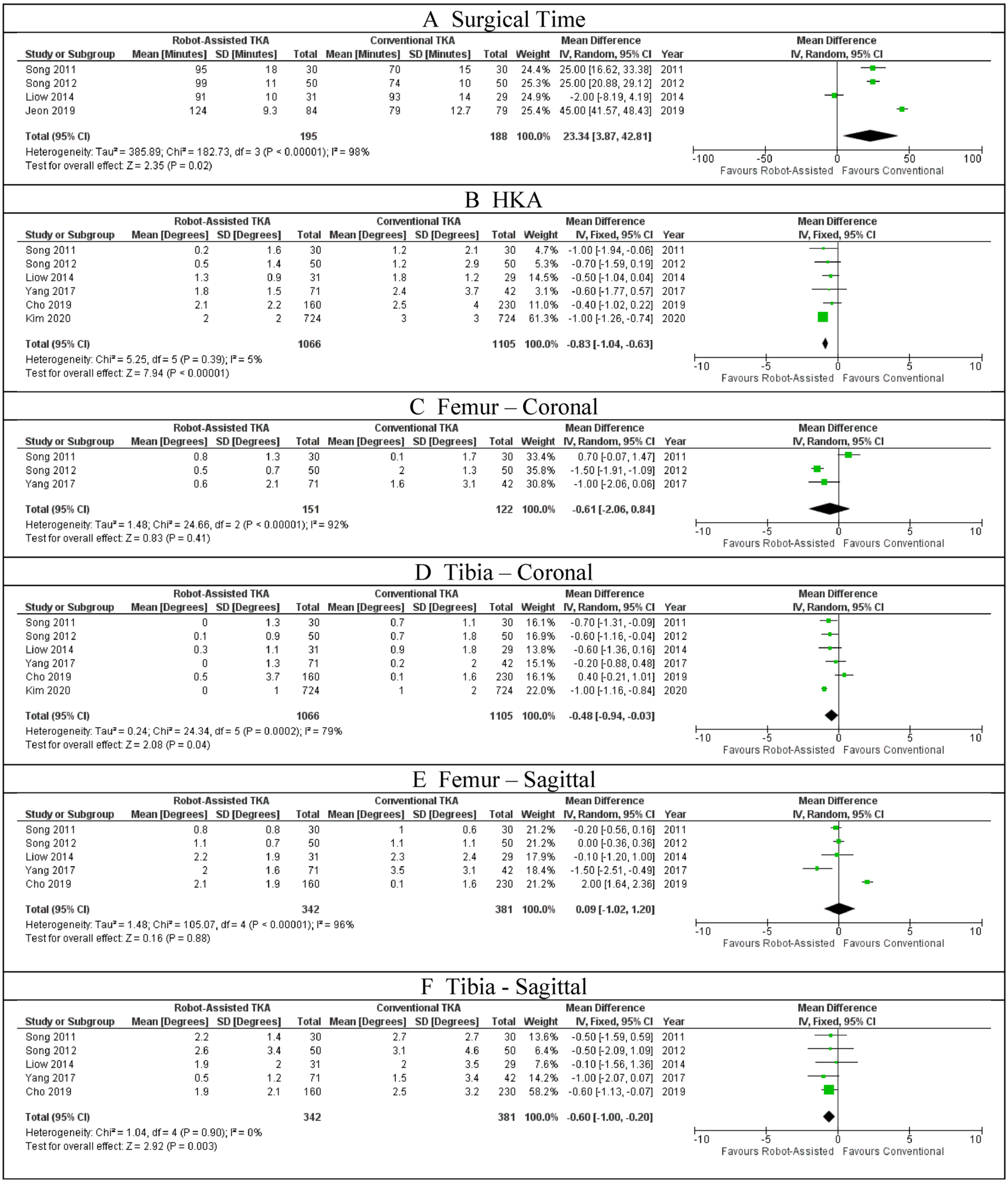

Fig. 2 The forest plots of the meta-analysis performed regarding the studies comparing conventional with robot-assisted total knee arthroplasty with the ROBODOC system. **A** Surgical time. **B** Precision of hip–knee–ankle axis. **C** Precision of coronal femoral component position. **D** Precision of coronal tibial component position. **E** Precision of sagittal femoral component position. **F** Precision of sagittal tibial component position

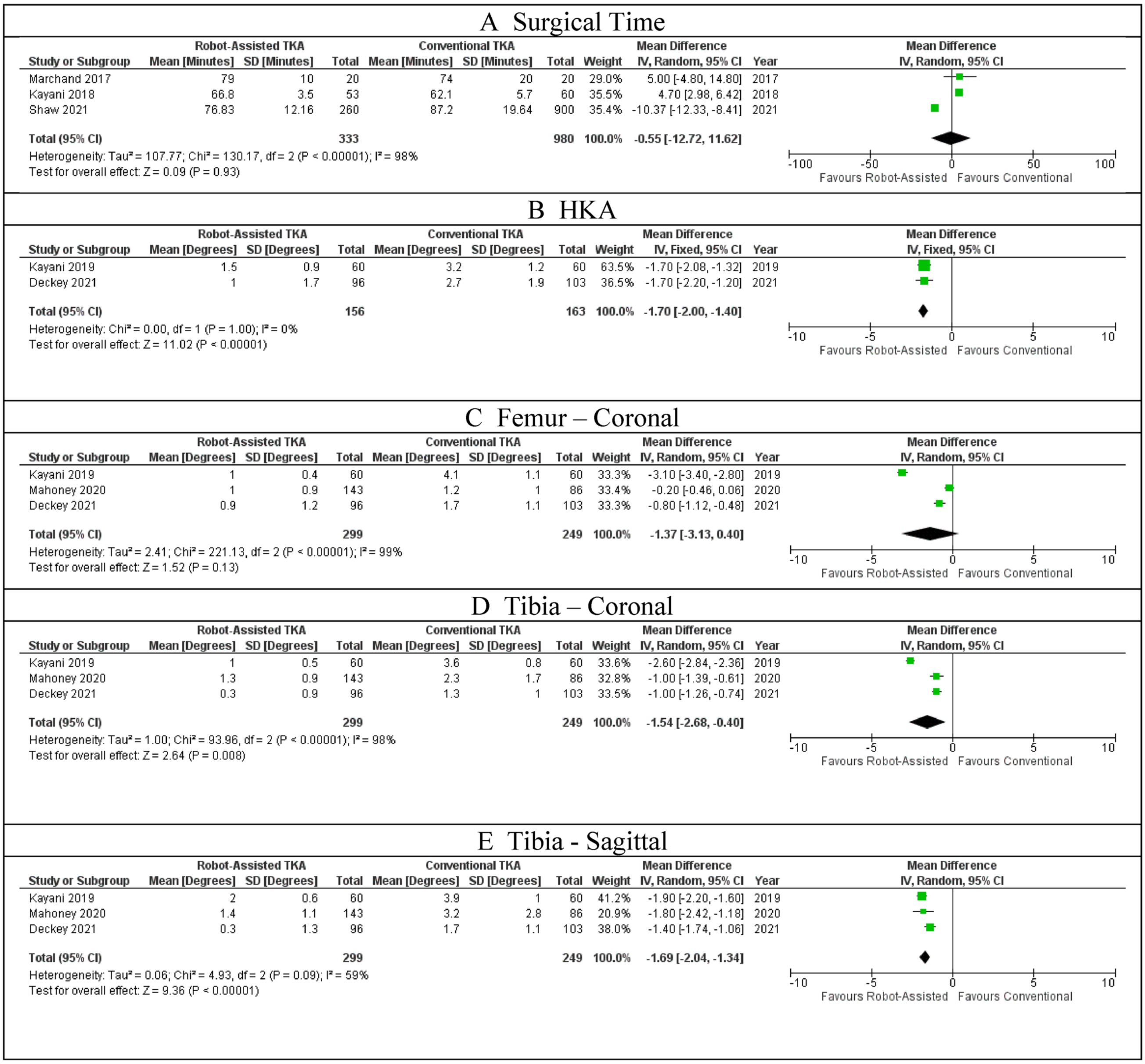

Fig. 3 The Forest plots of the meta-analysis performed regarding the studies comparing conventional with robot-assisted total knee arthroplasty with the MAKO system. **A** Surgical time. **B** Precision of the hip–knee–ankle axis. **C** Precision of the coronal femoral component position. **D** Precision of the coronal tibial component position. **E** Precision of the sagittal femoral component position. **F** Precision of the sagittal tibial component position

was no long-term data available on revision rates. In half of the included studies (10/20) on the MAKO platform, there was a potential conflict of interest.

NAVIO/CORI

Despite the promising results concerning the implant positioning and limb alignment, with superior precision to achieve the intended HKA ($p < 0.001$, Fig. 4), there was only one study, by Held et al., evaluating clinical outcomes without clear improvements when comparing conventional to RATKA [15]. According to Bell et al. and Savov et al. the learning curve encompasses the completion of 7–11 cases [3, 48]. Joint balance, when assessed with sensor technology, was improved with the application of the robotic system compared to the conventional technique [15]. Several studies have assessed surgical time, possibly demonstrating an increase in surgical time with the NAVIO robot compared to conventional TKA. There was no data available on the complications and revision rates. There was a potential conflict

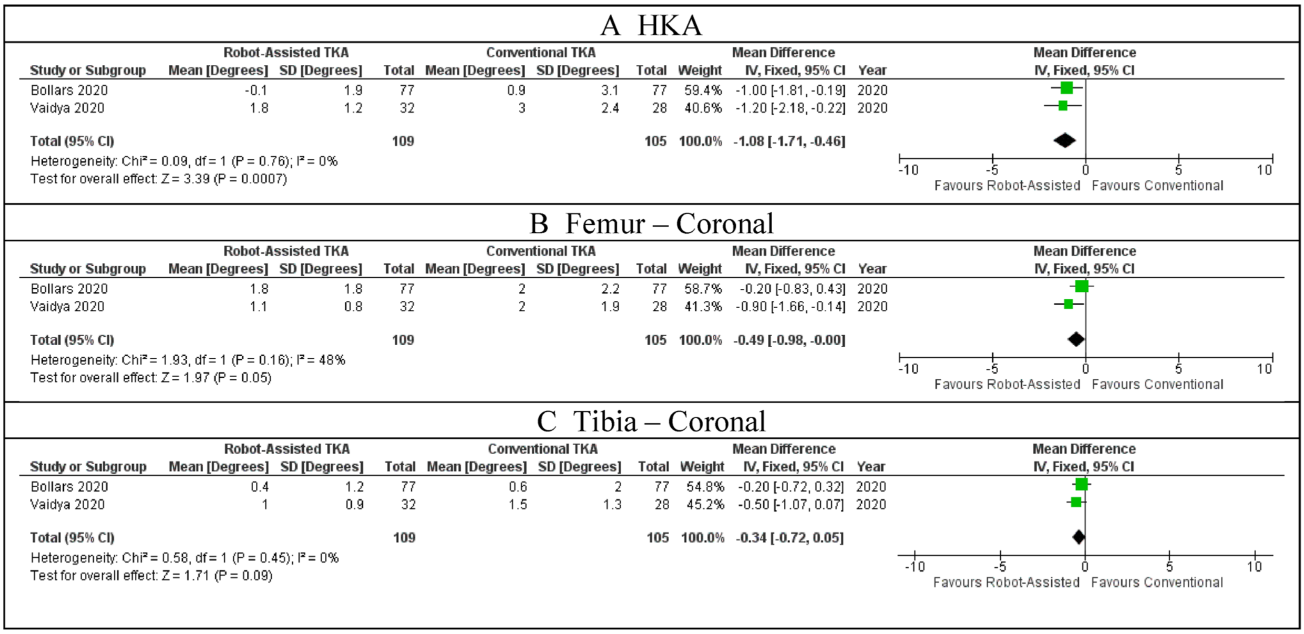

Fig. 4 The forest plots of the meta-analysis performed regarding the studies comparing conventional with robot-assisted total knee arthroplasty with the NAVIO/CORI system. **A** Precision of the hip–knee–ankle axis. **B** Precision of the coronal femoral component position. **C** Precision of the coronal tibial component position

of interest or industry funding in 57% (4/7) of the included studies on the NAVIO/CORI system.

ROSA

There was no data available on clinical outcomes or possible complications. Compared to the intraoperative plan, the system obtained high surgical precision [64]. The learning curve regarding operative time would be completed after 6–11 performed cases with the system [64]. The operative time of the robotic procedure required on average 18 additional minutes compared to the conventional TKA [64]. There was a potential conflict of interest or research funding for the one study on the ROSA system included in this review.

Discussion

The primary aim of this systematic review was to give an overview of the capabilities of each robotic system for total knee arthroplasty and to identify gaps in currently available scientific literature. The main finding of this systematic review is the current evidence regarding each robotic system being diverse in quantity and quality, and consequently the generic term of robotic should be banned from general conclusion. For most systems, although not all, surgical precision was seen to be superior with robot assistance compared to conventional TKA. Long-term clinical benefit of any robot-assisted procedure is yet to be determined. However, some short-term clinical benefit has been reported compared to conventional TKA. When using a robot for TKA, surgical time is increased for most systems, albeit there is potential to reach identical surgical times of conventional TKA. There was no difference in the amount of complications between RATKA and conventional TKA. The most profound benefit of these robotic systems is the superior surgical precision compared to the conventional technique (Appendix 3) [6, 8, 11, 13, 18, 19, 26, 27, 31, 33, 36, 42, 44, 48, 50, 51, 55, 56, 59–62, 64, 67]. Most evidence is found in lower outlier rates, although fewer studies identifying direct superiority of implant positioning in the RATKA are available. For ROSA and VELYS, clinical studies identifying its validated surgical precision are still yet to be published. Interestingly, Kayani and colleagues identified better soft tissue protection while maintaining high precision during surgery, which might stress an additional benefit of stereotactic boundary control with the robot-assisted systems [20].

The literature on clinical outcomes with currently available robotic systems is not available for the ROSA and VELYS robotic systems and still limited for the other platforms. Up to date, there are no clear long-term clinical improvements after total knee surgery when comparing any robotic system to its conventional counterpart (Appendix 2). Unfortunately, patient-reported outcomes and functional outcomes were deemed to heterogeneously due to different time intervals per individual robot to perform a meaningful meta-analysis. There are some studies advocating early improved patient outcomes, although this trend did not continue after 6 months to 1 year postoperatively [15, 22, 32, 39–41, 52]. Of note, especially for ROBODOC, is that the clinical studies were mainly based on a principle of mechanical alignment. The superior precision of the robotic systems opens doors for more individualised alignment techniques, theoretically avoiding major limitations of surgical error (e.g., early failure with aseptic loosening or implant migration) with the conventional technique [12, 34, 46]. However, these individualised alignment strategies are in need of further refinement and proven clinical benefit before becoming the golden standard [47].

Besides good surgical precision, an additional added value of multiple robotic systems is the capability of assessing ligament tension. Currently, there are three options of assessing ligament tension. First, the laxity assessment with the robotic assisted system could be performed manually. The surgeon exerts a significant varus and valgus force on the knee, with or without tensioner. This assessment is dependent on the strength and evaluation of the surgeon, on the depth of anaesthesia, and the BMI or the physical stature of the patient. The ligament balancing is thus not entirely objective and dependent upon the surgeon's experience of with the system. Second, with the MAKO platform, sensor-guided technology can objectify soft tissue balance with a wireless and disposable articular loading quantification device, which is inserted in the tibial component tray during the surgery, after the tibial and femoral cuts are completed [14]. Third, standardised distraction of the joint is possible with the BalanceBot, due to the option to apply variable or fixed, but known, forces during full range of motion [24, 66]. The BalanceBot requires a tibial first technique to insert the device, which limits the influence of tibial osteophytes on ligament balance. Studies on both the sensor and the standardised distraction device have shown promising results with superior clinical outcomes when specific balance targets are met [14, 15, 24, 28, 66]. However, due to heterogeneous assessment, comparing these systems is not possible. In the end, long-term randomised controlled studies are still necessary to confirm these findings.

The learning curve of most systems seems to be similar between all available robotic systems, except for the OMNIBOT and VELYS systems, which have not been assessed yet (Appendix 4) [3, 19, 37, 48, 54, 64, 65]. However, Keggi and Plaskos have published the learning curve of the OMNIBOT system in a conference abstract, which resulted in a learning curve of seven cases based on surgical time [23] At first sight though, there was a wider variation of the amount of cases necessary to complete the learning curve with the MAKO robot (7–43 cases) compared to other systems (6–12), possibly due to the fact that more studies have been published on the MAKO robot, possibly with the learning curve of a more diverse audience. The initial studies on a surgical system might involve surgeons involved in the robot design. As such, these might be biased towards faster learning curves. According to this systematic review, there was no clear difference in the learning curve between image-based and imageless devices, based on operative time and implant positioning. After completion of the learning curve, some studies have advocated the possibility to achieve time identical surgical times with RATKA compared to the conventional technique [54, 65]. These studies were performed by mostly high-volume and experienced joint replacement surgeons, which makes it difficult to apply to a low-volume or less experienced surgeon.

Literature on surgical complications is available for ROBODOC and MAKO. These studies on the ROBODOC and MAKO could not present any difference in complications between the conventional technique and RATKA (Appendix 5) [8, 33, 56, 67]**.** However, surgeons should remain cautious when using tracker pins, since periprosthetic fractures through tracking pin sites could occur in up to 5% of cases, as has been reported by Smith et al. [53]. Long-term revision rates are only available for ROBODOC system, which could not demonstrate any superiority of RATKA. However, these studies have been performed with a principle of mechanical alignment. Revision rates for the other systems are still to be published, as the time of commercial release lies within the past couple of years.

Surgical time is important as well in the consideration of robot-assisted versus conventional TKA. Although not present for the MAKO system in our meta-analysis, in almost all individual studies included in this review, the total knee arthroplasty required more time to complete when performed with robot-assistance (Appendix 6). Any increase of operative time and additional personnel in the operating room should be approached with caution, as it could potentially increase infection rates [57]. However, more than operative time, which is from skin incision to skin closure, should be considered. As an example, the time needed for set-up of the robotic systems has an influence on the capability to use operating time efficiently as well. Kayani et al. have found an average set-up time of 9.2 min was necessary for the MAKO platform [19]. While it is a large system yet easily moved, the set-up time necessary for other systems is still unknown.

In the included studies, a conflict of interest or research funding by the orthopaedic company was present in (more than) half of all cases, except for the ROBODOC system (17% of all studies). The reader of future studies on RATKA should be aware conflicts of interest are not scarce in this topic.

The available robotic systems, besides the VELYS system, all have demonstrated their technical capabilities in some degree. However, cost-effectiveness is a factor which cannot be ignored when assessing the introduction of robotic systems in current daily practice. As such, up to now, there is only limited evidence on the cost-effectiveness of the MAKO platform. According to Cool et al. and Pierce et al. RATKA was associated with lower health-related costs compared to the conventional technique due to fewer readmissions and economically beneficial discharge destinations [10, 45]. However, these studies did not take into account confounding variables which might be present based on the patient's deliberate choice for robot-assisted surgery.

The limitations of this review relate to the level of available evidence and the inherent lack of homogenous high quality data, incomplete reporting of surgical experience. There is a paucity of trials and level 1 data regarding all systems available for RATKA. However, promising studies are underway [21]. As well, as only English language manuscripts were included together with the requirement of full text access, some relevant studies could have been excluded. Next, in the assessment of all included studies, the fact that these were performed by experienced surgeons working in high-volume arthroplasty centres should be highlighted, potentially introducing bias. It is unlikely that the conclusions of these studies can be extrapolated to less experienced and lower volume surgeons.

Conclusion

The current systematic review demonstrates there are certainly gaps in the current literature on robot-assisted total knee surgery. The available robotic platforms have high surgical precision and are associated with similar learning curves, without evidence of clear improved patient outcomes for most of them. However, as high patient satisfaction and patient function with a durable prosthesis remain the ultimate goal, the implementation of these precise systems and gap balancing opportunities could potentially unlock the door to improved patient outcomes. To provide solid scientific evidence of such improvement, the main recommendation is that each system must be assessed for its own value and the generic term of robotic should be banned from general conclusion.

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Declarations

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