Robotic-assisted revision total joint arthroplasty: a state-of-the-art scoping review

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- *Background:* During the past decades, robotic-assisted technology has experienced an incredible advancement in the field of total joint arthroplasty (TJA), which demonstrated promise in improving the accuracy and precision of implantation and alignment in both primary total hip arthroplasty (THA) and total knee arthroplasty (TKA). However, revision TJA remains a technically challenging procedure with issues of large-scale bone defects and damage to nearby anatomical structures. Thus, surgeons are trying to harness the abilities of robotic-assisted technology for revision TJA surgery.
- *Methods:* PubMed, Embase, Cochrane Library, and Google Scholar were comprehensively searched to identify relevant publications that reported the application of robotic-assisted technology in revision TJA.
- *Results:* Overall, ten studies reported the use of the robotic system in revision TJA, including active (ROBODOC) and semi-active (MAKO and NAVIO) systems. One clinical case reported conversion from hip fusion to THA, and three studies reported revision from primary THA to revision THA. Moreover, four studies reported that robotic-assisted technology is helpful in revising unicompartmental knee arthroplasty (UKA) to TKA, and two case reports converted primary TKA to revision TKA. In this study, we present the latest evolvements, applications, and technical obstacles of robotic-assisted technology in the revision of TJA and the current state-of-the-art.
- *Conclusion:* Current available evidence suggests that robotic-assisted technology may help surgeons to reproducibly perform preoperative plans and accurately achieve operative targets during revision TJA. However, concerns remain regarding preoperative metal artifacts, registration techniques, closed software platforms, further bone loss after implant removal, and whether robotic-assisted surgery will improve implant positioning and long-term survivorship.

Keywords

▶ robotic-assisted
▶ revision
▶ total joint arthroplasty
▶ total hip arthroplasty
▶ total knee arthroplasty
▶ unicompartmental knee arthroplasty
▶ scoping review

Introduction

Long-term clinical outcomes and implant survivorship of total hip arthroplasty (THA) and total knee arthroplasty (TKA) are dependent on the accurate restoration of hip and knee biomechanics and optimal position of implant components (1, 2, 3, 4, 5, 6). Therefore, during the past decades, robotic-assisted total joint arthroplasty (TJA) has extensively been explored in this domain, with the expectation that robotic-assisted technology would significantly improve the accuracy of bone cuts and precision of implantation and alignment, and finally contribute to improved clinical outcomes and long-term implant survivorship (7, 8, 9, 10, 11, 12). Recent studies with short-term follow-ups have demonstrated satisfying radiological and clinical outcomes, while longer-term follow-ups are lacking (13, 14, 15, 16, 17, 18).

However, compared with primary TJA, revision TJA remains a considerable challenge to orthopedic surgeons. Revision TJA is a technically complex procedure fraught with challenging issues such as massive bone loss, which compromises anatomical structures and landmarks, poor bone quality, and soft tissue contracture, all of which will induce a high incidence of complications (19, 20, 21). Given that revision TJA requires more accurate preoperative planning and precise intraoperative

identification of anatomical landmarks and resection of bone, robotic-assisted technology that combines accurate patient-specific preoperative planning and robotic-arm-assisted bone cutting may comparatively lead to better implant positioning, higher functional scores, and better clinical outcomes. Thus, along with the technological advancement and familiarity with the procedure, surgeons believe robotic-assisted technology could have done so much more; hence, they tried to harness the abilities of robotic-assisted technology for the revision of TJA. Considering that there has been some pioneering work in applying the robotic system in revision TJA (22, 23, 24, 25, 26, 27, 28, 29, 30, 31), and robotic-assisted technology may have more extended applications in the future, we performed a scoping review of the literature and narrative synthesis to present the current state-of-the-art.

Of note, the FDA has currently approved robotic-assisted technology for primary joint arthroplasty, including unicompartmental knee arthroplasty (UKA), THA, and TKA; the technique described here represents an off-label indication. This study was not funded by industry support.

Materials and methods

This scoping review of robotic-assisted revision TJA was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (32).

Search strategy

We systematically searched PubMed, Embase, the Cochrane Library, and Google Scholar, from inception to July 12, 2022. The computer-based literature searches were performed using Medical Subject Heading (MeSH) terms and appropriate corresponding keywords. The searches were limited to human subjects and imposed no language restrictions. The search was complemented by manually screening reference lists of retrieved articles and relevant reviews to identify additional potentially eligible studies missed by the search strategy. The detailed search strategy is provided in Appendix 1 (see section on supplementary materials given at the end of this article).

Study selection

All potential references were imported into Endnote X8 (Thomson Reuters, Carlsbad, California, USA), and duplicates were removed. Two reviewers independently screened titles and abstracts for eligibility and labeled records as included, excluded, or requiring further assessment. The full text of each potentially eligible study was then independently examined, and in case of uncertainty, a third reviewer was consulted to arrive at a consensus about final study inclusion.

Eligibility criteria

All languages and types of publications were considered eligible if they met the following criteria: (i) population: adults undergoing robotic-assisted revision TJA, no matter conversion to THA or TKA; (ii) study design: all types of study design were included; (iii) intervention: robotic-assisted revision TJA; (iv) comparison: unlimited or no comparison; (v) publication type: unlimited, both full-text articles and conference abstract were included.

Data extraction

The following information was collected in a predefined data collection form: first author, publication year, country, study design, patient demographics, revision surgery, robotic systems, prosthetic designs, registration techniques, and reported outcomes. Extracted data were entered into a pre-generated standardized Excel (Microsoft Corporation) file. We also sought supplementary appendices of included trials or contacted authors whenever additional information was required. Two authors independently extracted the data, and discrepancies were resolved by discussion with a third reviewer.

Results

Study selection

A detailed flowchart of the search and selection results is shown in Fig. 1. The initial search identified 390 records through electronic search, and 3 additional records were identified through other sources. Overall, 180 records
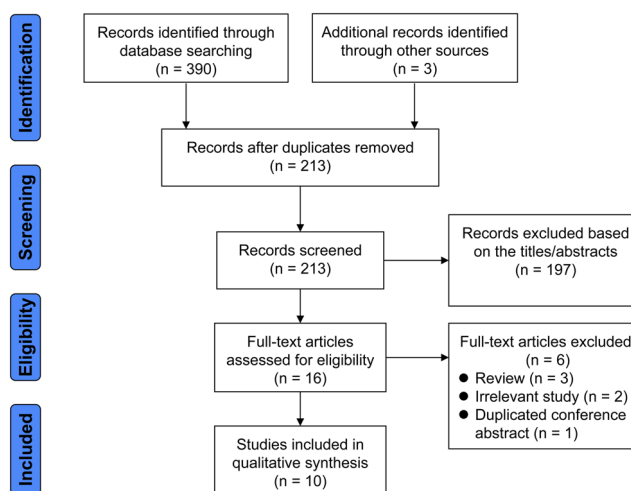

Figure 1

PRISMA flow diagram showing the process of literature screening, study selection, and reasons for exclusion. PRISMA, preferred reporting items for systematic reviews and meta-analyses.

were excluded for duplicates, 197 records were identified as irrelevant by screening titles and abstracts, and the remaining 16 records were assessed for eligibility by reviewing full-text articles. After applying the inclusion criteria, ten studies were included in the present scoping review (22, 23, 24, 25, 26, 27, 28, 29, 30, 31).

Study characteristics

The main characteristics of included studies are summarized in Table 1. Ten studies reported the use of the robotic system in revision TJA (22, 23, 24, 25, 26, 27, 28, 29, 30, 31), one published in 1998 (23), while the others were published between 2020 and 2022 (22, 24, 25, 26, 27, 28, 29, 30, 31). Among them, one study reported revision from primary THA to revision THA (RTHA) using an active robotic system (ROBODOC) (23), one clinical case reported conversion from hip fusion to THA using a semi-active robotic system (MAKO) (22), and two studies reported revision from primary THA to RTHA using a semi-active robotic system (MAKO) (24, 25). Moreover, four studies reported that semi-active robotic-assisted technology is helpful in revising unicompartmental knee arthroplasty (UKA) to TKA (MAKO and NAVIO) (26, 27, 28, 29), as well as two clinical cases reported conversion from primary TKA to revision TKA (RTKA) (30, 31).

Conversion from hip fusion to THA

Adil *et al.* presented a unique case using a MAKO robotic arm system to assist the conversion of hip arthrodesis to THA (22). This patient experienced two unsuccessful hip surgeries and finally underwent hip arthrodesis. Technical challenges include the location of the native acetabular fossa, avoiding the existing hardware (anterior and posterior columnar reconstruction plates) when positioning the acetabular component, decreased off-set (16 mm), and leg length discrepancy (49 mm). For the acetabular side, an exact position and orientation of the acetabular component was proposed, which not only avoids the deep hardware but is also close to the native acetabulum, and the acetabular component was accurately placed with robot-arm assisted (positioned at 35° of acetabular abduction and 20° of anteversion). For the femoral side, a primary hip stem was chosen in preoperative planning, but a revision hip stem was used intraoperatively, mainly because the closed platforms cannot template with revision implants.

Revision from THA to RTHA

Bargar *et al.* reported applying the first active robotic system (ROBODOC) in THA revision surgery, which can not only gently remove large and deep cement mantles but also prepare the cavity simultaneously (23). This study confirmed that the robot could remove the cement safer

and faster than in manual mode, but more details were not provided (23).

Zhou reported 71 cases of robot-assisted hip revision and proposed three3 types of registration techniques (extra acetabular bone surface based, liner based, metal shell-based or cage surface-based) on the acetabular side (24). This conference abstract suggested that accurate intraoperative registration could be achieved through different methods, and favorable acetabular cup reconstruction could be realized with robot arm-assisted. Postoperatively, the mean cup abduction and anteversion were 40.87° ± 4.39° and 13.87° ± 4.24°, respectively, and 91.2% cases (62 of 68 cups) were within the Lewinnek safe zone, and 80.9% cases (55 of 68 cups) were within the Callanan safe zone (24).

Zhang *et al.* described the adoption of robotic-assisted technology in second-stage revision surgery, and the main challenge is the severe acetabular defect (Paprosky type IIIB), so a customized augment was designed to fill the bone defect (25). They suggested that robotic-assisted technology minimized bone loss as only one acetabular reaming was required with accurate preoperative planning and robot arm-assisted reaming, while conventional procedure often needs several attempts. The predetermined target cup angle was at an abduction angle of 40° and an anteversion angle of 20°, intraoperative robotic measurements showed 38° of abduction and 19° of anteversion after position, and postoperative measurements by ORTHVIEW software showed 42° of abduction and 21° of anteversion, with a 2 mm leg length discrepancy. They further criticized that the closed planning software could not simulate the implantation of the augment, which may lead to errors.

Revision from UKA to TKA

Kalavrytinos *et al.* presented the first described case of robotic-assisted conversion of failed UKA to TKA (26). Similarly, the closed planning software was also unable to simulate the implantation of the tibial augment, and the preoperative planning was modified intraoperatively to achieve satisfactory implantation of the tibial augment, and manual intervention was required for the adjustment of the medial tibial cut.

Wallace *et al.* reported four cases of conversion from UKA to TKA, highlighting that robotic-assisted technology contributes to preserving bone stock as the preoperative planning does not use the UKA implant as part of calculations and extremely accurate intraoperative bone cuts as well (27).

Yun *et al.* retrospectively reviewed 34 patients with failed UKA, half of which were converted robotically to TKA, while half were converted manually (28). No revision components were used in either group. All conversions were performed using primary implants. They observed

Table 1   Characteristics of included studies.

Reference	Year	Region	Study design	Patient demographics	Revision surgery	Robotic system	Prosthetic designs	Registration techniques	Follow-up
Adil et al. (22)	2021	USA	Case report	45-year-old male	Hip fusion converted to THA	MAKO	Stryker tritanium revision acetabular component+Smith and Nephew Redapt stem	Superior ilium away from the hip fusion mass+most lateral portion of the proximal femur	1 year
Bargar et al. (23)	1998	USA, Germany	Case series	30 patients	THA converted to RTHA	ROBODOC	Both cement and cementless implants	—	—
Zhou (24)	2021	China	Case series	71 patients (68 cup revisions+68 stem revisions)	THA converted to RTHA	MAKO	—	Three types of registration techniques (extra acetabular bone surface based, liner based, metal shell-based or cage surface-based) on the acetabular side	—
Zhang et al. (25)	2022	China	Case report	67-year-old male	THA converted to RTHA	MAKO	Corail revision femoral stem+tritanium acetabular cup+customized augment	Acetabulum and surrounding bone with good bone quality	6 months
Kalavrytinos et al. (26)	2020	Greece	Case report	87-year-old female	UKA converted to TKA	MAKO	Stryker triathlon implants+tibial augment	Similar to primary TKA	1 year
Wallace & Moriarty (27)	2020	UK	Case report	4 cases	UKA converted to TKA	MAKO	—	Similar to primary TKA with the UKA implant in situ	—
Yun et al. (28)	2020	USA	Case series	17 cases robotically+17 cases manually	UKA converted to TKA	MAKO	Primary implants	Registration of bone with retained metal implants	1 year
Tuecking et al. (29)	2021	UK	Retrospective case–control study	20 cases+20 matched controls	UKA converted to TKA	NAVIO	Journey II BCS prothesis	—	—
Steelman et al. (30)	2021	USA	Case report	68-year-old male	TKA converted to RTKA	MAKO	Stryker triathlon knee revision system+femoral and tibial cones+medial and lateral posterior femoral augments	The implants were treated as native bone and registrated on the existing components	6 months
MacAskill et al. (31)	2022	USA	Case report	54-year-old female+79-year-old male	TKA converted to RTKA	MAKO	Stryker triathlon knee revision system+tibial cones	Registering the anterior flange, posterior condyles, and distal extent of the femoral implant and the periphery of the tibial component as well as the medial and lateral epicondyles and anterior tibial metaphysis	6 months

THA, total hip arthroplasty; TJA, total joint arthroplasty; TKA, total knee arthroplasty; RTHA, revision total hip arthroplasty; RTKA, revision total knee arthroplasty; UKA, unicompartmental knee arthroplasty.

a significant difference in the use of augments, with 29% (5 of 17 cases) of knees manually converted requiring augments, whereas 0% (0 of 17 cases) of robotically converted knees requiring augments. The authors suggested that computer mapping of the residual bone surface after implant removal was a helpful guide in minimizing resection depth, and the preoperative CT scans were unexpectedly helpful in establishing mechanical alignment and resection depth in the absence of typical anatomic landmarks to guide conventional methods.

Tuecking *et al.* performed a retrospective case–control study comparing patients undergoing imageless robotic-assisted revision arthroplasty from UKA to TKA and those undergoing imageless robotic-assisted primary TKA (29). They demonstrated that robotic-assisted conversion from UKA to TKA is a precise technique in revision arthroplasty and shows similar alignment outcome parameters compared to robotic-assisted primary TKA, including overall limb alignment ($178.6° \pm 1.9°$ vs $176.0° \pm 2.5°$; $P = 0.221$), medial proximal tibia angle (mPTA) ($88.5° \pm 1.5°$ vs $88.9° \pm 1.1°$; $P = 0.837$), lateral distal femoral angle (lDFA) ($87.6° \pm 2.2°$ vs $89.5° \pm 2.5°$; $P = 0.493$), and outlier rate (5% vs 5%; $P > 0.999$). They also infer that robotic-assisted technique may help to preserve the bone stock and avoid using revision augmentation material and higher constraint implants.

Revision from TKA to RTKA

Steelman *et al.* presented a case in which robotic-assisted technique was used to revise a failed primary TKA (30). In this case, a revision implant system was utilized with both femoral and tibial cones and medial and lateral posterior femoral augments. The authors were able to perform very minimal fresh cuts with robot arm-assisted and adjust the posterior femoral cut to place augments both medially and laterally.

MacAskil *et al.* also described the use of robotic-assisted technology in RTKA (31). The authors suggested that the presence of metal artifacts on the preoperative CT scan makes it challenging to register certain points, so they did not follow the proposed standard registration pattern of primary TKA, and added extra points on bony surfaces and implant components.

Discussion

Main findings

This scoping review of the current literature suggested that the advent of robotic-assisted technology may be conducive to a reproducibly preoperative plan, contribute to accurate bone cuts and preserve more bone stock, and precise positioning of the implant in revision TJA. In general, these studies confirmed the feasibility of robotic-

assisted technology in revision TJA and demonstrated potential advantages over conventional techniques in minimizing bone loss and reducing augment utilization. Notably, several technical issues are still to be optimized before robotic-assisted revision TJA could be considered as a standard procedure, including preoperative metal artifacts, registration techniques, closed software platform, further bone loss after implant removal, and whether robotic-assisted surgery will improve long-term functional outcomes and implant survivorship.

Implications for clinicians and manufacturers

Metal artifacts and intraoperative registration

For revision TJA, metal artifacts on the CT scan are unavoidable, and the radiation scatters are most pronounced at the edge of the implant, degrading the image quality and making the surface of the bone more challenging to identify with precision (33). Although the preoperative CT scan data could be further processed with MAKOplasty protocol and treated the existing implants as native bone during the preoperative planning, intraoperative registration following the standard registration pattern of primary TJA is not feasible. Some surgeons treated the existing implants as native bone (26, 30, 31), some surgeons did not and finished registration with metal artifacts (28), and both methods passed the 0.5 mm threshold of the robotic system. At present, they does not have registration patterns or routine checkpoints in revision TJA yet, but the optimal registration methods and techniques will be developed along with the accumulation of experience (24).

Software platform

The software platform of the robotic systems could be classified as 'closed' or 'open' based on whether the implant choice is limited or not (8, 12). Robotic systems with open platforms (e.g. ROBODOC) provide combability with different implant companies and designs and give the surgeon more freedom regarding implant choice tailored to the patient's anatomy. However, newer robotic systems are predominantly closed platforms (e.g. MAKO), which limit implant choice and cannot realize different configurations for multiple prostheses, and surgeons may have to use alternative implants compared to their usual practice to utilize such robotic systems (8, 12). As this proof of concept study demonstrated the feasibility of the clinical application of robotic-assisted technology in revision TJA, manufacturers should open the software platform and allow for simulation with various implants, augments, and even customize 3D-printed implants.

Bone loss

Although severe bone loss during implant removal and resection in revision cases has long been a concern (34),

it was not a primary focus of robotic-assisted technology in revision TJA in these studies, which may be attributed to surgeons' expertise. The accurate robotic arm-assisted acetabular reaming and bone cutting theoretically preserved the remaining bone volume and may reduce the augment use (28), but these findings may also be attributable to limited sample size and surgeons' preferences, which warrant further investigation.

Adjustment of the preoperative plan

Although robot arm-assisted technology could accurately execute the preoperative plan, the preoperative plan often needs adjustment intraoperatively for the placement of revision implant components or augments. However, even though the current robotic arm-assisted system allows the surgeon to change or adjust the implant placement and size intraoperatively, at any stage, manual bone cutting is still required (22), which demands critical thinking and problem-solving ability of the surgeon.

Benefits and risks

Current available studies suggest that robotic-assisted technology in revision TJA is not inferior to the conventional method, mainly in terms of accurate preoperative planning and robot arm-assisted operation guidance. For RTHA, the benefits include precise acetabular reaming and cup placement, balanced length of the lower limbs, restored off-set, and appropriately combined anteversion. For RTKA, the benefits mainly include accurate bone cutting and the ability to locate the component alignment and mechanical alignment, which is often a challenge due to the loss of bony reference points after implant removal. However, robotic-assisted technology requires preoperative CT scan data, which have long been a concern raised as to the potential harm associated with radiation exposure (e.g. 0.16 mSv for standard knee CT and 4.8 mSv for Makoplasty protocol) (31). In addition, except for the staggering initial cost of the robot systems and maintenance cost, there are extra direct costs per episode of care related to the additional need for disposable elements (e.g. optical array disposables) and preoperative CT scans (35). As long-term functional outcomes and implant survivorship are the most convincing indexes, surgeons shall provide both short-term and long-term follow-up data to weigh the benefits and risks of adopting robotic-assisted technology in revision TJA.

Call for future studies

Currently, only limited data are available on robotic-assisted revision TJA, and with robotic-assisted technology becoming increasingly popular worldwide, additional exploration is expected to provide more convincing evidence. Secondly, further studies are needed not only to evaluate whether short-term clinical outcomes and radiological outcomes are improved with robotic-assisted technology but also to evaluate whether robotic-assisted technology can improve the longevity of implants or patient-reported functional outcomes. Thirdly, with the advances in robotic technologies and software capabilities, combined with potential beneficial effects, robotic-assisted technology may have broader indications in the future, such as shoulder arthroplasty, high tibial osteotomy, complex revision of RTHA and RTKA, and mega-prosthetic reconstruction after extremity sarcoma resection (36).

Limitations

This study has several limitations. First and foremost, there is limited literature regarding the application of robotic-assisted technology in revision TJA, and most of the available studies are case reports and case series, which may weaken the strength and generalizability of the evidence. Secondly, other intrinsic risks of biases in these studies were limited sample size and short follow-up period, which reduced statistical power and compromised study validity. This limitation necessitates us to recommend caution when drawing conclusions and makes it necessary to subject this technology to further evaluation. Last but not least, this scoping review may be limited by reporting bias, whereby surgeons who applied the robotic-assisted technology in revision TJA but aborted due to surgical challenges and converted to conventional surgery may be reluctant to report or publish the failed experiences, despite these experiences were also highly valuable.

Regulatory approval

The use of robotic-assisted technology in revision TJA is not yet licensed or approved by the FDA and the European Commission's Medical Device Coordination Group (MDCG), even though such an application appears to be a reasonable technical option in the management of complex revision surgery. Therefore, written informed consent should be obtained when using this off-label technique.

Conclusions

In conclusion, the current evidence confirmed the feasibility of robotic-assisted technology in revision TJA, which may help surgeons to perform preoperative plans and accurately achieve operative targets. However, concerns remain regarding the preoperative metal artifact, registration techniques, closed software platform, further bone loss after implant removal, and whether robotic-assisted surgery will improve implant positioning and long-term survivorship, so further studies are warranted.

Author contribution statement
X-D Wu: contributed substantially to conception and design, acquisition of data, analysis, and interpretation of data; drafted the article; gave final approval of the version to be published; agreed to act as a guarantor of the work; Y Zhou: contributed substantially to conception and design, acquisition of data, analysis, and interpretation of data; revised it critically for valuable intellectual content; gave final approval of the version to be published; agreed to act as a guarantor of the work; H Shao: contributed substantially to the acquisition and interpretation of data; revised it critically for valuable intellectual content; gave final approval of the version to be published; agreed to act as a guarantor of the work; D Yang: contributed substantially to the acquisition and interpretation of data; revised it critically for valuable intellectual content; gave final approval of the version to be published; agreed to act as a guarantor of the work; S-J Guo: contributed substantially to the acquisition and interpretation of data; revised it critically for valuable intellectual content; gave final approval of the version to be published; agreed to act as a guarantor of the work; W Huang: contributed substantially to the acquisition and interpretation of data; revised it critically for valuable intellectual content; gave final approval of the version to be published; agreed to act as a guarantor of the work.

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