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Total Knee Arthroplasty With Robotic and Augmented Reality Guidance: A Hierarchical Task Analysis

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ABSTRACT

Background: Total knee arthroplasty (TKA) is a commonly performed procedure that has traditionally utilized reproducible steps using a set of mechanical instruments. The number of TKAs performed using robotic assistance is increasing, and augmented reality (AR) navigation systems are being developed. Hierarchical task analysis (HTA) aims to describe the steps of a specific task in detail to reduce errors and ensure reproducibility. The objective of this study was to develop and validate HTAs for conventional, robotic-assisted, and AR-navigated TKA.

Methods: The development of HTAs for conventional TKA involved an iterative review process that incorporated the input of 4 experienced arthroplasty surgeons. The HTAs were then adapted for robotic-assisted and AR-navigated TKA by incorporating specific steps associated with the use of these systems. The accuracy and completeness of the HTAs were validated by observing 10 conventional and 10 robotic-assisted TKA procedures.

Results: HTAs for conventional, robotic-assisted, and AR-navigated TKA were developed and validated. The resulting HTAs provide a comprehensive and standardized plan for each procedure and can aid in the identification of potential areas of inefficiency and risk. Robotic-assisted and AR-navigated approaches require additional steps, and there are an increased number of instances where complications may occur.

Conclusions: The HTAs developed in this study can provide valuable insights into the potential pitfalls of robotic-assisted and AR-navigated TKA procedures. As AR-navigation systems are developed, they should be optimized by critical analysis using the developed HTAs to ensure maximum efficiency, reliability, accessibility, reduction of human error, and costs.

Introduction

Robotic platforms for total knee arthroplasty (TKA) have been developed in an attempt to improve implant positioning, soft tissue balance, patient-reported outcomes, and early recovery [1]. The accuracy and reliability of these systems have led to increased uptake by orthopaedic surgeons with a coinciding increase in patient demand partly due to increased marketing [2–6]. Despite limited evidence of improved patient outcomes, in addition to increased costs and longer operative times, there has been an exponential increase in the utilization of robotic-assisted TKA [1,7].

Augmented reality (AR) systems are designed to overlay relevant information directly into a surgeon's field of vision via a head-mounted display [8]. Intraoperatively, this allows surgeons to maintain their view of the surgical field while also viewing information such as medical imaging or input from navigation software. Relating to TKA, this information can be interpreted by the surgeon to guide accurate implant placement, gap balancing, and help

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interpret joint stability and range of motion intraoperatively [8,9]. These systems are largely still under development and rarely utilized relative to robotic-assisted TKA. However, early clinical and preclinical models have displayed promising results regarding femoral and tibial cut accuracy on artificial bone models, cadavers, and patient cases [10,11].

Due to the increasing uptake and development of these technologies, it is important to understand the key steps and potential pitfalls. The widespread integration of these systems into the operating room will affect workflow relative to conventional TKA; however, these modifications have not been clearly defined. Importantly, the specific steps associated with the risk of patient complications have not been defined for robotic or AR-navigated TKA.

A hierarchical task analysis (HTA) is designed to develop a standardized plan for a predetermined task. This identifies the key steps in a procedure, allowing inefficiencies or adverse events to be mapped to a specific step. HTA enables the systematic deconstruction of intricate surgical operations or procedures, facilitating a clear delineation of the actions involved. This method makes it easier to identify associations between particular actions and errors, leading to a more straightforward elicitation of errors. Additionally, it allows for a more focused evaluation of specific technical skills [12]. In the realm of orthopaedics, HTAs have been employed previously to generate a HTA tree tailored to rotator cuff surgery with the aim of facilitating the development of quantifiable metrics for the assessment of trainee performance [13].

HTA is the main component behind the Systematic Human Error Reduction and Prediction Approach, which aims to identify causes of error associated with a sequence of human activity related to human-machine systems [14]. As TKA procedures inevitably become more closely linked with different technological navigation and robotic systems, accurately mapping the workflow and likely disruption is integral. This study was designed to develop and validate a HTA workflow for conventional and robotic-assisted TKAs to guide the development of AR-navigated TKA systems, including the correlation of steps to potential patient complications.

Material and methods

Development of HTA for conventional TKA

All HTAs were developed for cemented primary TKAs. This involved an iterative process to ensure the accuracy and comprehensiveness of the workflow. Input was first obtained from a combination of published literature and the expertise of 4 experienced, fellowship-trained orthopaedic surgeons. These surgeons have collectively performed over 5000 TKAs and have extensive experience with robotic and AR platforms. Over multiple rounds of review, the HTA was developed and validated. The procedure was broken down into individual tasks and subtasks, and any optional tasks were identified where relevant. Next, the tasks and subtasks were arranged in a hierarchical structure based on the expected sequence of events. Each step of the HTA was then reviewed and correlated with potential TKA complications. This allowed for the identification and incorporation of best practices and generalizability across multiple surgeons, ultimately resulting in a comprehensive and standardized plan for the conventional approach.

Adaptation of HTA for robotic-assisted TKA

Another HTA was then developed for robotic-assisted TKA procedures. The HTA for conventional TKA was modified to accommodate the specific steps associated with the use of robotic systems. The input of the same 4 expert orthopaedic surgeons who validated the HTA for conventional TKA was crucial in ensuring the accuracy and completeness of the adapted HTA for robotic-assisted TKA. These authors have experience with 3 different robotic knee systems, and the HTA aims to be inclusive of all robotic knee systems currently available. This HTA reflects the key steps involved in a robotic-assisted TKA procedure. This initial creation process aimed to generate an HTA that was comprehensive and reliable for use in clinical settings.

Validation of conventional and robotic HTAs

To validate the developed conventional and robotic-assisted HTAs for primary cemented TKA, 10 of each TKA procedure was observed by the research team while correlating them to the HTA protocols. The observed procedures were conducted by 2 surgeons at 2 different institutions to ensure the generalizability of the HTAs. During the observation, the research team collected feedback from the operating surgeons, and any deviations from the HTA were documented for further analysis, and the HTAs were updated accordingly.

Development of AR HTA

The HTA for AR-navigated TKA was then developed by the research team. The workflow of an AR system was analyzed, and the specific tasks and subtasks involved in the AR-navigated TKA procedure were identified. We also conducted a literature search using OVID Medline and Embase databases to identify all primary articles on the application of AR for TKA. The developed HTA for AR-navigated TKA was reviewed and validated by one of the expert orthopaedic surgeons with over 4 years of experience developing an AR-navigated TKA platform. This surgeon's expertise in AR technology ensured the accuracy and completeness of the most up-to-date available version of an AR-navigated TKA system.

Incorporation of potential complications in HTAs

Potential complications arising from each step were then incorporated into the HTAs. A list of potential complications that can occur during TKA was adapted from the standardized list and definitions developed by The Knee Society in 2013 [15]. This allowed for the accurate classification of potential complications associated with TKA procedures.

The identified complications were then correlated with each step in the conventional and robotic HTAs. The experience and feedback of the expert orthopaedic surgeons who validated the HTAs were critical in this process. Their input and feedback allowed for the refinement of the HTAs to account for potential complications associated with each step in the procedure. Quantitative validation of the highest-risk steps for each complication was not possible due to the low incidence.

Potential complications were also incorporated into the HTA for AR-navigated TKA. The correlation of potential complications with each step in the AR-navigated HTA was reviewed and validated by reviewing the literature and the orthopaedic surgeon with AR expertise.

Results

Hierarchal task analysis for conventional, robotic-assisted, and AR-navigated TKA is demonstrated in Figures 1-3, respectively. For conventional TKA, the procedure was divided into 11 tasks. An additional task was added to both robotic-assisted and AR-

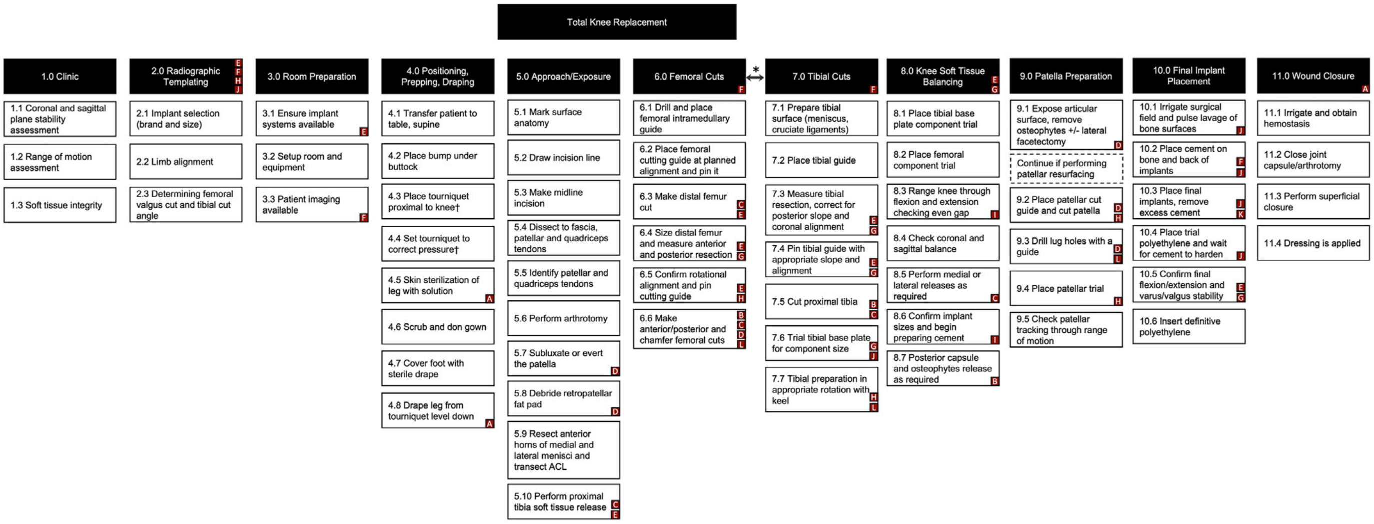

Figure 1. Hierarchical task analysis for conventional, primary cemented total knee arthroplasty. *Step order interchangeable. †Routine tourniquet use is surgeon-dependent.

navigated procedures. The HTA was divided into 2 sections: preoperative preparations and intraoperative procedures.

For the conventional HTA, preoperative preparation included clinical evaluation, radiographic templating, room preparation, and patient positioning, prepping, and draping. In the clinical evaluation step, we included coronal plane stability, sagittal plane stability, and range of motion assessment to determine any potential ligamentous pathology which could impact implant choice or positioning. A soft tissue integrity assessment step allows for identification of previous scars or defects in the surgical field. The radiographic templating step includes the size and type of the implant to achieve optimal alignment and stability. Operating room preparation step included the sterilization of the operating room and the setup of the necessary equipment for the TKA procedure. Patient positioning, prepping, and draping step involved positioning the patient on the operating table and prepping and draping the surgical site to maintain a sterile field during the procedure.

The major tasks of the intraoperative steps of conventional HTA included approach and exposure, followed by femoral and tibial cuts, and knee soft tissue balancing to ensure the proper tension of the ligaments surrounding the knee joint. This is followed by patellar preparation, implant placement, and finally wound closure. Optional steps in the HTA included use of tourniquet, which is surgeon dependent, and whether the patella was resurfaced. Steps for femoral and tibial cuts are interchangeable in the HTA, based on surgeon preference.

Additional preoperative steps required for robotic-assisted and AR-navigated TKA includes ensuring appropriate preoperative imaging is acquired and procedure-specific templating is performed. Both systems are also required to be set-up, the systems draped, the limb prepped and draped to accommodate tracking pins, and the limb positioned appropriately. Intraoperatively, anatomical registration is required for both systems. Visualization of anticipated medial and lateral knee gaps is done with both systems. With robotic-assisted TKA, this is performed by the surgeon adjusting tibial and femoral cut targets on the associated robotic monitor, while in AR this is performed directly at the surgical field through an AR control panel. Guides are then placed onto the femur and tibia following the plan and cuts are made.

The HTAs are annotated with potential complications, correlated to those listed in Table 1. These are the major intraoperative complications associated with each step of the TKA. These are

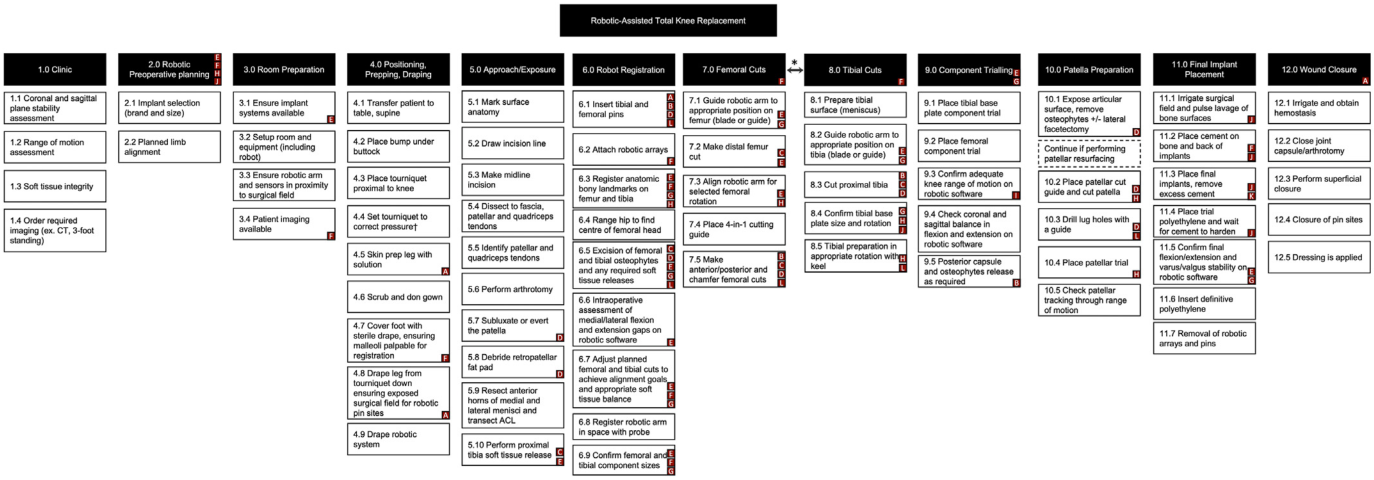

Figure 2. Hierarchical task analysis for augmented reality-guided, primary cemented total knee arthroplasty. *Step order interchangeable. †Routine tourniquet use is surgeon-dependent.

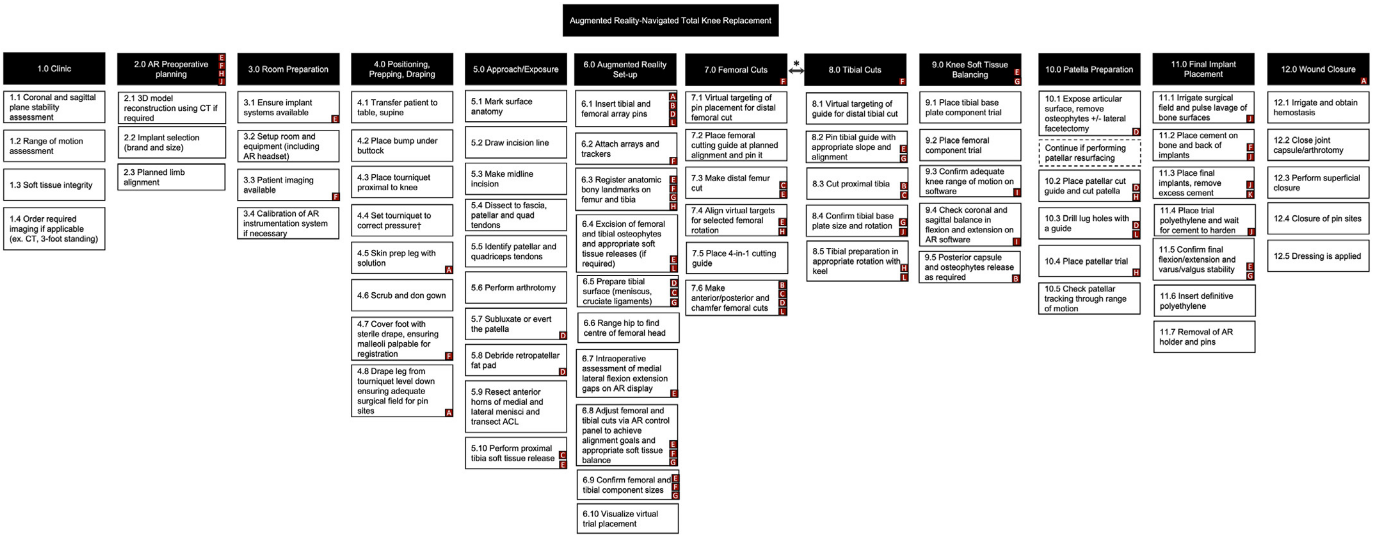

Figure 3. Hierarchical task analysis for robotic-assisted, primary cemented total knee arthroplasty. *Step order interchangeable. †Routine tourniquet use is surgeon-dependent.

divided into soft tissue and implant-related complications. Table 2 demonstrates the number of potential major complications associated with each procedure at each group of steps of the TKA workflow.

To annotate the AR-navigated TKA HTA with potential complications, a comprehensive literature search was performed. Table 3 demonstrates the major studies that have investigated the application of AR in TKA. These studies were mostly preclinical studies on artificial bone models and small clinical case series and case reports on patients. Based on our search, overall, 26 AR-navigated TKA procedures in live patients have been published in the literature. Potential complications associated with AR were synthesized based on the literature search and the expert surgeon's experience (Fig. 3).

Discussion

HTA is a valuable tool for developing a standardized plan for a specific task, using the division of the task into a set of subgoals [22,23]. HTAs are commonly developed in industrial engineering and medical device design, allowing for the identification of sources of error associated with a sequence of human activity related to human-machine systems [23]. In this study, we utilized HTA to develop and validate a workflow for conventional TKA and robotic-assisted TKA. We then developed a HTA workflow for AR-navigated TKA. The resulting HTAs provide comprehensive insights into the key steps of the procedure and how to integrate these technologies into practice.

Table 1
Intraoperative complications are potentially preventable by augmented reality.

Label	Intraoperative complications
Soft tissue	
A	Wound complication
B	Neural deficit/vascular injury
C	Medial or lateral collateral ligament injury
D	Extensor mechanism disruption
Implant alignment	
E	Instability
F	Malalignment
G	Stiffness
H	Patellofemoral dislocation
I	Tibiofemoral dislocation
J	Implant loosening
K	Implant fracture or tibial insert dissociation
L	Periprosthetic fracture

The development of standardized tasks and subtasks for TKA procedures that incorporate robotic and AR technology will aid in increasing the uptake of these systems. Standardization of procedures can help to reduce human error and increase efficiency, resulting in improved patient outcomes. While conventional instrument-guided TKAs and robotic-assisted TKAs are commonly performed across North America, AR-navigated TKAs are still in their infancy, as identified by our literature review. HTAs have been used in other industries such as the boating and forestry industries, aiding to improve safety in emergencies, training, and efficiency [24,25]. The AR-navigated TKA HTA developed in this study can form the basis for studying human reliability analysis when developing AR systems or for surgeons transitioning from performing conventional or robotic TKAs to AR-navigated TKAs [26].

Potential complications at each step of the procedures were annotated. During the preoperative phase of TKA, the primary error that can occur is improper patient selection, implant selection, or inaccurate templating [27–29]. Determining the implants and ensuring correct bone cuts and implant positioning are the most essential steps for every TKA, regardless of the technology used.

Table 2
Number of major potential complications identified at each step during total knee arthroplasty (TKA) for conventional, robotic-assisted, and augmented reality TKA.

Stage	Step	Conventional TKA	Robotic-assisted TKA	Augmented reality TKA
Preoperative	Clinic	-	-	-
	Preoperative planning	4	4	4
	Room preparation	2	2	2
	Positioning, prepping, and draping	2	3	3
Intraoperative	Approach/exposure	4	4	4
	System registration	-	21	18
	Femoral cuts	10	11	9
	Tibial cuts	10	11	9
	Knee soft tissue balancing	4	4	5
	Patella preparation	6	6	6
	Final implant placement	8	8	8
	Wound closure	1	1	1

Table 3
Studies on the application of augmented reality in total knee arthroplasty (TKA).

Study	Country	AR system	Aim	Subjects	Control	Method of assessment	Conclusion
Tsukada 2019 [16]	Japan	AR-KNEE	Assessing accuracy of proximal tibial resection by AR	**Preclinical** 10 tibial sawbones models operated on using an AR-based navigation system	-	Computed tomography (CT) of sawbones	**AR navigation system provided reliable accuracy for coronal, sagittal, and rotational alignment in tibial bone resection on sawbones.**
Tsukada 2021 [10]	Japan	AR-KNEE	Assessing accuracy of distal femoral resection by AR compared to conventional	**Preclinical** 10 femoral sawbones models operated on using an AR-based navigation system	72 patients undergoing conventional TKA	CT of sawbones Standing long-leg radiographs of patients	**AR navigation system has the potential to enhance the precision of distal femoral resection during TKA in comparison to the traditional intramedullary guides based on sawbones.**
Iacono 2021 [17]	Italy	Knee + augmented reality navigation (Pixee Medical Company, Besancon, France)	Assessing accuracy of TKA by AR	**Clinical** 5 patients underwent total knee arthroplasty utilizing an augmented reality navigation system	-	Full-leg-length weight-bearing radiographs, anteroposterior radiographs, and lateral radiographs of the knee	The procedure was accurate and effective.
Fucentese 2021 [18]	Switzerland	NextAR TK (Medacta International SA, Castel San Pietro, Switzerland)	Narrative Study: AR workflow description	-	-	-	-
Su 2022 [19]	China	Unspecified AR platform	Assessing accuracy of TKA by AR	**Clinical** 1 patient underwent total knee arthroplasty utilizing an augmented reality navigation system	-	CT of the knee postoperatively	The procedure was accurate and effective.
van der Putten [20]	Netherlands	Microsoft HoloLens 2 + Microsoft Dynamics 365 Remote Assist Software	Providing unplanned remote assistance	**Clinical** 1 patient undergoing total knee arthroplasty	-	-	**The study demonstrated the feasibility of providing immediate telesurgical support by an industry representative using AR.**
Bennett 2023 [21]	Australia	Knee + augmented reality navigation (Pixee medical company, Besancon, France)	Assessing accuracy of TKA by AR	**Clinical** 20 patients underwent total knee arthroplasty utilizing an augmented reality-assisted navigation system (ARAN)	-	CT of knees postoperatively	Acceptable accuracy in coronal and sagittal alignment of the femoral and tibial bone cuts.

Improper selection of implants can lead to instability of components and suboptimal outcomes [27–29]. Robotic and AR navigation systems enable preoperative planning of precise component position, increasing the relative time required during this period. However, implant position is then adjusted intraoperatively by the surgeon via the robotic screen or AR interface to appropriately balance joint gaps. While preoperative planning reduces some intraoperative cognitive burden and allows for more accurate component placement, it adds more time to preoperative planning [30,31]. During the intraoperative phase, errors related to implant positioning can result in malalignment, instability, stiffness, early aseptic loosening, and patellar maltracking. In conventional TKA, this is due to poorly aligned or placed cutting guides, while the robotic and AR systems rely on accurate navigation registration or displacement of the optical arrays.

By identifying potential areas of inefficiency and risk, the HTA aims to minimize operative errors and ultimately improve patient care. The use of robotic-assisted and AR-navigated TKA may help to reduce human error and improve patient outcomes by improving implant positioning, patient-reported outcomes, and early recovery [32]. In our analysis, we demonstrated that robotic-assisted and AR-navigated approaches had an increased number of steps. However, these additional steps do not necessarily represent an increase in the likelihood of complications. Despite a higher number of steps with the potential for complication, these additional steps may decrease the overall likelihood of a patient experiencing soft tissue or implant-related complications. This may be achieved by optimizing knee gap balancing, improving joint stability, and reducing the requirement for soft tissue releases, therefore minimizing the risk of iatrogenic injury [33,34]. Incorporating additional steps associated with new technology introduces an increased vulnerability to errors. The complexity and interdependence of these additional steps in surgery may amplify the potential for inaccuracies or complications in the overall workflow. It should be noted that the sources of error we identified in robotic-assisted and AR-navigated TKA systems are more dependent on surgical planning and maintained accuracy of the software and hardware throughout the duration of the case than purely technical skills as in conventional approaches.

These systems are associated with additional costs, and robotic-assisted TKA has been associated with longer operative times [35,36]. By critically developing and analyzing procedural steps using an HTA framework, more efficient systems can be designed, potentially reducing costs and allowing these technologies to become more accessible to a wider patient population. This is done by identifying unnecessary steps, educating providers, and developing more efficient systems. On average, the cost of acquiring a robotic system is approximately $1 million USD and includes additional costs of service contracts, maintenance, and disposables [18,37]. Although early results show improved accuracy and precision in implant positioning, improvements in long-term patient-reported outcome measures and implant survival rates have yet to be reported compared to conventional guides [38]. Compared to robotic-assisted TKA, TKA with AR navigation has the potential to be a more efficient and cost-effective solution [18]. This is due to the improved accessibility and user interface of the heads-up display compared to a traditional monitor. Further cost analysis studies would be required to determine the long-term cost-effectiveness of AR-navigated TKA compared to conventional and robotic-assisted surgeries, as the initial investment cost for the robotic systems is significant and may impact healthcare budgets.

This study is novel in that it is the first to develop and validate HTAs for conventional, robotic-assisted, and AR-navigated TKA, the latter of which is a relatively new technology still largely under development. While the HTA developed in this study provides valuable insights into the potential applications of robotic and AR technology in TKA procedures, there are several limitations to consider. Firstly, the HTA was developed and validated by a small group of highly experienced orthopaedic surgeons, which may limit the generalizability of the findings. We addressed this issue by utilizing 4 fellowship-trained surgeons who had experience with 3 different robotic-assisted TKA systems, thereby improving external validity. Secondly, the study only observed a limited number of TKA procedures, and further validation to capture each of the potential complications of the HTAs is necessary. However, these complications are extremely rare, and auditing TKAs while following the HTA until each complication is captured is unfeasible. Finally, the study did not include an analysis of efficiency (planning time, set-up, and duration of surgery time) or cost analysis. The long-term cost-effectiveness of AR-navigated TKA compared to conventional and robotic-assisted surgeries needs to be evaluated.

By using the AR-navigated HTA developed in this study, AR developers can identify specific areas in the TKA procedure where AR technology can be further developed to improve efficiency and reduce human error. For example, the study identified potential areas of inefficiency and risk during the preoperative and intra-operative phases of TKA, such as poor templating and errors related to implant positioning. These areas could be targeted for further development of AR technology, such as improved preoperative image processing using machine learning algorithms and templating or real-time tracking of implant position during surgery [39,40]. Additionally, the HTA can be used to identify potential sources of error associated with the use of AR technology itself, such as calibration errors or inaccuracies in tracking. By addressing these areas of improvement, the use of AR technology in TKA procedures can become even more effective and ultimately lead to better patient outcomes.

Conclusions

we developed and validated hierarchical task analyses for conventional, robotic-assisted, and AR-navigated TKA. AR-navigated TKAs are currently under development, but once widely commercially available, our developed hierarchal workflows may aid in the safer integration of this technology into practice. By comparing them to conventional TKA, these HTAs can be used to assist in the integration of these technologies into a conventional TKA surgeon's practice. Robotic-assisted and AR-navigated TKA systems have the potential to reduce human error by improving reliability, but the efficiency of these systems needs to be optimized to reduce costs and increase accessibility. Further studies should investigate the long-term effects of these systems on patient outcomes and the development of more efficient and accessible systems.

Conflicts of interest

D. J. Backstein has ownership in Augmented Joint Reality Inc., an augmented reality technology company. All other authors declare no potential conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2024.101389.

CRediT authorship contribution statement

Robert Koucheki: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Data curation, Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources. **Jesse I. Wolfstadt:** Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Justin S. Chang:** Supervision, Writing – review & editing, Conceptualization, Formal analysis, Methodology, Resources. **David J. Backstein:** Writing – review & editing, Supervision, Conceptualization. **Johnathan R. Lex:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

References

[1] Siddiqi A, Horan T, Molloy RM, Bloomfield MR, Patel PD, Piuzzi NS. A clinical review of robotic navigation in total knee arthroplasty: historical systems to modern design. EFORT Open Rev 2021;6:252–69. https://doi.org/10.1302/2058-5241.6.200071.

[2] Ren Y, Cao S, Wu J, Weng X, Feng B. Efficacy and reliability of active robotic-assisted total knee arthroplasty compared with conventional total knee arthroplasty: a systematic review and meta-analysis. Postgrad Med J 2019;95:125–33. https://doi.org/10.1136/postgradmedj-2018-136190.

[3] Adamska O, Modzelewski K, Szymczak J, Świderek J, Maciąg B, Czuchaj P, et al. Robotic-assisted total knee arthroplasty utilizing NAVIO, CORI imageless systems and manual TKA accurately restore femoral rotational alignment and yield satisfactory clinical outcomes: a randomized controlled trial. Medicina (Kaunas) 2023;59:236. https://doi.org/10.3390/medicina59020236.

[4] Vaidya NV, Deshpande AN, Panjwani T, Patil R, Jaysingani T, Patil P. Robotic-assisted TKA leads to a better prosthesis alignment and a better joint line restoration as compared to conventional TKA: a prospective randomized controlled trial. Knee Surg Sports Traumatol Arthrosc 2022;30:621–6. https://doi.org/10.1007/s00167-020-06353-2.

[5] Banerjee S, Cherian JJ, Elmallah RK, Jauregui JJ, Pierce TP, Mont MA. Robotic-assisted knee arthroplasty. Expert Rev Med Devices 2015;12:727–35. https://doi.org/10.1586/17434440.2015.1086264.

[6] Brinkman JC, Christopher ZK, Moore ML, Pollock JR, Haglin JM, Bingham JS. Patient interest in robotic total joint arthroplasty is exponential: a 10-year google trends analysis. Arthroplast Today 2022;15:13–8. https://doi.org/10.1016/j.artd.2022.02.015.

[7] Kim Y-H, Yoon S-H, Park J-W. Does robotic-assisted TKA result in better outcome scores or long-term survivorship than conventional TKA? A randomized, controlled trial. Clin Orthop Relat Res 2020;478:266–75. https://doi.org/10.1097/CORR.0000000000000916.

[8] Lex JR, Koucheki R, Toor J, Backstein DJ. Clinical applications of augmented reality in orthopaedic surgery: a comprehensive narrative review. Int Orthop 2022;47:375–91. https://doi.org/10.1007/s00264-022-05507-w.

[9] Laverdière C, Corban J, Khoury J, Ge SM, Schupbach J, Harvey EJ, et al. Augmented reality in orthopaedics: a systematic review and a window on future possibilities. Bone Joint Lett J 2019;101-B:1479–88. https://doi.org/10.1302/0301-620X.101B12.BJJ-2019-0315.R1.

[10] Tsukada S, Ogawa H, Nishino M, Kurosaka K, Hirasawa N. Augmented reality-assisted femoral bone resection in total knee arthroplasty. JB JS Open Access 2021;6:e21.00001. https://doi.org/10.2106/JBJS.OA.21.00001.

[11] Tsukada S, Ogawa H, Kurosaka K, Saito M, Nishino M, Hirasawa N. Augmented reality-aided unicompartmental knee arthroplasty. J Exp Orthop 2022;9:88. https://doi.org/10.1186/s40634-022-00525-4.

[12] Sarker SK, Chang A, Albrani T, Vincent C. Constructing hierarchical task analysis in surgery. Surg Endosc 2008;22:107–11. https://doi.org/10.1007/s00464-007-9380-z.

[13] Demirel D, Yu A, Cooper-Baer S, Dendukuri A, Halic T, Kockara S, et al. A hierarchical task analysis of shoulder arthroscopy for a virtual arthroscopic tear diagnosis and evaluation platform (VATDEP). Int J Med Robot 2017;13: 10.1002/rcs.1799. https://doi.org/10.1002/rcs.1799.

[14] Embrey D. SHERPA: a systematic human error reduction and prediction approach. Contemporary Ergonomics 1984-2008 selected papers and an overview of the Ergonomics Society Annual Conference; Humar Reliability Associates Ltd, School House, Higher Lane, Dalton, Parbold. Lancashire, WN87RP England. In: ; 2009. p. 113–9., https://www.researchgate.net/publication/289967701_SHERPA_A_systematic_human_error_reduction_ancitations. [Accessed 21 April 2024].

[15] Healy WL, Della Valle CJ, Iorio R, Berend KR, Cushner FD, Dalury DF, et al. Complications of total knee arthroplasty: standardized list and definitions of the Knee Society. Clin Orthop Relat Res 2013;471:215–20. https://doi.org/10.1007/s11999-012-2489-y.

[16] Tsukada S, Ogawa H, Nishino M, Kurosaka K, Hirasawa N. Augmented reality-based navigation system applied to tibial bone resection in total knee arthroplasty. J Exp Orthop 2019;6:44. https://doi.org/10.1186/s40634-019-0212-6.

[17] Iacono V, Farinelli L, Natali S, Piovan G, Screpis D, Gigante A, et al. The use of augmented reality for limb and component alignment in total knee arthroplasty: systematic review of the literature and clinical pilot study. J Exp Orthop 2021;8:52. https://doi.org/10.1186/s40634-021-00374-7.

[18] Fucentese SF, Koch PP. A novel augmented reality-based surgical guidance system for total knee arthroplasty. Arch Orthop Trauma Surg 2021;141: 2227–33. https://doi.org/10.1007/s00402-021-04204-4.

[19] Su S, Lei P, Wang C, Gao F, Zhong D, Hu Y. mixed reality technology in total knee arthroplasty: an updated review with a preliminary case report. Front Surg 2022;9:804029. https://doi.org/10.3389/fsurg.2022.804029.

[20] van der Putten K, Anderson MB, van Geenen RC. Looking through the Lens: the reality of telesurgical support with interactive technology using microsoft's hololens 2. Case Rep Orthop 2022;2022:5766340. https://doi.org/10.1155/2022/5766340.

[21] Bennett KM, Griffith A, Sasanelli F, Park I, Talbot S. Augmented reality navigation can achieve accurate coronal component alignment during total knee arthroplasty. Cureus 2023;15:e34607. https://doi.org/10.7759/cureus.34607.

[22] 14 - Human factors and human error. In: Mannan S, editor. Lees' loss prevention in the process industries (third edition). Burlington: Butterworth-Heinemann; 2005. 14/1–14/92.

[23] French A, Taylor LK, Lemke MR. Chapter 6 - task analysis. In: Privitera MB, editor. Applied human factors in medical device design. Cambridge, MA: Academic Press; 2019. p. 63–81.

[24] Navas de Maya B, Komianos A, Wood B, de Wolff L, Kurt RE, Turan O. A practical application of the Hierarchical Task Analysis (HTA) and Human Error Assessment and Reduction Technique (HEART) to identify the major errors with mitigating actions taken after fire detection onboard passenger vessels. Ocean Eng 2022;253:111339. https://doi.org/10.1016/j.oceaneng.2022.111339.

[25] Dreger FA, Englund M, Hartsch F, Wagner T, Jaeger D, Björheden R, et al. Hierarchical task analysis (HTA) for application research on operator work practices and the design of training and support systems for forestry harvester. Forests 2023;14:424. https://doi.org/10.3390/f14020424.

[26] Guglielmi D, Paolucci A, Cozzani V, Mariani MG, Pietrantoni L, Fraboni F. Integrating human barriers in human reliability analysis: a new model for the energy sector. Int J Environ Res Public Health 2022;19:2797. https://doi.org/10.3390/ijerph19052797.

[27] Savov P, Windhagen H, Haasper C, Ettinger M. Digital templating of rotating hinge revision and primary total knee arthroplasty. Orthop Rev 2018;10:7811. https://doi.org/10.4081/or.2018.7811.

[28] Boonen B, Schotanus MGM, Kort NP. Preliminary experience with the patient-specific templating total knee arthroplasty. Acta Orthop 2012;83:387–93. https://doi.org/10.3109/17453674.2012.711700.

[29] Tanzer M, Makhdom AM. Preoperative planning in primary total knee arthroplasty. J Am Acad Orthop Surg 2016;24:220–30. https://doi.org/10.5435/JAAOS-D-14-00332.

[30] Deckey DG, Rosenow CS, Verhey JT, Brinkman JC, Mayfield CK, Clarke HD, et al. Robotic-assisted total knee arthroplasty improves accuracy and precision compared to conventional techniques. Bone Joint Lett J 2021;103-B:74–80. https://doi.org/10.1302/0301-620X.103B6.BJJ-2020-2003.R1.

[31] Bell SW, Anthony I, Jones B, MacLean A, Rowe P, Blyth M. Improved accuracy of component positioning with robotic-assisted unicompartmental knee arthroplasty: data from a prospective, randomized controlled study. J Bone Joint Surg Am 2016;98:627–35. https://doi.org/10.2106/JBJS.15.00664.

[32] Backstein DJ, Bellamy JL, Browne JA, Jones LC, Krebs VE, Mason JB, et al. Augmented reality from the benchtop to the practice of joint arthroplasty: is it feasible? J Arthroplasty 2022;37:1671–2. https://doi.org/10.1016/j.arth.2022.07.015.

[33] Orsi AD, Wakelin EA, Plaskos C, Gupta S, Sullivan JA. Predictive gap-balancing reduces the extent of soft-tissue adjustment required after bony resection in robot-assisted total knee arthroplasty—a comparison with simulated measured resection. Arthroplast Today 2022;16:1–8. https://doi.org/10.1016/j.artd.2022.03.025.

[34] Gordon AC, Conditt MA, Verstraete MA. Achieving a balanced knee in robotic TKA. Sensors (Basel) 2021;21:535. https://doi.org/10.3390/s21020535.

[35] Nogalo C, Meena A, Abermann E, Fink C. Complications and downsides of the robotic total knee arthroplasty: a systematic review. Knee Surgery, Sport Traumatol Arthrosc 2023;31:736–50. https://doi.org/10.1007/s00167-022-07031-1.

[36] Rajan PV, Khlopas A, Klika A, Molloy R, Krebs V, Piuzzi NS. The cost-effectiveness of robotic-assisted versus manual total knee arthroplasty: a markov model-based evaluation. J Am Acad Orthop Surg 2022;30:168–76. https://doi.org/10.5435/JAAOS-D-21-00309.

[37] Moschetti WE, Konopka JF, Rubash HE, Genuario JW. Can robot-assisted unicompartmental knee arthroplasty Be cost-effective? A markov decision analysis. J Arthroplasty 2016;31:759–65. https://doi.org/10.1016/j.arth.2015.10.018.

[38] Zhang J, Ndou WS, Ng N, Gaston P, Simpson PM, Macpherson GJ, et al. Robotic-arm assisted total knee arthroplasty is associated with improved accuracy and patient reported outcomes: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc 2022;30:2677–95. https://doi.org/10.1007/s00167-021-06464-4.

[39] Lex JR, Di Michele J, Koucheki R, Pincus D, Whyne C, Ravi B. Artificial intelligence for hip fracture detection and outcome prediction: a systematic review and meta-analysis. JAMA Netw Open 2023;6:e233391. https://doi.org/10.1001/jamanetworkopen.2023.3391.

[40] Burge TA, Jones GG, Jordan CM, Jeffers JRT, Myant CW. A computational tool for automatic selection of total knee replacement implant size using X-ray images. Front Bioeng Biotechnol 2022;10:971096. https://doi.org/10.3389/fbioe.2022.971096.