Biomechanical Success of Traditional Versus Robotic-Assisted Total Hip Arthroplasty

Abstract Total hip arthroplasty (THA) is known to be a very successful surgical technique. Restoration of normal biomechanical functions and physiological hip restoration are key surgical goals for success of THA. Robotics is a recently tested method for advancing outcomes of THA. In this review, the advantages and disadvantages of robots' use during THAs from a biomechanical standpoint are analyzed. It has been observed that analysis of revision rates, hip dislocation, accurate cup positioning, and implant design and placement plays a crucial role in biomechanical success. Additionally, robotics technologies are proven to have better precision and cup placements when compared to surgeon-only THAs. Challenges faced for robotics' use during THA include surgeon training, extended surgical hours, and economical costs. Analysis of dislocation and revision rates provides mixed results for robotics success during THAs; however, these mixed results can be due to factors such as surgeon's success during the surgery, programming success of the robot for the particular application, and planning of the surgery noting that robots are shown to have successful precision in the literature.

1 Introduction

Total hip arthroplasty (THA) is one of the most successful orthopedic operations ever devised with the end goal of restoration of the normal hip physiology [3]. The progress in hip implant development motivated researchers to focus on several aspects of failure modes with biomechanical consequences [1]. Revision surgeries occur frequently after THA to correct recurrent dislocation of hip implant due to ever-changing factors including implant design, cup positioning and femoral head diameters impacting the outcomes of THA [4], surgeon's successful reconstruction of the hip biomechanics [5], and the surgical technique applied [2]. Several of these biomechanics-impacting factors can be improved while some others are still debated. For instance, the debate on whether the direct anterior approach (DAA) or the posterior approach (PA) allows better restoration of hip biomechanics after THA continues [6], while 10-year follow-up on THA by using new generations of dual-mobility

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cups results in very few to no implant-related dislocations [7, 8]. An extensive analysis on 337,647 THA procedures revealed 0.34% of early revisions for periprosthetic fracture with 44% of these incidences occurring within 90 days of surgery, and the factors that played key roles are observed to be collarless stem, non-grit-blasted finish, and triple-tapered design [9]. In parallel to classical THA surgical techniques, robotic-assisted surgical procedures are tested for success over the years.

Advancement of robotics recently started to impact the number of robotic-assisted THAs with the measured successes observed on surgical outcomes. Robotic systems used during THAs included Kuka's LBR iiwa © [15, 71], Mako © [18–30, 67], Robodoc © [31–38], Orthodoc © [39], da Vinci ©, and CASPAR © [40]. Success levels of robots were measured with their strengths and weaknesses in different ways after THA surgeries. Several advantages of these robotic systems' utilization included high accuracy of implant positioning and orientation [10], minimal invasiveness during surgeries that result in less recovery time, and higher patient satisfaction upon realizations on patient-reported outcome measures (PROM) [11]. Some of the challenges of using such robotics systems included surgeon training, extended surgical hours, and economical costs [12]. This review focuses on advantages and disadvantages of using existing modern robotic systems and their comparisons to the traditional surgeon-based THA factors from a biomechanical perspective. Next section is devoted to a variety of robots used for THA surgeries with their pros and cons observed in the literature. The last section contains concluding remarks on the robotic-assisted versus surgeon-driven THAs and potential improvements on THAs in future applications.

2 Robotics and Manual THA Operational Differences

The impact of robotics during surgical procedures is an extensively studied area due to the increasing interest of robotics use in surgical procedures. Robot-assisted surgeries are shown to improve clinical outcomes and reduce revision rates [13]. The proportion of surgeons utilizing robot-assisted arthroplasty increased from 6.8% to 17.7% just in the New York area from 2007 to 2017 [14]. New robots such as Kuka's LBR iiwa are also introduced for THA use, and testing of such robots increased the results attained for robotic-assisted THAs in the research literature [15]. Robotics allow better mechanical control and stability in applications that may help reducing human errors; however, it offers challenges such as training the surgeon to be able to use robots in THA applications, surgeries lasting longer, and expenses that are associated with robots' utilization and maintenance. Improvements in applications of robots during surgery include improving the accuracy when cutting the femur, reaming the acetabulum, and placing the implant components. It has been shown that the use of robotics can help with reducing inaccuracy as much as 94%. Precision in implant sizing and location particularly helps to minimize risks of leg length discrepancies, dislocations, and other complications of conventional hip replacement [17]. There are limited number of extensive studies that compare robotic-assisted and manual THA surgeries. If we focus on robotic-assisted THA in comparison to manual THA that included 20 or more participants for both surgical strategies, there are only 7 peer-reviewed articles. In these studies, approximately 51% of the 658 patients had gone under robotic-assisted surgeries. Even though PROM appeared to be statistically insignificant (i.e., $p < 0.05$) in most of these studies, assessment of radiographic outcomes indicated robotic THA results to be more consistent and accurate for component placement in six studies. The robot brands used in applications go well beyond these seven studies.

There are well-known robots used during surgeries such as Mako® [18–30], Robodoc® [31–38], Orthodoc® [39], da Vinci®[16], and CASPAR® [40]. The direct cutting of bone to the final planned cut or indirect planning landmarks to adjust placement or holding of cutting jigs has been conducted using robotics. The applications of robotics can be divided into three categories depending on the applications to surgical incisure/cutting operations: (1) autonomous, (2) haptic control [20, 41], and (3) boundary control [42, 43]; therefore, robotic systems can be fully automated, hybrid, and completely manual depending on robot's involvement during the process. Autonomous applications are fully robotics driven with the mechanical limitations depending on the mechanical stability and precision of the robot along with the precision of the algorithm that robot follows. Depending on the application, the results of a robotics use can be harmful noting that the robot would not necessarily follow the footsteps of a successful surgeon. Haptic control requires surgeon involvement in several applications such as cutting, milling, or drilling in which case mechanical stability of the operations may alter between the robot and the surgeon. Boundary control allows independent task management without direct human manipulation by using algorithms based on associated preprogramming with defined parameters of bone resection. Robodoc (THINK Surgical®) surgical system [44] was the first active robotic system used in THA surgery that allowed complete robotic assistance without continuous control by the surgeon throughout the procedure. In particular, the placement of the polyethylene-based cartilage on the bone by using a robot is a fine application of the robotics for implant production; however, in many applications, complete control robots are not found to be feasible for safety reasons.

Da Vinci robot developed and manufactured by Intuitive Surgical Inc., displayed in Fig. 1 (reproduced and used with permission from © 2018 Intuitive Surgical, Inc.), is a completely manual surgical robot system requiring surgeon's full control during the surgery and used for many different surgical applications. Biomechanical analysis of robots' effectiveness during THAs is mainly focused on hybrid systems' analysis that requires comparison of robotic-assisted surgeon THA outcomes to manual surgeries.

Robodoc, a technology developed by Curexo Technology Corporation, Fremont, California, USA, is a robotic system used for THAs utilizing CT scans that can be converted into three-dimensional virtual images for preoperative planning and computer-guided drilling [45]. Preoperative CT scans are used for Robodoc computer assistance for milling a femoral canal automatically and stem implant positioning. Majority of the surgical applications of Robodoc, 50% (four out of eight),

Fig. 1 An image of da Vinci robot simulator (permitted by CESI of Hartford HealthCare)

has been posterolateral [32, 35, 39, 48], while 37.5% (three out of eight) was posterior [14, 34, 37], and only one was anterolateral [31]. Accurate positioning cup placement is observed in several of these studies [32, 34, 39] impacting the biomechanics of THA and a reduction on revision surgeries.

There are studies in the literature which resulted in minimal statistical significance between hybrid and manual surgeries. For instance, no differences are found between the hybrid and manual procedures in [35] after 1-year and 5-year follow-ups, while robotic-assisted THA had significantly higher outcomes at 2- and 3-year follow-ups. Honl et al. [31] reported 18% (13/74) attempted hybrid surgeries among the 154 THAs needing conversion to manual implantations as a result of failure of the system, and the rest of the surgeries were manual; dislocation rate was higher in hybrid surgical procedures with 11 occurrences in 61 patients accounting for approximately 18% while the same rate was 3 occurrences in 8 manual operations with $p < 0.001$. The research outcomes in other Robodoc applications were mainly positive for robotic-assisted THA surgeries. For instance, one of the comprehensive studies focused on the application of Robodoc system investigated in the United States and Germany that was designed to address potential human errors in performing cementless THA [46]. The system consisted of a preoperative planning computer workstation called Orthodoc®, and a robotic arm with a high-speed milling device as an end effector was used. One- and two-year follow up- were conducted on 127 and 93 patients, respectively. Radiographs were evaluated by an independent bone radiologist and demonstrated to be statistically better fitting and positioning of the femoral component in the Robodoc group. There were three cases of intraoperative femoral fracture in the control group and none in the robotic-assisted group.

The majority of the studies focused on stem placement for Robodoc-assisted THAs' comparison with manual surgeries. Bargar et al. [34] observed better trends in clinical outcomes for robotic-assisted THA when compared to manual surgical procedures with no statistical significance but favoring use of robotics; the Robodoc system is determined to be safe and effective in producing radiographically superior implant fit, eliminating femoral fractures, and better implant positioning for biomechanical success. Hananouchi et al. [37] did not find significant differences between robotic-assisted and manual THA surgeries by analyzing the Merle d'Aubigne scores. Lim et al. [35] observed on average about 10 min longer operational milling time for robotic-assisted surgeries; however, superior results are attained for stem alignment and leg length equality by using robots. As a result, there were only two intraoperative femoral fractures occurred in the manual rasping group. During the 2-year follow-up, Nishihara et al. [39] did not find any intraoperative femoral fractures. Upon 10 years follow-up, Nakamura et al. [48] did not determine any significant differences in functional scores between the two methods. Bargar et al. [38] determined robotic-assisted surgeries to require less revision rates as a result of 14-year follow-up with $p > 0.05$, while Honl et al. [31] determined the opposite as a result of 2-year follow-ups. Upon Robodoc use, dislocation rates are determined to be higher than the manual surgeries in [31, 34], and [32], while opposite is observed in [38]. Figure 2a demonstrates the Robodoc surgical system's hardware components [65], and Fig. 2b displays the Robodoc's robotic arm in action during a live surgery.

There are several models of Mako technologies that are utilized for THA applications. Mako THA system, developed by Stryker®, Mahwah, NJ, utilizes predefined physiological parameters and preprogrammed algorithms to allow surgical procedure without surgeon's control. The design of MAKOplasty THA® by Stryker Corporation allows direct posterolateral and anterior approaches for assisting with

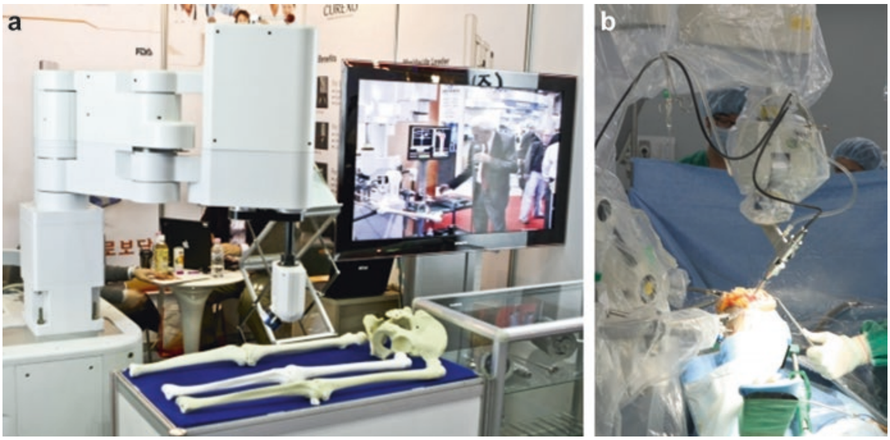

Fig. 2 (**a**) Robodoc surgical system by Curexo Technology Corporation [65]. (**b**) Robodoc's live operation use during a surgery [66]

the acetabular cup and navigation of the femoral stem that enhances the ability to navigate the femoral osteotomy line and the femoral rotation. The surgeon is still responsible for the appropriate approach of THA; however, specific anatomical landmarks are predetermined for placement of acetabular component by using the coronal plane measurements determined prior to each surgery by using patient-specific CT scan and CAD information [47]. These measured markings and Mako's ability to track the landmarks throughout the surgery make the robot a success during the surgery [49]. The precision of coronal plane tracing makes it biomechanically more precise when compared to the manual counterpart. Mako has been used in a variety of surgical approaches including posterolateral [51, 55], posterior [22, 25, 52–54], posterior or direct anterior [30, 50, 56, 57], and direct lateral [58]. Mako systems' success rates are analyzed by observing surgical revision rates, cup displacement, and hip mechanical stability.

There are two major recent studies in this area of interest with more than 100 observations with at least 2 years of follow-up after surgeries. Domb et al. [50] compared acetabular cup placement using direct anterior or posterior surgical approaches using Mako robotics on 66 patients and manual application on 66 patients with a p-value of 0.479. Banchetti et al. [27] compared Mako robotics application on 56 patients to manual applications on 51 patients based on acetabular cup placement and determined a p-value of 0.7276 that favors advantages of robotics usage after a 2-year follow-up. Comparison of manual and robotic surgical success differences did not find high statistical differences between robotics and manual THA surgical methods; however, this outcome is likely to be due to the high success rate of the manual THA. Clement et al. [52] observed Mako robots to present significantly greater functional outcomes when compared to manual operations. Hadley et al. [58] observed success of robotic-assisted THAs to be significantly higher than the manual THAs. Analysis of 896 manual and 135 robotic-assisted THA by Singh et al. [57] showed significant advantages of using robotics for 1-year hip disability, osteoarthritis outcome score, and joint replacement scores. Kamara et al. [53] reported robotic techniques delivering significant and immediate improvement in the precision of acetabular component positioning that also has challenges of using robotics. Kong et al. [25] identified comparable scores between manual and robotic THA surgeries when posterior approach is used. Kong et al. [54] did not find differences between the robotic-assisted and manual THA operations as a result of Mako use. Manual THA is determined to have less stability and weaker functional outcomes by Bukowski et al. [51] than the robotic-assisted surgeries, while overall complication rates are found to be the same for the two methods upon 1-year follow-up. Two years after surgeries, functional outcome scores of robotic-assisted surgery are determined to be better than the manual counterpart, while the pain levels are determined to be higher for THA patients by Perets et al. [56]. One-year follow-up of both Mako system-assisted THA and manual surgery follow-ups by Peng et al. [55] did not indicate differences in gait asymmetry between the two cohorts. Contralateral hip mechanics analysis based on the range of motion, walking speed, and gait mechanics for hybrid and manual THAs are compared. No differences are found in peak range of motion in the frontal or axial planes for hybrid surgeries, while net sagittal plane range of motion was significantly reduced. After 5 years, Domb et al. [50] analyzed PROMs indicating robotic-assisted surgeries to perform better than the manual counterpart. Using Mako Stryker, the robotic arm and traditional surgical procedures are compared in [60], and it is concluded that robotic-assisted surgery reduced postoperative pain and surgical time as well as reduced days of independent walking. The revision rates of robotic-assisted surgeries determined to be either same [59] or lower [50, 51, 56] for the use of Mako surgical systems, while only one study determined Mako systems to have 1% more revision rate than manual THA [53]. The dislocation rates observed for Mako systems utilization is controversial; lower dislocations are determined in [51, 54] while the contrary is observed in [50, 53]. Figure 3 displays the Mako surgical system integrated to da Vinci robot in a surgical room.

Kuka's LBR iiwa robot is a recent robotics technology when compared to Mako and Robodoc that is used as a haptic device to provide high-force feedback for an orthopedic surgeon while performing the reaming of the acetabula in a virtual environment [15]. It is shown that the designed robotic-assisted surgery is intuitive and reliable from users' perspective. Mechanical properties on hip reaming are modeled in [51], resulting in a tissue-based material model of the acetabulum for force feedback by using virtual reality (VR) hip reaming simulator. The resulting forces were delivered using Kuka's iiwa robotic arm as a force feedback device. Mechanical data is attained using high-force surgical interventions as a baseline data for

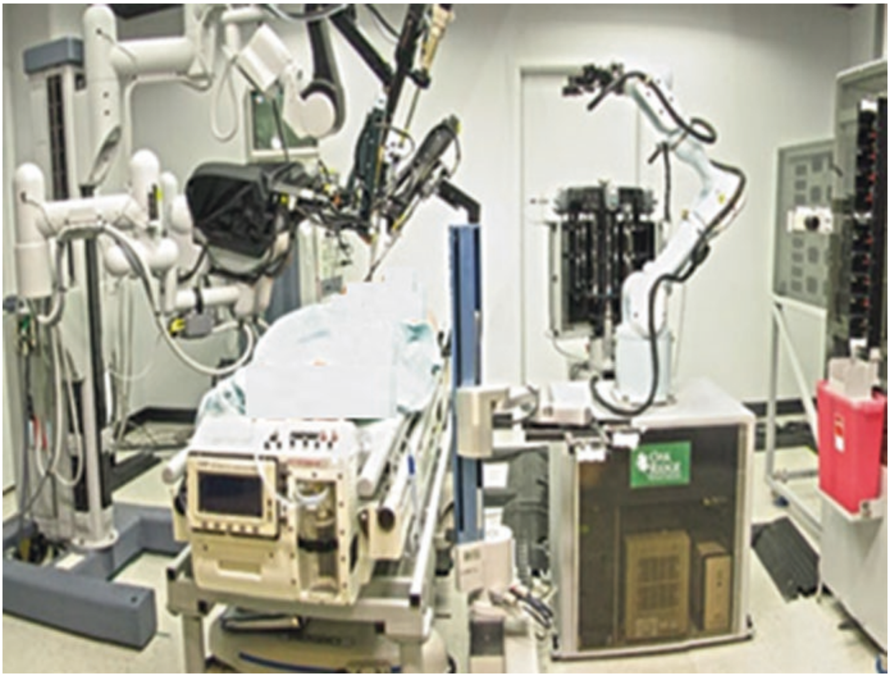

Fig. 3 Mako surgical system shown on the side robotic-assisted surgery [68]

material models and biomechanical considerations; the model developed by the authors allows THA surgeons to train with a variety of machining hardness levels of acetabula for haptic VR acetabulum reaming [51].

Cyclic loading and motion of the hip joint induce micromotions at the bone-implant interface of cementless total hip replacements. Osseointegration and long-term survival are observed to be impacted by initial stability of THA [61]. Noting the impacts of robotics on cup placement precision, while fixation of femoral stems achieves good clinical results and therefore biomechanical success, the fixation of acetabular components remains a challenge.

As much as the robots may be useful for surgical procedures, surgical teams' level of experiences may limit the design and implementation of surgical robots that may relate to exploring how to provide haptic feedback during the robotic surgery [62, 63]. Additionally, a critical factor to be incorporated in robotic surgery is the use of techniques such as drilling [37]. The selection of hole drilling location and method of incision with the corresponding site selection can be identified and specified during computer-assisted systems with the use of robots for surgical procedures. This approach can either be used as a guide to the surgeon or provide information to the robot that can be used for surgical procedures. Figure 4 is an image of a Kuka robot used for medical technology to attain optimum solutions for robot-based medical products [70].

CASPAR systems are used similarly to Robodoc; preoperative CT scans are used for this system with computer assistance for milling a femoral canal automatically and stem implant positioning. Revisions of surgeries, complications, and heterotopic ossification appeared to be higher for CASPAR systems, although both positive and negative results are attained as a part of the surgical procedures from robotics application perspective; CASPAR robots are no longer available for surgical procedures [64].

Fig. 4 Kuka robot used for medical technology: optimum solutions for robot-based medical products [70]

3 Conclusions and Future Research Directions

THA is one of the most successful orthopedic operations ever devised with the end goal of restoration of the normal hip physiology [3]. Restoration of normal hip anatomy and biomechanics is a key surgical goal for success of THA [40]. Analysis of revision rates, hip dislocation, accurate cup positioning, and implant design and placement plays a crucial role in biomechanical success. The majority of the research results focused on two robotic systems, Mako and Robodoc, which are used for THA. Robotics technologies are proven to better precision and cup placements during THA. Challenges faced for robotics use in these applications include surgeon training, extended surgical hours, and economical costs. Consequences of biomechanical success can be measured by analyzing dislocation rates and revision rates. Neither Mako nor Robodoc systems display a consistent positive outcome for either one of dislocation rates or revision rates; however, the surgical follow-ups have shown high PROM values and better accuracy rates for implant sizing and location that help to minimize risks of leg length discrepancies, dislocations, and other complications of conventional hip replacements. Newer technologies such as Kuka can be used with VR. Future of the advanced and successful THAs may be upon the successful integration of technologies such as robotics, VR, and Artificial Intelligence (AI). Noting that robotics systems have existing success records in THA for assisting surgeons, factors such as surgeon's success, programming of the robot for THA procedures, and physiological conditions can be other factors impacting the successful outcomes of robotic-assisted surgeries.

References

1. Heckmann ND, et al. Spinopelvic biomechanics and total hip arthroplasty: a primer for clinical practice. J Am Acad Orthop Surg.: September 15, 2021. 2021;29(18):e888–903. https://doi.org/10.5435/JAAOS-D-20-00953.
2. McGoldrick NP, et al. Supine versus lateral position for total hip replacement: accuracy of biomechanical reconstruction. Arch Orthop Trauma Surg. 2021; https://doi.org/10.1007/s00402-021-04179-2.
3. Learmonth ID, et al. The operation of the century: total hip replacement. Lancet. 2007;370(9597):1508–19. https://doi.org/10.1016/S0140-6736(07)60457-7.
4. Wang J, et al. Kinematic and kinetic changes after total hip arthroplasty during sit-to-stand transfers: systematic review. Arthroplasty Today. 2021;7:148–56.
5. Vandeputte F-J, et al. Capsular resection versus capsular repair in direct anterior approach for total hip arthroplasty: a randomized controlled trial. Bone Jt J. 2021;103(2):321–8.
6. Pujol O, et al. Restoring hip biomechanics during the learning curve of a novice surgeon: direct anterior approach vs posterior approach. J Orthop. 2021;26:72–8.
7. Prudhon JL, Ferreira A, Verdier R. Dual mobility cup: dislocation rate and survivorship at ten years of follow-up. Int Orthop. 2013;37(12):2345–50.
8. Caton JH, et al. A comparative and retrospective study of three hundred and twenty primary Charnley type hip replacements with a minimum follow up of ten years to assess whether a dual mobility cup has a decreased dislocation risk. Int Orthop. 2014;38(6):1125–9.

9. Lamb JN, et al. A calcar collar is protective against early periprosthetic femoral fracture around cementless femoral components in primary total hip arthroplasty: a registry study with biomechanical validation. Bone Jt J. 2019;101(7):779–86.
10. Kayani B, et al. The learning curve of robotic-arm assisted acetabular cup positioning during total hip arthroplasty. Hip Int. 2021;31(3):311–9.
11. Chen X, et al. Robotic arm-assisted arthroplasty: The latest developments. Chin J Traumatol. 2021;
12. Randell R, Alvarado N, Honey S, et al. Impact of robotic surgery on decision making: perspectives of surgical teams. AMIA Annu Symp Proc. 2015;2015:1057–66. Published 2015 Nov 5
13. Sousa PL, et al. Robots in the operating room during hip and knee arthroplasty. Curr Rev Musculoskelet Med. 2020;13(3):309–17. https://doi.org/10.1007/s12178-020-09625-z.
14. Boylan M, Suchman K, Vigdorchik J, et al. Technology-assisted hip and knee arthroplasties: an analysis of utilization trends. J Arthroplasty. 2017;33:1019e1023.
15. Panariello D, et al. Using the KUKA LBR iiwa robot as haptic device for virtual reality training of hip replacement surgery. 2019 Third IEEE International Conference on Robotic Computing (IRC); 2019. p. 449–50.
16. Concept Idea for a New da Vinci Surgical System, published by Medgadget, accessed Nov. 25, 2021. https://www.medgadget.com/2018/02/concept-idea-new-da-vinci-surgical-system.html
17. American Hip Institute, The benefits of robotics in hip replacement surgery, accessed November 2nd 2021., https://www.americanhipinstitute.com/blog/the-benefits-of-robotics-in-hip-replacement-surgery-19431.html
18. Tarwala R, Dorr LD. Robotic assisted total hip arthroplasty using the MAKO platform. Curr Rev Musculoskelet Med. 2011;4(3):151–6.
19. El Bitar YFE, Stone JC, Jackson TJ, et al. Leg-length discrepancy after total hip arthroplasty: comparison of robot-assisted posterior, fluoroscopy-guided anterior, and conventional posterior approaches. Am J Orthop (Belle Mead NJ). 2015;44:265–9.
20. Tsai T-Y, Dimitriou D, Li J-S, Kwon Y-M. Does haptic robot-assisted total hip arthroplasty better restore native acetabular and femoral anatomy? Robot-assisted total hip arthroplasty better restores hip anatomy. Int J Med Robot. 2016;12:288–95.
21. Suarez-Ahedo C, Gui C, Martin TJ, et al. Robotic-arm assisted total hip arthroplasty results in smaller acetabular cup size in relation to the femoral head size: a matched-pair controlled study. Hip Int. 2017;27:147–52.
22. Domb BG, Redmond JM, Louis SS, et al. Accuracy of component positioning in 1980 total hip arthroplasties: A comparative analysis by surgical technique and mode of guidance. J Arthroplasty. 2015;30:2208–18.
23. Kayani B, Konan S, Huq SS, et al. The learning curve of robotic-arm assisted acetabular cup positioning during total hip arthroplasty. Hip Int. 2019:112070001988933.
24. Heng YY, Gunaratne R, Ironside C, Taheri A. Conventional vs robotic arm assisted total hip arthroplasty (THA) surgical time, transfusion rates, length of stay, complications and learning curve. J Arthritis. 2018;7:4.
25. Kong X, Yang M, Jerabek S, et al. A retrospective study comparing a single surgeon's experience on manual versus robot-assisted total hip arthroplasty after the learning curve of the latter procedure – a cohort study. Int J Surg. 2020;77:174–80. https://doi.org/10.1016/j.ijsu.2020.03.067.
26. Kanawade V, Dorr LD, Banks SA, et al. Precision of robotic guided instrumentation for acetabular component positioning. J Arthroplasty. 2015;30:392–7.
27. Banchetti R, Dari S, Ricciarini ME, et al. Comparison of conventional versus robotic-assisted total hip arthroplasty using the Mako system: an Italian retrospective study. J Health Soc Sci. 2018;3:37–48.
28. Perets I, Walsh JP, Close MR, et al. Robot-assisted total hip arthroplasty: Clinical outcomes and complication rate. Int J Med Robot. 2018;14:e1912.
29. Illgen RL, Bukowski BR, Abiola R, et al. Robotic-assisted total hip arthroplasty: outcomes at minimum two-year follow-up. Surg Technol Int. 2017;30:365–72.

30. Domb BG, El Bitar YF, Sadik AY, et al. Comparison of robotic-assisted and conventional acetabular cup placement in THA: a matched-pair controlled study. Clin Orthop Relat Res. 2014;472:329–36.
31. Honl M, Dierk O, Gauck C, et al. Comparison of robotic-assisted and manual implantation of a primary total hip replacement: a prospective study. J Bone Jt Surg Am. 2003;85:1470–8.
32. Nakamura N, Sugano N, Nishii T, et al. A comparison between robotic-assisted and manual implantation of cementless total hip arthroplasty. Clin Orthop Relat Res. 2010;468:1072–81.
33. Schulz AP, Seide K, Queitsch C, et al. Results of total hip replacement using the Robodoc surgical assistant system: clinical outcome and evaluation of complications for 97 procedures. Int J Med Robot. 2007;3:301–6.
34. Bargar WL, Bauer A, Börner M. Primary and revision total hip replacement using the Robodoc® system. Clin Orthop. 1998;354:82–91.
35. Lim S-J, Ko K-R, Park C-W, et al. Robot-assisted primary cementless total hip arthroplasty with a short femoral stem: a prospective randomized short-term outcome study. Comput Aided Surg. 2015;20:41–6.
36. Xin Chen, et al, Robotic arm-assisted arthroplasty: the latest developments., Chinese Journal of Traumatology, 2021
37. Hananouchi T, Sugano N, Nishii T, et al. Effect of robotic milling on periprosthetic bone remodeling. J Orthop Res. 2007;25:1062–9.
38. Bargar WL, Parise CA, Hankins A, et al. Fourteen year follow-up of randomized clinical trials of active robotic-assisted total hip arthroplasty. J Arthroplasty. 2018;33:810–4. https://doi.org/10.1016/j.arth.2017.09.066.
39. Nishihara S, Sugano N, Nishii T, et al. Comparison between hand rasping and robotic milling for stem implantation in cementless total hip arthroplasty. J Arthroplasty. 2006;21:957–66.
40. Siebel T, Käfer W. Klinisches Outcome nach Roboter-assistierter versus konventionell implantierter Hüftendoprothetik: Prospektive, kontrollierte Untersuchung von 71 Patienten. Z Für Orthop Ihre Grenzgeb. 2005;143:391–8.
41. Nawabi DH, et al. Haptically guided robotic technology in total hip arthroplasty: A cadaveric investigation. Proc Inst Mech Eng H. 2013;227:302–9.
42. DiGioia AM, Jamaraz B, Picard F, Nolte L-P. Computer and robotic assisted hip and knee surgery. Oxford University Press; 2004.
43. Netravali NA, Shen F, Park Y, Bargar WL. A perspective on robotic assistance for knee arthroplasty. Adv Orthop. 2013;2013:1–9.
44. EFORT. Open Rev, vol. 4; 2019. p. 618–25. https://doi.org/10.1302/2058-5241.4.180088.
45. Netravali NA, Börner M, Bargar WL. The use of ROBODOC in total hip and knee arthroplasty. In: Ritacco L, Milano F, Chao E, editors. Computer-assisted musculoskeletal surgery. Cham: Springer; 2016. https://doi.org/10.1007/978-3-319-12943-3_16.
46. Bargar, WL. et al, Clinical Orthopaedics and Related Research (1976–2007): September 1998, 354 82–91
47. Murray DW. The definition and measurement of acetabular orientation. J Bone Joint Surg Br. 1993;75(2):228–32.
48. Nakamura N, Sugano N, Sakai T, Nakahara I. Does robotic milling for stem implantation in cementless THA result in improved outcomes scores or survivorship compared with hand rasping? results of a randomized trial at 10 years. Clin Orthop Relat Res. 2018;476:2169–73. https://doi.org/10.1097/CORR.0000000000000467.
49. Kouyoumdjian P, et al. Current concepts in robotic total hip arthroplasty. SICOT J. 2020;6:45. https://doi.org/10.1051/sicotj/2020041.
50. Domb BG, Chen JW, Lall AC, et al. Minimum 5-year outcomes of robotic-assisted primary total hip arthroplasty with a nested comparison against manual primary total hip arthroplasty: a propensity score-matched study. J Am Acad Orthop Surg. 2020;28:847–56. https://doi.org/10.5435/JAAOS-D-19-00328.
51. Bukowski BR, Anderson P, Khlopas A, et al. Improved functional outcomes with robotic compared with manual total hip arthroplasty. Surg Technol Int. 2016;29:303–8.

52. Clement ND, Gaston P, Bell A, et al. Robotic arm-assisted versus manual total hip arthroplasty a propensity score matched cohort study. Bone Jt Res. 2020;10:22–30. https://doi.org/10.1302/2046-3758.101.BJR-2020-0161.R1.
53. Kamara E, Robinson J, Bas MA, et al. Adoption of robotic vs fluoroscopic guidance in total hip arthroplasty: Is acetabular positioning improved in the learning curve? J Arthroplasty. 2017;32:125–30. https://doi.org/10.1016/j.arth.2016.06.039.
54. Kong X, Yang M, Li X, et al. Impact of surgeon handedness in manual and robot-assisted total hip arthroplasty. J Orthop Surg Res. 2020;15:1–8. https://doi.org/10.1186/s13018-020-01671-0.
55. Peng Y, Arauz P, Desai P, et al. In vivo kinematic analysis of patients with robotic-assisted total hip arthroplasty during gait at 1-year follow-up. Int J Med Robot. 2019;15:e2021. https://doi.org/10.1002/rcs.2021.
56. Perets I, Walsh JP, Mu BH, et al. Short-term clinical outcomes of robotic-arm assisted total hip arthroplasty: a pair matched controlled study. Orthopedics. 2020; https://doi.org/10.3928/01477447-20201119-10.
57. Singh V, Realyvasquez J, Simcox T, et al. Robotics versus navigation versus conventional total hip arthroplasty: does the use of technology yield superior outcomes? J Arthroplasty. 2021; https://doi.org/10.1016/j.arth.2021.02.074.
58. Hadley C, Grossman E, Mont M, et al. Robotic-assisted versus manually implanted total hip arthroplasty: a clinical and radiographic comparison - Pubmed. Surg Technol Int. 2020;28:371–6.
59. Singh JA. Epidemiology of knee and hip arthroplasty: a systematic review. Open Orthop J. 2011;5:80–5. https://doi.org/10.2174/1874325001105010080.
60. Shibanuma N, Ishida K, Matsumoto T, et al. Early postoperative clinical recovery of robotic arm-assisted vs. image-based navigated Total hip Arthroplasty. BMC Musculoskelet Disord. 2021;22(314) https://doi.org/10.1186/s12891-021-04162-3.
61. Crosnier E, Keogh P, Miles A. The effect of dynamic hip motion on the micromotion of press-fit acetabular cups in six degrees of freedom. Med Eng Phys. 2016;38(8):717–24. https://doi.org/10.1016/j.medengphy.2016.04.014.
62. Bark K, et al. In vivo validation of a system for haptic feedback of tool vibrations in robotic surgery. Surg Endosc. 2013;27(2):656–64.
63. Koehn J, Kuchenbecker K. Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery. Surg Endosc. 2014; https://doi.org/10.1007/s00464-014-4030-8.
64. Perets I, Mu BH, Mont MA, Rivkin G, Kandel L, Domb BG. Current topics in robotic-assisted total hip arthroplasty: a review. Hip Int. 2020;30(2):118–24.
65. Korea IT Times, Introduce Dr. Robodoc, accessed 26 Nov 2021. http://www.koreaittimes.com/news/articleView.html?idxno=11294
66. Kim Y-r, Precise and accurate surgery with Robodoc, Korea IT Times, accessed 26 Nov 2021, http://www.koreaittimes.com/news/articleView.html?idxno=11945
67. Arundhati Parmar, Stryker launches expensive Mako robot for knee replacement in cost-conscious era, accessed 11 Nov 2021, https://medcitynews.com/2017/03/stryker-launches-expensive-mako-robot-knee-replacement-cost-conscious-era/
68. Robin Young, Was Mako's miss a hit on surgical robotics? June 4th, 2012, accessed 11 Nov 2021, Source: Wikimedia Commons and SRI International, https://ryortho.com/2012/06/was-makorsquos-miss-a-hit-on-surgical-robotics/
69. KUKA LBR IIWA 7 R800., https://www.robots.com/robots/lbr-iiwa-7-r800
70. KUKA robots for medical technology: optimum solutions for robot-based medical products, https://www.kuka.com/en-us/industries/health-care/kuka-medical-robotics
71. Klodmann J, Schlenk C, Hellings-Kuß A, et al. An introduction to robotically assisted surgical systems: current developments and focus areas of research. Curr Robot Rep. 2021;2:321–32. https://doi.org/10.1007/s43154-021-00064-3.