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ORIGINAL ARTICLE • KNEE - ARTHROPLASTY

Outcomes of robotic-arm-assisted medial unicompartmental knee arthroplasty: minimum 3-year follow-up

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Abstract

The purpose of this study was to determine implant survivorship, complications, and re-operation rates, after robotic arm-assisted unicompartmental knee arthroplasty (UKA) at intermediate follow-up. Patient satisfaction and clinical outcome were further investigated, in addition to an analysis of restoration of knee alignment. Fifty-one patients, who received a robotic arm-assisted medial UKA, were prospectively studied, and followed for a minimum of 3 years (mean 51.4 ± 4.5 months). Survival of implants, complications, reoperations, and patients' overall satisfaction were evaluated. WOMAC scores, as well as knee flexion, varus deformity and flexion contracture were further analyzed, before and after surgery. No implant failure or implant-related complication was recorded, and no revision surgery was performed at the last follow-up in any patient. Overall satisfaction was excellent; 96.1% of patients, at the latest follow-up, was satisfied or very satisfied, while none was dissatisfied or very dissatisfied. Total WOMAC score and each score's component was significantly improved after surgery. Knee alignment was significantly improved, as flexion increased, varus decreased, and flexion contracture also decreased. In conclusion, robotic-arm-assisted UKA, through accurate implant positioning, significantly improves range of motion and coronal plane alignment, in appropriately selected patients. Excellent overall satisfaction rates and clinical outcomes can be expected, at intermediate follow-up, along with excellent survival of implants and minimal to none surgery-related morbidity.

Keywords Robotic-arm-assisted UKA · Robotics · MAKO · Unicompartmental knee arthroplasty · Clinical outcome · Implant survivorship

Introduction

Unicompartmental knee arthroplasty (UKA) has been introduced as a good alternative to total knee arthroplasty (TKA) when only one compartment of the knee is involved [1–4]. It has been shown that compared to TKA, UKA more closely approximates native knee kinematics, while associated with less blood loss and need for blood transfusion, quicker return of function, less pain medication requirements, better range of motion (ROM), and shorter length of hospital stay [4–7]. Despite excellent functional outcomes achieved for the majority of patients, long-term survival has been the most pressing issue concerning the viability of conventional UKA, while the main complications after UKA (femorotibial osteoarthritis of the contralateral compartment and tibial implant loosening) are frequently due to suboptimal implant positioning [3]. In fact, one of the greatest challenges regarding the ultimate success of the procedure has been the technically demanding nature of the surgery [8]. Poor prosthesis alignment has been associated with early failure of UKA and is likely to contribute to the higher revision rate observed with UKA in comparison with TKA (1.4% versus 4.6% at 3 years), while at the same time, strong evidence suggests that surgeons undertaking low volumes of UKA have higher revision rates, reflecting the complexity of the surgery [2, 8, 9].

Recently, robotic-assisted UKA has been shown to reliably improve lower leg alignment [10–12], soft tissue balancing [13] and implant positioning [14–17] when compared to conventional surgery, subsequently the application of robotics in reconstruction surgery of the knee has been suggested to present better clinical outcomes, as failure of UKA is commonly associated with technical errors of malalignment, instability and implant malpositioning [2, 13, 18, 19].

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It is a fact that robotic-assisted surgery has become an attractive method for ensuring accurate execution of the surgical plan [2], and although there have been some studies in the past years demonstrating superior results for robotic-assisted UKA, more studies are needed to draw safe conclusions on the subject. Additionally, published studies, in their majority, focus individually on either restoration of alignment or clinical and functional outcomes. The purpose of this study was to determine implant survivorship, complications, and re-operation rates, and further investigate patient satisfaction, clinical and functional outcome at intermediate follow-up, in addition to an analysis of the restoration of knee alignment after robotic arm-assisted UKA.

Materials and Methods

In this prospective study, we followed for a minimum of 3 years (mean follow-up 51.4 ± 4.5 months; range 37–56 months) 51 patients, who received a robotic arm-assisted medial UKA between February 2014 and September 2015, and represent the initial series of robotic-assisted UKAs performed in our country (Table 1). No patient was lost to follow-up. All procedures were performed with the Robotic Arm Interactive Orthopedic System (RIO; MAKO Stryker, Fort Lauderdale, Florida), which is a haptic system (Fig. 1). A haptic system is a semi-active robot, which provides passive haptic restraints for surgical resection, in contrast to computer-assisted surgery that provides only passive guidance and feedback. Haptic sensation is provided to the surgeon through auditory (beeping), tactile (vibratory), and visual (color change on the computer screen) [18]. These alerts trigger and provide feedback to the surgeon as the defined resection parameters are approached; this prevents over resection and malpositioning during the procedure. The process relies on quantitative data rather than surgeon feel and intuition to facilitate clinical decision-making. Additionally, another form of semi-active technology controls the speed and depth of the working instrument. Once a defined bone resection plan is created and the procedure is begun, the semi-active system correlates the position of the burr within the operative field [18]. When the burr approaches the border of the planned resection (i.e., depth or medial/lateral), the computer system will slow the speed of the burr or retract the burr into the hand piece, effectively decreasing the potential for over resection of the bone. This technology allows the surgeon to perform the bone resection within defined parameters with feedback and controls that limit error and improve accuracy [18]. The only haptic system available today is Stryker's Mako. The haptic assistance is consisted first in limiting bone preparation exactly as planned and protecting anatomic structures like posterior crucial ligament and other soft tissues, and second to guide the robotic-arm-assisted cutting tool which can be a burr or saw exactly at the cutting site at a precision under a millimeter. The combination of visual and acoustic feedback of the robotic-arm-assisted system together with the haptic feedback is the key of the efficiency of the system.

Table 1 Patient demographics and perioperative data, and clinical outcomes regarding implant survival and overall satisfaction, at the last follow-up

Age (years)	71.7 ± 9.1
Gender (*n*)	
Female	29
Male	22
BMI (kg/m^2)	27.2 ± 3.5
Follow-up (months)	51.4 ± 4.5
ASA grade	1.7 ± 0.9
Blood transfusions (number of units)	2
Length of surgery (min)	101.2 ± 16.1
Length of hospital stay (days)	2.6 ± 1
Reoperations/implant survival (%)	0/100
Overall satisfaction (%)	
Very satisfied	80.4 (*n* = 41)
Satisfied	15.7 (*n* = 8)
Neutral	3.9 (*n* = 3)

Parametric data expressed as mean values ± standard deviation and range; ASA grade, American Society of Anesthesiologists; the two blood transfusions were performed in two consecutive patients

Western Ontario and McMaster Universities Arthritis Index Survey (WOMAC™) [20] scores were collected before surgery and at the last follow-up, to assess the clinical and functional outcome of patients after surgery; higher scores correlate with worse mobility and function. At the last follow-up, patients were asked whether their expectations with respect to surgery were met, and whether they would undergo again the same procedure. Their status of independence was also evaluated, with respect to their dependence on others for the performance of daily activities. Patients' overall satisfaction was further evaluated on a 5-level Likert scale: "very dissatisfied", "dissatisfied", "neutral", "satisfied", or "very satisfied". Data regarding complications, revision surgeries, and implant survivorship were available for all patients.

We further assessed the following parameters, before and after surgery: knee flexion, varus deformity, and flexion contracture. Tibial slope, after implant positioning, was also calculated, while the measured error of implant positioning was determined by comparing the preoperatively planned position for each tibial component with the postoperatively achieved alignment (coronal and sagittal) of each tibial component.

Data were tabulated in a Microsoft Excel® sheet (Microsoft Corporation, Redmond, Washington, USA). A paired

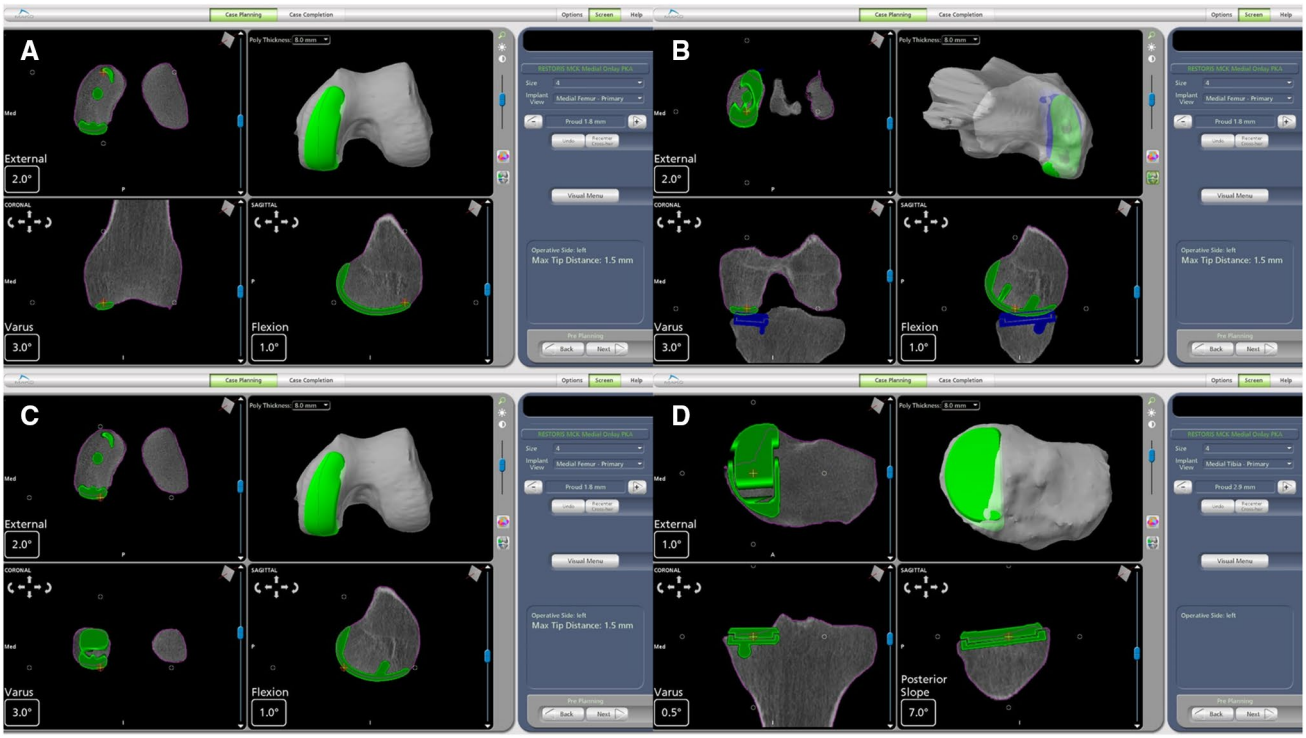

Fig. 1 Computed tomography-based preoperative planning for robotic-arm-assisted medial unicompartmental knee arthroplasty (screen capture from software) in a 70-year-old woman; planned positioning of the femoral (**a**–**c**), and tibial (**d**) component. The desired knee alignment (varus, flexion, rotation, tibial slope) is achieved through the precise translation of the preoperative plan, by the robotic arm, intraoperatively

samples analysis was performed comparing alignment parameters, and total WOMAC score and its components (pain, stiffness, physical function), before and after surgery. The independent *t* test was used for the comparison of these measurements among patients grouped by BMI. A comparative analysis of categorical variables among groups was also performed using the Chi-square test. Data were analyzed using the SPSS v.18.0 (SPSS Inc. Chicago, IL, USA) statistical package for personal computers. The level of significance was set to 0.05.

Results

A significant clinical improvement was noticed after surgery; total WOMAC score and each one component decreased significantly after surgery (Table 2). All patients stated that their expectations were met regarding surgery, and that they would undergo again the index surgical procedure. None of the patients stated any dependence on others. With respect to overall satisfaction with their operated knee, 41 patients (80.4%) reported feeling very satisfied, eight (15.7%) were satisfied and two (3.9%) were neither satisfied nor dissatisfied (Table 1). At the last follow-up, no implant failure occurred, no surgical or other complications were recorded, and no revision surgeries were performed. With respect to alignment parameters, statistical significant differences were recorded after surgery, thus indicating an improvement in patients' ROM: knee flexion increased, while varus deformity and flexion contracture both decreased (Table 2). Lastly, after surgery the mean value of tibial slope was 3.2° ± 0.7°, while the average error (Root Mean Square error—RMS) of

Table 2 Comparison of WOMAC scores, flexion, and coronal alignment parameters before and after robotic-arm-assisted UKA

	Before surgery	After surgery	*p*
WOMAC pain	6 ± 2.4	1.6 ± 1.3	*< 0.001*
WOMAC stiffness	3.3 ± 1	0.6 ± 0.9	*< 0.001*
WOMAC physical function	53.6 ± 5.4	45.7 ± 8.5	*< 0.001*
WOMAC total	62.8 ± 4.2	47.8 ± 8.2	*< 0.001*
WOMAC (%)	65.4 ± 4.4	49.8 ± 8.5	*< 0.001*
Flexion (°)	134.7 ± 4	142 ± 4.6	*< 0.001*
Varus deformity (°)	5.5 ± 2.5	2.9 ± 1.4	*< 0.001*
Flexion contracture (°)	3.6 ± 1.1	1.5 ± 0.9	*< 0.001*

Paired samples analysis, mean values ± standard deviation (SD), significant differences in italics

component positioning was within one degree; 0.4° ± 0.5° in the coronal plane, and 0.7° ± 0.6° in the sagittal plane (Fig. 2).

Discussion

In this prospective study, survival and satisfaction rates, as well as clinical outcomes of 51 robotic-arm-assisted UKAs were assessed at a minimum of 3 years after surgery. Patients in this series had excellent implant survivorship and satisfaction rates, and equally significant improved clinical outcomes at a mean follow-up of 4 years, as it was implied by the significant improvement in WOMAC scores for pain, stiffness, and function. These results are in concordance with the observed improvement in knee flexion and alignment, which suggest an overall improvement in patients' ROM.

No revision surgery was performed, and no implant failure occurred during the study period, resulting, to our knowledge, to the highest survivorship (100%) reported in literature, although we should acknowledge the fact that this could be probably due to the limited number of study participants. Nevertheless, larger studies, like the prospective multicenter study contacted by Pearle et al. [4], demonstrated also excellent survival of implants (98.8%), after robotic arm-assisted UKA at short term, in addition to great satisfaction rates; 92% of patients were very satisfied or satisfied and, according to authors, this survivorship rate was the highest of any large cohort studies reported in the literature [4]. Kleeblad et al. [21], in another prospective multicenter study of robotic arm-assisted UKAs, reported also a survivorship of 97.5%, with 91% of patients being very satisfied or satisfied at mid-term follow-up. Regarding satisfaction, the rates in our study are among the highest reported for either robotic-assisted or conventional UKA; 96.1% of patients were very satisfied or satisfied at a mean follow-up of 4 years (51.4 months). In fact, greater rates have been reported only by Wong et al. [22] (98%), while excellent or good satisfaction rates generally range between 77.5 and 94.5% at the short- and mid-term after conventional UKA [4]. We agree with others that a possible explanation for these excellent survivorship and satisfaction rates of robotic arm-assisted UKA is the ability to perfectly control surgical variables [4, 21]. Our results, in conjunction with previous data, indicate that accurate implant positioning and optimal lower limb alignment can result in excellent survival of implants and high patients' satisfaction rates.

In fact, the accuracy of robotic systems and the superiority of robotic-assisted over conventional UKA, in terms of implant positioning and knee kinematics, have been already shown in previous studies [2, 3, 14, 23, 24]. The results from our study, regarding alignment and implant positioning, are in accordance with the existing literature; therefore, we will further emphasize to the following observations: coronal plane alignment was improved to 2.9° varus, flexion was increased to 142°, and tibial slope was 3.2° after surgery. In the coronal plane, Gaudiani et al. [23], recently reported similar results of 2.76° varus after surgery, which according to authors, have the best clinical results and survivorship, and should be the typical target alignment [23,

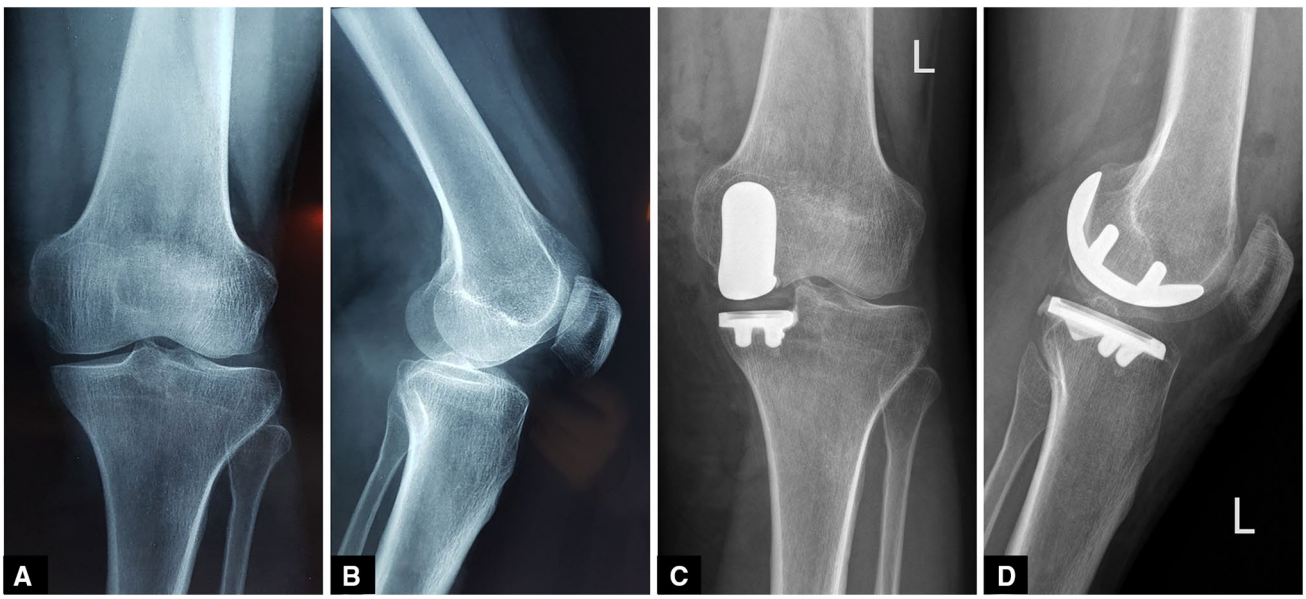

Fig. 2 **a** Anteroposterior and **b** lateral radiograph in a 70-year-old woman with isolated arthritis of the medial compartment of the left knee, before surgery. **c** Anteroposterior and **d** lateral radiograph after robotic arm-assisted UKA, in the same patient, show precise placement within a fraction of a degree of the preoperative plan

25]. In fact, a slight minor varus of one to four degrees has been shown to be the ideal alignment with good clinical results [26], while greater than five degrees varus has been associated with poor outcome and early loosening [27]. With respect to knee flexion, Roche et al. [24] reported, for the first 73 patients receiving robotic-arm-assisted UKA, that mean knee flexion increased from 123° before surgery to 129° after the procedure, thus indicating an improvement in patients' ROM, which was also the case in the present study, since flexion increased approximately by 7°. In fact, the 142° final flexion achieved in the present study was attributed to careful patient selection, since mean flexion before surgery was 135° in these patients, rendering them as appropriate candidates for UKA. The relative satisfactory preoperative flexion indicates that patients probably had a localized arthritic degeneration, but joint architecture and balance was nevertheless maintained. Regarding posterior tibial slope, its role in outcomes after UKA is yet to be fully understood. However, more than 5° to 7° of posterior slope have been previously associated with poor outcomes [27, 28], while an in vitro biomechanical model suggested that a target sagittal slope of three degrees from the mechanical axis (6° to 7° from tibial crest axis), would present the best strain response [29]. Posterior tibial slope in the present series lies within the optimal values reported in current literature, and after taking into consideration that patients presented excellent clinical outcomes, it could be suggested that these may represent the target values for tibial sagittal inclination. However, it should be kept in mind that patients' tibial slope varies considerably, and therefore should be always individually adjusted to better restore native kinematics [30].

Accuracy in executing the patient specific preoperative templating is undoubtedly of great importance in UKA, and this is something facilitated by the robot, which allows for templating and precise implant positioning with significantly less errors than conventional UKA. In an early study comparing robotic-arm-assisted to manual UKA, it was shown that the robotic-arm system showed more accurate and less variable tibial component alignment compared to manual UKA [17]. More accurate implant positioning of both components using a robotic-arm system was also found in a cadaveric study [15], while in a clinical study, the MAKO system was more precise in the coronal and tibial plane in base plate positioning compared to manual UKA [31]. Therefore, at least in theory, robotic-assisted UKA should yield better results than the conventional technique, through proper implant positioning and alignment. However, most studies investigate individually either outcomes, in terms of function and satisfaction, or restoration of alignment and technique's precision. To our knowledge, very few studies present combined results [23, 24], and this might be the most important element of the present study. Apart from the above analyzed knee alignment results, patients in this series had excellent implant survivorship and satisfaction rates, and equally significant improved clinical outcomes at a mean follow-up of 4 years, as it was shown by the significant improvement in WOMAC scores for pain, stiffness, and function. Two more studies have reported similar clinical findings; in one, Knee Society Scores improved significantly at the short-term [24], and in another, both Knee Society Scores and WOMAC scores improved significantly at the mid-term [23]. Additionally, all patients in the present study reported no dependence on others, their expectations regarding surgery were met, and they all stated that they would undergo the same procedure again—even those who stated neither satisfied nor dissatisfied. Consequently, it could be hereby implied that improved ROM and restoration of coronal plane alignment after robotic-arm-assisted UKA, may lead to excellent implant survivorship, good and excellent patient satisfaction rates and, most importantly, excellent clinical and functional outcomes, at short- and mid-term intervals.

This study has several limitations that should be noted. First, the limited number of patients and the lack of comparison between robotic-assisted and conventional UKA do not allow for conclusions regarding the superiority of the robotic technique vs the conventional procedure. Nevertheless, these patients were the first to receive robotic-arm-assisted UKA in our country, they represent a single-surgeon (KD) case series, and all data were collected prospectively, thus limiting bias. Second, not all knee alignment parameters were studied; therefore, safe conclusions regarding knee kinematics could not be drawn. However, the accuracy of the technique and the mechanical balance achieved after robotic-assisted UKA have been previously demonstrated, and our study was mostly intended to show whether patients' outcomes are associated with the technique and the restoration of knee alignment, in terms of flexion and coronal plane deformity.

Conclusion

At least 3 years after surgery, excellent implant survivorship and patient satisfaction rates can be expected after robotic-arm-assisted UKA. Pain, stiffness and function are significantly improved, in addition to restoring patients' knee range of motion. These results combined indicate that robotic-arm-assisted UKA is a safe and efficient technique. As it was hereby shown, optimal implant positioning and improvement of knee alignment can lead to excellent clinical outcomes, at intermediate follow-up, with minimal to none surgery-related morbidity.

Compliance with ethical standards

Conflict of interest All the authors declare that they have no conflict of interest.

Ethical approval This article does not contain any experimental studies with human participants or animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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