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Midterm Survivorship and Patient Satisfaction of Robotic-Arm-Assisted Medial Unicompartmental Knee Arthroplasty: A Multicenter Study

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Background: Studies have showed improved accuracy of lower leg alignment, precise component position, and soft-tissue balance with robotic-assisted unicompartmental knee arthroplasty (UKA). No studies, however, have assessed the effect on midterm survivorship. Therefore, the purpose of this prospective, multicenter study was to determine midtem survivorship, modes of failure, and satisfaction of robotic-assisted medial UKA.
Methods: A total of 473 consecutive patients (528 knees) underwent robotic-arm-assisted medial UKA surgery at 4 separate institutions between March 2009 and December 2011. All patients received a fixed-bearing, metal-backed onlay tibial component. Each patient was contacted at minimum 5-year follow-up and asked a series of questions to determine survival and satisfaction. Kaplan-Meier method was used to determine survivorship.
Results: Data were collected for 384 patients (432 knees) with a mean follow-up of 5.7 years (5.0-7.7). The follow-up rate was 81.2%. In total, 13 revisions were performed, of which 11 knees were converted to total knee arthroplasty and in 2 cases 1 UKA component was revised, resulting in 97% survivorship. The mean time to revision was 2.27 years. The most common failure mode was aseptic loosening (7/13). Fourteen reoperations were reported. Of all unrevised patients, 91% was either very satisfied or satisfied with their knee function.
Conclusion: Robotic-arm-assisted medial UKA showed high survivorship and satisfaction at midterm follow-up in this prospective, multicenter study. However, in spite of the robotic technique, early fixation failure remains the primary cause for revision with cemented implants. Comparative studies are necessary to confirm these findings and compare to conventional implanted UKA and total knee arthroplasty.
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Unicompartmental knee arthroplasty (UKA) has shown to be a reliable treatment option for medial compartment knee osteoarthritis (OA) [1,2]. Some have advocated for the use of UKA over total knee arthroplasty (TKA) emphasizing the benefits of preservation of bone stock, reduced blood loss, decreased perioperative morbidity, lower risk of infection, improved range of motion, and faster rehabilitation [3–7]. Despite these advantages, however, survival rates of UKA reported in cohort (94.8%) as well as registry (93.1%) studies are lower than TKA survivorship (97.7% and 96.8%, respectively) at midterm follow-up [8–12].

Over the recent years, many technological advances have aimed for control and improvement of surgical variables in order to

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optimize UKA survivorship. As such, robotic-assisted surgery has been implemented, which allows anatomic restoration with improved soft-tissue balancing, reproducible leg alignment, accurate implant position, and restoration of native knee kinematics with UKA [13–21]. To lower revision rates, precise control of these surgical factors is essential, as most common failures of medial UKA are related to lower leg malalignment, instability, and component malposition [19,22,23]. Several studies have shown that robotic-arm-assisted medial UKAs were more accurately implanted on a consistent basis compared to conventional UKAs [15,20,24–26]. Besides a more precise technique, robotic-assisted surgery could also be considered a more reproducible technique, which can be beneficial as UKA surgery is often contemplated as a technically demanding procedure [21,24,26]. Therefore, it might be expected that survivorship and patient satisfaction will improve with the use of robotic assistance [16,19,20,27]. Recently, the first short-term results of robotic-arm-assisted medial UKA have been published, and Pearle et al [28] showed a 98.8% survivorship rate at 2.5-year follow-up. Although high survivorship of medial UKA at short-term follow-up has been shown, no studies have assessed the outcomes of robotic-arm-assisted surgery at midterm or long term.

Therefore, the purpose of this prospective, multicenter study was to determine the survivorship, modes of failure, and satisfaction rate following robotic-arm-assisted medial UKA at a minimum of 5-year follow-up. The hypothesis of this study was that robotic-arm-assisted UKA shows high survivorship and patient satisfaction compared to current literature, using conventional implant techniques.

Methods

Study Design

This study represents the initial series of robotic-arm-assisted MCK Medial Onlay UKA (Stryker Corp., Mahwah, NJ) performed by 4 surgeons, starting from the implant release date of March 2009. In this prospective, multicenter study, all patients were included who received a medial UKA with fixed-bearing, metal-backed onlay tibial component between March 2009 and December 2011 [28]. All medial UKAs were implanted using the Robotic-Arm Assisted System (Mako, Stryker Corp., Mahwah, NJ), a third-generation robot tactile-guided surgical instrument, which was released simultaneously. All surgeons were trained before this study by means of a knee course, which included performing 2 to 5 robotic-arm-assisted medial UKA on cadaveric knees.

The surgical indications for medial UKA included isolated medial compartment OA, intact cruciate ligaments, passively correctable varus deformity <15°, and fixed flexion deformity of <10° [29]. Surgical exclusion criterion was diagnosis of inflammatory arthritis. The procedural volume of the participating surgeons ranged from 107 to 161 robotic-arm-assisted UKA during the study period (4.4 to 5.9 procedures per month). This study was approved under the (Western) institutional review board for all centers and all patients were consented before data collection.

Robot Characteristics

The Robotic-Arm Assisted System is an image-based system that uses a preoperative computed tomography to preplan the component size, position, and bone resection. The preoperative planning is checked and approved by the surgeon before surgery. Intraoperatively, the plan is verified and possibly adjusted based on the patient's specific kinematics before surgical resection of any bone. During the procedure, the robotic-arm system provides tactile feedback to prevent bone resection outside the executed plan. The system ensures mechanical alignment to be accurate within 1.6° and soft-tissue balancing within 0.53 mm of the preoperative plan at all flexion angles [15,20]. In addition, component positioning is accurate within 0.8 mm and 0.9° for the femoral component and within 0.9 mm and 1.7° for the tibial component in all directions [20,24,25,30].

Data Collection

All patients were contacted by a research coordinator from each site and completed a short survey by phone at a minimum of 5 years postoperatively. The survey consisted of a series of questions to determine their implant survivorship and satisfaction with the function of their operated knee. The questions included a confirmation of the patient's surgeon, implant, side, and whether they have had their implant removed, revised, or reoperated for any reason. If the patient answered yes, the patient was asked for the date and reason of revision or reoperation, and whether they returned to their original surgeon. The patients who were not revised were asked to rate their overall satisfaction with their operated knee on the following 5-level Likert scale: “very satisfied,” “satisfied,” “neutral,” “dissatisfied,” or “very dissatisfied”, as used in previous studies [28,31–33]. Satisfaction of the revised patients was not recorded, because this would reflect the satisfaction with their revised arthroplasty (ie, TKA). Patients were considered lost to follow-up after phone contact was attempted 3 times.

Statistical Analysis

All statistical analyses were performed using SPSS version 24 (SPSS Inc, Armonk, NY). For all sites, descriptive analyses were performed to calculate means, standard deviations (±), and frequencies (%). Kaplan-Meier analyses were executed to determine survivorship for the primary outcome with conversion to TKA as an end point, and secondary, all revisions for any reason [34,35]. To evaluate any differences in age and body mass index (BMI) of the revised patients, annual revision rates (ARR), rate ratios, and 95% confidence intervals (CI) were calculated. The ARR was defined as “revision rate per 100 observed component years” and calculated by dividing the number of failures by the total observed component years [12,36,37]. In this study, groups were classified according to age at time of surgery (ie, ≤59 years, 60-69 years, 70-79 years, and ≥80 years) and BMI according to the World Health Organization (ie, normal weight [18.5-24.9], overweight [25.0-29.9], moderate overweight [30.0-34.9], and severe overweight [≥35.0]). Statistical significance was defined as *P* value <.05.

Results

A total of 473 patients (528 knees) underwent robotic-assisted medial UKA surgery. Twenty-five patients declined study participation, 16 patients were deceased, and 49 patients were lost to follow-up, leading to a follow-up rate of 81.2%. A total of 384 patients (432 knees) were included at a mean follow-up of 5.7 years ± 0.8 (range, 5.0-7.7), of which 224 were men (58%) and 160 women (42%). Of all included patients, 48 patients (12.5%) received bilateral UKA, while 336 (87.2%) received unilateral UKA. The average age was 67.3 years ± 8.9 (range, 45-98), and average BMI was 29.7 kg/m^2 ± 4.7 (range, 19-42, BMI was missing in 14 patients; (Table 1).

The primary outcome was conversion to TKA, in total 11 revisions were reported in 432 knees, resulting in a survivorship of 97.5% (95% CI, 95.9-99.1) with a mean time to conversion of 2.44 years (Fig. 1). The corresponding ARR was 0.44 revisions per year. Using all revisions for any reason as an end point, a total of 13 revisions were reported including 2 UKA to UKA revisions, which

Table 1
Demographic Characteristics by Revision Status.

	Revision (13 Knees)	No Revision (419 Knees)	*P* Value
	Mean ± SD (OR%)		
Age (y)	66.1 ± 11.4	67.4 ± 8.9	.619
BMI (kg/m^2)	31.5 ± 5.1	29.6 ± 4.6	.148
Male gender	6 (46%)	243 (58%)	.395
Bilateral[a]	1 (8%)	95 (23%)	.359

BMI, body mass index; SD, standard deviation; UKA, unicompartmental knee arthroplasty.
[a] Forty-eight bilateral UKAs were performed in 96 knees.

corresponds to a survival rate of 97.0% (95% CI, 95.2-98.8) and an ARR of 0.52 (Fig. 2). The mean time to any revision was 2.27 years.

Evaluating the ARR in different age-groups, it was found that younger patients (≤59 years) reported the highest revision rate compared to other age-groups (Table 2). When comparing ARRs by BMI, the rates rise with increasing BMI, resulting in the highest annual revision rate (1.22) in BMI group greater than or equal to 35 kg/m^2 (Table 3). However, no significant differences in rates were observed between the groups.

Concerning modes of failure, 7 UKAs were revised because of aseptic loosening (fixation failure; 54%), 4 of unexplained pain (31%), and 1 of progression of OA (8%), and for 1 patient it was not reported (Table 4). Six patients were revised by their initial orthopedic surgeon, and 7 were revised at another institution. Furthermore, 14 reoperations were reported (Fig. 3), of which 6 for a lateral meniscal tear at a mean of 3.13 years postoperatively. Three patients developed chondromalacia of the patella and underwent arthroscopic surgery at a mean of 3.28 years after initial UKA surgery. One patient underwent reoperation for synovitis, 1 for a loose body, 1 for limited range of motion, 1 for saphenous nerve neuritis, and 1 for severe lateral OA at 2.00, 1.49, 0.11, 2.26, and 4.81 years, respectively.

With regard to the reported satisfaction rates at midterm follow-up, 69% of all unrevised patients was very satisfied with their overall knee function and 22% was satisfied, while only 4% was either dissatisfied or very dissatisfied (3% and 1%, respectively). The remaining 5% of patients scored their knee function as neutral, meaning neither satisfied nor dissatisfied.

Discussion

In this prospective, multicenter study, survival and satisfaction rates of 432 robotic-arm-assisted medial UKAs were assessed at a minimum of 5 years postoperatively. High survivorship (97.0%) was found, with fixation failure as the most common mode of failure leading to revision (54% of all failures). Furthermore, 91% of the patients were either very satisfied or satisfied with their knee function at a mean follow-up of 5.7 years.

When comparing our findings to recent literature, robotic-arm-assisted medial UKA seems to demonstrate higher survivorship (97.0%) than other large cohort studies (average of 94.2%, Table 5) at midterm follow-up, using revision for any reason as an end point. Of those cohort studies published over the last decade, the vast majority described the outcomes of UKA implanted using conventional techniques [35,41,45,48,49]. Although comparative studies are necessary, it may be that the favorable survivorship found in this study can be explained by the improved control and precision provided by the robotic-arm system [24]. Several authors have

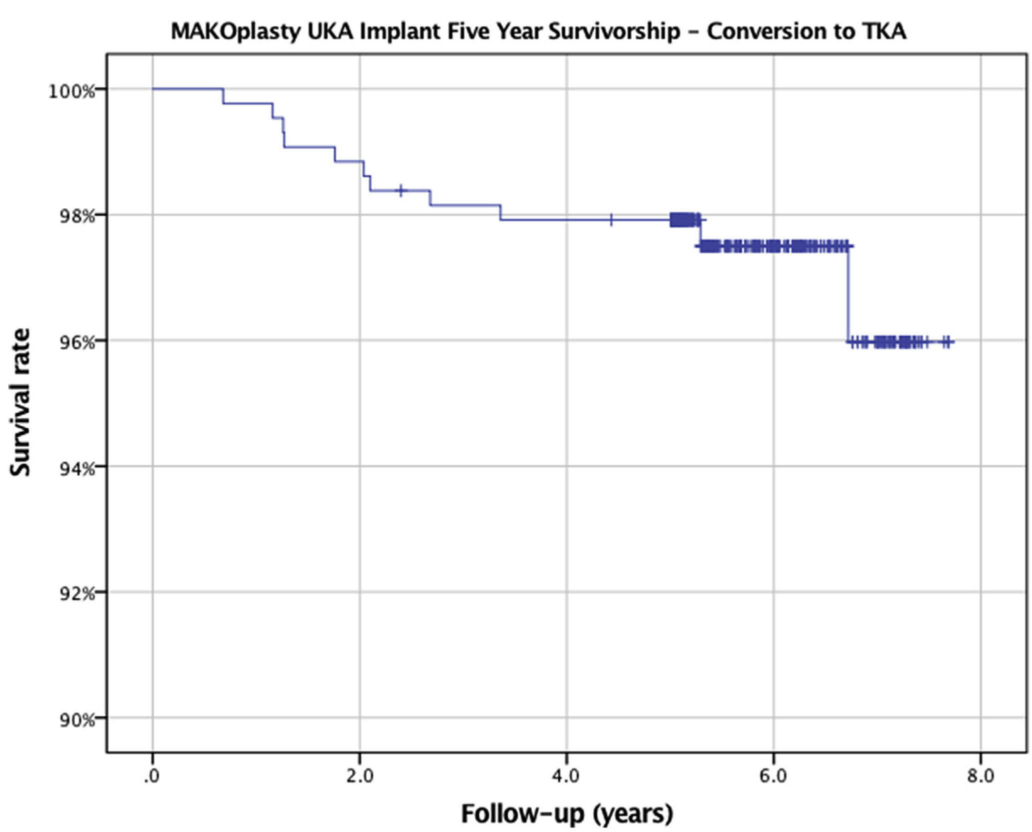

Fig. 1. Kaplan-Meier curve showing the survivorship of 432 robotic-arm-assisted medial UKAs, with revision to TKA as end point. TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty.

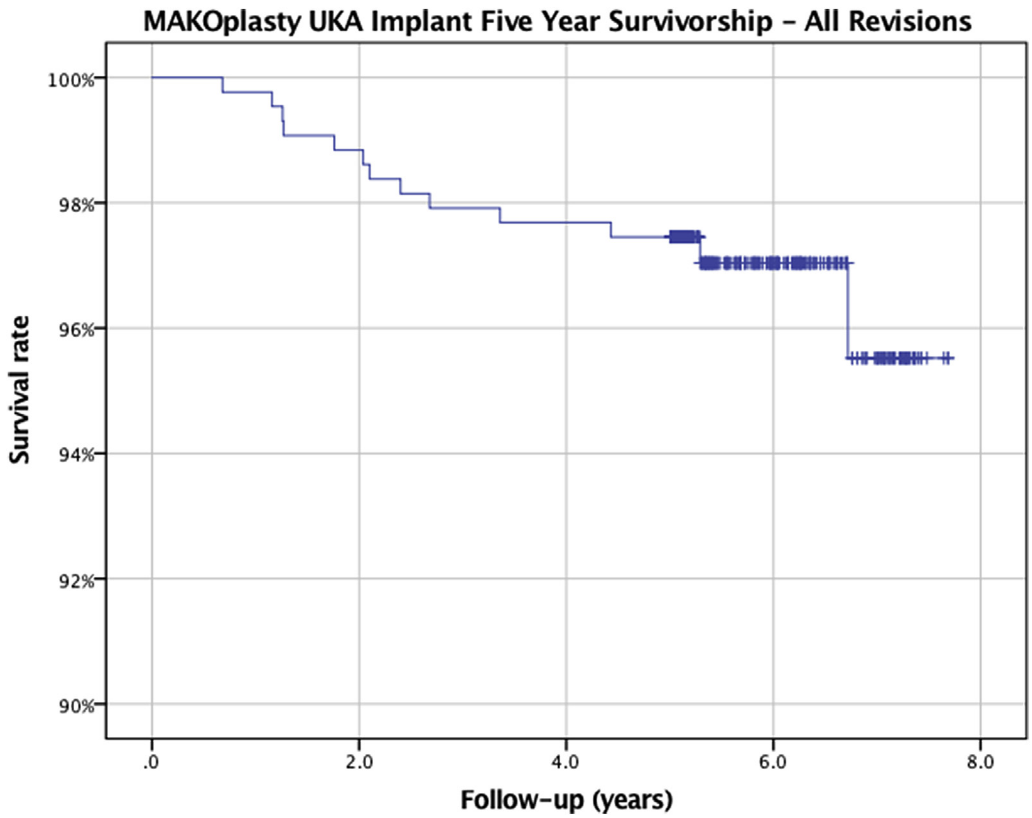

Fig. 2. Kaplan-Meier curve showing the survivorship of 432 robotic-arm-assisted medial UKAs, with revision for any reason as end point.

demonstrated that lower limb alignment is reliably controlled, component position is improved, and soft-tissue balance is precisely restored with the use of robotic assistance [15,20,25,51,52]. In theory, creating the ability to not only control but also optimize these surgical variables could improve the survival rate of medial UKA, as failures due to malalignment and instability are expected to decrease [13,18,19,53,54]. Although this is, to our knowledge, the first study assessing midterm survivorship of robotic-arm-assisted medial UKA, our propitious results support this theory, but comparative studies are needed to confirm these findings.

More specifically, this study may be suggestive of higher survivorship of a fixed-bearing UKA (97.0%) compared to other large cohort studies using either fixed-bearing or mobile-bearing designs (average 93.0% and 95.6%, respectively, Table 5). While several authors have described the technological advantages of fixed-bearing over mobile-bearing UKA, such as less overcorrection of the mechanical axis, the survivorship of fixed-bearing UKAs is reported to be lower than that of mobile-bearing designs in large cohort studies (Table 5) [55,56]. However, Peersman et al [57] performed a meta-analysis and found no major differences between survival rates of both designs after stratification by age and follow-up time. The systematic review by Cheng et al [56] showed similar findings with regard to the comparable survivorship. Another explanation for the difference in survival rates between fixed-bearing and mobile-bearing as presented in Table 5 may be that it only contains large cohort studies reporting midterm survivorship, and systematic reviews, on the contrary, include studies of all cohort sizes [58].

Furthermore, several studies have shown that younger age is associated with higher revision rates [18,59,60]. In our study, 5 of 13 revisions were reported in patients younger than 59 years, resulting in a higher annual revision rate of 1.04 compared to the average of 0.52. A number of explanations have been proposed for the lower survivorship in younger patients [61,62]. Firstly, these patients often have higher demands and activity levels compared to the older population, therefore loading the knee to an increasing extent, which can potentially lead to accelerated polyethylene wear [63–65]. Another explanation concerns the natural history of a pathologic process of OA, meaning that the nonsurgical knee compartments could also be affected by this degenerative disease over time. Finally, the threshold of revising UKA is thought to be lower than revising a TKA, especially in case of unexplained pain, as

Table 2
All Revisions per 100 Observed Years (Annual Revision Rate) in Different Age-Groups.

Age-Group	Number of UKA	Mean Follow-Up (y)	Number of Revisions	Total Observed (y)	Annual Revision Rate	95% CI
≤59 y	85	5.6	5	477.3	1.04	0.34-2.45
60-69	177	5.7	3	1011.9	0.30	0.01-0.87
70-79	133	5.9	4	779.8	0.51	0.01-1.31
≥80 y	37	5.8	1	214.4	0.47	0.01-2.60
Total	432	5.7	13	2483.6	0.52	0.29-0.87

CI, confidence interval; UKA, unicompartmental knee arthroplasty.

Table 3
All Revisions per 100 Observed Years (Annual Revision Rate) in Different BMI Groups.

BMI (kg/m^2)	Number of UKA	Mean Follow-Up (y)	Number of Revisions	Total Observed (y)	Annual Revision Rate	95% CI
Missing	14	6.2	0	87.3	0.00	
18.5-24.9	55	5.8	0	317.8	0.00	
25.0-29.9	188	5.7	6	1075.2	0.56	0.02-1.21
30.0-34.9	117	5.8	3	676.3	0.44	0.09-1.30
≥35	58	5.6	4	327.0	1.22	0.33-3.13
Total	432	5.7	13	2483.6	0.52	0.29-0.87

BMI, body mass index; CI, confidence interval; UKA, unicompartmental knee arthroplasty.

more bone stock is preserved after UKA surgery [66–69]. In this study, 4 patients were revised for unexplained pain; however, none of those patients were younger than 59 years.

In addition, the BMI subgroup analysis showed a higher annual revision rate in patients with BMI exceeding 35 kg/m^2 (1.22) compared to patients with normal weight (0.00) or slightly overweight patients (0.56). Similar to the outcomes of a recent meta-analysis by Van der List et al [2], these data show a trend of increased likelihood for revision in obese patients. However, BMI in the setting of UKA remains controversial, as some authors showed higher failure rates of UKA in obese patients, but others have found comparable clinical outcomes between patients with obesity and normal weight [70–76]. More specifically, Murray et al [74] performed a large cohort study of 2438 mobile-bearing UKAs and showed that an increasing BMI was not associated with an increased failure rate. Furthermore, a recent study by Plate et al [72], concerning 746 robotic-arm-assisted UKA at a mean follow-up of 34.6 months, noted no difference in revision rates between BMI groups. When taking into consideration the results of this study and all previously mentioned studies, in general caution should be taken when performing UKA on obese patients.

With regard to modes of failure, the majority of UKAs (n = 7, 54%) were revised because of fixation failure (aseptic loosening). The second most common cause was unexplained pain (n = 4, 31%), which in some cases may be due to loss of component fixation. These results correspond to the findings of recent systematic reviews on modes of failure and the large cohort study by Epinette et al, which demonstrated that aseptic loosening was the most common reason for revision in early failures (<5 years) [23,27,57]. Even with the use of optimized techniques, such as robotic-assisted surgery, early fixation failure remains the primary cause of revision of cemented UKA. It has been suggested that cement fixation strategies in UKA may be challenged due to high loads concentrated on a relatively small fixation surface area [27,77]. Using a synthetic bone model, Scott et al [78] found significantly higher tensile strains at the cement-bone interface in metal-backed implants compared to controls, when applying loads of 1500 N (level walking) and 2500 N (stair descent). Combining these data on occurrence of strain shielding with the knowledge that 60%-70% of the loads across the knee pass through the medial compartment, it can be argued that stability of the cement-bone interface has the potential to be overwhelmed [79–81]. This is of special importance for medial UKA, because the loads are distributed over a smaller surface area when compared to TKA [78,82]. Furthermore, the Oxford group has showed a much lower incidence of early fixation failure with cementless UKA at midterm follow-up compared to our findings [77,83]. Therefore, survivorship of medial UKA might benefit from cementless fixation.

This study has several limitations. The main limitation was that only survivorship and satisfaction rate of robotic-arm-assisted UKA surgery were assessed. Ideally, functional and radiographic outcomes would have been obtained, but as the participating centers are either secondary or tertiary referral centers, patients are widely dispersed across the country. To reduce the burden for patients, including costs, all patients received a phone call to determine survivorship, which was indeed the primary study goal [84]. Additionally, over the last decade, several authors have reported on the radiologic outcomes by means of accuracy and alignment, radiolucent lines, and short-term to midterm functional outcomes of robotic-assisted surgery [20,24,25,51,72,85,86]. Furthermore, 49 patients (10.4%) were lost to follow-up and 25 patients (5.3%) declined participation, leading to a potential selection bias. The final follow-up rate was 81.2% at 5.7 years after surgery, which exceeds most other large multicenter studies which reported midterm follow-up rates ranging from 64% to 83% [50,87–90]. A third limitation was due to the nature of a multicenter study, the preplanning of the surgery and changes made intraoperatively were left to the discretion of each individual surgeon. This could not

Table 4
Summary of Revised Robotic-Arm-Assisted Medial UKA Cases.

Patient	Gender	Age (y)	Time to Revision (y)	Reason for Revision	Revision Surgery
Revision from UKA to TKA					
1	Female	63.5	0.7	Pain	Primary TKA
2	Female	69.0	1.2	Pain	Primary TKA
3	Female	79.0	1.3	Aseptic loosening	Primary TKA
4	Female	79.0	1.3	Aseptic loosening	Primary TKA
5	Male	76.6	1.8	Pain	Primary TKA
6	Male	51.5	2.0	Aseptic loosening	Primary TKA
7	Female	53.5	2.1	Aseptic loosening and patellofemoral OA	Primary TKA
8	Male	81.5	2.7	Not reported	Primary TKA
9	Male	73.0	3.1	Progression lateral OA	Primary TKA
10	Female	55.0	3.4	Aseptic loosening	Primary TKA
11	Female	59.6	5.5	Pain	Primary TKA
Revision from UKA to UKA					
12	Male	68.7	2.4	Tibial loosening	Tibial component replacement and insert
13	Male	49.6	4.4	Femoral loosening	Femoral component replacement and insert

OA, osteoarthritis; TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty.

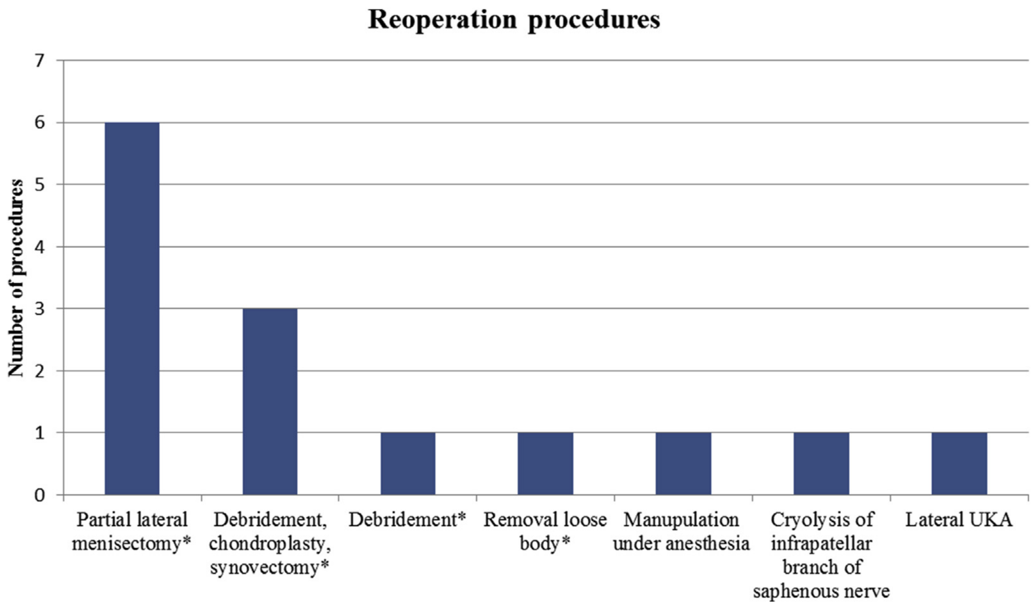

Fig. 3. Specification of the 14 reoperations performed, excluding revision procedures. *Arthroscopic procedures.

be standardized, as this is patient specific based on anatomy, laxity, and severity of the disease [20]. Survivorship and modes of failure will be reassessed at 10 years postoperatively, as all patients will be contacted once more at minimum 10-year follow-up.

Conclusion

In this multicenter study, robotic-arm-assisted UKA showed high survivorship and good to excellent satisfaction rates at midterm follow-up. However, in spite of the robotic-arm technique, fixation failure remains a problematic issue with cemented implants, particularly in the younger as well as the obese populations. Although these early survival results look promising and may be comparable to TKA outcomes, comparative studies with longer follow-up are necessary in order to compare survivorship and satisfaction of robotic-arm-assisted UKA to conventional UKA and TKA.

Table 5
Cohort Studies Reporting 5- to 6-Year UKA Survivorship

Author	Year Published	Start Cohort	End Cohort	UKA (N)	Survivorship at 5- to 6-y Follow-Up
Cohort Studies Conventional UKA					
Fixed-Bearing UKA Designs					
Baur et al [38]	2015	2006	2010	132	87.7%
Eickmann et al [39]	2006	1984	1998	411	93.0%
Forster-Horváth et al [40]	2016	2002	2009	236	94.1%
Hamilton et al [41]	2014	2001	2004	517	92.0%
Naudie et al [42]	2004	1989	2000	113	94.0%
Vasso et al [43]	2015	2005	2011	136	97.0%
Whittaker et al [44]	2010	1990	2007	150	96.0%
				Total	93.0%
Mobile-Bearing UKA Designs					
Burnett et al [34]	2014	2003	2011	467	98.5%
Kuipers et al [45]	2010	1999	2007	437	84.7%
Liebs et al [46]	2013	2002	2009	401	93.0%
Lim et al [47]	2012	2001	2011	400	96.7%
Matharu et al [48]	2012	2000	2008	459	94.4%
Pandit et al [49]	2011	1998	2009	1000	97.5%
Vorlat et al [50]	2006	1988	1996	149	94.6%
Yoshida et al [35]	2013	2002	2011	1279	97.7%
				Overall total	95.6%
Cohort studies				Overall total	94.2%

UKA, unicompartmental knee arthroplasty.

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