THE ROLE OF ROBOTICS IN UNICOMPARTMENTAL KNEE ARTHROPLASTY IMAGING, SURVIVAL AND OUTCOMES

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Introduction and Aims

INTRODUCTION

ANATOMY

The knee is a synovial hinge joint, which allows flexion and extension as well as some degree of internal and external rotation. Motion arises from two articulations; the tibiofemoral and patellofemoral joint. The tibiofemoral articulation consists of the medial and lateral compartment, each with distinct anatomical and biomechanical features. The medial tibia plateau has a convex shape, in contrast to the concave contour of the lateral side, articulating with the medial and lateral femoral condyle respectively. The articular surface medially is considered more congruent, leading to different kinematics in the medial compartment compared to the lateral compartment. Due to the smaller size of the lateral compartment, the medial femoral condyle rotates on the tibia and translates to some extent during flexion. Conversely, the lateral femoral condyle tends to roll backwards with flexion, resulting in increased anteroposterior motion in the lateral compartment.[1–4] The patellofemoral articulation is formed by the posterior surface of the patella and the trochlea on the anterior distal femur. Primary stability of the knee is provided by four ligaments, two cruciate and two collateral ligaments. Anteroposterior and rotational stability are provided by the anterior and posterior cruciate ligaments (ACL and PCL).[5] Valgus and varus motion are controlled by the collateral ligaments, consisting of the medial collateral ligament (MCL) and lateral collateral ligament (LCL). The MCL has a superficial and deep portion, with the superficial portion contributing the knee stability in terms of preventing tibial valgus and external rotation.[6] Lateral stability is conferred by the LCL and the iliotibial band, acting as restraints to varus motion.[7] The anatomy of the individual compartments and knee stabilizers determine the position of the femur relative to the tibia, and therefore, control joint congruency. Both joint congruence as well as the position of the knee relative the hip and ankle joint influence the load distribution across the knee.

KNEE ALIGNMENT AND LOAD DISTRIBUTION

Static alignment in the coronal plane is referred to as mechanical axis or hip-knee-ankle (HKA) angle. The mechanical axis represents the line of load transmission in the lower limb and is constructed based on a line drawn from the center of femoral head to center of the talus on long leg radiographs. In neutrally aligned knees, this line passes through the center of the tibial spines.[8] This is different from the HKA angle, which is formed by the angle between the mechanical axis of the femur and tibia and is 180° in neutral alignment. Mechanical alignment refers to the load distribution across the articular surface by proportionately sharing load between the medial and lateral knee compartment. In the setting of neutral alignment, the medial compartment bears 60%

– 70% of the load across the knee during weight-bearing activity.[9,10] Deviation from neutral alignment can alter the loading pattern.[11] Varus alignment results in increased forces across the medial tibiofemoral compartment, whereas load shifts more laterally in valgus aligned knees.[10,11]

KNEE OSTEOARTHRITIS

Osteoarthritis (OA) is a degenerative joint disease, which affects cartilage, subchondral bone, and soft-tissues, depending on the extensiveness of the disease. OA is one of the leading causes of physical disability and pain in working-age adults and elderly and disease occurrence is expected to increase in the upcoming ten years. Currently, the estimated prevalence of OA in the United States and the Netherlands is approximately 10-13%, which is projected to increase over the upcoming years.[12–15] Age-specific projections show an even greater increase of the OA incidence in patients between 45 and 65 years, related to a predicted increase in body mass index (BMI) and knee-related injuries.[15–18] Furthermore, life expectancy of the aging population is increasing, consequently, there is substantially more time for greater disability to occur.

Based on these projections, future demand for treatment of knee OA is expected.[19] The choice of treatment depends on several factors, such as patient demographics and anatomy as well as the severity and location of the disease. OA can develop in all three knee compartments (tricompartmental) or be limited to one compartment (unicompartmental).[11] Depending on the loading pattern, which is partly related to alignment, OA can be isolated when overloading one compartment, leading to progressive loss of articular cartilage.[20] Medial OA is often located anteromedial and associated with varus leg alignment, in contrast to lateral OA, which is associated with valgus leg alignment. The prevalence of unicompartmental OA is estimated at 10% to 22% for the medial compartment and 1% to 9% for the lateral compartment of the OA population.[21,22]

TREATMENT OF OSTEOARTHRITIS

The treatment of OA consists of a range of options, both non-surgical and surgical. After exhausting conservative treatments, consisting of physical therapy, weight loss and intra-articular injections, surgical options can be considered. In the setting of unicompartmental knee OA, high tibial osteotomy (HTO), unicompartmental knee arthroplasty (UKA) or total knee arthroplasty (TKA) are established treatment options. HTO is an extra-articular procedure which corrects the axial leg alignment by off-loading the affected compartment. This procedure is designed to increase the life span of articular cartilage by unloading and redistributing the mechanical forces over

the non-affected compartment.[23] The literature supports strict adherence to patient indications to optimize clinical outcomes. HTO is indicated for young (age <60 years), normal-weight, active patients with radiographic mild unicompartmental knee OA. Although short-term results following HTO may be promising, long-term studies have shown a significant deterioration in clinical outcome scores and survival free of knee arthroplasty.[24,25] Therefore, the concept of UKA as a less invasive procedure than TKA was introduced, in which only the affected compartment is replaced and others are preserved.[26] The first results of UKA were dissatisfying, therefore, Kozinn and Scott proposed strict patient selection criteria to improve outcomes of UKA.[27] Over the last decade, studies have showed significant improvement in outcomes, although not approaching survivorship of TKA yet.[28] Although UKA offers potential functional advantages over TKA, the use of UKA is challenged by a surgeon's consideration and the technically demanding nature of the surgery. UKA is considered a joint preserving surgery; moreover, associated with less blood loss, lower infection rates, larger range of motion (ROM) and faster rehabilitation compared to TKA.[29–32] However, the success of UKA surgery is dependent on both patient as well as surgical factors. Patient factors are age, BMI, presence of patellofemoral OA and functionality of the ACL. Important surgical factors that affect outcome are leg alignment, stability, joint congruence and component position.[33] Several studies have showed that leg malalignment, component malposition, and instability are associated with early failure and may contribute to the lower survival of UKA compared to TKA.[34,35] In addition, a large registry study from England evaluated the effect of caseload on revision rates of UKA and TKA. The authors demonstrated an important effect of caseload on the revision rate following UKA, with a fourfold difference in revision rate between the lowest and highest-caseload surgeons. Similarly, a caseload effect in TKA was noted, although not as marked as it was in UKA. Furthermore, it was found that low-volume surgeons revise UKAs for different reasons than high-volume surgeons, with low-volume surgeons being more likely to revise for aseptic loosening, unexplained pain, or malalignment. This could indicate a higher rate of technical errors (resulting in a higher rate of revision for malalignment and loosening) or that low-volume surgeons apply a lower revision threshold.[36,37]

SURGICAL TECHNIQUES

Conventional UKA operations are carried out using standard manual instrumentation appropriate to the specific prosthesis. For most implants, standard instrumentation includes pinning a tibial cutting guide to the tibia, providing a flat surface to guide manual resection of the bone using a handheld saw. This tibial guide is aligned using visual and palpable anatomic landmarks. On the femoral side, an intramedullary rod is inserted into the distal femur to align the femoral cutting guide using visual landmarks. The standard instrumentation jigs and accompanying operating technique provide fixed target values for all patients, without the opportunity for tailoring of implant position to each patient's anatomy.[38] The success of UKA relies on proper component position and alignment, which is intricately associated with soft tissue balancing as UKA is intended to restore the normal height of the affected compartment to obtain a balanced flexion-extension gap and varus-valgus stability.[34,39] While advances in surgical instrumentation with improved alignment guides and cutting blocks have improved component positioning, balancing the knee is still dependent on surgeon ability and experience. Achieving adequate ligament tension throughout the flexion-extension cycle and avoiding tightness or laxity are complex and partly rely on component size and position.[34,40] Increased soft tissue tightness may limit the range of motion and increases wear, while laxity may result in joint instability and knee pain.[39,40] Since the introduction of patient selection criteria for UKA in 1989, survivorship of UKA has improved.[41] However, recent systematic reviews and large registry studies have demonstrated a difference in survival in favor of TKA compared to UKA. Motivated by a desire to improve clinical outcomes and reduce complications, there have been many technological advances, such as computer navigation, robotic systems, and patient-specific implants in the last two decades. Several studies have shown that tight control of lower leg alignment, soft tissues balance, joint line maintenance, type of fixation, and precise component position can improve survivorship and patient satisfaction following UKA.[34,35,40,42,43] Computer navigation was developed to allow a higher level of precision of implantation through the use of a passive system that provides information and guidance to a surgeon that uses conventional instrumentation to perform the surgery. The system uses optical or magnetic sensors to track the bones, surgical tools or implants, but does not perform action independently.[44,45] Studies have found improved accuracy in computer-assisted UKA, however, failed to show superiority in clinical outcomes compared to conventional UKA.[45–47] To address this issue, robotic technology has been introduced in the field of knee arthroplasty. The use of robotics allows surgery to be tailored to the patient's anatomy, with a more accurate reconstruction of the knee surfaces and the potential for more natural knee kinematics. Robotic-assisted surgery does not use a femoral intramedullary rod, which avoids additional surgical trauma. However, this benefit may be offset by the use of additional bone pins in the femur and tibia intra-operatively, which are necessary for the navigation trackers. The robotic system uses a robotic arm-mounted burr, this may prevent excessive heat-associated bone necrosis and might facilitate more minimal bone resection, both of which may lead to less post-operative pain.[48,49] During conventional UKA surgery, soft tissue balance is assessed with the trial components in

place and with subjective varus-valgus stress testing by a surgeon's hand, commonly at 0° and 90° of flexion. Using a robotic UKA system, the surgeon has the ability to measure ligament tension objectively during dynamic, real-time analysis by the system. Therefore, proper ligamentous tightness can be restored based on objective measurements.[40] Introducing robotic surgery may improve precision and outcomes, but the ultimate acceptance of robotic-assisted surgery into common orthopedic practice will also depend on its cost effectiveness. The variables most influential to the cost effectiveness of a robotic UKA system are case volume, costs of the robotic system, and revision rates.[50] Hypothetically, the costs of a robotic system could be compensated by saving money on decreased hospital length of stay, lower complication and revision rates, as well as the potential increase in volume of patients attracted to the hospital by this new technology.[51,52] Current drawbacks of robotic surgery are the associated costs and radiation in case of an image-based system, which necessitates a preoperative computed tomography (CT) scan.[53,54] Furthermore, there is a significant amount of education required for surgeons and staff to optimize the safety and usefulness of the system. Operative time may be longer, especially during the learning curve, with use of robotics, and the preferred robotic system of a surgeon may not be compatible with their preferred implant. To summarize, the associated costs of using robotic technology result from the robot itself, maintenance costs, possibly changing OR set-up and instruments, as well as longer operative times. The important question will be if the incremental benefit from improved implant survival is worth the additional costs in the long run. To date, there are two different systems available for UKA, the MAKO system (Stryker Corp, Mahwah, NJ, USA), which is most commonly used for UKA, and Navio system (Smith & Nephew).[53] Previous studies have demonstrated a high degree of accuracy with regard to lower leg alignment, component position and soft tissue balancing with the use of the MAKO system.[40,54–56] Despite the fact that the system is accurate in the variables it aims to control, the question remains if the use of robotic assistance leads to better patient care, improved outcomes and potentially allow for broader patient indications with widespread use of robotic-assisted surgery. This thesis assesses certain facets of robotic-assisted UKA surgery using the MAKO system, focusing on the patient selection, role of imaging, and clinical outcomes.

The aim of Chapter 2 is to provide an overview of different aspects concerning UKA in terms of diagnostics, indications, patient selection, surgical techniques, clinical outcomes and geographical differences. The following part of this thesis will aim to answer the following questions:

1. Is it possible to predict the feasibility of correcting the mechanical axis with medial unicompartmental knee arthroplasty of patients with large preoperative varus deformities?

In patients with isolated medial compartment OA, the varus alignment originates mostly from a progressing intra-articular deformity, which can be corrected with a medial UKA to a certain extent. In Chapter 3, a study was performed to assess to what extent patients with large varus deformities undergoing robotic-assisted medial UKA were correctable. Furthermore, the predictive role of several radiographic deformity measurements on long leg radiographs in patients with large preoperative varus deformities was determined in order to estimate the feasibility of the correction.

2. What is the incidence of radiolucency in cemented fixed-bearing medial UKA and does it affect functional outcomes?

Although the aetiology of radiolucency remains unknown, the study in Chapter 4 evaluates the different aspects of physiological tibial and femoral radiolucency around cemented medial UKA, both the incidence, time of onset, localization, as its relationship to outcomes.

3. Could magnetic resonance imaging be a complementary tool for assessing symptomatic UKA by quantifying appearances at the bone-component interface?

Stable implant fixation with adequate cement penetration to underlying bone is essential in preventing failure in cemented UKA. To assess the bone-component interface and detect specific modes of failure, conventional radiographs are often of limited value. Therefore, in Chapter 5, the role of MRI with the addition of a sequence that substantially reduces the susceptibility artifacts near metallic implants was evaluated as a diagnostic modality for characterization of the bone-component interface in patients with painful UKA.

The second part of this thesis aims to assess the outcomes of robotic-assisted medial UKA and provide answers to the following questions:

4. What are the clinical outcomes of robotic-assisted medial fixed bearing UKA compared to all-polyethylene UKA and TKA at mid-term follow-up?

Over the recent years, many technological advances have aimed for control and improvement of surgical variables in order to optimize UKA survivorship, as such, robotic-assisted surgery has been implemented. A prospective, multicenter study was performed to determine the survivorship, modes of failure, and satisfaction rate following robotic-arm-assisted medial UKA at a minimum of 5-year follow-up of which the outcomes are discussed in Chapter 6. In Chapter 7, a comparative study was performed to assess differences in functional outcome scores of two different UKA designs and TKA.

5. Do young patients report better outcomes after UKA compared to TKA when systematically reviewing the literature?

In younger patients with end-stage OA, the most suitable surgical option (UKA or TKA) remains controversial. Surgical concerns include accelerated failure rates due to higher activity levels as well as increased likelihood of need for multiple subsequent revision surgeries. To gain more insight in the younger arthroplasty population, in Chapter 8, a systematic review was conducted to assess survivorship, functional outcomes and activity levels of medial UKA and TKA in patients less than 65 of age.

6. Are patients satisfied with their postoperative sports participation and what type of activities are they engaging in after UKA surgery?

Patients' expectations determine their assessment of the success of joint replacement surgery, and therefore strongly influence the postoperative outcome and patient satisfaction. There is a lack of information with regard to satisfaction with return to sports and the maximum level of sport attained after UKA. Therefore, in Chapter 9 a study was performed to inform and help manage patients' expectations regarding their ability to return to sports postoperatively based on patient characteristics and type of preoperative sporting activities.

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Unicompartmental Knee Arthroplasty: State of the Art

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ABSTRACT

The popularity of unicompartmental knee arthroplasty (UKA) for the treatment of isolated compartment osteoarthritis of the knee has risen over the past 2 decades. Currently, UKA covers 10% of all knee arthroplasties worldwide. Although indications have been extended, results have proven that patient selection plays a critical role in the success of UKA. From current perspective, age, body mass index, patellofemoral osteoarthritis, anterior cruciate ligament deficiency and chondrocalcinosis are no longer absolute contraindications for UKA. Motivated by the desire to improve survivorship rates, patient-reported outcomes and reduce complications, there have been many technological advances in the field of UKA over the recent years. The aim of this review was to evaluate the current indications, surgical techniques, modes of failure and survivorship results of UKA, by assessing a thorough review of modern literature. Several studies show that innovations in implant design, fixation methods and surgical techniques have led to good-to-excellent long-term survivorship, functional outcomes, and less complications. Until now, resurgence of interest of cementless designs is noted according to large national registries to address problems associated with cementation. The future perspective on the usage of UKA, in particular the cementless design, looks promising. Furthermore, there is a growing interest in robotic-assisted techniques in order to optimize result by controlled soft-tissue balancing and reproduce alignment in UKA. Future advances in robotics, most likely in the field of planning and setup, will be valuable in optimizing patient-specific UKA.

INTRODUCTION

CLINICAL PROBLEM: PREVALENCE AND SOCIAL IMPACT

Knee osteoarthritis (OA) is highly prevalent worldwide. It is the leading cause of musculoskeletal disability and associated with activity limitation, working disability, reduced quality of life and increased health care costs.[1,2] Partial or total joint replacement of the affected knee is a surgical intervention to treat the disease when conservative strategy fails. Both procedures are commonly performed in developed countries and the number is expected to increase dramatically in the upcoming decade.[2,3] Unicompartmental knee arthroplasty (UKA) recently gained popularity because several studies have shown that it is less invasive and has a reduced operative time, larger postoperative range of motion (ROM), improved pain relief, earlier return to daily activities and sports, and cost reduction in comparison to total knee arthroplasty (TKA).[4–8] National and annual registries show similar usage with an increasing incidence over the past 10 years, currently ranging from 5 to 11% globally in 2014.[9–14] The aim of this review is to provide an overview of different aspects concerning UKA in terms of diagnostics, indications, patient selection, surgical techniques, clinical outcomes and geographical differences.

HISTORICAL PERSPECTIVE OF UKA AND ITS UPSWING

The concept of replacement of a single compartment of the knee joint originated in the 1950s, when McKeever[15] and MacIntosh introduced the metallic tibial plateau. In 1972, the first contemporary UKA, resurfacing both femur and tibia of a single knee compartment, was performed by Marmor.[16] Despite the theoretical advantages of this design, the survivorship rates were disappointing with more than 30% of patients undergoing revision surgery within 10 years.[17] Tibial loosening, subsidence and accelerated polyethylene wear were the dominant reasons for implant failure.[18] In 1976, Insall and Walker[19] reported similar disappointing results at 2-4-year follow-up, finding good-to-excellent results in only 11 out of 24 UKAs and a 28% conversion rate to TKA. The reasons for these dissatisfying results were malposition of the implant, insufficient correction of the leg alignment and removal of the patella due to patellofemoral osteoarthritis (PFOA).[20] Subsequently, Laskin[21] reported outcomes using the Marmor knee (Richards Manufacturing Company) with pain relieve in only 65% of the patients and a 26% failure rate at a 2-year follow-up.[21] Following these disappointing results, interest for UKA further decreased and UKA was discouraged.[20,21] In 1989, Kozinn and Scott[22] sought to improve these outcomes by proposing the use of strict inclusion criteria. As a result, better results were reported in the literature. Berger et al[23] applied these criteria and showed a survival rate of 98% at 10-year follow-up, using the

Miller-Galante prosthesis (Zimmer, Warsaw, Indiana, USA). Clinically, outcomes were graded excellent in 78% of patients and good in 20% of patients.[23] Simultaneously, Murray et al[24] reported on 143 knees treated with a medial Oxford mobile-bearing UKA, revealing a survivorship of 97% with a mean follow-up of 10 years. The use of mini-invasive techniques was advocated to reduce tissue damage and improve the ease of revision surgery.[25] However, the results have been variable regarding the accuracy and reproducible of this approach compared to standard techniques.[25,26] Throughout the 1980s and 1990s, UKA usage continued, however, in varying degrees with corresponding results. Over the course of the years, surgeons sought to better understand the biomechanics and modes of failure of these devices to improve on the original UKA designs. In addition, special instrumentation was designed and better patient selection criteria were developed, all of which laid the groundwork for the eventual revival of UKA.

MAIN ARTICLES: REVIEWS, STATE OF THE ART AND CURRENT CONCEPTS

Over the past decades, several reviews have been published about UKA. As time has progressed, reviews moved from patient selection criteria to surgical techniques and modes of failure. Recently, many authors emphasize different fixation methods, prostheses designs, and new technologies (e.g., robot-assisted surgery) as is shown in box 1.

Box 1. Key articles on unicompartmental knee arthroplasty

- ▶ Insall and Walker[19] introduced the first unicompartmental knee arthroplasty in the 1970s.
- ▶ In 1989, Kozinn and Scott[22] described the strict patient selection criteria for UKA after disappointing results from the past.
- ▶ Murray et al[24] reported 10-year survivorship of 98%, showing that long-term outcomes of UKA can be achieved in strictly selected patients.
- ▶ Pandit et al[27] demonstrated the unnecessary contraindications for mobile-bearing UKA, and thereby proposed to expand the indications for UKA.
- ▶ Liddle et al[28] showed good to excellent results at 10-year follow-up of 1000 cementless UKAs after resurgence of interest in the late 90's.
- ▶ Chatellard et al[29] emphasized the high level of accuracy required for optimal position of the tibial component, to restore knee kinematics and prevent implant wear.
- ▶ Pearle et al[30] were the first to demonstrate successful robot-assisted UKA placement in a series of ten patients, showing improvement of the accuracy in regard to component positioning and leg alignment.
- ▶ Van der List et al[31] performed a systematic review demonstrating high survivorship rates of medial and lateral UKA, combined with high functional outcomes scores.
- ▶ Epinette et al[32] identified modes of failure of UKA in a large French multicenter study. They assessed the differences between early, midterm, and late stages of the arthroplasty.
- ▶ Jacofsky et al[33] reviewed the current robotic systems for UKA and comment on future innovations in robotics.

CURRENT STATE OF THE ART

DIAGNOSTICS

Physical and radiographic evaluation remains the cornerstone in the diagnostic process of knee OA and is particularly important to assess whether a knee with unicompartmental OA (medial or lateral) would be indicated for UKA. Evaluation of the presence of unicompartmental knee OA through medical history, physical examination and imaging is essential and all contribute to precise patient selection. Furthermore, it provides valuable information in surgical decision-making after diagnostic criteria are met.

Physical Examination

To assess whether or not a patient is indicated for UKA depends on many factors. On physical examination, it is important to evaluate the location of the pain over the joint line (medial or lateral), ROM, leg deformity, state of the anterior cruciate ligament (ACL), and patellofemoral (PF) discomfort. Pain should be isolated to one compartment, either medial or lateral, to be indicated for UKA. Assessing knee stability, the Lachman or anterior drawer test can be used to evaluate the integrity of the ACL clinically. Furthermore, varus and valgus stress tests assess the collateral ligaments and amount of correctability of a leg deformity if present.

Radiographic Assessment

Traditionally, knee OA is diagnosed on anteroposterior (AP) and lateral weight-bearing radiographs of the knee. Rosenburg et al's[34] views and additional lower leg alignment radiographs are performed as part of the standard radiological work-up of patients with unicompartmental knee OA. This additional 45° posteroanterior flexion weightbearing radiograph has a high sensitivity and specificity of detecting isolated lateral OA.[34] For evaluation of both patella and trochlear surfaces of the femur, an adequate Merchant view may be helpful in determining gross malalignment and presence of PFOA. The severity of knee OA is classified according to the Kellgren-Lawrence (KL) Grading System[35] or Ahlbäck classification[36] (table 1). The most limiting aspect of classification based on radiographic imaging is that it detects joint degeneration only in a more advanced stage.[37]

Table 1. Radiographic Grading Scales

Grade	Kellgren–Lawrence	Ahlbäck
1	Doubtful joint space narrowing and osteophyte formation	Joint space narrowing (<3mm)
2	Definite osteophyte formation with possible joint space narrowing	Joint space obliteration
3	Multiple osteophytes, definite joint space narrowing, sclerosis and possible bony deformity	Minor bone attrition (0-5mm)
4	Large osteophytes, marked joint space narrowing, severe sclerosis and definite bony deformity	Severe bone attrition (>10mm)
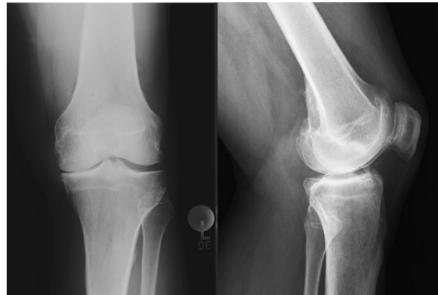
Fig. 1. Preoperative anteroposterior and lateral radiographs showing medial osteoarthritis of the left knee.

To overcome this limitation, the clinical utility of MRI becomes more important to assess the early detection of OA in the contralateral compartment. Subtle degenerative changes in the subchondral bone, cartilage, abnormalities in bone marrow, ligaments, menisci, synovium and joint fluid are all well detected with MRI technology.[37,38] The radiographic indications for UKA is unicompartmental knee OA (Fig. 1), with preservation of the contralateral compartment as shown on both weight-bearing and valgus/varus stress radiographs.[39] Preoperatively, stress view radiographs could provide information by means of determining correctability of the deformity, ensuring maintenance of the contralateral joint space, and indirectly assessing the integrity of the ACL and medial collateral ligaments.[39–41] Advocates of stress radiographs require the deformity to be correctable to neutral, with preservation of the contralateral joint space.[22] However, a pre-operative MRI is more often used to document the absence of significant degenerative changes in the contralateral or PF compartment.[37,38]

INDICATIONS AND CONTRAINDICATIONS

Kozinn and Scott's[22] original inclusion criteria included that the patient had to be older than 60 years at the time of surgery, weigh < 82 kg, should not be physically active or performing heavy labor and have movement-related pain. Furthermore, during physical examination the patient needed to have a preoperatively flexion of the knee of more

than 90°, maximum flexion contracture of 5°, varus of valgus deformity of < 15° and passively correctable to neutral. Although strict adherence to these recommendations led to the improvements of the results, the criteria were generated at a time that surgical techniques and implant designs were not yet optimized. Therefore, questions arise whether these criteria should still be used today or can be extended.

Age
Several authors, including the Oxford Group, reassessed age above 60 years as a contraindication for UKA surgery. They demonstrated similar survival rates (97.3%) and functional outcomes at 10-year follow-up compared with patients older than 60 years (95.1%).[27,42] The fear of early polyethylene wear in younger patient, mostly more active patients at that age, is therefore not supported. Interestingly, a trend of better functional outcomes is seen in this group.[43] This may be explained by the fact that younger patients have high activity levels and high functional demands which are met by UKA, including quicker recovery after surgery and wider ROM.[6,7,42]

Body Mass Index
A general increase in the number of obese patients has been noted in orthopaedic practice over the past few decades, and this trend is likely to continue. Reticence in performing surgery on these patients is due to a possibly increased risk of perioperative complications and poor survival due to early implant failure secondary to component loosening and/or excessive wear.[44] This concern may be particularly relevant with UKA, on account of the potential of point loading at the small area of the bone-implant interface. However, Murray et al[44] performed a large retrospective study and divided 2438 patients into the specific subgroups (body mass index (BMI) <25, 25-30, 30-35, 35-40, 40-45, >45 kg/m^2). They demonstrated that the survival rate of the Oxford UKA does not decrease with increasing BMI, no statistical differences were found between any of the groups at 5-year or 10-year follow-up.[44] Similar results have been found by other authors and systematic reviews as well.[27,42,45,46]

Patellofemoral Osteoarthritis
The most contentious potential contraindication relates to the state of the PF joint. According to Kozinn and Scott selection criteria, PFOA was one of the contraindications for UKA. However, in 1986, Goodfellow and O'Connor[47] performed a bicompartmental study of the Oxford knee in a series of 125 patients and found no relationship between the state of the PF joint, as seen during surgery, and the outcomes. Therefore, the Oxford group made the recommendation of ignoring the grade of PFOA when deciding whether or not to implant a UKA.[27,48] Current literature confirms this by not showing

a relationship between preoperative PFOA and inferior outcomes.[27,42,48] Beard et al[48] examined 824 consecutive knees, in which 16% had full-thickness cartilage loss at any location in the PF joint. These patients did not report worse outcomes than those with a normal or near-normal joint surface.[48]

Recent reports suggest that this might be the result of indirect PF joint congruence improvement as a result of medial UKA implantation.[48,49] By restoring the alignment, the contact forces over the PF joint are lowered.[49] Despite the lack of level I evidence, these previously mentioned studies all suggest that PFOA does not influence UKA outcomes.[27,42,43,47-50]

Anterior Cruciate Ligament

From a historical perspective, it was generally accepted that UKA is contraindicated if the ACL is functionally deficient. The first reports highlighted a higher incidence of complications following UKA surgery in ACL-deficient knees, in terms of tibial loosening and higher revision rate.[51,52] Mancuso et al[53] summarized the evidence in the literature concerning ACL deficiency in UKA surgery; they concluded that combining ACL reconstruction and UKA is the preferred treatment option for patients with ACL deficiency and bone-on-bone medial OA. Simultaneous or staged ACL reconstruction tends to provide superior outcomes, in particular in younger and more active patients. In the elderly, UKA without ACL reconstruction seems to be a reasonable and attractive option if a fixed bearing design is used, but careful patient selection is necessary.[53] The literature shows no statistical difference between survival rates of UKAs implanted in ACL-deficient and ACL-intact knees.[54] However, a cautious approach is required, since long-term results are lacking.

Chondrocalcinosis

Chondrocalcinosis, deposition of calcium pyrophosphate crystals in fibrocartilage and hyaline cartilage, is commonly seen in knees with OA.[55] It is believed that chondrocalcinosis leads to a more aggressive form of OA, potentially leading to accelerated contralateral compartment OA following UKA. Despite the limited number of series, literature does not support this theoretical disadvantage. Hernigou et al[55] proved the incorrectness of this theory, only 11% of their patients showed progression of OA of the other compartment, which is equivalent or less than UKA knees without chondrocalcinosis.[43] Another report by the Oxford Group, showed no significant difference in survival between patients with radiological chondrocalcinosis undergoing medial UKA and controls without chondrocalcinosis. The relevance of histological chondrocalcinosis in UKA patients remains unclear. Although it is associated with a significantly higher revision rate, these

patients report significantly better functional outcomes.[56]

To summarize, over the past two decades the original contraindications to performing UKA surgery have been reassessed by multiple investigators and now the current literature would suggest that age, BMI, PFOA, chondrocalcinosis and ACL integrity are not absolute contraindications for UKA.

OPERATIVE TREATMENT

UKA is most frequently performed on the medial tibiofemoral articulation (90%).[11,31] There are many variables in the surgical technique of UKA, including differences between cemented or uncemented fixation, mobile-bearing or fixed-bearing design, metal backed or all-polyethylene tibial components and conventional or robotic implant positioning (boxes 2-4).

Box 2. Validated outcome measures and classifications

- ▶ Hospital for Special Surgery (HSS) score
- ▶ Knee Society Score (KSS)
- ▶ Oxford Knee Score (OKS)
- ▶ Tegner Activity Score
- ▶ Western Ontario and McMaster Universities Arthritis Index (WOMAC)

Box 3. Tips and tricks for successful unicompartmental knee arthroplasty (UKA)

- ▶ Patient selection is essential in UKA surgery, in which single knee compartment osteoarthritis and correctable leg deformity are the most important factors.
- ▶ Surgical goal is slight undercorrection of the deformity of the long leg axis (MUKA: 1-4º varus, LUKA: 3-7º valgus).
- ▶ In UKA, correct ligament balance is restored by positioning the components accurately and inserting an appropriate thickness of bearing.
- ▶ In high functional demand patients it is recommended to reconstruct the anterior cruciate ligament (ACL) simultaneous or staged in addition to UKA.

Box 4. Major pitfalls of unicompartmental knee arthroplasty (UKA)

- ▶ Osteoarthritis in the contralateral compartment is contraindicated for UKA, therefore MRI could be useful to assess chondral surface in case of doubt.
- ▶ Overcorrection during MUKA or LUKA is associated with progression of osteoarthritis in the contralateral compartment and therefore should be avoided.
- ▶ Residual post-operative axis >8-10⁰ varus following MUKA increases the rate of failure from poly-ethylene wear and loosening.

SURGICAL TECHNIQUES

Cemented versus Cementless

Initially, both cemented and cementless designs were used. However, the cementless designs were less reliable with failure rates up to 20% 10 years after surgery.[57]

Cementation has proven to be an adequate fixation method for UKA, and therefore considered the standard technique. It has shown high survivorship rates and good functional outcomes.[26,58] The most common cause of failure of the cemented implant is aseptic loosening according to the joint registries and large systematic reviews.[10,11,13,32,43] Errors in cementation, thermal necrosis, misinterpretation of radiolucent lines (RLLs), and formation of fibrocartilage and fibrous tissue at bone-cement interface could all contribute to loosening of the cemented UKA.[59,60] As a result, a resurgence of interest in cementless fixation has been noted over the past decade to address these perceived disadvantages of cemented fixation. Modern advances, such as the use of porous titanium and especially hydroxyapatite coating, are responsible for an improved fixation of the cementless UKA. Osseous stability, either by ingrowth or ongrowth, and press-fit fixation of both components are key elements in cementless fixation. Currently, the Oxford UKA is most commonly used cementless prosthesis. The possible downside of the press-fit fixation is an increased risk of periprosthetic fractures, particularly on the tibial side in older osteopenic women.[32,61] More impaction is required to introduce the components with good primary fixation in cementless replacement. Despite early conflicting results, recent evidence shows good results on the effectiveness and safety of cementless UKA in mid-term follow-up with randomized controlled trials and case series.[28,61] Summarized in a recent systematic review by Campi et al.[61], the cementless technique has many advantages in comparison to cemented UKA, including shorter surgical time, avoidance of cementation errors, lower incidence of RLLs and reliable fixation. Despite these promising results, longer follow-up data are required to assess the long-term advantage of cementless UKA.

Fixed versus Mobile Bearing

The first available UKAs were fixed-bearing designs, which often had a flat tibial articular surface. These were less conforming as flexion occurred, and therefore led to higher point loading on the surface.[62] As a result, higher stress within the polyethylene were noted, which increased the risk of component loosening and polyethylene wear.[40,62] In order to minimize polyethylene wear, Goodfellow and O'Conner[47] designed a mobile-bearing metal-backed UKA in 1986. The articulating surfaces of the components are congruent over the entire ROM in most mobile-bearing designs. Large contact areas and small contact stresses diminish the likelihood of wear and decouple the forces at the implant bone interface, which should reduce the incidence of aseptic loosening.[47] Stability of the insert is created by ligamentous tension and, to a much lesser extent, by the components itself. Therefore, it is mandatory to produce equal flexion and extension balance to maintain stability and reduce the risk of bearing dislocation. Impingement of the mobile-bearing insert is another complication inherent to mobile

implants and careful assessment intra-operatively of bearing tracking should alleviate this problem. Bearing dislocation was observed more often in lateral UKAs (11%) with mobile-bearing designs, caused by a more lax lateral compartment in flexion compared to a tighter medial compartment.[63] This allows the lateral compartment to be distracted by about 7 mm, compared to 2 mm on the medial side.[64] To overcome this problem, the Oxford Group developed a new lateral mobile-bearing tibial component. The Domed Lateral Oxford UKA (Biomet UK) has a spherically convex and domed tibial plateau.[65] Additionally, the biconcave bearing has a 7 mm entrapment anteriorly and posteriorly in order to reduce the likelihood of dislocation. Survival rates of lateral UKA increased up to 92% at a mean follow-up of 4 years and good functional outcomes were reported by Weston-Simons et al.[65] Comparative studies on medial UKAs were performed by Parratte et al[66] and Whittaker et al;[67] they found equivalent mid-term and long-term functional outcomes and survivorship rates of mobile-bearing versus fixed-bearing implants. The predominant reasons for revision were progression of OA and aseptic loosening in both fixed-bearing and mobile-bearing UKA. Similar findings were reported by the national arthroplasty registries, suggesting no conclusive advantage of one bearing design over another.[11–13]

All-polyethylene vs. Metal-backed

Historically, two fixed-bearing designs have been utilized for tibial resurfacing when performing a UKA: (1) inlay (all-polyethylene) and (2) onlay (metal-backed). Inlay components are all-polyethylene implants cemented into a carved pocket on the tibial surface, thereby relying upon the subchondral bone to support the implant. Onlay components commonly have a metal base plate and are placed on top of a flat tibial cut, supported by a rim of cortical bone.[68,69] Walker et al[68] used a biomechanical model to compare inlay versus onlay implants, and showed superior load distribution over the tibial surface for the metal-backed onlay design. It has been suggested that this may be a mechanistic explanation for the improved pain relief demonstrated by the onlay components.[68] An additional benefit of metal-backed tibial trays is the possibility to apply cementless fixation. However, metal-backed designs allow a less conservative tibial cut when compared to all-polyethylene implants. In order to minimize contact stresses in the tibial component, a polyethylene thickness of 8 mm millimeters should be pursued when possible.[69,70] Taking into account the thickness of the polyethylene and the metal tray itself (3-4 mm), metal-backed designs necessitate a larger tibial cut.[69] In current practice, metal-backed as well as all-polyethylene tibial implants are being used. The metal-backed design may favor of the renewed interest of cementless fixation.

Surgical technique: Conventional vs. Robot-assisted

Conventional manual techniques have been routinely used in UKA surgery with implant position and alignment critical to short-term and long-term outcomes.[31,51,71] These variables are most often manually controlled with the aid of extramedullary and intramedullary alignment guides. Although national registries reported lower rates, a recent systematic review showed the 10-year survivorship of medial and lateral UKA of 92% and 91%, respectively.[10–14,31] As is described, the accuracy of implant alignment is an important prognostic factor for long-term implant survival; therefore, tight control is recommended.[43,51,71]

Over the past decade, there has been a growing interest in surgical quantifiable variables that can be controlled intraoperatively, which include lower leg alignment, soft tissue balancing, joint line maintenance and component alignment.[72–75] Technical innovations in UKA surgery have led to the development and usage of computer navigation systems, with the purpose of more accurate and tight control of the aforementioned surgical factors.[76–78] Meta-analyses have reported improvement of alignment and surgical cutting accuracy, however, failed to show the superiority of functional outcomes in comparison to conventional techniques.[76,78] As a result, robot-assisted systems have been developed to control these variables intra-operatively, and in addition, refine and enhance the accuracy of the procedure.[30,79] The fundamental goals of robotic-assisted surgery are to be patient-specific, minimally invasive and highly precise. Most importantly, the robotic systems are 'semiactive', meaning that the surgeon retains ultimate control of the procedure while benefiting from robotic guidance within target zones and surgical field boundaries. Preoperative CT-based planning was essential in earlier systems; however, new technology allows image-free robotic assistance (Fig. 2).[30,80,81] Through mapping condylar landmarks and determination of alignment indices, the volume and orientation of bone to be removed is defined. Continuous intraoperative visual feedback provides quantification of soft-tissue balancing and component alignment (Fig. 3).[73,79] Compared to conventional UKA, robotic-assisted systems have demonstrated improved surgical accuracy, lower leg and component alignment.[79,82–84] Another benefit in the use of the robotic system may be a shorter or rapid progression up the learning curve, which can minimize failures related to surgeon workload.[30]
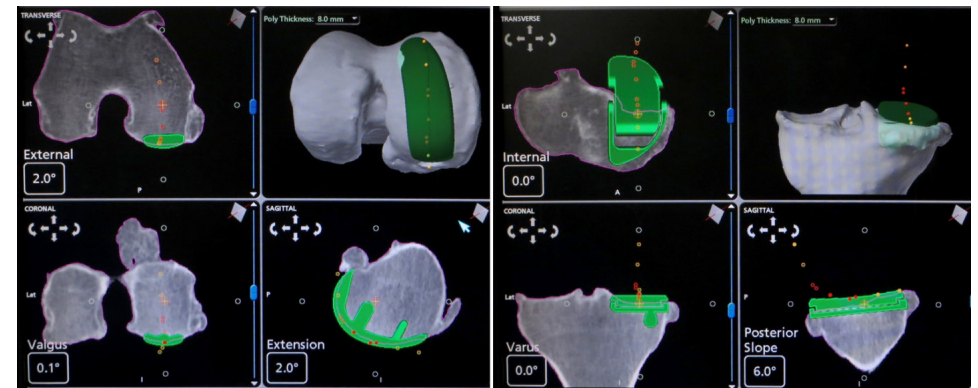
Fig. 2. Robot-assisted surgery of unicompartmental knee arthroplasty, preoperative planning of the femur and tibia component position, however being able to adjust these variables intraoperatively.

Cobb and colleagues[82] performed a randomized control trial to compare conventional techniques with robot-assisted surgery on 27 patients with medial UKA. They found that the robotic-assisted group had a mechanical axis within two degrees of neutral, while only 40% of the conventional group was in that range. Furthermore, they assessed functional outcomes according to the Western Ontario and McMaster Universities Arthritis Index (WOMAC) score and noted a trend towards improvement in performance with increasing accuracy at 6 weeks and 3 months postoperatively.[82] The optimal alignment for medial UKA is between 1° and 4° varus; this was associated with a better outcome and mid-term to long- term survivorship.[29,50,72] For lateral UKA, valgus alignment of 3°-7° was correlated with the best functional outcomes at 2 years postoperatively.[85] Pearle et al[86] reported the preliminary results of a multicenter study of 854 patients and found a survivorship of 98.9% and satisfaction rate of 92% at minimum 2-year follow-up. Comparing these results to other large conventional UKA cohorts may suggests that robotic-assisted surgery could possibly improve survivorship at short-term follow-up.[26,58,87]

Drawbacks of robot-assisted surgery are high overall costs and radiation; however, the implementation of the image-free robotic assistance has significantly decreased the radiation by eliminating the CT preoperatively. Furthermore, Moschetti et al[88] has shown that robot-assisted UKA is cost-effective compared to conventional UKA when the annual case volume exceeds 94 UKAs per year. Another disadvantage in comparison to conventional techniques is the necessity of pin tracts for the required optical tracking arrays, which is necessary for some robot-assisted systems. They could

create a stress riser in the cortical bone when the pins are applied.[81] Nevertheless, prospective clinical studies with longer follow-up are required to assess the additional value of robotic-assisted UKA surgery, despite the promising short-term results.
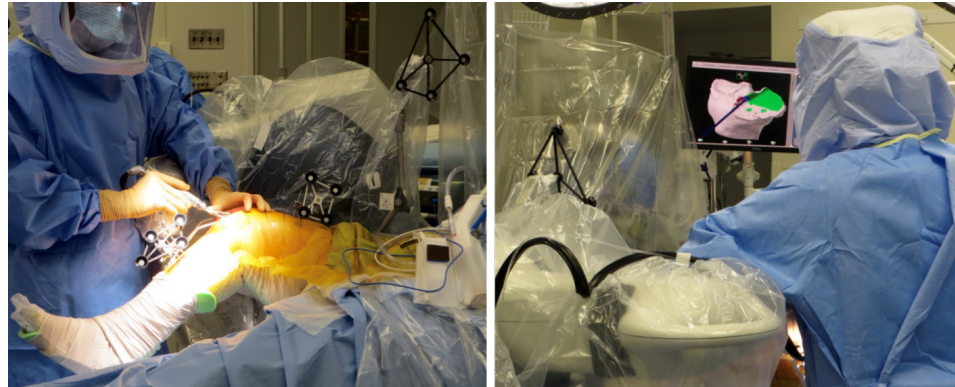
Fig. 3. Robot-assisted surgery of unicompartmental knee arthroplasty, tibial cut using Stryker/ MAKO haptic guided robot (MAKO Surgical Corp.) with continuous intraoperative visual feedback.

SURVIVORSHIP

In 2015, a systematic review was published concerning UKA survivorship rates of medial and lateral UKAs.[31] The authors showed that the survivorship of medial UKA at 5, 10, 15 and 20 years was 93.9%, 91.7%, 88.9% and 84.7%, respectively. Lateral UKA is considered a technically more challenging surgery than medial UKA, because of differences in anatomy and kinematics, as well as implants designs and lower surgical volume as compared to medial UKA. However, no statistical difference was found between survivorship in medial and lateral UKA.[31] The reported survivorship rates of lateral UKA at 5, 10 and 15 years were 93.2%, 91.4% and 89.4%, respectively. A notable factor of alterations in survivorship displayed in cohort-, case-, and registry-based studies is the differences in volume of surgical procedures. It has been shown that the risk of revision decreases as both center and surgeon UKR volume increase.[89] Overall, registry-based studies report lower survivorship compared to cohort-based studies. The most likely explanation for the dissimilarities between cohort-based and registry-based studies is the fact that cohort studies are often high-volume centers reporting outcomes, whereas registry-based studies also report low-volume center outcomes. As is suggested by a few authors, it would be of additional value if registries and registry-based studies separate the survivorship of medial and lateral UKA.[31,89] Thereby, it would be possible to compare the survivorship of both UKA procedures in both high-volume and low-volume centers. In addition, the long-term survivorship of lateral UKA could be assessed based on registry studies, which is difficult because of the small number of knees in cohort studies.

MODES OF FAILURE

Several studies have been published on modes of failure after UKA, using different classification systems based on cause or time stages. Over the past two decades, several developments have been made in UKA surgery. The ongoing development of new prosthesis designs and surgical techniques has ensured that the modes of failure have altered as well.

Aseptic Loosening

A French multicenter study of 418 failed knees concluded that aseptic loosening was the most common cause of failure in their population, accounting for 44% of all cases.[32] Similar findings were shown by van der List et al[43] and Citak et al[90], both reported aseptic loosening and progression of OA as the most common modes of failure in medial UKA. Tibial loosening was seen more often than femoral loosening; moreover, it developed significantly earlier (37.7% within 2 years) when compared to femoral loosening. Noteworthy is the fact that aseptic loosening is much more common in medial than lateral UKA.[32]

Progression of Osteoarthritis

Progression of OA in the contralateral compartment accounts for the second most common cause of failure of UKA. Various studies reported progression of the underlying disease in up to 36% of the knees.[32,43,91] To minimize this progression, a high level of accuracy is required for optimal positioning of the components and restoration of the joint line. The restoration of the prosthetic joint space affects load transfers between the two femorotibial compartments. To that end, Khamaisy et al[74] proved a significant improvement of the congruity of the contralateral compartment following medial and lateral UKA implantation. Restoration of the appropriate joint line in the damaged compartment has an influence on survivorship. A joint space height difference of >2mm was significantly associated with shorter medial UKA survival.[29] Failures related to a lower position of the prosthetic joint line were due to loosening, whereas failures related to a higher position of the prosthetic joint space were due to early polyethylene wear and progression of OA in the contralateral compartment.[29,40,47,66] As Chatellard et al[29] stated, UKA acts as a wedge that compensates for the joint damage, which restores normal kinematics and blocking the vicious circle of medial femorotibial OA.[74]

Polyethylene Wear

As previously mentioned, wear is another mode of failure which is mostly seen in fixed-bearing designs of UKA.[43,66] Higher stresses are generated in these types of designs, often in combination with a metal-backed tibial tray, which allows only a certain polyethylene thickness. Thinner polyethylene is at risk for accelerated wear of the increased contact stresses.[70] Furthermore, leg alignment and the position of the components influences wear in the knee following medial UKA.[71] Hernigou and Deschamps[71] showed that a varus undercorrection was associated with increased polyethylene wear and recurrence of the deformity. Subsequently, the risk of lateral degeneration was increased in case of valgus overcorrection.[71] In contrast, no significant correlation was found between polyethylene wear and BMI, gender or preoperative diagnosis of the patient.[69,90]

Pain

Unexplained pain is important source of failure following UKA surgery. Among 4-23% of the patients with UKA experience pain postoperatively without any obvious reason after the traditional examinations.[32,43,92] Park et al[93] recently performed a diagnostic MRI-based study, in order to create a greater insight into the etiologie of the symptomatic patients where physical and traditional radiographs were not aberrant. MRI examination was found to be instrumental in diagnosing these patients. The most common pathologies based of MRIs included loose bodies, osteolysis, tibial loosening, synovitis, stress fractures and infection[93]. Baker et al[92] compared the proportion of UKA and TKA revisions that were performed because of unexplained pain as recorded in the National Joint Registry of England and Wales[92]. The risk of revision was greater following UKA, and proportionally more unicompartmental implants were revised for unexplained pain. Some potential explanations were suggested by the authors. First, UKA revision is perceived as an easier procedure to revise than a TKA and this likely lowers the threshold of both patient and surgeon to proceed with pain as the only indicator. However, registry-based studies have shown that revising a UKA results in a poorer result than a primary TKA, with survival and patient-reported outcomes similar to revising a TKA.[94] They conclude that a demonstrable cause for the revision, rather than unexplained pain, should be the reason for conversion to TKA. Second, inexperienced surgeons faced with an unhappy patient with a UKA with no obvious diagnosis are more likely to blame the unresurfaced compartment.[92] This situation is similar to TKA with an unresurfaced patella, where the patellar is subsequently resurfaced as it is assumed that the pain must be coming from this articulation. Revision procedures in these patients only result in 25% satisfaction rates, even in the presence of a 'hot' nuclear bone scan.[92] Aseptic loosening, progression of OA, polyethylene wear, bearing

dislocation, and unexplained pain are the most common failure modes following UKA surgery. To a much lesser extent instability, infection, malalignment, fracture, and tibial subsidence are reported as a cause of failure in current literature.[32,43,90]

Postoperative Imaging Evaluation

Postoperatively, standardized knee radiographs are obtained immediately after surgery and repeated after 6 weeks, 6 months, 12 months and then yearly. They include AP, lateral and long leg radiographs for the postoperative evaluation of the mechanical axis (Fig. 4 and 5). The clinical importance of the frequent radiographs is to monitor the presence of RLLs and progression of OA in the unreplaced compartments. As is described by Goodfellow et al,[52] two types of RLLs exist; physiological radiolucency ($\leq$2mm, stable, and well-defined) is most commonly seen following UKA. Pathological RLLs are >2mm thick, progressive and poorly defined, hence associated with component loosening or infection.[52,95] Moreover, correction of the leg alignment can be calculated after surgery. Taking into account minor varus alignment of the leg ($\leq7^0$) is associated with better functional outcomes and mid-term to long-term survivorship of medial UKA compared to neutral or close-to-neutral alignment.[72]
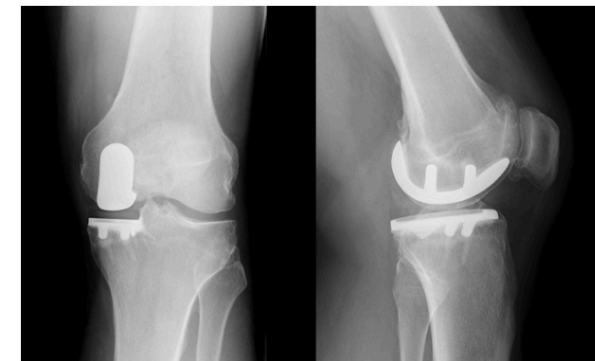
Fig. 4. Postoperative anteroposterior and lateral radiographs showing a left medial UKA.
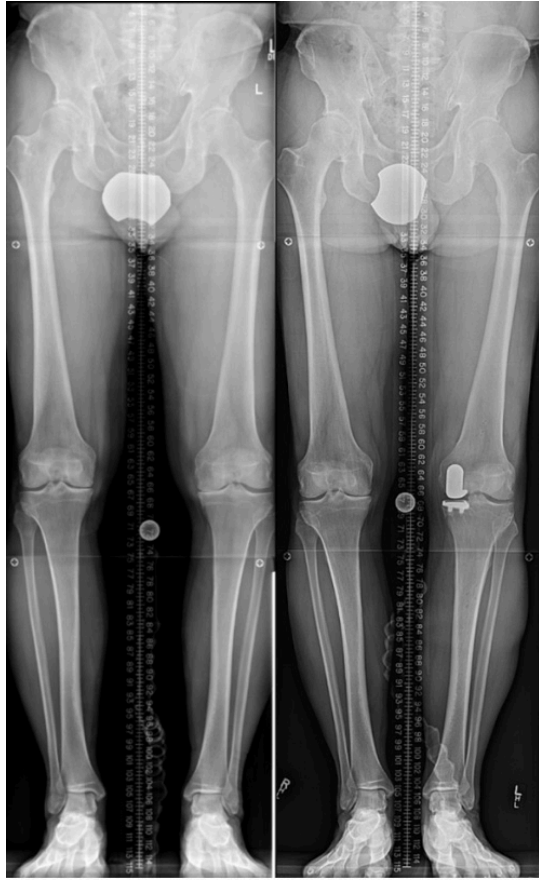
Fig. 5. Weight-bearing long leg radiographs preoperative and postoperative to assess leg alignment.

POSTOPERATIVE CARE AND REHABILITATION

Rehabilitation after UKA surgery is similar to TKA protocols recommending full weight-bearing exercises directly. However, faster rehabilitation was noted after UKA compared to TKA, particularly after introducing new anesthetic and pain control protocols (ie, Rapid Recovery).[96] Early mobilization allows adequate ROM faster and decreases the risk of complications, such as deep vein thrombosis, pulmonary embolism, chest infection and urinary retention. A short length of stay should also help minimize the risk of hospital acquired infection; in addition, patients are more comfortable at home.[96]

RETURN TO SPORTS AFTER UNICOMPARTMENTAL KNEE ARTHROPLASTY

As a consequence of higher patient expectations regarding physical activity after UKA, clinicians are increasingly forced to express an opinion to what extent participation of

sports is possible after surgery. Furthermore, there is a growing interest in what specific activities are acceptable after knee arthroplasty. Witjes et al[7] recently performed a systematic review on return to sports and physical activity after TKA and UKA. A limited number of seven studies were included, which reported the return to sports following UKA surgery. They concluded that participation in sports seems more likely after UKA than TKA. Return to the type of sport was subdivided by their impact. Return to sports after UKA for low-impact sports was 93%; >100% for intermediate sports, and 35% for high-impact sports. Physical activity scores of these patients confirmed these findings. Moreover, time to return to sports was registered at 12 weeks after UKA (91%, concerning low-impact sports).[7] No difference in timing of return to sports between UKA and TKA patients was found by Walton et al.[97] However, patients with UKA were significantly more likely to increase or maintain their preoperative level of sports activity after surgery than patients with TKA.[97]

GEOGRAPHICAL DIFFERENCES

The cementless designs of UKA are increasingly being used in Europe, Australia and New Zealand as is shown in Table 2. All of which are depending on conventional surgical techniques to align the components. The most commonly used cementless UKA is from the Oxford Group. The advantages of cementless fixation have been thoroughly mentioned earlier in this review. Furthermore, a recent systematic review showed good-to-excellent survivorship of different cementless designs[98]. In 2218 cementless UKA procedures, 62 failures are reported, which can be extrapolated to 5-year, 10-year and 15-year survivorship of cementless UKA of 96.4%, 92.9% and 89.3%, respectively[98]. Primarily, a broader adoption of robotic technology was impeded in Asia and Europe. There is skepticism regarding the importance of optimizing precision in UKA as well as expense, inconvenience, delays and risks associated with preoperative imaging with this technology.[81] In the USA, three robotic systems are FDA-approved for UKA. The Stryker/MAKO haptic guided robot (MAKO Surgical Corp.) has the largest market share with 20% for UKA. Since the introduction in 2005, over 50,000 have been performed with nearly 300 robotic systems nationally.[33,80,84] A caution approach is needed when discussing the geographical differences on UKA, because the data is based on national registries. However, not every country has a national registry or the type of arthroplasty is not specified.

FUTURE PERSPECTIVES

Based on the advantages, and good-to-excellent survivorship and functional outcomes of cementless designs, it is expected that cementless UKA will gain more popularity in the upcoming years.[28,98] Therefore, more companies will most likely launch cementless

designs in the near future. Currently, the total usage of UKA ranges from 8% to 11% according to national registries.[9–14] Over the past two decades, advances in implant design and surgical technique have generated promising survivorship rates, faster recovery and rehabilitation, increased pain relief, and good postoperative ROM.

As a consequence of these results, an increase of application of UKA is expected. However, orthopaedic surgeons need to be aware of the possibility of UKA for treating isolated knee OA, though the candidacy for UKA to treat unicompartmental knee OA was large according to Willis et al.[99] Out of 200 consecutive patients, 47.6% was a potential candidate for UKA based on radiographical findings,[99] hence the conclusion that UKA has to be considered as a treatment option more often in the future (Table 3). Robotic-assisted surgery is beginning to change the landscape of orthopaedics. Initially, robotic systems were introduced to improve precision, accuracy, and patient's overall outcome and satisfaction rates.[30,79,83,86] Robotic-assisted surgery has the potential to achieve these goals by enhancing the surgeon' ability to generate reproducible techniques through an individualized surgical approach. Future innovations will most likely continue to improve the planning, setup, and workflow during robotic-assisted UKA surgery. These advances will be implemented by means of simplifying the process and minimizes the learning curve. Critical domains will possibly include preoperative analysis, intraoperative sensors, and robotically controlled instrumentation.[84] Currently, some sort of imaging modality is necessary in order to preform preoperative planning, depending on the type of robotic system. The next step will be to extend image-free preoperative planning. This may create options to go beyond imaging to appreciate the kinematics of the operative joint before altered by the pathology of arthritis.[81] The preoperative plan will be used to recreate the desired anatomic and kinematic framework. Furthermore, it is difficult to predict the array of technological innovations in the field of implant development.[33]

Table 3. Key issues of patient selection for UKA

▶ Isolated medial or lateral OA osteoarthritis	Kellgren-Lawrence 3-4
▶ Leg alignment (correctable to neutral)	MUKA: <15^0 varus
	LUKA: <10^0 valgus
▶ Fixed flexion deformity	<10^0
▶ Anterior cruciate ligament	Intact (relative indication)

LUKA, lateral UKA MUKA, medial UKA; UKA, unicompartmental knee arthroplasty

Box 6. Robotic and computer navigation systems utilized in unicompartmental knee arthroplasty (UKA)[33,76,80,84]

Robotic systems	Characteristics
Navio Precision Free-Hand Sculptor (PFS) system (Blue Belt Technologies) Semi-active robotic system	• Image-free, no preoperative imaging required • Robotic arm under direct control of the surgeon • Uses optical-based navigation, creating a virtual model of the osseous knee • Ability to adjust component position, alignment, and soft-tissue balance during procedure • Open platform (allows different implant designs)
Stryker/Mako haptic guided robot (Mako Surgical Corp.) Semi-active tactile robotic system	• Preoperative imaging required (CT-scan) • Robotic arm under direct control of the surgeon • Real-time tactile feedback intra-operatively • Ability to adjust component position, alignment, and soft-tissue balance during procedure • Closed platform (implant specific)
Computer navigation systems	Characteristics
Ci Navigation (Ci-Navigation-System, DePuy I-Orthopaedics, Munich, Germany)	• Image-free navigation system • Optical tracking unit that detects reflecting marker spheres by an infrared camera • Controlled by a draped, touch-screen monitor • Implant specific (Preservation, DePuy) • Specific fine adjustable cutting devices
Orthopilot (Orthopilot, Aesculap AG, Tuttlingen, Germany)	• Image-free system • Allows different implant designs • Relative motion of four infrared localizers calculate the center of rotation • Bony resection is performed with classical saw
Stryker navigation (Stryker Navigation, Kalamazoo, Michigan, USA)	• Image-free system • Allows different implant designs • Infrared stereoscopic camera to track skeletal reference frames
Treon plus (Medtronic Inc., Minnesota, USA)	• Image-free navigation system • Dynamic tracking of the instruments relative to the patient's position allowed hands-free alignment of the resection guides

Table 2. Geographical differences in unicompartmental knee arthroplasty based on registry data

Registry	Year	% of Total		Bearing type (%)		Fixation (%)		Most common prostheses			Survival (%)	Most common failure modes		
		UKA	PFA	Fixed	Mobile	Cement	Cement-less	1	2	3	10 yrs.	1	2	3
New Zealand	2014	8.8	0.8	7.3	92.7	44.1	55.9	Oxford	Zimmer	Oxford 3	88.7	Pain	Aseptic loosening	Infection
Australia	2014	4.2	0.4	51.6	48.4	66.7	33.3	ZUK	Oxford	Oxford 3	85.5	Aseptic loosening	Progression of OA	Pain
United Kingdom & Wales	2014	8.1	1.1	40.5	58.7	*not provided*		Oxford 3	Zimmer	Sigma HP	87.5	Aseptic loosening	Pain	Dislocation
Sweden	2014	3.5	0.4	6.6	93.4	80.4	19.6	Oxford	Link Sled	ZUK	87.6	Aseptic loosening	Progression of OA	Polyethylene wear
Norway	2015	10.5	0.6	1.0	99.0	66.8	33.2	Oxford 3	Oxford	Link Sled	82.0	Aseptic loosening	Pain	Progression of OA
USA	2014	4.2					*No specific details mentioned on UKA in the registry*							
Canada	2014	0.6	0.3				*No specific details mentioned on UKA in the registry*							

Oxford: Oxford cementless UKA, Oxford 3: Oxford Partial Knee (cemented).
OA, osteoarthritis PFA, patellofemoral arthroplasty UKA unicompartmental knee arthroplasty.

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Predicting the Feasibility of Correcting Mechanical Axis in Large Varus Deformities with Unicompartmental Knee Arthroplasty

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ABSTRACT

INTRODUCTION

Due to disappointing historical outcomes of unicompartmental knee arthroplasty (UKA), Kozinn and Scott proposed strict selection criteria, including preoperative varus alignment of ≤15º, to improve the outcomes of UKA. No studies to date, however, have assessed the feasibility of correcting large preoperative varus deformities with UKA surgery. The study goals were therefore to (1) assess to what extent patients with large varus deformities could be corrected, and (2) determine radiographic parameters to predict sufficient correction.

METHODS

In 200 consecutive robotic-arm assisted medial UKA patients with large preoperative varus deformities (≥7°), the mechanical axis angle (MAA) and joint line convergence angle (JLCA) were measured on hip-knee-ankle radiographs. It was assessed what number of patients were corrected to optimal (≤4°) and acceptable (5°-7°) alignment, and whether the feasibility of this correction could be predicted using an estimated MAA (eMAA, preoperative MAA - JLCA) using regression analyses.

RESULTS

Mean preoperative MAA was 10º of varus (range 7°-18°), JLCA was 5° (1°-12°), postoperative MAA was 4º of varus (-3° to 8°), and correction was 6° (1°-14°). Postoperative optimal alignment was achieved in 62% and acceptable alignment in 36%. The eMAA was a significant predictor for optimal postoperative alignment, when corrected for age and gender (P < .001).

CONCLUSION

Patients with large preoperative varus deformities (7°-18°) could be considered candidates for medial UKA, as 98% was corrected to optimal or acceptable alignment, although cautious approach is needed in deformities >15°. Furthermore, it was noted that the feasibility of achieving optimal alignment could be predicted using the preoperative MAA, JLCA and age.

INTRODUCTION

Unicompartmental knee arthroplasty (UKA) has proven to be an effective treatment for isolated medial compartment knee osteoarthritis in appropriate selected patients.[1] Historically, however, outcomes of UKA were disappointing and, as a result, Kozinn and Scott[2] proposed strict selection criteria in their landmark paper in 1989. One of the criteria was that medial UKA should only be performed in patients with a preoperative varus deformity of 15° or less that is correctable to neutral.[2] This is based on the rationale that it is less feasible to restore the mechanical axis angle (MAA) to neutral or close to neutral in patients who have not fulfilled these criteria. A consequence of excessive residual varus alignment is increased compartment forces by overloading medially, which can ultimately lead to UKA failure from polyethylene wear or aseptic loosening.[3–9]

It would be important to develop radiographic predictors of deformity correction after UKA, especially because several studies have shown that better outcomes were found in patients with a postoperative MAA of ≤7° of varus.[4,10,11] More specifically, recent studies showed that postoperative varus alignment between 1° and 4° was associated with the most optimal functional outcomes after medial UKA.[6,12] The correctability of the preoperative MAA depends on multiple factors; including the existence of femoral deformity, tibial plateau depression, and joint line convergence due to lateral collateral ligament laxity and medial compartment cartilage loss.[13] In current literature, however, there is a discrepancy to which extent large varus deformities are correctable with medial UKA surgery. Some authors suggested that most patients with a preoperative MAA of ≥10° of varus could not be corrected to neutral, indicating that patients with large preoperative varus deformities might be at risk for undercorrection.[14,15] Therefore, it could be argued that medial UKA might not be the ideal treatment option for patients with large varus deformities. On the other hand, in patients with isolated medial compartment knee osteoarthritis, the varus alignment originates mostly from a progressing intra-articular deformity.[16–18] There are, however, patients with preexistent varus alignment, even before the added degenerative intra-articular deformity. A concern may be that after correction of the articular deformity with UKA, varus alignment would still remain.[19] Chatellard et al showed that correcting the joint line obliquity through medial UKA improves the postoperative MAA and outcomes. Moreover, others emphasized that medial UKA restores the contralateral joint space width and improves joint congruence in patients with a mean preoperative varus deformity of 9°.[18,20] This implies that varus deformities can be corrected by restoring joint line obliquity during medial UKA.[18,20]

Therefore, a study was performed assessing the predictive role of several radiographic deformity measurements on the postoperative mechanical axis following medial UKA in patients with large preoperative varus deformities (≥7°). The purpose of this study was 2-fold; first, determine to what extent patients with large varus deformities undergoing robotic-assisted medial UKA were correctable. Second, evaluate the predictive value of an estimated MAA (eMAA) based on the preoperative radiographic deformity measurements, in particular the preoperative MAA and joint line obliquity.

MATERIALS AND METHODS

STUDY DESIGN AND PATIENT SELECTION

After institutional review board approval, an electronic registry search was performed using a prospective database which contains over 800 medial onlay UKAs, all performed by the senior author (ADP). Surgical inclusion criteria consisted of isolated medial osteoarthritis as primary indication, intact cruciate ligaments, passively correctable varus deformity, and less than 10° fixed flexion deformity. Surgical exclusion criterion was inflammatory arthritis. Study inclusion criteria were patients with a preoperative MAA of ≥7° of varus who had preoperative and postoperative hip-knee-ankle (HKA) radiographs. Exclusion criteria consisted of ipsilateral total hip arthroplasty (THA) or total ankle arthroplasty (TAA), or a history of lower extremity fracture. The goal was to include 200 consecutive patients who matched these criteria, as this was considered a representative group. A total of 499 patients were screened between November 2008 and November 2013, of which 245 were excluded for preoperative MAA<7°, 44 for lack of preoperative and/or postoperative HKA radiographs, 9 for ipsilateral THA or TAA, and 1 for a history of lower extremity fractures.

The postoperative alignment was categorized as optimal (≤4° of varus), acceptable (5° - 7° of varus), and undercorrected (>7° of varus), which is commonly used in recent literature.[4,6,10–12]

IMPLANT AND SURGICAL TECHNIQUE

All surgeries were performed by one surgeon (ADP) and carried out using a robotic-arm assisted surgical platform (MAKO System, Stryker, Mahwah, NJ), as described previously.[21,22] All patients received a cemented fixed-bearing RESTORIS MCK Medial Onlay implant (Stryker, Mahwah, NJ, USA). The surgical goal was to establish a relative undercorrection within the range of 1°- 7° of varus, in order to avoid degenerative progression on the lateral compartment.[11,18] The surgeon considered a final lower limb

alignment of 1°- 4° to be optimal, but accepted a navigated final alignment between 5°- 7° if further correction was not possible without release of the medial collateral ligament (MCL). The MCL was carefully protected and there were no cases where an MCL release or a piecrusting of the MCL was performed.
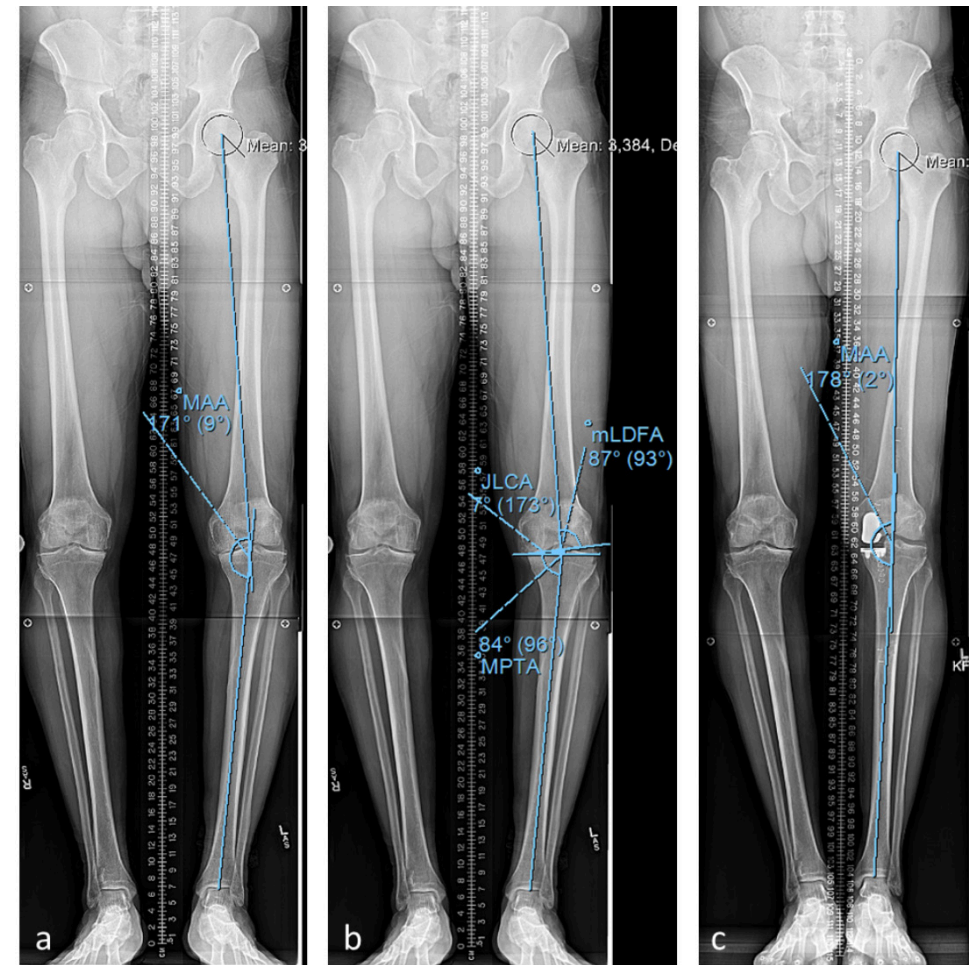
Fig. 1. Example of the radiographic assessment of the (a) preoperative mechanical axis angle (MAA), (b) mechanical lateral-distal-femoral-angle (mLFDA), medial proximal tibial angle (MPTA), joint line convergence angle (JLCA), and (c) the postoperative MAA. These hip-knee-ankle radiographs show a preoperative MAA of 9° of varus, mLFDA of 87°, MPTA of 84°, JLCA of 7°, displaying an eMAA of 2°, which matches the postoperative MAA of 2° of varus.

RADIOLOGICAL ASSESSMENT

Radiographic evaluation was performed in a Picture Archiving and Communication System (PACS, Sectra Imtec AB, Version 16, Linköping, Sweden). HKA standing radiographs were obtained as standard work-up preoperatively and six weeks postoperatively. Patients were instructed to stand straight with both knees fully extended and evenly distribute their body weight between both limbs. The patellas were aligned with the direction of the X-ray beam. The X-ray beam was centered at the distal pole of the patella, aligning the image parallel to the tibial joint line in the frontal plane. In each HKA radiograph, the source to image distance was standardized to 122 cm by a standard 256 0.25–mm AISI 316 stainless steel calibration sphere (Calibration Unit; Sectra), to account for any magnification effects.[23] The radiographic assessment was performed by one assessor (LJK) according to the validated methods used by Paley et al.[13,16,24,25] Using Ortho Toolbox (PACS feature), the MAA, mechanical lateral distal femoral angle (mLDFA), medial proximal tibial angle (MPTA), and joint line convergence angle (JLCA) were determined for each patient.[16,17,26] The MAA is defined as the angle between the femoral mechanical axis (center of hip to intercondylar notch of knee) and the tibial mechanical axis (center of tibial spines to center of the distal tibia). The mLDFA is the lateral angle formed between the femoral mechanical axis and the knee joint line of the femur in the frontal plane. Defining the MPTA, the proximal medial angle formed between the tibial mechanical axis and the knee joint line of the tibia in the frontal plane. The angle formed between femoral and tibial joint orientation lines is called the JLCA.[13,26] In case of medial OA, there is medial JLCA convergence often due to medial cartilage loss.[13,17] Postoperatively, only the MAA was determined, because the joint orientation lines were indistinctive by use of the polyethylene insert. Marx et al. showed good to excellent intra- and inter-observer reliability of lower extremity alignment measurements using a corresponding method (0.97 and 0.96, respectively).[24] The correction was defined as the change in MAA, comparing the preoperative MAA relative to the postoperative MAA. All measured angles are displayed in Fig. 1.

STATISTICAL ANALYSIS

All analyses were conducted using SPSS version 24 (SPSS Inc., Armonk, NY, USA) and SAS version 9.3 (SAS Inc., Cary, NC). Descriptive analyses were reported using means and standard deviations (SD) for continuous variables and frequencies with percentages for discrete variables. With regard to the first research question, it was assessed to what extent patients were corrected to an optimal MAA (≤4° of varus) and acceptable MAA (5° - 7° of varus), which was based on the aforementioned recent literature.[4,6,10,12] Furthermore, a subgroup analysis was performed based on the preoperative MAA to describe the distribution of postoperative alignment and JLCA. For the second research question regarding the feasibility of achieving this optimal postoperative alignment, an eMAA was calculated by subtracting the JLCA from the preoperative MAA (preoperative MAA − JCLA). The predictive value of the eMAA was tested by means of a correlation analysis and chi-square test. The role of extra-articular deformities in achieving optimal postoperative alignment was assessed using MPTA and mLDFA. Finally, a multivariable logistic regression model was fitted to examine the feasibility of achieving an optimal MAA (≤4° of varus), based on the eMAA and corrected for patient-related factors (age, gender, body mass index). A P value <.05 was considered statistically significant.

Table 1. Demographic characteristics

	Mean ± SD (range)
Age (years)	64.7 ± 10.1 (43.4 − 86.6)
BMI	30.4 ± 5.9 (18.6 − 52.9)
Gender ratio	124 men : 76 females

RESULTS

A total of 200 consecutive medial UKA patients were included, with a mean age of 64.7 years (SD, 10.1; range 43.3 - 86.6), mean body mass index of 30.4 kg/m² (SD, 5.9; range 18.6 - 52.9), and of which 124 patients (62%) were male (Table 1). The mean preoperative varus deformity was 10° (SD, 2.3; range 7° - 18°), mLDFA was 89° (SD, 1.9; range 85° - 95°), MPTA was 84° (SD, 6.1; range 78° - 91°); JLCA was 5° (SD, 1.8; range 1° - 12°). Mean correction following medial UKA was 6° (SD, 2.5; range 1° - 14°) in this cohort of patients with a preoperative MAA ≥7° (Table 2).

Table 2. Preoperative and postoperative angle measurements according to the method of Paley et al.

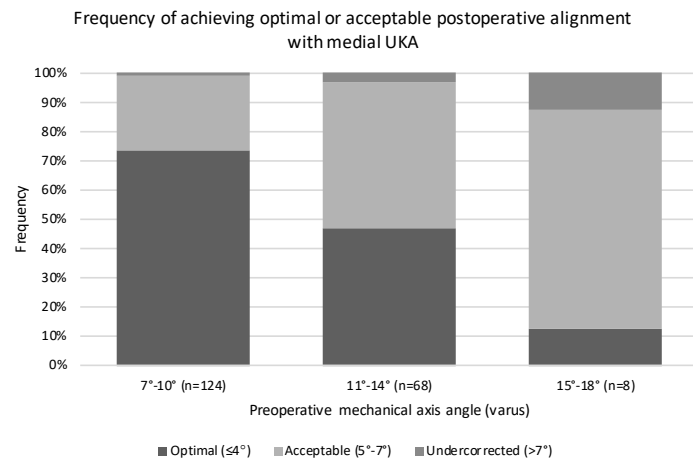|	Mean ± SD	Minimum	Maximum
Preoperative			
Mechanical axis angle (MAA, varus)	10° ± 2.3	7°	18°
Mechanical lateral distal femur angle (mLDFA)	89° ± 1.9	85°	95°
Medial proximal tibial angle (MPTA)	84° ± 6.1	78°	91°
Joint line convergence angle (JLCA)	5° ± 1.8	1°	12°
Postoperative			
Mechanical axis angle (MAA, varus)	4° ± 2.1	-3°	8°
Correction	6° ± 2.5	1°	14°

SD, standard deviation

Reviewing all 200 patients, it was noted that 62% reached an optimal MAA postoperatively, 36% an acceptable MAA, and only 4 patients (2%) had undercorrection (>7° of varus). In patients with a preoperative MAA of 7°-10° of varus, the deformity was corrected to an optimal alignment range in 73%, acceptable range in 26% and undercorrected in 1%. In patients with a preoperative MAA of 11°-14° of varus, the deformity was in 47% corrected to optimal postoperative MAA, and in 50% to acceptable alignment. Of the patients with a preoperative MAA of 15° - 18°, optimal MAA was achieved in 13%, acceptable in 74%, and undercorrection in 13% (Table 3 and Fig. 2).

Table 3. Descriptive characteristics of the distribution of postoperative mechanical axis angle in the specific groups based on the preoperative mechanical axis angle.

	Postoperative MAA		
	Optimal: ≤4° (n=124)	Acceptable: 5°-7° (n=72)	Undercorrection: ≥7° (n=4)
Preoperative MAA			
7° - 10° (n=124)	91 (73%)	32 (26%)	1 (1%)
11° - 14° (n=68)	32 (47%)	34 (50%)	2 (3%)
15° - 18° (n=8)	1 (13%)	6 (74%)	1 (13%)

MAA, mechanical axis angle (varus)

Frequency of achieving optimal or acceptable postoperative alignment with medial UKA

Fig. 2. Frequency of achieving optimal and acceptable postoperative varus alignment stratified by the preoperative MAA.

The dispersion of JLCA within the subgroups is shown in Table 4. Of all patients with a preoperative varus deformity of 7° - 10°, 47% had a medial JLCA of 1° - 4° and 50% had a medial JLCA of 5° - 8°. When the MAA increased to ranges of 11° - 14° and 15° - 18°, it was noted that most patients had a medial JLCA of 5° - 8° (74% and 75%, respectively). A significant positive correlation was noted between the eMAA (preoperative MAA - JLCA) and the postoperative MAA (0.467, $P < .001$). Furthermore, in the univariate analysis, a significant higher percentage of patients achieved optimal alignment in the eMAA ≤4° group (78%) when compared to the eMAA >4° group (50%; $P < .001$). The odds of achieving postoperative MAA ≤4° was 3.4, which indicates that it is more likely to achieve optimal alignment when the eMAA is ≤4° compared to eMAA >4° (Table 5).

Table 5. Predicted probability of achieving a postoperative mechanical axis angle within 4° of varus based on the estimated mechanical axis angle.

	Postoperative MAA			
	≤4°	>4°	Chi-square	Odds ratio
eMAA ≤4°	66 (78%)	19 (22%)	p<0.001	3.4
eMAA >4°	58 (50%)	57 (50%)		

MAA, mechanical axis angle (varus) eMAA, estimated MAA
Estimated MAA: preoperative MAA – JLCA.

The role of extra-articular deformities in estimating optimal postoperative alignment was assessed using independent t-tests (Table 6). With regard to tibial deformities, patients with an eMAA ≤4° had a mean MPTA of 85.5° (range, 81° - 91°), whereas patients with an eMAA >4° had a mean MPTA of 83.3° (range, 78° - 89°) (p<0.001). Using the normal values of Paley et al, it was noted that patients with an eMAA >4° had an abnormal MPTA (<85°) more frequently compared to patients with eMAA ≤4° (70% vs 31%, $P < .001$). Regarding femoral deformities, patients with eMAA ≤4° had a mean mLDFA of 88.5° (range, 85° - 95°) compared to a mean mLDFA of 90.0° (range, 86° - 94°) in the eMAA >4° group ($P < .001$). An abnormal mLDFA was noted in 8% of the patients with an eMAA ≤4° and in 35% of the patients with an eMAA >4° ($P < .001$).

Table 6. Role of extra-articular deformities in estimating optimal postoperative varus alignment using mechanical proximal tibial angle and mechanical lateral distal femur angle.

| | Mechanical proximal tibial angle (MPTA) | | | | |
	Mean ± SD	Minimum	Maximum	p-value	Abnormal (<85°)
eMAA ≤4°	85.5° ± 1.9	81°	91°	<0.001	31%
eMAA >4°	83.3° ± 2.0	78°	89°		70%
	Mechanical lateral distal femur angle (mLDFA)				
	Mean ± SD	Minimum	Maximum	p-value	Abnormal (>90°)
eMAA ≤4°	88.5° ± 1.8	85°	95°	<0.001	8%
eMAA >4°	90.0° ± 1.8	86°	94°		35%

MAA, mechanical axis angle (varus) eMAA, estimated MAA SD, standard deviation
Estimated MAA: preoperative MAA − JLCA.
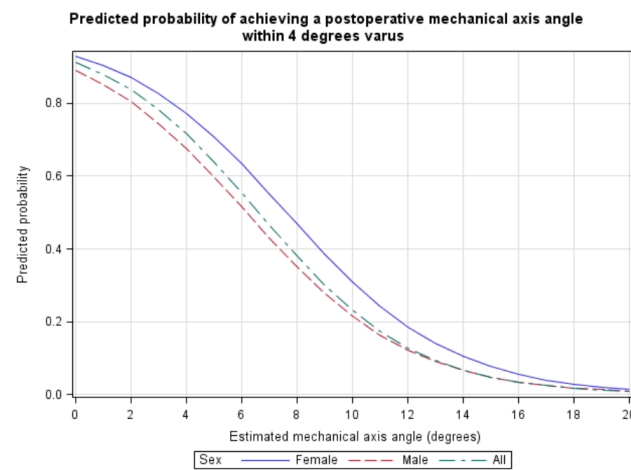
Fig. 3. Predicted probability of achieving optimal postoperative alignment with medial UKA, when correcting for age and gender using a logistic regression model.

Using a logistic regression model, the correctability of large varus deformities to a postoperative MAA ≤4° was assessed by using the eMAA ≤4°, age and gender. The odds of achieving an optimal postoperative MAA, when the eMAA is ≤4°, was 3.62 higher in comparison to an eMAA >4° of varus ($P < .001$) when correcting for age and gender. Similarly, age as the continuous variable of age was noted to be a significant predictor (OR 0.97, $P = .026$), indicating that the chance of achieving optimal alignment decreases with 3% with every year a patient gets older (Table 7). As shown in Figure 3, the predicted probability of achieving postoperative varus alignment within 4° decreases when the eMAA increases. When the eMAA exceeds 6.5° of varus, the likelihood of achieving optimal alignment is less than 50% (predicted probability 0.5).

Table 7. Predictive model to assess the likelihood of achieving a mechanical axis angle within 4° of varus corrected for gender and age using a logistic regression model.

| | Postoperative MAA ≤ 4° | | |
	Odds ratio	95% C.I.	p-value
Female gender	1.79	0.94 – 3.38	0.075
Age	0.97	0.94 – 0.998	0.026
eMAA ≤4°	3.62	1.90 – 6.90	<0.001

MAA, mechanical axis angle (varus) eMAA, estimated MAA
Estimated MAA: preoperative MAA − JLCA.

DISCUSSION

The purposes of this study were to (1) determine to what extent patients with large varus deformities were correctable to optimal (≤4°) or acceptable alignment (5° - 7°) and (2) evaluate the feasibility of optimal postoperative alignment based on the eMAA in medial UKA patients. The main findings of this study were that optimal or acceptable postoperative alignment was achieved in 98% (62% and 36%, respectively) of the patients with preoperative varus deformity of ≥7° undergoing robotic-assisted medial UKA using a technique where the MCL is carefully preserved. Second, the eMAA was found a significant predictor to evaluate the feasibility of achieving optimal postoperative alignment (≤4°).

In our cohort, 62% of the patients were corrected to optimal alignment (≤4°), and in an additional 36% acceptable alignment (5°- 7°) was achieved. Based on several studies, the surgical goal in medial UKA surgery is to achieve minor varus alignment postoperative and not exceed 7° of varus.[10,18,27,28] Avoiding severe undercorrection is recommended to prevent medial compartment overload, which is associated with accelerated polyethylene wear as was showed in the subgroup analysis of Hernigou and Deschamps and several other studies.[4,5,9,10] Furthermore, many authors noticed that overloading the medial compartment increases the risk of aseptic loosening.[4,10,18,29] In the absence of malalignment, almost 70% of the load across the knee passes through the medial compartment.[5,17,30] When a varus deformity increases from 4° to 6°, the load through the medial compartment approaches 90%.[30] With the presumption that undercorrection increases the risk of early polyethylene wear and aseptic loosening, many authors have, therefore, advocated to aim for minor residual varus alignment postoperatively in medial UKA patients.[6,7,10,18] Furthermore, Vasso et al and Zuiderbaan et al noted significantly higher patient-reported outcome scores (International Knee Society and Western Ontario and McMaster Universities Osteoarthritis Index, respectively) in patients with a postoperative varus alignment ≤4°.[6,12] Taking these

studies into account, it could be argued that minor varus alignment (≤4°) after medial UKA is optimal.

Subsequently, across the different subgroups it has been shown that in the vast majority of patients, optimal or acceptable alignment was achieved after robotic-assisted medial UKA. However, the frequencies of achieving optimal and acceptable alignment differed between the subgroups of 7°-10°, 11°-14°, 15°-18° (73% and 26%, 47% and 50%, and 13% and 74%, respectively). Our results were different from those of Kreitz et al., as they suggested that only 7.7% of their patients with a preoperative MAA of ≥10° of varus could reach neutral or beyond based on valgus stress radiographs.[14] Furthermore, Berger et al. showed that in 17% of their patients (mean preoperative MAA of 8° of varus) the surgical goal (≤5° of varus) could not be achieved.[31] Though, two dissimilarities should be addressed; their surgical goal was slightly different, and the use of conventional methods instead of robot assistance. Robot-assisted surgery concerning medial UKA has been proven to be more accurate and less variable when compared to computer navigation or conventional UKA.[6,21,32] Studies showed that postoperative MAA was consistent within 1°-2° of preplanned position using robot-assistance, a similar degree of accuracy was only achieved in 40% of conventional UKA.[21,32] Furthermore, robot-assisted surgery allows tight control, as well as improvement, of the lower leg alignment intraoperatively.[33] Therefore, the use of robot-assistance might contribute favorably to the feasibility of achieving optimal or acceptable alignment during medial UKA. This study shows that 98% of the patients with large varus preoperative deformities (≥7°) were corrected within optimal or acceptable range using robot-assisted surgery.

We hypothesized that the lower limb realignment after medial UKA is driven primarily by the correction of the joint line deformity (as measured the medial JLCA) in these patients. This was based on the rationale that medial UKA restores the joint height and improves joint congruence, as was shown by Chatellard et al and Khamaisy et al.[18,20] By restoring the joint space height and congruence within the knee joint, the joint obliquity returns to neutral or close to it.[13,18,20] Using this theory, the degree of correctability of the MAA in medial UKA patients could be estimated based on the preoperative MAA and JLCA. Consequently, the eMAA (preoperative MAA - JCLA) was compared with the achieved postoperative MAA to test its predictive value. A significant correlation was found between the eMAA and the achieved postoperative MAA (0.467, *P* < .001). Indeed, 78% of the patients with an eMAA of ≤4° of varus achieved optimal postoperative alignment. Our results suggest that calculating an eMAA preoperatively is useful to predict the feasibility of achieving optimal postoperative alignment. When correcting for age and

gender, the chance of achieving optimal postoperative alignment was 3.6 times greater when the eMAA was within similar range. Furthermore, it was noted that for every year a patient gets older the likelihood of achieving optimal postoperative alignment decreases with 3%. This could be explained by a less compliance in the soft tissue envelop resulting in a stiffer, less predictable correction in these knees.[1,34] Therefore, difficulty might be encountered when correcting varus deformities in the elderly.

As shown in Table 6, extra-articular deformities were more frequent in patients with an eMAA >4° compared to the eMAA ≤4° (p<0.001). More specifically, the mean MPTA was within normal range in the eMAA ≤4° group, whereas the mean MPTA was outside normal range in the eMAA >4° group according to Paley et al.[26,35] In our cohort, especially more tibial deformities were observed in the eMAA >4° group compared to the eMAA ≤4° group (70% and 31%, respectively). This indicates that in patients with an eMAA >4° the presence of extra-articular deformities using the MPTA and mLDFA should be evaluated. Moreover, when combining these findings with the significantly lower predicted probability of achieving optimal postoperative alignment (Fig. 3), other treatments, such as high tibial osteotomy and distal femoral osteotomy, may be considered in this subgroup of patients.[36–39]

This study has several limitations. Firstly, there were only eight patients included with a preoperative MAA >15°; therefore, cautious interpretation of the results of this group is necessary. Furthermore, stress views were not obtained in this study. The stress views are an established means of evaluating the flexibility of a varus deformity. However, stress views may be difficult to obtain, are operator dependent, and are non-weightbearing. It remains unclear if stress views are predictive of lower leg alignment correction after UKA; future studies may be directed at incorporating stress view data into realignment prediction after medial UKA. Another limitation was the use of Ortho Toolbox which permitted calibration of each HKA radiograph, but measured angles using rounded numbers. Measurements could not be performed using decimals; consequently, a standard measurement error of 0.5° has to be taken into account when interpreting the results. This method was chosen as several studies showed high reliability, and more importantly, high accuracy of this method.[15,24,40,41] Finally, the registration data concerning the intraoperative correctability and ligament tension recorded by the robotic system was not saved and therefore could not be compared to the eMAA and postoperative MAA. The role of soft-tissue balancing in correcting the mechanical axis with UKA could be assessed in future studies, as a previous TKA study already suggested an extrinsic contribution to the bony deformity, such as a tight soft-tissue envelope, in patients with a varus deformity >10°.[42]

In conclusion, in this study it was noted that patients with a preoperative varus deformity between 7° and 18° could be considered candidates for medial UKA as 98% was restored to either optimal (62%) or acceptable (36%) postoperative alignment. However, a cautious approach is needed in patients with a deformity exceeding 15° of varus. Furthermore, the eMAA was a significant predictor for optimal postoperative alignment with medial UKA, when correcting for age and gender. Future studies are necessary to assess the functional outcomes and revision rates in medial UKA patients with large preoperative varus deformities.

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Femoral and Tibial Radiolucency in Cemented Unicompartmental Knee Arthroplasty and the Relationship to Functional Outcomes

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ABSTRACT

BACKGROUND
Femoral and tibial radiolucent lines (RLL) following unicompartmental knee arthroplasty (UKA) can be categorized in physiological and pathological radiolucencies. Although physiological tibial radiolucency is assessed extensively in literature, studies reporting femoral radiolucency are lacking. Therefore, a retrospective study was performed to assess physiological femoral RLL and its relationship to short term functional outcomes.

METHODS
A total of 352 patients were included that underwent robotic-assisted medial UKA surgery and received a fixed-bearing metal-backed cemented medial UKA. Radiographic follow-up consisted of standard anteroposterior and lateral radiographs. Functional outcomes, using the Western Ontario and McMaster Universities Arthritis Index questionnaire, of patients with RLL were compared with a matched cohort, based on gender, age and body mass index.

RESULTS
In this cohort, 101 patients (28.8%) had physiological regional radiolucency around the femoral (10.3%) and/or tibial (25.3%) component, of which 6.8% concerned both components. Tibial RLL were more frequently seen compared to femoral RLL (*P* < .001). Our data suggest that the time of onset of femoral radiolucency develops later (1.36 years) than tibial radiolucency (1.00 years, p=0.02). No difference in short-term functional outcomes was found between the RLL group and the matched cohort group without radiolucency.

CONCLUSION
This study acknowledges that tibial and femoral physiological radiolucency may develop following cemented medial UKA. Furthermore, this was the first study showing that physiological femoral RLL occurs later than tibial RLL. Prospective studies with longer follow-up and larger numbers are necessary in order to compare radiolucency in different UKA designs and the relationship to outcomes.

INTRODUCTION

Unicompartmental knee arthroplasty (UKA) is a common treatment option for isolated medial knee osteoarthritis (OA), with good to excellent results at 5 and 10-year follow-up.[1-4] Recently, a large systematic review showed survivorship of 94% after 5 years and 92% after 10 years [3]. Concerning the modes of failure following UKA surgery, several studies and national registries have noted that aseptic loosening is one of the most frequent causes of revision.[5-10]

Importantly, periprosthetic RLL following UKA can be divided into pathologic and physiologic types of radiolucencies.[11] As Goodfellow et al[11-13] described, pathological radiolucent lines (RLL) are >2mm, poorly defined, and often related to aseptic loosening. On the contrary, physiological RLL are 1-2mm and well defined. The presence of these RLL is neither related to symptoms nor indicative or predictive of loosening according to current literature.[11,12,14] The etiology of radiolucency remains unknown; although, association between postoperative leg alignment and the emergence of RLL has been suggested by several authors.[11,15,16] Many studies have reported on the incidence of physiological tibial RLL, ranging from 62%-96%, which were clinically not related to inferior functional outcomes.[13,14,17,18] However, only a few older studies have assessed RLL around the femoral component, when different UKA designs were used.[2,19] There are no recent studies which assess the different aspects of physiological femoral radiolucency around cemented medial UKA, especially relative to the frequency of tibial radiolucency.

Therefore, this study assessed the incidence of physiological femoral and tibial radiolucency in cemented UKA. Aims of this article were to evaluate the incidence of RLL of the femoral component in relationship to the tibial component in different alignment ranges. Furthermore, the time of onset of radiolucency and its correlation with short-term patient-reported functional outcomes was assessed. We hypothesized that physiological femoral RLL are commonly seen regionally around the femoral component, but are not correlated with inferior functional outcomes after UKA.

MATERIAL AND METHODS

STUDY DESIGN AND PATIENT SELECTION
Our study was carried out at Hospital for Special Surgery, with a prospective database that included over 900 UKAs, which were performed over the last 8 years by the senior

author (A.D.P.). After institutional review board's approval (IRB 2013-056), an electronic registry search was performed for all patients who underwent medial UKA between April 2008 and December 2015. The surgical indications were medial compartment OA, no significant joint space narrowing in the lateral compartment, an intact anterior cruciate ligament, a correctable varus deformity, and a fixed-flexion-deformity of $<10^0$. Surgical contraindications included the presence of Kellgren-Lawrence grade III or greater OA of the lateral compartment, patellofemoral-related pain symptoms, or inflammatory arthritis. Obesity was not a contraindication, as several studies have shown that increasing body mass index (BMI) is not associated with increasing failure or worse outcomes.[20–24] Inclusion criteria for this study were (1) medial onlay UKA, (2) baseline radiographs at 2 weeks post-operatively, (3) available functional outcomes. Patients with bicompartmental arthroplasty or different type of UKA than the study implant were excluded.

IMPLANT AND SURGICAL TECHNIQUE

All patients received the identical cemented fixed-bearing Medial Onlay implant (RESTORIS MCK, Stryker, Mahwah, NJ). All surgeries were carried out by the senior author (A.D.P.), using a robotic-arm-assisted surgical platform (MAKO System, Stryker, Mahwah, NJ).[25,26] The surgical goal was to establish a relative undercorrection of the preoperative varus alignment in order to avoid osteoarthritic progression on the lateral compartment.[27,28]

RADIOLOGIC ASSESSMENT

Radiographic evaluation was performed in Picture Archiving and Communication System (PACS, Sectra Imtec AB, Version 16, Linköping, Sweden). The anteroposterior (AP) and lateral radiographs were obtained 2 weeks postoperatively, repeated after 6 weeks and during follow-up visits after surgery. In addition, hip-knee-ankle (HKA) radiographs were taken at 6-week-follow-up, in order to assess the post-operative leg alignment. All radiographs were taken according to a standardized protocol, consisting of AP weightbearing view, lateral view at 30^0 of flexion and HKA standing radiograph, for which the x-ray beam was aligned with the patella and foot and centered at the distal pole of the patella, aligning the image parallel to the tibial joint line in the frontal plane.[29] The radiographic assessment for this study was performed by a single assessor (L.J.K.), according to current and validated standards in the literature.[14,18,30] The radiographic assessment was conducted blinded to clinical scores. Similar to previous studies assessing radiolucency, the AP radiograph was used to assess tibial RLL, dividing the area underneath the tibial tray into 5 zones (Fig. 1a).[14,17,18,31] Femoral RLL were assessed using lateral radiographs, because the component-bone interface is not visible on the AP view.

Therefore, the flat area at the anterior and posterior femoral condyle was examined on the lateral view, as well as the area around the 2 pegs of the implant (Fig. 1b).[17,31] Radiolucency is quantified by physiological and pathological RLL. Physiological RLL are well-defined, 1-2mm thick, accompanied with a radiodense line, in contrast to pathological RLL that are >2mm thick, poorly defined and have no radiodense line.[11]

The time of onset of RLL on the radiographs was scored by screening every radiograph from direct post-operative until the most recent one; however, this was depending on the regularity of the follow-up visits. The time of onset was related to patient-reported outcomes to compare the 2 groups (RLL vs non-RLL). Furthermore, the postoperative leg alignment (HKA angle) was measured on HKA radiographs of all patients.

FUNCTIONAL OUTCOMES

Patient-reported functional outcome scores were collected using the Western Ontario and McMaster Universities Arthritis Index (WOMAC). The WOMAC is a validated questionnaire in the setting of knee OA and quantifies the patient-reported outcome using 24 Likert-scale questions.[32,33] Questionnaires were collected during clinic visits or electronically by email, preoperatively and at 1-, 2-, and 5-year follow-up. Functional outcomes of patients with RLL were compared with a matched cohort without any RLL, based on gender, age, and BMI. All patients with WOMAC scores after the occurrence of RLL were matched with a patient without radiolucency, based on gender, age (within range of 3 years), and BMI (within range of 3 kilograms per square meter).
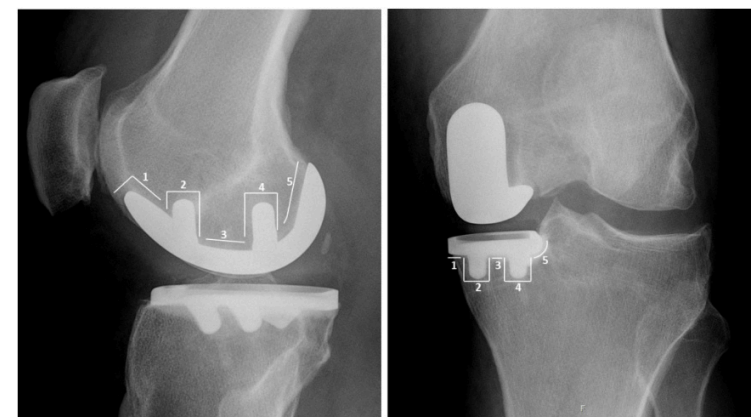
Fig. 1. Distribution of radiolucent lines (RLL) per zone, (a) anteroposterior radiograph which shows RLL around the tibial component and (b) lateral radiographs which assesses RLL around the femoral component of unicompartmental knee arthroplasty.

STATISTICAL ANALYSIS

Analyses were carried out using Excel 2010 (Microsoft Corp, Redmond, WA) and SPSS version 24 (SPSS Inc., Armonk, NY. The clinical details including gender, age, BMI, date of surgery, date of radiographic follow-up, and frequency of femoral and tibial RLL were assessed using descriptive statistics, consisting of mean, range values, and frequencies reported as percentages. Chi-square test was used to assess the differences between the incidence of femoral and tibial RLL. Furthermore, an analysis of variance was conducted to test for any differences in clinical characteristic features among the 3 patient groups (femoral RLL, tibial RLL, and both component RLL). Finally, continuous outcomes were used to compare functional outcomes in RLL group and non-RLL group. Paired t-tests were performed to compare both groups based on their WOMAC scores. Statistical significance was set at $P < .05$.

RESULTS

Between April 2008 and December 2015, 964 medial UKA were performed, 613 patients were excluded for this study. The reasons for exclusion were missing baseline radiographs or usage of different UKA design than MAKO Onlay. Three hundred fifty-one patients with minimum radiographic follow-up of 3 months were screened for radiolucency (Fig. 2). Radiographic assessment showed femoral and/or tibial physiological radiolucencies in 101 patients (28.8%), of which 57 (56%) were male and 44 (44%) were female. Mean age was 63.4 years (range 44.6-85.0 years), and mean BMI was 29.6 kg/m² (range 18.6-52.9 kg/m²). At baseline (2 weeks postoperative) no femoral or tibial RLL were noted. The mean follow-up was 18 months (range 4 – 77 months).
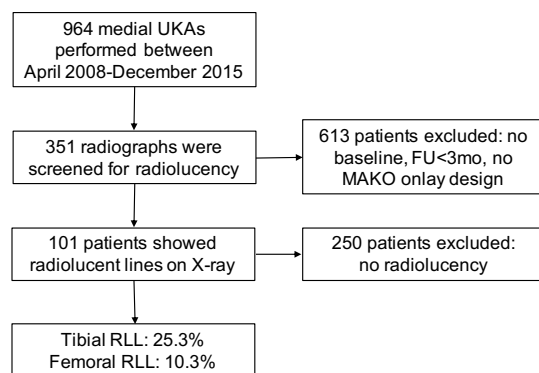
Fig. 2. Flow chart of the inclusion process.

In our cohort, the incidence of femoral and tibial physiological RLL was 10.2% and 25.3% respectively, of which 6.8% concerned both components. Tibial RLL were more frequently seen compared to femoral RLL ($P < .001$) (Table 1). No significant characteristic differences among the patients with femoral RLL, tibial RLL, or both femoral and tibial RLL were present regarding male gender (45%, 58%, and 54%, respectively, $P = .715$), age (68.9, 62.7, and 63.1, respectively, $P = .114$), or BMI (28.8, 29.4, and 30.1, respectively, $P = .809$).

Table 1. Incidence of regional tibial and femoral radiolucency in medial unicompartmental knee arthroplasty.

	No radiolucency	Radiolucency detected	Incidence	Chi-square
Tibial component (n=351)	263	89	25.3%	p<0.001
Femoral component (n=351)	316	36	10.3%	

The HKA angles were measured on all 351 patients, mean HKA angle in RLL group was 2.89° varus and in the non-RLL group 2.47° varus. No significant difference was noted ($P =.115$). In Table 2, femoral and tibial RLL were subdivided into different alignment ranges. No relationship was noted between the incidence of RLL and the HKA angle postoperatively.

Table 2. Incidence of regional femoral and tibial radiolucent lines in different alignment groups based on hip-knee-ankle angle.

	Femoral RLL (n=12)	Tibial RLL (n=65)	Combined RLL (n=24)	Non-RLL (n=250)
Postoperative HKAA				
<1° (n=91)	4.4%	15.4%	5.5%	74.7%
1°-4° (n=167)	1.8%	20.4%	7.2%	70.7%
>4° (n=93)	5.4%	18.3%	7.5%	68.8%
Chi-square (p-value)	0.263	0.615	0.836	

HKAA, hip-knee-ankle angle

Distribution of radiolucency per zone according to the aforementioned classification (Fig. 1) revealed that femoral RLL were most common in zone 1 and 5, 37.0% and 52.2% respectively. A similar trend was noted on the tibial side, of all tibial radiolucencies 59.6% was located in zone 1 and 73.0% in zone 5 (Table 3).

Table 3. Distribution of tibial and femoral radiolucent lines per zone.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Tibial RLL (n=90)	59.6%	13.5%	20.2%	10.1%	73.0%
Femoral RLL (n=36)	44.4%	22.2%	0.0%	33.3%	63.9%

RLL, radiolucent lines

In our cohort, the mean time of occurrence of tibial RLL was 1.00 years (standard deviation 0.77) compared to 1.36 years (standard deviation 0.88) for the femoral component based on the available radiographic data. This significant difference (P = .02) in time of onset of radiolucency was showed in Fig. 3, where the majority of tibial RLL developed within the first year after surgery.

Fig. 3. Time of onset of all patients with femoral and tibial radiolucent lines (RLL) is showed. The horizontal lines represent the mean time of onset per component: blue line represents the tibial component (1.00yr), and the red line represents the femoral component (1.36yr).

Forty patients (38.8%) had reported WOMAC scores after the onset of RLL. Average age and BMI were comparable with the matched group (Table 4). Pre-operatively and at 1-, 2- and 5-year follow-up, the total WOMAC scores of the RLL group were 55, 91, 81, and 92, respectively, whereas these were 53, 86, 89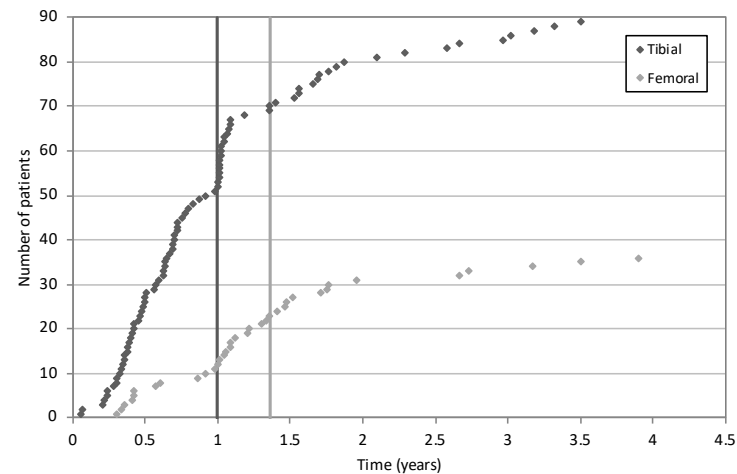, and 87 for the non-RLL group, respectively. The difference between the two groups was not significant on all follow-up moments (P > .188).

At final review, one patient had been revised to a total knee arthroplasty; and in another patient the femoral component was revised, both showing pathological RLL. The reason for revision to TKA was tibial subsidence and the femoral component was replaced because of component loosening. Three patients have had an arthroscopic procedure (i.e., partial lateral meniscectomy, debridement patella, loose body), all showed physiological RLL.

Table 4. Demographic information and WOMAC scores of with means and standard deviation in the two groups; radiolucent lines (RLL) and the matched non radiolucent lines (non-RLL).

	RLL group (n=40)	Non-RLL group (n=40)	p-value
Gender			
Male	18 (46%)	18 (46%)	
Female	22 (54%)	22 (54%)	
Age (yrs.)	64.2 (± 8.9)	64.0 (± 8.9)	0.915
Body mass index (kg/m^2)	28.7 (± 5.6)	28.9 (± 4.0)	0.855
WOMAC scores			
Pre-operatively	55 (± 14)	53 (± 16)	0.718
1-yr Follow-up	91 (± 8)	86 (± 12)	0.366
2-yr Follow-up	81 (± 23)	89 (± 12)	0.188
5-yr Follow-up	91 (± 8)	87 (± 13)	0.284

DISCUSSION

Data from this study confirmed that physiological RLL may develop under the tibial component of the cemented medial UKA. This study is one of the first assessing the presence of femoral RLL around the cemented medial UKA. Furthermore, our data suggests that the time of onset of femoral RLL is significantly later than tibial RLL. Both tibial and femoral radiolucencies were not correlated with inferior functional outcomes. These results should be interpreted with caution, because of the retrospective data collection and the technique of assessing radiolucency.

The first finding was the incidence of physiological radiolucency around cemented UKA, both femoral and tibial (10.2% and 25.3%, respectively). Comparing these results to the results found in literature, the incidence of tibial radiolucency was indeed lower than found by other studies (range 62%-96%).[13,14,19] There are many factors which could have contributed to this discrepancy.

Firstly, the UKA design is different as most studies assessed radiolucency around the Oxford UKA, whereas this study described RLL around the MAKO UKA.[13,14] The shape of both femoral and tibial component is different, as the MAKO UKA has 2 femoral pegs compared to the cemented Oxford design, which has one peg and is evaluated in most previous studies assessing radiolucency. The current cemented Oxford design UKA has 2 pegs as well. Furthermore, the surface of the tibial tray facing the bone is shaped differently. The Oxford tibial tray has from anterior to posterior a vertical stabilizer, whereas the MAKO UKA has 2 short pegs to stabilize the component. Secondly, each design was implanted using different surgical techniques, conventional techniques for Oxford UKA and robotic-assistance for MAKO UKA.

Concerning the post-operative leg alignment, our results showed mean HKA angle of 2.91° varus in RLL group compared to 2.48° varus in the non-RLL group. Furthermore, no relationship was noted between the incidences of femoral or tibial RLL in the specific alignment ranges. Gulati et al. found no statistical relationship between the incidence of tibial RLL and the residual varus deformity, which corresponds with our results.[14] According to several authors, an HKA angle of 1°-4° should be pursued to optimize subjective results, especially in the WOMAC domains of pain, function, and total scores compared HKA angle ≤1° or ≥4° [16,34]. These findings correspond to the results of Vasso et al., which reported higher International Knee Society Scores among patients with a mild postoperative varus deformity (1°-7°) compared to neutral alignment.[16] A number of hypotheses have been proposed to explain the etiology of radiolucency, of which postoperative leg alignment is one. However, in this cohort it is questionable if the HKA angle plays a role, because both groups fit within the optimal range. To get more insight in the etiology of radiolucency, prospective studies are required to assess the theoretical hypotheses and possible attributable factors.

Although much is known about tibial RLL, limited number of studies have reported incidence of femoral radiolucencies. Possible explanations could be the lower incidence of femoral RLL or the follow-up is too short to show femoral RLL.[35,36] Berger et al. have described the occurrence of femoral radiolucency, and this study was performed more than 15 years ago. In their study, they found an incidence of femoral RLL 14%, which is slightly higher than our findings (10.2%).[19] Furthermore, Kalra et al. performed a radiographic assessment of physiological and pathological femoral lucency in patients who required revision because of suspected loosening. A matched control group was created to be able to compare the both groups.

Results showing a greater frequency of physiological lucency on the femoral side in the revision group, however, no significant difference was noted. A similar trend was noted for the pathological RLL.[17]

It is important to emphasize that there is a difference between cemented and uncemented prostheses in the evaluation of radiolucency around UKA. A few more recent studies by the Oxford group described the incidence of radiolucencies around uncemented UKA compared with cemented UKA.[30,31,36] Pandit et al[36] proposed that radiolucency occurred less frequently in the uncemented UKA, 6.3% vs 75% in cemented UKA. It has been argued the cemented UKAs show a higher incidence of radiolucencies, because of possible incomplete cementation, (thermal) osteonecrosis, and formation of fibrous tissue.[37,38] These arguments relate to our second finding concerning the zone distribution of the radiolucencies and the possible causes, both tibial and femoral zones 1 and 5 were most commonly affected. Comparing our results to the current literature, a similar trend is noted in tibial RLL.[13,14,17] Zone 5 is considered to be a non-weight-bearing area and a site where the component does not fixate.[14] Therefore, Gulati et al[14] suggested that it could be considered as clinically irrelevant. Interestingly, femoral radiolucencies were often located in zone 1 and 5, which is anteriorly and posteriorly. More theories have been proposed in the literature. Riebel et al[39] performed a cadaver study to explain early failure of the femoral component in UKA. They found that the cause of failure could be high shear and tensile stresses developed at the bone-prosthesis interface. These stresses will cause failure of the cement column, allowing rocking of the implant at the apex of the bone-prosthesis interface as the implant cycles through physiologic flexion and extension.[39] Future radiostereometric analysis studies would be informative in order to confirm this theory. It has also been suggested that the underlying cause of the occurrence of radiolucency may be micromotion between the implant or cement surface, or both, and the bone. The associated mechanical stress is thought to promote the migration of synoviocytes into the space along the cement-bone and implant-bone interfaces. Therefore, creating a "synovium-like" or "fibrous" membrane and release osteoclast-stimulating cytokines that contribute to adjacent bone resorption.[40,41] However, Kendrick et al demonstrated that whether there is no, partial or complete RLL beneath the tibial component, there is always some direct contact between cement and bone. In the case of direct contact, the cement interdigitation with the bone demonstrates that the interface is stable and not loose.[38] The strength of the bone-cement interface is dependent on cement penetration and interdigitation into cancellous bone. However, cement penetration into bone can lead to increased interface temperatures during polymerization of the cement.[42] For thermal necrosis to occur temperatures need to exceed 44° C.[43] As

was showed by Seeger et al., the highest temperature inside the cancellous measured was 25.7° C, and therefore it seems unlikely that thermal necrosis occurs during UKA cementation.[44] Concluding, our results and the previous mentioned studies suggest that there is an obvious relation between UKA and radiolucency. However, a definite answer on the etiology question is still based on multiple explanations and hypotheses. Therefore, future studies are necessary to test the proposed theories and mechanisms.

Our third finding was the significant difference in the time of onset of tibial and femoral RLL (1.00 and 1.36 years, respectively) in this cohort. Comparing results with those in literature, physiological radiolucency tends to develop most often within the first 2 years following surgery.[13,36,45] However, no difference in onset of tibial and femoral RLL has been described earlier in literature. Although it is still unclear why RLL appear, the finding of a different time of onset of tibial and femoral RLL might be explained by different etiological mechanisms of both RLL. Berger et al[19] showed that there was a difference in location of partial radiolucencies in femoral and tibial RLL with most of the femoral RLL occurring at the cement-prosthesis interface and tibial RLL occurring at the cement-bone interface.[19] Regarding the mechanisms, Riebel et al found in a cadaveric study that femoral RLL occurs with a rocking phenomenon of the femoral component, while several studies have suggested that tibial RLL occurs by compressive loading of the component, which is likely to generate fibrocartilage.[13,38,39,46] Although this has not been studied extensively, this might be a possible explanation for the difference in time of occurrence of RLL in both components. Future studies are necessary to confirm our finding and further assess this.[39] Current literature only states the time to revision for tibial and femoral loosening, however, failed to show the relationship to radiolucencies.[6] Epinette et al assessed 418 failed UKAs based on their modes of failure, and they found aseptic loosening to be the main reason for revision. Furthermore, they showed that tibial loosening developed significantly earlier than did femoral (54% vs 40% within 2 years, respectively).[6] Therefore, it could be argued that there might be a difference in time of onset of radiolucencies as well. Our results confirm this theory; however, prospective studies with frequent follow-up are necessary to address this more carefully.

Our results show no correlation between femoral or tibial radiolucency and inferior functional outcomes when comparing the RLL group with the non-RLL group. Comparing both group based on their WOMAC scores after the occurrence of RLL, a trend of even better results in the RLL group was noted. As discussed previously, Pandit et al proposed that tibial radiolucency was less frequently seen in the uncemented UKA at 1 year after surgery. Although the varied incidence of RLL, they failed to show

any significant differences between clinical scores and fixation techniques. Therefore, it was suggested that both uncemented as well as cemented UKA were similarly effective at 1-year follow-up.[36] To our knowledge, this is the first study that assessed femoral RLL in relationship to functional outcomes following medial UKA surgery.

Several authors described the radiological results of the tibial component of the UKA, whereas the results of the femoral component were unknown.[13,14,19,36] It has been noted that different methods have been used to assess RLL around UKA, most studies used AP and lateral radiographs.[30,31,47] The Oxford group used fluoroscopically aligned radiographic technique to evaluate radiolucency to overcome the alignment issues of standard radiographs.[13,14,19,36] As discussed by Kalra et al., fluoroscopically guided radiographs are not routine practice in the United Kingdom. Instead, AP and lateral radiographs are routinely obtained clinically. The assessment of RLL of the tibial component, by means of accuracy and validity, have been emphasized in numerous studies.[13,17,45] The sensitivity and specificity of the tibial RLL for detecting radiolucency were 63.6% and 94.4%, respectively. The radiographic evaluation of the femoral component is a bit more challenging, with a sensitivity of 63.6% and specificity of 72.7%.[17]

This study has several limitations. Firstly, the large number of excluded patients because of lack of radiographic follow-up or usage of different UKA designs, could potentially lead to a selection bias. Furthermore, based on the aforementioned literature regarding the challenges faced by assessing RLL, the reliability of using plain radiographs might lead to an underestimation of the incidence.[17,45] For that reason, the Oxford group uses fluoroscopically guided radiographs to detect RLL. RLL around the tibial component may be missed because of their characteristic features are concealed by a nonparallel X-ray beam.[48] Computed tomography or magnetic resonance imaging would improve the assessment of periprosthetic lucency and bone-component interface; however, both are more invasive and associated with higher costs.[49,50] Another limitation is that component alignment was not assessed, as this was not the goal of this study. Although several studies have shown that component alignment plays a role in pathological RLL, no correlation has been found between component position and the occurrence of physiological RLL.[51–53] Moreover, the correlation between component alignment and physiological radiolucency should be assessed on computed tomography as this allows a more accurate evaluation of both the component position as periprosthetic lucency.[54,55] Finally, the number of patients with functional outcomes after the occurrence of radiolucency was 39% relative to all patients with RLL. To overcome this limitation a matched cohort group was composed similar to the approach of Gulati

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et al.[14] Taking into account these limitations, a caution approach is needed when interpreting the results of this study.

CONCLUSION

This study acknowledges that femoral and tibial physiological radiolucency may develop after fixed-bearing cemented UKA. Furthermore, this study showed that femoral RLL occur later than tibial RLL. No correlations regarding functional outcomes were found in the presence of femoral or tibial RLL. Prospective studies with longer follow-up and higher compliance on functional outcomes are necessary to assess radiolucency in different UKA designs and correlate this with outcomes.

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MRI Findings at the Bone-Component Interface in Symptomatic Unicompartmental Knee Arthroplasty and the Relationship to Radiographic Findings

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ABSTRACT

BACKGROUND

The most common modes of failure of cemented unicompartmental knee arthroplasty (UKA) designs are aseptic loosening and unexplained pain at short- to mid-term follow-up, which is likely linked to early fixation failure. Determining these modes of failure remains challenging; conventional radiographs are limited in capability of assessment of radiolucent lines (RLL), with only fair sensitivity and specificity for aseptic loosening

QUESTIONS/PURPOSES

We sought to characterize the bone-component interface of patients with symptomatic cemented medial unicompartmental knee arthroplasty (UKA) using magnetic resonance imaging (MRI) and to determine the relationship between MRI and conventional radiographic findings.

METHODS

This retrospective observational study included 55 consecutive patients with symptomatic cemented UKA. All underwent MRI with addition of multiacquisition-variable-resonance image combination (MAVRIC) at an average of 17.8 ± 13.9 months after surgery. MRI studies were reviewed by two independent musculoskeletal radiologists. MRI findings at the bone-cement interface were quantified, including bone marrow edema, fibrous membrane, osteolysis, and loosening. Radiographs were reviewed for existence of radiolucent lines. Inter-rater agreement was determined using Cohen's Kappa statistic (κ).

RESULTS

The vast majority of symptomatic UKA patients demonstrated bone marrow edema pattern (71% and 75%, respectively) and fibrous membrane (69% and 89%, respectively) at the femoral and tibial interface. Excellent and substantial inter-rater agreement was found for the femoral and tibial interface, respectively. Furthermore, MRI findings and radiolucent lines observed on conventional radiographs were poorly correlated.

CONCLUSION

MRI with addition of MAVRIC sequences could be a complementary tool for assessing symptomatic UKA and for quantifying appearances at the bone-component interface. This technique showed good reproducibility of analysis of the bone-component interface following cemented UKA. Future studies are necessary to define the bone-component interface of symptomatic and asymptomatic UKA patients.

INTRODUCTION

The longevity of unicompartmental knee arthroplasty (UKA) is determined by the stability of the component fixation, lower leg alignment, soft-tissue balance and component position.[1,2] Stable implant fixation with adequate cement penetration to underlying bone is essential in preventing failure in cemented UKA[3,4], most commonly through aseptic loosening and unexplained pain at short- to mid-term follow-up (likely linked to early fixation failure).[2,5–7] Detecting the modes of failure in UKA remains challenging; the capacity of conventional radiographs in assessing radiolucent lines (RLL) is limited, with only fair sensitivity and specificity in detecting aseptic loosening.[8] Over the past decade, several studies have shown the diagnostic value of supplemental magnetic resonance imaging (MRI) in the evaluation of symptomatic patients following joint replacement.[9,10] More specifically, MRI has been found useful in evaluating painful total knee arthroplasty (TKA), allowing assessment of the periprosthetic bone and soft tissues, which could influence clinical management.[9,11–13] Conventional fast spin-echo (FSE) techniques have improved visualization of periprosthetic soft tissues, although susceptibility artifacts can impair through-plane encoding of the signal and limit assessment of bone and soft tissues.[9,11] Most recently, multiacquisition variable-resonance image combination (MAVRIC) MRI sequence has been shown to substantially reduce susceptibility artifacts near metallic implants. By mitigating through-plane misregistration, it allows identification of early and subtle changes, such as osteolysis and bone marrow edema, near the bone-prosthesis interface. Hayter et al. reported that MAVRIC visualization of the synovium is significantly improved over FSE images, with high sensitivity and specificity.[14,15] Further, MAVRIC allows differentiation of certain synovial appearances associated with loosening and polyethylene wear and therefore can be valuable in the assessment of symptomatic patients.[15] Although multiple studies have assessed the bone-implant interface and soft-tissue changes around TKA, only a few small studies have evaluated the reliability or agreement of different MRI techniques around UKA.[16,17] UKA is of special interest because only a single knee compartment is replaced by a smaller prosthesis, compared with the multiple stabilizing pegs of TKA that can complicate the assessment of the bone-implant interface.

The aims of this retrospective observational study were to (1) describe and characterize the bone-implant interface in patients presenting with symptomatic medial UKA and (2) determine the inter-rater agreement of individual MRI findings at the bone-component interface. Also, the relationship between the osseous findings on MRI and on radiographic images was assessed.

We hypothesized that MRI with MAVRIC would facilitate excellent visualization of the bone-implant interface due to its tomographic nature and superior contract resolution with high inter-rater agreement for assessment of symptomatic UKA. We also expected that MR findings would correlate poorly with conventional radiographic findings due to the expected diminished sensitivity of radiography.

MATERIALS AND METHODS

After receiving institutional review board approval, an electronic registry search was performed using a prospective database, which included 874 medial UKAs. All surgeries were performed between September 2008 and March 2016 by the senior author (ADP). Patients who had been referred for MRI to evaluate symptomatic medial UKA at minimum of 3 months after surgery were included in this study. From 87 cases identified, 19 cases were excluded due to an all-polyethylene inlay design of tibial baseplate, 11 for lack of MAVRIC sequence for assessment, one for active infection, and one for history of amyloidosis. Data collected for the 55 patients who had received a robotic-arm-assisted cemented metal-backed UKA (Stryker, Mahwah, NJ, USA) included age, sex, BMI, length of time since UKA surgery, indication for MRI, and re-operations.

All subjects underwent MRI using standard clinical protocols designed to minimize metallic susceptibility artifact between March 2012 and July 2016. MRI was performed on a General Electric 1.5T clinical scanner (Waukesha, WI, USA), using a dedicated extremity coil and the institution's routine clinical knee arthroplasty imaging protocol (Table 1), which is optimized for imaging tissues surrounding metallic hardware. This MRI protocol includes sagittal MAVRIC inversion-recovery and sagittal MAVRIC proton-density-weighted images, in addition to high-resolution axial, sagittal and coronal proton-density-weighted FSE images obtained with metal artifact reduction parameter modifications. MAVRIC suppresses metal susceptibility artifact by combining individual three-dimensional image datasets at multiple frequency bands offset from the dominant resonant frequency utilizing a sum of squares algorithm to generate a final composite image, thereby mitigating through-plane encoding distortions. This imaging algorithm provides good spatial resolution through FSE images, as well as superior suppression of susceptibility artifact though MAVRIC pulse sequences.[14,18]

MRI studies were retrospectively reviewed by two fellowship-trained musculoskeletal radiologists (AJB and HCP), with more than 5 and 15 years of experience, respectively,

in MRI evaluation of joint arthroplasty. Imaging studies were reviewed independently by both observers in a blinded fashion, with respect to multiple imaging features pertaining to the implant-bone interface, including the presence and severity of bone marrow edema, fibrous membrane formation and osteolysis. Bone marrow edema pattern manifests as relative signal hyperintensity within the medullary bone adjacent to the implant on fat-suppressed fluid-sensitive (MAVRIC inversion recovery) images. Fibrous membrane formation was defined as a thin isointense-to-hyperintense linear interface with a sclerotic osseous margin along the implant-bone interface. Osteolysis was defined as bulky, lobular, isointense-to-hyperintense foci with well-circumscribed sclerotic margins along the implant interfaces. Bone marrow edema pattern was graded on a scale of 0 to 3 depending on the volume of marrow involved: 0 = no involvement, 1 = less than 1 cm^3, 2 = 1 to 2 cm^3, and 3 = more than 2 cm^3. The extent of fibrous membrane formation was graded on a scale of 0 to 3, depending on the percentage of the implant interface involved, with 0 = no involvement, 1 = less than 33% involved, 2 = 33 to 67% involved, and 3 = more than 67% involved. Osteolysis was quantified as 0 = absent, 1 = focal, and 2 = diffuse. Loosening was defined as either circumferential bone resorption by fibrous membrane formation around the component or extensive osteolysis.

Table 1. Routine clinical imaging protocol for knee arthroplasty at 1.5 T.

Parameter	Sagittal MAVRIC IR	Axial FSE	Sagittal FSE	Coronal FSE	Sagittal MAVRIC FSE
TR (ms)	4000-5000	4000-5000	4000-5000	4000-5000	4000-5000
TE (ms)	6	30	30	30	6
TI (ms)	150	NA	NA	NA	NA
BW (Hz/px)	488	488	488	488	488
NEX	0.5	4	4	4	0.5
FOV (cm)	20	16-18	16-18	16-20	20
Matrix	256 x 192	512 x 320	512 x 320	512 x 320	512 x 256
Slice/gap (mm)	3.6/0	3/0	2.5/0	4/0	3.6/0

BW bandwidth, FOV field-of-view, Hz/px Hertz per pixel, MAVRIC multiacquisition variable-resonance image combination, mm millimeter, ms millisecond, NEX number of excitations, TE echo time, TI inversion time, TR repetition time.

Radiographic evaluation was performed using our institutional Picture Archiving and Communication System (Sectra Imtec AB, Version 16, Linköping, Sweden). Anteroposterior (AP) and lateral radiographs, which corresponded to the MRI follow-up length, were compared to radiographs obtained 2 weeks post-operatively. All radiographs were acquired according to a standardized protocol, consisting of an AP weight-bearing view and lateral view with knee in 30° of flexion.[19–21] A single assessor

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(LJK) assessed the presence of RLL and osteolysis on the AP and lateral radiographs, blinded to the MRI findings. Similar to previous studies, we determined the existence of tibial RLL using AP radiographs.[19–21] Femoral RLL were assessed using lateral radiographs, due to the limited visibility of the flat area along the anterior and posterior femoral condyle and the area surrounding the two pegs.[8,22] Radiolucency was quantified as physiological or pathological RLL. Physiological RLL are well-defined, 1 to 2 mm thick, and accompanied with a radiodense line, in contrast to pathological RLL (more than 2 mm thick, poorly defined, and lacking a radiodense line).[23] Osteolysis was defined as an irregularly shaped radiolucent zone along the bone-implant interface, irregularly demarcated from the surrounding bone. Osteolysis was quantified as focal or diffuse.

Analyses were performed using SPSS version 24 (SPSS Inc, Armonk, NY, USA). The following parameters were collected; gender, age, BMI, date of surgery, date of MRI and radiographic follow-up, and indication for MRI. They were assessed using descriptive statistics, consisting of mean, standard deviation (±), range, and frequency reported as percentages. Inter-rater agreement of MRI findings at the bone-component interface was determined using Cohen's kappa statistic (κ); the characterizing guidelines are; 0.00-0.20, indicating poor agreement; 0.21-0.40, fair; 0.41-0.60, moderate; 0.61-0.80, substantial; and >0.81, excellent.[24] Prior to this study, Li and colleagues showed high diagnostic accuracy of synovial appearances using MAVRIC, and therefore it was not reassessed.[15] Spearman correlation analyses were conducted to test for any relation between MRI and radiographic findings around each component. Statistical significance was set at $p < 0.05$.

RESULTS

A total of 55 patients with symptomatic cemented metal-backed UKA were identified and included in this study. The mean age was 59.7 ± 8.2 years (range, 45.5−81.9), and BMI was 29.7 ± 5.8 kg/m^3 (range, 18.3−46.0, one patient was morbidly obese). Of all patients, 26 (47%) were male and 29 (53%) female. All patients underwent a post-operative MRI including FSE and MAVRIC sequences at an average of 17.8 ± 13.9-month post-surgery (when standard radiographs were unable to identify the underlying etiology). The most frequent indication for post-operative MRI was unexplained pain (n=37, 67.3%). Other indications for MRI were findings of physical examination (Table 2).

Table 2. Indications for obtaining postoperative MRIs

Indication	Number of cases (n=55)	Percentage
Unexplained pain	37	67.3%
Meniscal tear	4	7.3%
Chondral surfaces	3	5.5%
Loosening	2	3.6%
Integrity biceps femoris insertion	2	3.6%
Stress reaction	2	3.6%
Tibial spine fracture	1	1.8%
Integrity extensor mechanism	1	1.8%
Insert displacement	1	1.8%
Loose body	1	1.8%

MRI findings at both the tibial and femoral bone-implant interfaces are described in Table 3. In approximately half of the patients (range, 47% to 62%) mild bone marrow edema pattern and fibrous membrane were observed (Fig. 1a, b and Figure 3b, c). One patient's MRI showed diffuse osteolysis around the femoral component, which was also displaced (Fig. 2). No tibial components appeared loose on MRI.

Table 3. Categorization of the MRI findings using MAVRIC and FSE sequences

Findings	Tibial* (n=55)	Femoral* (n=55)
Bone marrow edema		
No	14 (25%)	16 (29%)
Mild (<1cm^2)	34 (62%)	26 (47%)
Moderate (1-2 cm^2)	5 (9%)	10 (18%)
Severe (>1cm^2)	2 (4%)	3 (5%)
Fibrous membrane		
No	6 (11%)	17 (31%)
Mild (<33%)	31 (56%)	34 (62%)
Moderate (33-67%)	16 (29%)	3 (5%)
Severe (>67%)	2 (4%)	1 (2%)
Osteolysis		
No	50 (91%)	47 (82%)
Focal	4 (7%)	8 (16%)
Diffuse	1 (2%)	1 (2%)
Loosening		
No	55 (100%)	54 (98%)
Loose	0 (0%)	1 (2%)

*The values are given as the number of components with the percentages in parentheses.
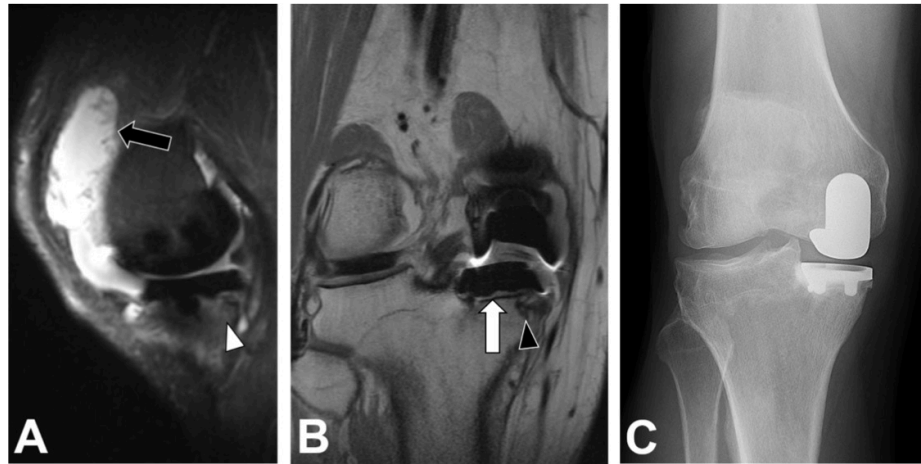
Fig. 1. Sagittal MAVRIC inversion recovery (A) and coronal fast spin echo proton density (B) images in a 55 year-old man with painful medial tibiofemoral unicompartmental knee arthroplasty demonstrates evidence of polymeric wear, with isointense debris containing synovitis (black arrow), tibial osteolysis (black arrowhead) and adjacent fibrous membrane formation (white arrow), as well as adjacent tibial marrow edema (white arrowhead) compatible with superimposed stress reaction. AP radiograph (C) was interpreted as negative.

The use of MRI with MAVRIC sequences showed excellent inter-rater agreement for assessment of the bone-component interface along the femoral component for all findings (κ > 0.830; 95% CI 0.671 − 0.998) (Table 4). The inter-rater agreement of bone marrow edema and fibrous membrane at the tibial interface were substantial (κ = 0.703; 95% CI 0.489−0.917 and κ = 0.740; 95% CI 0.464−1.0), respectively). None of the tibial components appeared loose; therefore, no inter-rater agreement could be determined (Table 4).

Table 4. Inter-rater agreement of the presence of MRI findings at the bone-component interface.

|	Inter-rater agreement (%)	Cohen's Kappa	95% confidence interval
Femoral component			
Bone marrow edema	96.4	0.912	0.792 − 1.0
Fibrous membrane	92.7	0.830	0.671 − 0.998
Osteolysis	98.1	0.936	0.813 − 1.0
Loosening	100	1.0	-
Tibial component			
Bone marrow edema	89.1	0.703	0.489 − 0.917
Fibrous membrane	94.5	0.740	0.464 − 1.0
Osteolysis	100	1.0	-
Loosening	-	-	-

The average time to conventional radiography after surgery was 17.6 ± 15.6 months, resulting in a mean time difference between MRI and radiograph of 2.3 ± 4.3 months. In total, 14 (25.5%) knees showed RLL, all categorized as physiological, except for one case (2%) that showed a displaced femoral component (Fig. 2). Of all knees with physiological RLL, seven (14.5%) showed RLL below the tibial baseplate, six (10.9%) showed only femoral RLL, and one (1.8%) had both tibial and femoral RLL. Forty-one (74.5%) patients did not show any RLL around either component. Radiographic osteolysis was not observed.
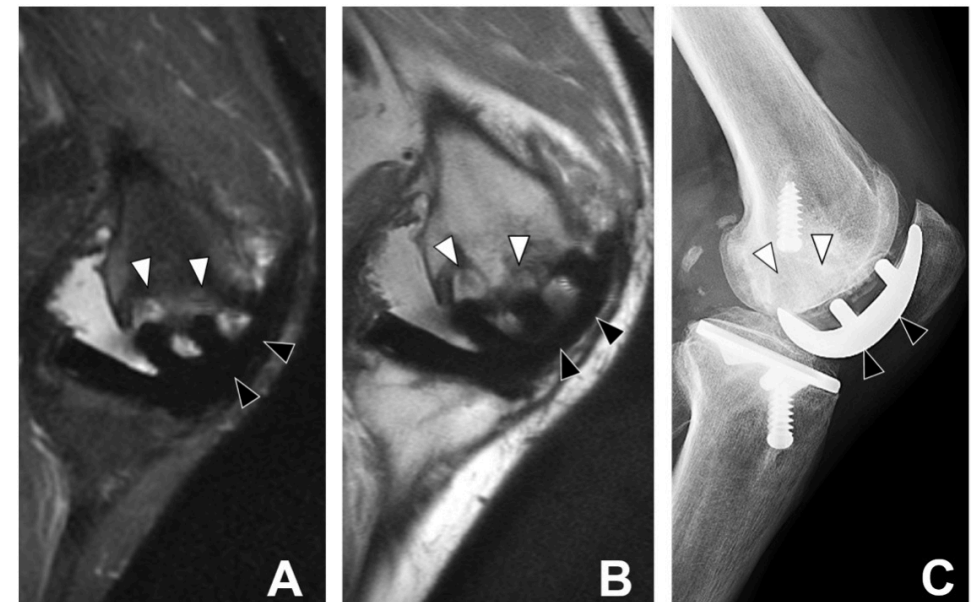
Fig. 2. Sagittal MAVRIC inversion recovery (A) and sagittal MAVRIC proton density (B) weighted images in a 54 year-old man with painful medial tibiofemoral unicompartmental knee arthroplasty demonstrate circumferential osseous resorption (white arrowheads) along the femoral component (black arrowheads), resulting in component loosening with anterior displacement of the component. Lateral radiograph (C), clearly demonstrates displacement of the component (black arrowheads), though the extent of osseous resorption (white arrowheads) is more clearly appreciated on MRI.

Spearman correlation analyses assessing the relation between the MRI appearances and radiographic findings showed a weak correlation between tibial RLL on radiographs and osteolysis and loosening on MRI (correlation coefficient (CC): 0.262, p = 0.040 and 0.329, p = 0.015; respectively). No additional correlations were found (Table 5).

Table 5. Relationship between conventional radiography and MRI findings at the bone-component interface divided by component.

Radiograph	MR finding	Correlation coefficient*	p-value
Femoral component			
Radiolucency (n=6)	Bone marrow edema	0.113	0.417
	Fibrous membrane	0.125	0.368
	Osteolysis	-0.147	0.287
	Loosening	-	-
Tibial component			
Radiolucency (n=8)	Bone marrow edema	0.156	0.259
	Fibrous membrane	0.027	0.845
	Osteolysis	0.280	0.040
	Loosening	0.329	0.015

*Spearman correlation, 2-tailed.

In one patient, the MRI and radiographic assessment revealed a displaced femoral component requiring revision of the femoral component and insert (Fig. 2). Moreover, 12 re-operations were performed, of which nearly all were arthroscopic procedures (Table 6).

Table 6. Specification of the 12 reoperations performed subsequent to MRI.

Patient	Reoperation
F, 51 yrs.	PLM, synovectomy, debridement fat pad*
M, 53 yrs.	PLM, chondroplasty of trochlea, removal loose body*
M, 55 yrs.	PLM, synovectomy, chondroplasty of PF joint*
M, 57 yrs.	Debridement, chondroplasty of trochlea and patella*
F, 58 yrs.	PLM, chondroplasty of PF joint*
M, 58 yrs.	PLM, chondroplasty of trochlea, debridement, femoral subchondroplasty*
F, 61 yrs.	PLM, removal loose body*
F, 62 yrs.	Debridement, PLM, chondroplasty of PF joint*
M, 62 yrs.	Debridement, removal loose body*
M, 66 yrs.	Arthrotomy, internal fixation of insufficiency stress fracture
M, 70 yrs.	Removal loose body, chondroplasty*
F, 73 yrs.	Removal of loose body*

*Arthroscopic procedures.
F female, M male, PF patellofemoral PLM partial lateral meniscectomy.
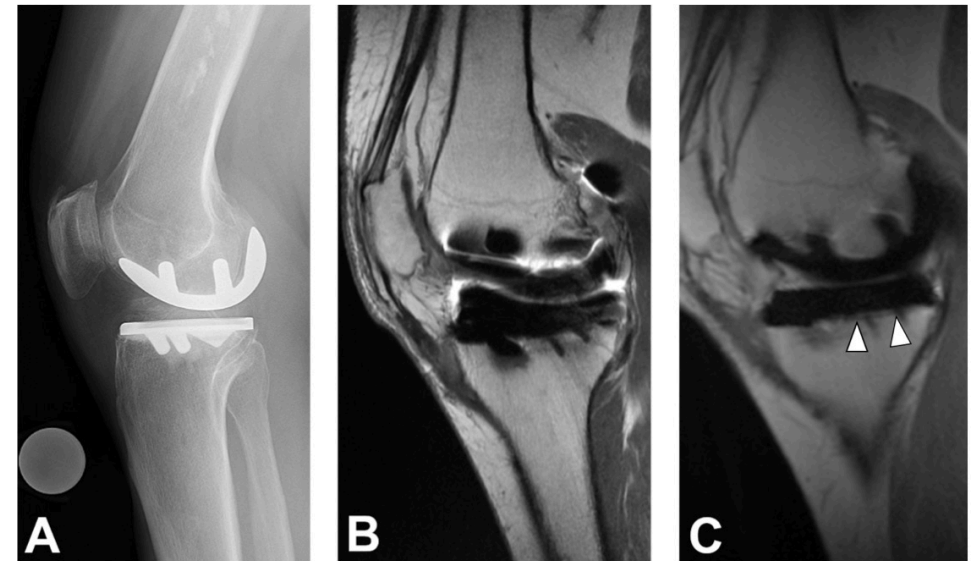
Fig. 3. Lateral radiograph (A) and sagittal proton density (B) images in a 57 year-old woman with painful medial tibiofemoral unicompartmental knee arthroplasty demonstrate no evidence of periprosthetic bone resorption; however, sagittal MAVRIC PD image (C), demonstrates a focal area of fibrous membrane formation along the tibial tray (white arrowheads).

DISCUSSION

MRI with MAVRIC technique showed good reproducibility in analyzing the implant-bone interface after cemented medial UKA. The inter-rater agreement of assessing bone marrow edema, fibrous membrane, osteolysis, and loosening was excellent around the femoral component and substantial at the tibial interface. Furthermore, a poor correlation was found between MRI findings and RLL using conventional radiographs. These data support the application of these imaging techniques to the assessment of implant integration (Figs. 1 and 3).

The current study has several limitations. First, by including consecutive patients undergoing MRI for symptomatic UKA, selection bias was considered low. However, no asymptomatic patients were included, which might still lead to a sampling bias. Furthermore, the MRIs after UKA were obtained for different indications. Although most patients had painful UKA (67%), these findings do not relate directly to a specific subgroup. Despite this limitation, it provided the ability to detect and report the prevalence of specific features of symptomatic UKA. Another limitation was that the

preserved knee compartments and other anatomical structures were not assessed in this study. However, Heyse et al. have showed excellent inter-rater agreement for the cruciate and collateral ligaments, lateral meniscus, and cartilage surfaces of the non-surgical areas following UKA.[25] Finally, this study is limited by lack of functional outcomes, but any subsequent clinical treatment following MRI was reported.

In accordance with our main findings, Malcherczyk and colleagues found excellent inter-rater reliability for the femoral bone-component interface and satisfactory results at the tibial interface of metal-backed UKA implants.[17] Evaluation of all components was performed applying a new scoring system in which the visibility and gap between component and underlying bone was assessed using FSE sequences. The authors showed 40% of the zones around the tibial component could not be evaluated due to metal artifact, resulting in a κ value of 0.722 on the tibial side.[17] Although interfaces are not necessarily artifact-free, MAVRIC results in a significant decrease in susceptibility artifact, usually resulting in improved visualization of implant interfaces relative to conventional sequences. Hayter and colleagues compared periprosthetic bone visualization between MAVRIC and FSE images in 21 TKA patients, and found significantly better visualization of bone on MAVRIC images than on FSE images (p < 0.01).[14] Therefore, they concluded that MAVRIC complements the information obtained from FSE images and may be useful in assessing osteolysis at the bone-component interface.

The κ values for bone marrow edema and fibrous membrane along the tibial interface were 0.703 and 0.740, respectively. Both are considered important in symptomatic UKA, as they could be indicative for aseptic loosening. Several authors have suggested that aseptic loosening is caused by micromotion between the implant or cement surface and the bone, leading to fibrous membrane formation, trabecular microtrauma, and subsequent bone marrow edema.[13,26] Therefore, the proposed cause of post-operative bone marrow edema is increased bone strain, which has been associated with component alignment and fixation technique.[13,27-29] Aseptic loosening can result from poor initial fixation, post-operative mechanical disruption of fixation, or biologic failure of fixation secondary to polyethylene wear and osteolysis.[10,30] Although findings of loosening have been described for multiple imaging modalities, prosthetic loosening has mostly remained a clinical diagnosis. In large part, imaging findings of all modalities are considered secondary, but studies have shown MRI findings supportive of a diagnosis of loosening when suspected.[11,31,32] Therefore, the term *loosening* is recommended for cases where MRI demonstrates circumferential osseous resorption and signs of implant displacement, subsidence, or rotation.[13]

Conventional radiographs can help detect gross prosthetic malposition, radiolucencies, and fractures[12], but they hold little value in the detection of the more common but subtle osseous abnormalities such as early loosening, minor implant malposition, infection, stress fractures or early stage osteoarthritis. Therefore, several authors have emphasized the additive value of MRI to radiographic imaging in determining the etiology of painful total joint arthroplasty.[1,11,12,15,33] Sofka et al. found that prospective and retrospective radiographs were non-contributory in the evaluation of painful TKA but observed varied and often multiple MRI findings in these knees, leading to subsequent clinical treatment in 20 patients.[11] A few studies have noted the very limited value of conventional radiographs in diagnosing painful UKA.[16,32] In this study only a poor correlation was found between radiographic and MRI features, which could indicate that symptomatic UKA may be inadequately assessed on radiographs alone. These findings were consistent with those of Park et al., which showed MRI examination was instrumental in a diagnosis that went undetected on radiographs for all 28 symptomatic UKA patients. They concluded that MRI is an effective imaging technique that provides greater insight into the etiology of the symptomatic patient following UKA.[32]

MRI with the addition of MAVRIC could be a valuable complement to radiographic evaluation in assessing symptomatic medial UKA and quantifying appearances at the bone-implant interface. However, future studies are necessary to define the bone-component interface of symptomatic and asymptomatic UKA patients. Additionally, excellent inter-rater agreement was found for the femoral bone-component interface and substantial agreement for the tibial bone-component interface. This MRI protocol may be helpful in detecting changes around symptomatic cemented UKA, especially in cases of unremarkable radiographic findings.

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6

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

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ABSTRACT

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 midterm 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 was 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.

INTRODUCTION

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 for 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 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, Pearle et al. showed a 98.8% survivorship rate at 2.5-year-follow-up.[28] 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, USA) 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 prior to 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 − 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 or not 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 endpoint, 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 (i.e., ≤59 years, 60−69 years, 70−79 years and ≥80 years) and BMI according to the World Health Organization (i.e., 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/m² ± 4.7 (range, 19 - 42, BMI was missing in 14 patients; Table 1).

Table 1. Demographic characteristics by revision status

|	Revision (13 knees)	No revision (419 knees)	p-value
	Mean ± SD (or %)		
Age	66.1 years ± 11.4	67.4 years ± 8.9	0.619
BMI	31.5 kg/m² ± 5.1	29.6 kg/m² ± 4.6	0.148
Male gender	6 (46%)	243 (58%)	0.395
Bilateral*	1 (8%)	95 (23%)	0.359

BMI, body mass index SD, standard deviation UKA, unicompartmental knee arthroplasty.
* Fourty-eight bilateral UKAs were performed in 96 knees.

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 endpoint, a total of 13 revisions were reported including 2 UKA to UKA revisions, which 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.
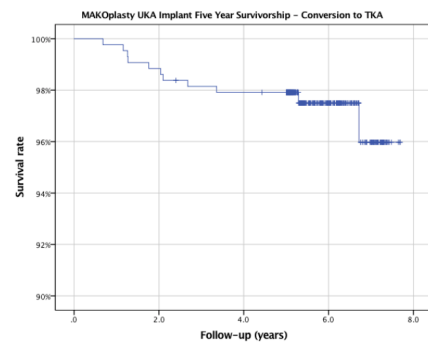
Fig. 1. Kaplan−Meier curve showing the survivorship of 432 robotic-arm-assisted medial UKAs, with revision to TKA as endpoint.
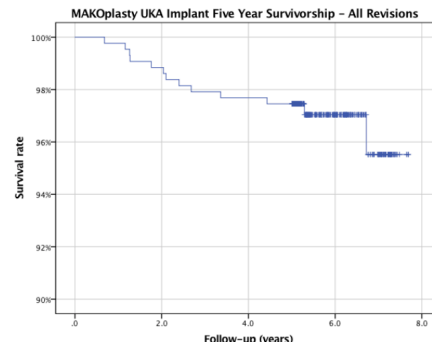
Fig. 2. Kaplan−Meier curve showing the survivorship of 432 robotic-arm-assisted medial UKAs, with revision for any reason as endpoint.

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 or equal to 35kg/m² (Table 3). However, no significant differences in rates were observed between the groups.

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 years	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 years	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/m²)	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.

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 osteoarthritis at 2.00, 1.49, 0.11, 2.26, and 4.81 years, respectively.
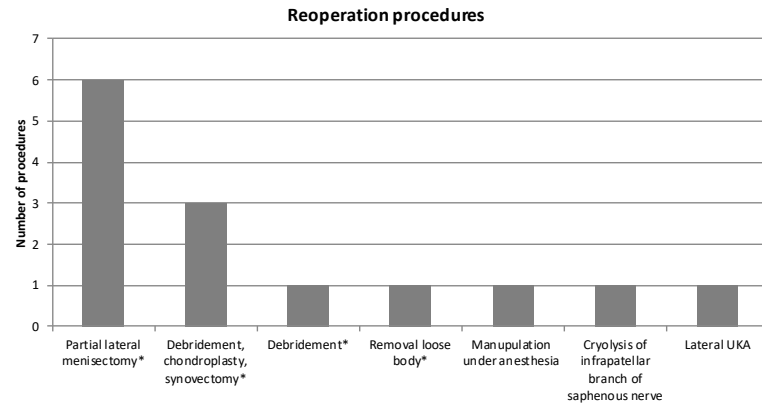
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Fig. 3. Specification of the 14 reoperations performed, excluding revision procedures. *Arthroscopic procedures

Table 4. Summary of revised robotic-arm-assisted medial UKA cases

Patient	Gender	Age (years)	Time to revision (years)	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 & 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 & insert
13	Male	49.6	4.4	Femoral loosening	Femoral component replacement & insert

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

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 endpoint. Of those cohort studies published over the last decade, the vast majority described the outcomes of UKA implanted using conventional techniques.[35,38–41] 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 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.[15,20,25,42,43] 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.[13,18,19,44,45] 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 lower than mobile-bearing designs in large cohort studies (Table 5).[46,47] However, Peersman et al[48] 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[47] 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.[49]

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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.[83]	2015	2006	2010	132	87.7 %
Eickmann et al.[84]	2006	1984	1998	411	93.0 %
Forster-Horváth et al.[85]	2016	2002	2009	236	94.1 %
Hamilton et al.[40]	2014	2001	2004	517	92.0 %
Naudie et al.[86]	2004	1989	2000	113	94.0 %
Vasso et al.[87]	2015	2005	2011	136	97.0 %
Whittaker et al.[88]	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.[39]	2010	1999	2007	437	84.7 %
Liebs et al.[89]	2013	2002	2009	401	93.0 %
Lim et al.[90]	2012	2001	2011	400	96.7 %
Matharu et al.[41]	2012	2000	2008	459	94.4 %
Pandit et al.[38]	2011	1998	2009	1000	97.5 %
Vorlat et al.[79]	2006	1988	1996	149	94.6 %
Yoshida et al.[35]	2013	2002	2011	1279	97.7 %
				Total	**95.6 %**
Cohort Studies				**Overall Total**	**94.2 %**

UKA, unicompartmental knee arthroplasty.

Furthermore, several studies have shown that younger age is associated with higher revision rates.[18,50,51] In our study, 5 of 13 revisions were reported in patients younger than 59 years old, 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.[52,53] 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.[54–56]

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 more bone stock is preserved after UKA surgery.[57–60] 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., these data show a trend of increased likelihood for revision in obese patients.[2] 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.[61–67] More specifically, Murray et al[65] 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., concerning 746 robotic-arm-assisted UKA at mean follow-up of 34.6 months, noted no difference in revision rates between BMI groups.[63] 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 due to 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).[23,27,48] 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.[27,68] Using a synthetic bone model, Scott et al. 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).[69] 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.[70–72] This is of special importance for medial UKA, because the loads are distributed over a smaller surface area when compared to TKA.[69,73] 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.[68,74] 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

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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.[75] 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.[20,24,25,42,63,76,77] 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%.[78–82] 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 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.

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Mid-Term Outcomes of Metal-Backed Unicompartmental Knee Arthroplasty Show Superiority to All-Polyethylene Unicompartmental and Total Knee Arthroplasty

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ABSTRACT

BACKGROUND
Two commonly used tibial designs for unicompartmental knee arthroplasty (UKA) are all-polyethylene "inlay" and metal-backed "onlay" components. Biomechanical studies showed that the metal baseplate in onlay designs better distributes forces over the tibia but studies failed to show differences in functional outcomes between both designs at mid-term follow-up. Furthermore, no studies have compared both designs with total knee arthroplasty (TKA).

QUESTIONS/PURPOSES
The goal of this study was to compare outcomes of inlay UKA and onlay UKA at mid-term follow-up and compare these with TKA outcomes.

METHODS
In this retrospective study, 52 patients undergoing inlay medial UKA, 59 patients undergoing onlay medial UKA, and 59 patients undergoing TKA were included. Western Ontario and McMaster Universities Arthritis Index scores were collected preoperatively and at mean 5.1-year follow-up (range: 4.0 − 7.0 years).

RESULTS
Preoperatively, no differences were observed in patient characteristics or outcome scores. At mid-term follow-up, patients undergoing onlay medial UKA reported significant better functional outcomes than inlay medial UKA (92.0 $\pm$10.4 vs. 82.4 $\pm$18.7, p = 0.010) and when compared to TKA (92.0 $\pm$10.4 vs. 79.6 $\pm$18.5, p <0.001) while no significant differences between inlay medial UKA and TKA were noted. No significant differences in revision rates were found.

CONCLUSION
Functional outcomes following onlay metal-backed medial UKA were significantly better compared to inlay all-polyethylene medial UKA and to TKA. Based on results of this study and on biomechanical and survivorship studies in the literature, we recommended using metal-backed onlay tibial components for unicompartmental knee arthroplasty.

INTRODUCTION

Unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) are two reliable treatment options for medial knee osteoarthritis (OA). UKA is increasingly popular[1] and has distinct advantages over TKA including faster recovery[2–4], better range of motion[5], better function[6–10], and more cost-effectiveness[11–14], while TKA has a higher survivorship.[15–18]

Two commonly used fixed-bearing UKA tibial components are all-polyethylene "inlay" components and metal-backed "onlay" components. Inlay components are cemented into a carved pocket on the tibial surface and therefore rely more on the subchondral bone (Fig. 1A) ,while onlay components are cemented on top of a flat tibial cut with a metal baseplate and therefore rely on cortical bone as well as subchondral bone (Fig. 1B).[19,20] Studies have shown that inlay components have higher peak stress at the tibial surface compared to onlay components[21,22], which could be explained by the fact that onlay components rest on cortical bone and that the metal backing distributes forces over the tibia.[21,22] Perhaps, as a result, higher incidence of tibial subsidence[3, 66] and revisions are seen with inlay designs.[23–25]

It has further been suggested that this increased stress can cause pain and inferior outcomes.[19,26] Although one study reported inferior clinical outcomes with inlay components at short-term follow-up, at mid-term follow-up no clear significant or clinically relevant difference between both components is seen in functional outcomes.[24,27] Because of this discrepancy, the first goal of this study was to compare outcomes of onlay and inlay medial UKA at mid-term follow-up. Robotic-assisted UKA surgery was used which provides tighter control of variables, such as lower leg alignment, gap balancing and component positioning.[20,28–33] Furthermore, although many recent studies have shown superior outcomes of UKA compared to TKA[7,10,34–38], none of the studies have, to our knowledge, compared both inlay and onlay designs to TKA within one study. Therefore, the second goal of this study was to compare onlay and inlay designs with TKA to assess if both components are superior to TKA.

METHODS

In this retrospective study, a search was performed in the digital database of the senior author for patients undergoing medial UKA and TKA between May 2007 and March 2012. Surgical inclusion criteria were unicompartmental medial OA or multicompartmental OA for medial UKA and TKA surgery, respectively.

Patients were excluded from the search if they (I) had ACL deficiency or (II) did not undergo robotic-assisted UKA or computer navigated TKA surgery. A total of 170 patients had minimum 4- and maximum 7-year follow-up, of which 52 underwent inlay medial UKA; 59 onlay medial UKA; and 59 underwent TKA. Of these patients, 116 completed the Western Ontario and McMaster Universities Arthritis Index (WOMAC) questionnaire (36 inlay medial UKA patients, 42 onlay medial UKA patients and 38 TKA patients). Baseline characteristics are displayed in Table 1.

Table 1. Patient demographics of patients undergoing medial UKA and TKA

|	MUKA Inlay (n = 52) Mean (±SD)	MUKA Onlay (n = 59) Mean (±SD)	TKA (n = 59) Mean (±SD)	ANOVA p-value
Age (years)	61.7 (±10.2)	64.6 (±8.7)	64.3 (±7.5)	0.305
BMI (kg/m^2)	31.3 (±5.7)	29.3 (±6.3)	31.5 (±6.4)	0.220
Gender (M:F)	30:22	31:28	21:38	0.048*
OA severity MC (KL)	3.2 (±0.7)	3.1 (±0.8)	3.0 (±0.9)	0.789
OA severity LC (KL)	0.3 (±0.5)	0.6 (±0.7)	1.4 (±1.0)	<0.001**
OA severity PFC (KL)	0.9 (±0.2)	0.6 (±0.7)	1.4 (±1.0)	<0.001**
Preoperative alignment (°)	6.4 (±4.0)	7.1 (±3.7)	4.3 (±8.2)	0.144
Postoperative alignment (°)	2.9 (±3.3)	2.0 (±2.0)	0.9 (±3.2)	0.018***
Alignment correction (°)	4.2 (±1.7)	5.0 (±2.8)	3.1 (±7.8)	0.342

MUKA indicates medial unicompartmental knee arthroplasty; TKA, total knee arthroplasty; ANOVA, one-way analysis of variance; SD, Standard Deviation; BMI, Body Mass Index; M, male; F, female; OA, osteoarthritis; KL, Kellgren-Lawrence grade; MC, medial compartment; LC, lateral compartment; PFC, patellofemoral compartment. Varus alignment is displayed as positive value, valgus alignment is negative value.

* TKA patients included more females when compared to both medial UKA cohorts. No differences were noted between both medial UKA cohorts.

** TKA patients had more severe OA of the lateral and patellofemoral compartment when compared to medial UKA Onlay and Inlay patients (all $p < 0.05$). No differences were seen between both medial UKA procedures ($p > 0.05$).

*** TKA patients had more neutral alignment when compared to medial UKA Inlay patients ($p < 0.05$). No differences were seen between TKA and medial UKA Onlay or between medial UKA Onlay and medial UKA Inlay.

One author (A.D.P.) performed all surgeries. Medial UKA surgery was performed using robotic-assistance (MAKO Surgical Corp., Ft. Lauderdale, FL, USA)[20,39] and patients received a RESTORIS® MCK Medial Inlay or Onlay implant (MAKO Surgical Corp, Ft. Lauderdale, FL, USA). The surgical goal was relative alignment undercorrection in order to prevent OA progression at the contralateral compartment.[40–43] TKA surgery was performed using computer navigation-assistance. Patients received a posterior stabilized Vanguard® Total Knee (Biomet, Warsaw, IN, USA), and the goal was postoperative neutral alignment. Cementation was used in all surgeries and the patella was resurfaced in all TKA surgeries (Fig. 1).
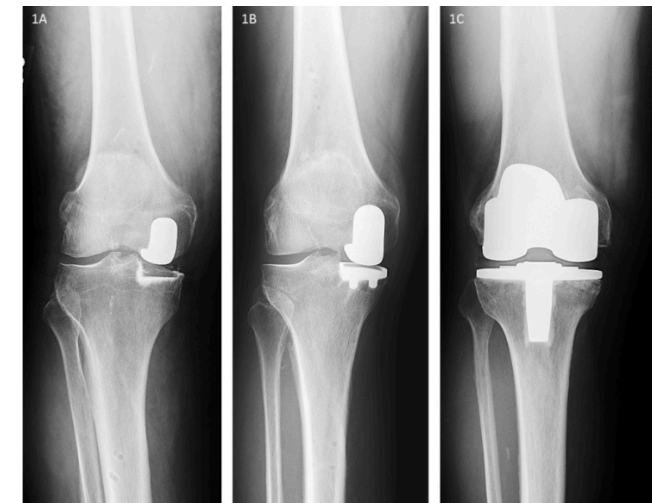
Fig. 1 a An all-polyethylene "inlay" medial unicompartmental knee arthroplasty. **b** A metal-backed "onlay" medial unicompartmental knee arthroplasty. **c** A total knee arthroplasty.

WOMAC scores were prospectively collected. WOMAC index is a questionnaire of 24 Likert-scale-based questions and is validated for knee OA.[44,45] This questionnaire reports overall outcome (all 24 questions) and the three subdomains: pain (five questions), stiffness (two questions), and function (17 questions). The overall score and subdomain scores were indexed with 0 as worst possible score and 100 as the best possible score. The WOMAC questionnaire was completed by 116 patients at mean 5.1-year follow-up (range: 4.0 – 7.0 years) (no significant difference in follow-up between groups), and 72 of these patients (62%) completed the preoperative questionnaire. Other data collected included age, BMI, gender, OA severity of medial, lateral and patellofemoral compartment using the Kellgren-Lawrence score[46], and lower leg alignment using hip-knee-ankle radiographs (Table 1).[47] Institutional Review Board approval was obtained.

Statistical analysis was performed using SPSS Version 21 (SPSS Inc., Armonk, NY, USA). One-way analysis of variance (ANOVA) and Chi-square tests were used to compare baseline characteristics and preoperative WOMAC scores between the three groups with additional post-hoc LSD tests. Independent t-tests were used to compare functional outcomes between inlay and onlay medial UKA, between inlay medial UKA and TKA and between onlay medial UKA and TKA. The Chi-square tests were used to compare revision rates between treatments. All tests were two-sided and difference was considered significant when $p < 0.05$. Sample size calculation showed that 35 patients were needed in every group to show a clinically relevant 10-point difference

in WOMAC score with an alpha of 0.05, power of 80%, enrollment ratio of 1:1 and standard deviation of 15.0.

RESULTS

No differences in patient demographics were found between groups in age and BMI, severity of medial compartment OA, preoperative alignment, or alignment correction. TKA patients were more often females, had more severe OA of the lateral and patellofemoral compartment and had more neutral postoperative alignment compared to patients undergoing medial UKA while no differences between inlay and onlay medial UKA were detected (Table 1). No significant or clinical relevant preoperative differences in overall outcome or subdomain scores were detected (Table 2).

Table 2. Preoperative scores of patients undergoing medial UKA and TKA

	MUKA Inlay (n = 29)	MUKA Onlay (n = 16)	TKA (n = 27)	ANOVA
	Mean (±SD)	Mean (±SD)	Mean (±SD)	p-value
WOMAC Total	61.8 (±16.1)	54.4 (±14.2)	52.0 (±16.4)	0.065
WOMAC Pain	61.2 (±16.3)	55.0 (±16.4)	52.1 (±15.5)	0.103
WOMAC Stiffness	49.8 (±18.4)	48.7 (±19.3)	41.8 (±21.0)	0.289
WOMAC Function	63.3 (±18.1)	54.7 (±14.1)	53.1 (±18.4)	0.074

MUKA indicates medial unicompartmental knee arthroplasty; TKA, total knee arthroplasty; ANOVA, one-way analysis of variance; SD, Standard Deviation; WOMAC, Western Ontario and McMaster Universities Arthritis Index; PCS, Physical Composite Scale score; MCS, Mental Composite Scale score; EQ-5D, EurQuol health status questionnaire

At mean 5.1-year follow-up, patients undergoing onlay medial UKA reported significant better overall functional outcomes (92.0 ± 10.4 vs. 82.4 ± 18.7, p = 0.010) when compared to those of inlay medial UKA. Similarly, patients undergoing onlay medial UKA noted less pain (93.2 ± 10.1 vs. 86.0 ± 16.5, p = 0.048), less stiffness (85.6 ± 17.4 vs. 71.6 ± 25.2, p = 0.005), and better function (92.4 ±10.4 vs. 82.6 ±19.6, p = 0.010) (Table 3, Figs. 2 and 3).

Table 3. Postoperative scores of patients undergoing medial UKA and TKA

	MUKA Inlay (n = 36)	MUKA Onlay (n = 42)	TKA (n = 38)	ANOVA
	Mean (±SD)	Mean (±SD)	Mean (±SD)	p-value
WOMAC Total	82.4 (±18.7)	92.0 (±10.4)	79.6 (±18.5)	0.002 [a,b]
WOMAC Pain	86.0 (±16.5)	93.2 (±10.1)	81.3 (±20.2)	0.005 [a,b]
WOMAC Stiffness	71.6 (±25.2)	85.6 (±17.4)	76.8 (±22.1)	0.018 [a]
WOMAC Function	82.6 (±19.6)	92.4 (±10.4)	79.5 (±18.6)	0.002 [a,b]

MUKA indicates medial unicompartmental knee arthroplasty; TKA, total knee arthroplasty; ANOVA, one-way analysis of variance; SD, Standard Deviation; WOMAC, Western Ontario and McMaster Universities Arthritis Index.
[a] Indicates significant difference (p < 0.05) between MUKA Inlay and MUKA Onlay
[b] Indicates significant difference (p < 0.05) between MUKA Onlay and TKA

Significantly better outcomes in onlay medial UKA were noted when compared to TKA (92.0 ±10.4 vs. 79.6 ±18.5, p <0.001). Patients undergoing onlay medial UKA also reported less pain (93.2 ±10.1 vs. 81.3 ±20.2, p = 0.001) and better function (92.0 ±10.4 vs. 79.6 ±18.5, p = <0.001) compared to those of TKA (Table 3, Figs. 2 and 4). Neither significant nor clinically relevant differences could be detected between inlay medial UKA and TKA for overall outcomes or subdomain scores (Table 3, Figs. 2 and 5).
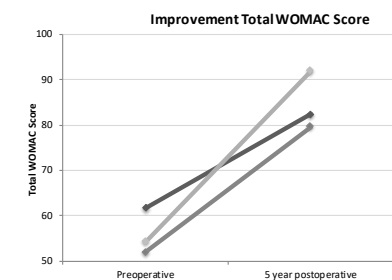
Fig. 2. Improvement of the functional outcome scores of the different groups.
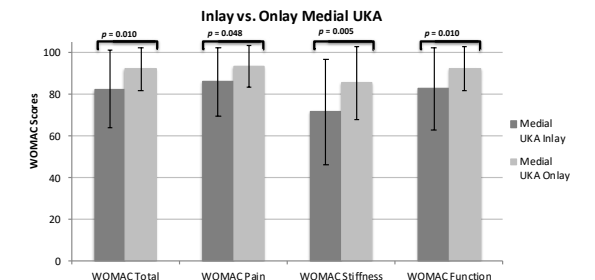
Fig. 3. Differences in total WOMAC score and subscores between the medial UKA inlay and onlay.

In the inlay medial UKA group, four patients were revised (7.7%), of which three were converted to TKA (two for tibial loosening and one for OA progression) and one was converted to onlay medial UKA due to pain. In the onlay medial UKA group, two patients were converted to TKA (3.4%), both for tibial loosening. Three patients in the TKA group had bearing exchange (5.1%), two for instability and one for an infection. Fewer revisions were noted in the medial UKA onlay group when compared to medial inlay group (p = 0.047), but not between other groups (Table 4).
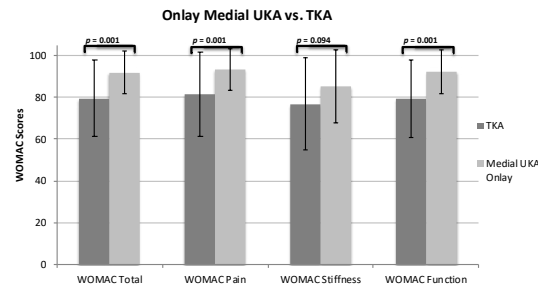
Fig. 4. Differences in total WOMAC score and subscores between the medial UKA onlay and TKA.
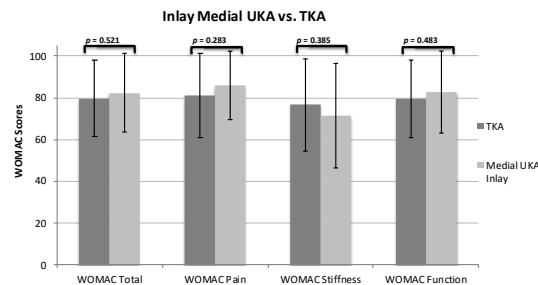
Fig. 5. Differences in total WOMAC score and subscores between the medial UKA inlay and TKA.

Table 4. Revisions and reoperations following medial UKA and TKA procedures

Prosthesis	N	Revisions	Reoperations	All surgeries	Survivorship revisions	Survivorship all surgeries
MUKA Inlay	83	4	3	7	95.2%	91.6%
MUKA Onlay	194	2	3	5	99.0%	97.4%
TKA	143	3	7	10	97.9%	93.0%
Inlay vs. Onlay		0.047	0.280	0.028		
Onlay vs. TKA		0.423	0.073	0.052		
Inlay vs. TKA		0.256	0.652	0.692		

MUKA indicates medial unicompartmental knee arthroplasty; TKA, total knee arthroplasty;

DISCUSSION

The main finding of this study was that patients undergoing metal-backed onlay medial UKA reported significantly better functional outcomes when compared to patients undergoing all-polyethylene inlay medial UKA at mid-term follow-up. Patients undergoing onlay medial UKA reported better functional outcomes compared TKA while no differences were noted between patients undergoing inlay medial UKA and TKA.

Amalgamating the biomechanical and survivorship data, studies suggest that metal-backed onlay tibial components are superior to all-polyethylene inlay components. This study further demonstrates the superior patient-reported outcomes of metal-backed components over all-polyethylene components. Indeed, to our knowledge, this is the first study demonstrating this finding at mid-term follow-up. Furthermore, this is the first study that compared outcomes of both UKA tibial components with those of TKA. Several limitations are also present in this study. First of all, this is a retrospective study and there was no randomization of the UKA procedures. The senior surgeon switched from the inlay to onlay technique when the onlay prosthesis was clinically released in 2010. Secondly, only 64% of patients completed preoperative WOMAC questionnaire and therefore no improvement analysis could be performed. However, preoperatively no significant or clinical relevant differences were seen between all three groups. Moreover, a trend towards better preoperative outcomes was seen in inlay medial UKA compared to onlay medial UKA which would even more dramatically show superiority in functional outcomes of onlay medial UKA (Fig. 2). Finally, robotic-assisted surgery was used for UKA implantation and computer-assisted surgery for TKA implantation and therefore outcomes of this study might not be applicable to manual surgical techniques. However, usage of computer navigation and robot-assistance provided tighter control of other factors that could influence outcomes of knee arthroplasty such as alignment, gap balancing and component positioning[23,29–31,43,48], which can highlight the differences in the performance of the implants.

Recently, it has been shown that survivorship of medial UKA at 5-, 10-, and 15-year follow-up is 94, 92, and 89%, respectively.[18] A recent systematic review has shown that aseptic loosening is the most common failure mode in medial UKA[42], while others have shown that this loosening is more common at the tibial side.[49] Therefore, much attention has been paid to tibial designs. Results in the literature regarding onlay or inlay tibial components are mixed as both treatment options have distinct advantages. All-polyethylene inlay components have a thicker polyethylene insert[50], which has the advantage of a decreased risk for revision for polyethylene wear or insert fractures.[51] Metal-backed onlay components require a tibial cut of less depth which has the advantage of relying on cortical bone while also the polyethylene insert can be replaced in case of polyethylene wear or insert fracture without replacing tibial or femoral components.[52] Furthermore, biomechanical studies have assessed the stress on the tibial bone with both tibial components designs.

Small et al. assessed the maximum shear stress in 12 positions within 3 cm distal to the tibial component and found that the onlay design generates a more favorable

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strain distribution.[21] Walker et al. also found that inlays generated six times more peak stress than onlay designs, which would increase to 13.5 times when softer bone was present at the tibia.[22] Scott et al. found that inlay implants had a significant increase in damage at the microscopic level compared with onlay implants.[53] It has been suggested that this increased peak stress could result in tibial subsidence or aseptic loosening[25,54] and pain[26], which could lead to lower survivorship or inferior functional outcomes, respectively. Although several studies have shown that excellent long-term survivorship can be achieved using both onlay[55,56] and inlay tibial implant design[57], Zambianchi et al. found an inlay 5-year survivorship of 86% and onlay 5-year survivorship of 100%.[25] Five of these failures were caused by unexplained pain, two by aseptic loosening, two by polyethylene wear and one for OA progression and one for joint stiffness. Furthermore, Aleto et al. retrospectively reviewed 32 revised UKAs of which 22 were onlay and 10 were inlay components.[54] They found that medial tibial subsidence was the failure mode in 87% of failed inlay components while this was only 53% in onlay components. Furthermore, other studies have reported suboptimal results of all-polyethylene tibial designs.[24,58–60] These studies may indicate that inlay components have a higher risk of failure due to an increased risk for unexplained pain, tibial subsidence and aseptic loosening. In this study, a small but significant difference in revision rate was noted between medial UKA onlay and inlay groups ($p = 0.047$), but studies with larger cohorts are necessary to draw strong conclusions regarding to the revision rates. Because aforementioned studies have also shown differences in revision rates, we expect that more revisions likely occur following a medial UKA inlay procedure in studies with larger cohorts or meta-analysis.

Fewer studies have assessed functional outcomes of inlay and onlay components. Gladnick et al. compared inlay versus onlay components at 2-year follow-up.[19] Patients in their study underwent, similar to this current study, robotic-assisted UKA surgery, and the authors also reported superior WOMAC scores in patients undergoing metal-backed. Furthermore, they noted a higher revision rate in inlay components compared to onlay components although it was non-significant. Reviewing the biomechanical studies and studies reporting survivorship, one might also expect better functional outcomes with metal-backed components at longer follow-up. In our study, it was indeed noted that metal-backed designs resulted in better outcomes compared to inlay designs at mid-term follow-up.

Furthermore, it was noted that patients undergoing onlay medial UKA reported better outcomes, less pain and better function when compared to those of TKA, while this difference was not seen between inlay medial UKA and TKA. Other studies, however, have failed to show differences at mid-term follow-up. Hutt et al. performed a randomized clinical trial of onlay versus inlay medial UKA implants.[24] The authors reported survivorship at 7-year follow-up of onlay of 94% and inlay of 57%, which was significantly higher. Interestingly, they reported better WOMAC scores in patients undergoing inlay medial UKA at mid-term follow-up, although they did not find any differences in KOOS scores or satisfaction rates. They concluded that reasonable functional results were achieved with both component designs and recommended that inlay medial UKA had unsatisfactory results compared to onlay medial UKA. Heyse et al. performed a subgroup analysis in their mid-term results of fixed-bearing UKA.[27] Interestingly, they found that males (but not females) undergoing inlay medial UKA reported significantly better Knee Society Score (KSS) Function score compared to those of cemented onlay medial UKA. Finally, Hyldahl et al. could not find any short-term differences in Hospital for Special Surgery scores between inlay and onlay designs.[50]

Although many studies have assessed functional outcomes following UKA to TKA[2,6–8,10,34–37,61–67], most of these studies are mobile bearing UKA designs, are mixed onlay and inlay fixed-bearing, or a combination of these. A few studies have compared patient-reported outcomes of fixed-bearing UKA versus TKA.[6–8,10] Two studies compared the all-polyethylene St George Sled UKA with TKA.[6,8] Ackroyd et al. did not find any significant differences in Bristol Knee Scores (BKS)[6], while Newman et al. also could not find any significant difference in BKS between both procedures.[8] Two studies have compared metal-backed onlay UKA with TKA and both found significant better outcomes in UKA patients.[7,10] Manzotti et al. reported better KSS Function scores in UKA patients[7] while Zuiderbaan et al. found that UKA patients had less joint awareness during activities.[10] These studies suggest that onlay components may have better outcomes than TKA while inlay components are not superior to TKA, similar as was found in our study.

In conclusion, the results of this study show that superior functional outcomes were reported at mid-term follow-up in patients undergoing metal-backed medial UKA compared to all-polyethylene medial UKA. Furthermore, metal-backed medial UKA had superior functional outcomes when compared to TKA while outcomes following all-polyethylene medial UKA were equivalent to TKA. Based on the results of this study and other studies in the literature, we recommended the use of metal-backed onlay tibial components for unicompartmental knee arthroplasty.

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Larger Range of Motion and Increased Return to Activity, but Higher Revision Rates Following Unicompartmental versus Total Knee Arthroplasty in Patients under 65: a Systematic Review

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ABSTRACT

PURPOSE
Due to the lack of comparative studies, a systematic review was conducted to determine revision rates of unicompartmental and total knee arthroplasty (UKA and TKA), and compare functional outcomes, range of motion and activity scores in patients less than 65 years of age.

METHODS
A literature search was performed using PubMed, Embase, and Cochrane systems since 2000. 27 UKA and 33 TKA studies were identified and included. Annual revision rate (ARR), functional outcomes, and return to activity were assessed for both types of arthroplasty using independent t-tests.

RESULTS
Four level I studies, 12 level II, 16 level III, and 29 level IV were included, which reported on outcomes in 2224 UKAs and 4737 TKAs. UKA studies reported 183 revisions, yielding an ARR of 1.00 and extrapolated 10-year survivorship of 90.0%. TKA studies reported 324 TKA revisions, resulting in an ARR of 0.53 and extrapolated 10-year survivorship of 94.7%. Functional outcomes scores following UKA and TKA were equivalent, however, following UKA larger ROM (125° vs. 114°, p=0.004) and higher UCLA scores were observed compared to TKA (6.9 vs. 6.0, n.s.).

CONCLUSION
These results show that good-to-excellent outcomes can be achieved following UKA and TKA in patients less than 65 years of age. A higher ARR was noted following UKA compared to TKA. However, improved functional outcomes, ROM and return to activity were found after UKA than TKA in this young population. Comparative studies are needed to confirm these findings and assess factors contributing to failure at the younger patient population. Outcomes of UKA and TKA in patients younger than 65 years are both satisfying, and therefore, both procedures are not contra-indicated at younger age. UKA has several important advantages over TKA in this young and frequently more active population.

INTRODUCTION

Medial unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) are both effective treatment options for medial compartment knee osteoarthritis (OA). However, in younger patients with end-stage OA the most suitable surgical option remains controversial. Surgical concerns include accelerated failure rates due to higher activity levels as well as increased likelihood of need for multiple subsequent revision surgeries.[1-3]

Recent studies have shown good long-term survivorship and functional outcomes following TKA in younger patient cohorts.[1,3,4] Over the last decade, UKA has gained popularity as a viable alternative for TKA in the case of isolated medial OA.[5-8] In the general knee arthroplasty population, increased postoperative range of motion (ROM) and greater bone stock preservation were noted following UKA compared to TKA. These benefits are of special interest for younger patients with higher sports participation rates, and increased risk for multiple revisions due to longer life expectancy.[9-15] Based on registry data, however, survival rates of medial UKA tend to be lower than TKA in young patients.[16-18] To our knowledge, comparative studies assessing overall UKA and TKA survivorship in younger patient cohorts are lacking. Outcomes of prior non-comparative cohort studies are difficult to generalize to the younger patient population, as only a low percentage of patients undergoing knee arthroplasty are generally aged less than 65 years. This is the first study to systematically review the literature on outcomes of UKA and TKA in patients under 65.

To gain more insight in the younger population, a systematic review was conducted to assess survivorship, functional outcomes and activity levels of medial UKA and TKA in patients less than 65 of age. The study aims were to (1) determine revision rates of both arthroplasty types in cohort studies, and (2) compare functional outcomes and activity scores following UKA and TKA in younger patients. The hypothesis was that good-to-excellent outcomes were achieved after both arthroplasty types in patients less than 65 years, and therefore, young age should not be considered a contraindication for either procedure.

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MATERIALS AND METHODS

SEARCH STRATEGY AND CRITERIA

A systematic literature search was performed in PubMed, EMBASE and Cochrane Library databases to identify studies reporting survivorship, functional outcomes and/or activity scores of TKA and UKA. Search terms consisted of "unicompartmental", "unicondylar", "partial, "UKA", "UKR", "PKA", "PKR", or "total" "TKA", combined with "knee arthroplasty", "knee replacement" or its Mesh term. Other keywords were "young", "younger", "middle-aged", "outcomes", "prosthesis failure" and its Mesh terms. Results were filtered for retrieval of only English-language studies published since 2000. After removal of duplicates, two authors (LJK and JPL) independently screened all entries by both title and abstract. Subsequently, all eligible studies were scanned for full texts against the inclusion and exclusion criteria. Survivorship studies were screened for differentiation of age groups or young patients. Additionally, references of scanned articles were checked for any missed studies. The third author (HAZ) was consulted in case of disagreement. Consensus was achieved with regards to inclusion and exclusion of all reviewed articles.

Inclusion criteria consisted of cohort studies that (1) reported survivorship, revision rates or functional outcomes in TKA and/or medial UKA patients aged < 65 years, (2) regarded primary OA as the main indication (> 70% of study cohort), (3) only included patients with intact ACLs for UKA, and (4) had minimum follow-up of two years. Exclusion criteria consisted of studies that (1) not reported cohort size and/or revisions separately for young patients or per age group, (2) assessed revision or complex primary procedures (e.g. bicondylar UKA, TKA in >15° valgus knees), (3) assessed specific subgroups (e.g., ACL-deficient and obese patients), (4) were performed using the same database, or (5) were case reports or systematic reviews.

METHODOLOGICAL QUALITY ASSESSMENT

Level of evidence was determined for all studies using the adjusted Oxford Centre for Evidence-based Medicine.[19] Methodological Index for Non-randomized Studies (MINORS) instrument was used to determine the methodological quality of studies and assess the risk of bias.[20] Mean scores and percentage of the maximum score were reported.

DATA EXTRACTION

PRISMA guidelines were used in order to perform this systematic review. The following data was collected in Excel 2016; study type, authors, year of publication, type of implant, age group and mean age, number of TKA or UKA, number of failures, mean follow-up, functional outcomes, ROM, and activity scores. Outcomes of this study included survivorship, revision rates, annual revision rate (ARR), patient-reported outcomes, ROM, and activity scores following UKA and TKA. ARR was defined as "revision rate per 100 observed component years", which provides an average failure rate per follow-up year. This metric corrects for varying follow-up intervals between populations, allowing direct comparison between studies with different follow-up lengths.[21–24] All outcome scores were reported as a percentage of the maximum score, which enabled comparison of different functional outcome scores. Collected outcome scores included Knee Society Score (KSS), Oxford Knee Score (OKS), Hospital for Special Surgery (HSS) score, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) score, and visual analog scale for pain (VAS). Raw scores were used for ROM, University of California at Los Angeles (UCLA) Activity Score, and Tegner Activity score. Satisfaction was recorded using Likert scales and reported as percentage of patients that scored good/excellent.

STATISTICAL ANALYSIS

Follow-up, age, revision rates of UKA and TKA were calculated using a weighted-mean to correct for different cohort sizes. Total number of revisions and observed component-years were extracted to calculate the ARR for each study. Log-transformed ARRs were pooled separately for UKA and TKA studies using Poisson-normal models with random effects. Pooled log-transformed ARRs were exponentiated to obtain pooled ARRs with 95% confidence intervals (CI). Between-study heterogeneity was tested using the χ^2 test and quantified using the I^2 statistic. These statistical analyses were performed using the Metafor package Version 2.0-0 (Maastricht University, Maastricht, the qNetherlands) implemented in R-software Version 3.3.1 (R Foundation for Statistical Computing, Vienna, Austria). Additionally, functional outcomes and activity scores following UKA and TKA were assessed using independent t-tests.

RESULTS

SEARCH RESULTS

After full-text review of 757 articles, a total of 61 cohort studies[3,4,7,9,25–81] were selected for inclusion. Only two comparative studies assessing functional outcomes after UKA and TKA were identified.[9,45] Twenty-four non-comparative UKA studies[7,27,31,33,34,38–40,43,46,51,56–58,65,67,69,71,73,74,76,78–80] and 35 TKA studies [3,4,25,26,28–30,32,35–37,41,42,44,47–50,52–55,59–64,66,68,70,72,75,77,81] reported revision rates and/or functional outcomes (Fig. 1).

QUALITY OF STUDIES AND RISK OF BIAS

Four level I randomized controlled trials were included[28,60,68,81]. Twelve studies were level II prospective studies[27,36,37,41,47,48,52–54,58,62]. The majority of studies were either level III retrospective observational studies[3,7,9,25,29,31,43,45,49,50,63,64,67,71,75,80] or level IV case-seri es[4,26,30,32–35,38–40,42,44,46,51,55–57,59,61,65,66,69,70,72–74,76,78,79]. Using the MINORS instrument, a mean score of 15.5 (standard deviation, SD 0.5) was observed for the two comparative studies, while 59 non-comparative studies scored 10.1 (SD 1.8), corresponding to 64.6% and 63.1% of the maximum, respectively. None of the included studies were blinded and only 5% reported power calculations. Heterogeneity mainly existed in type of prosthesis and surgical indication.
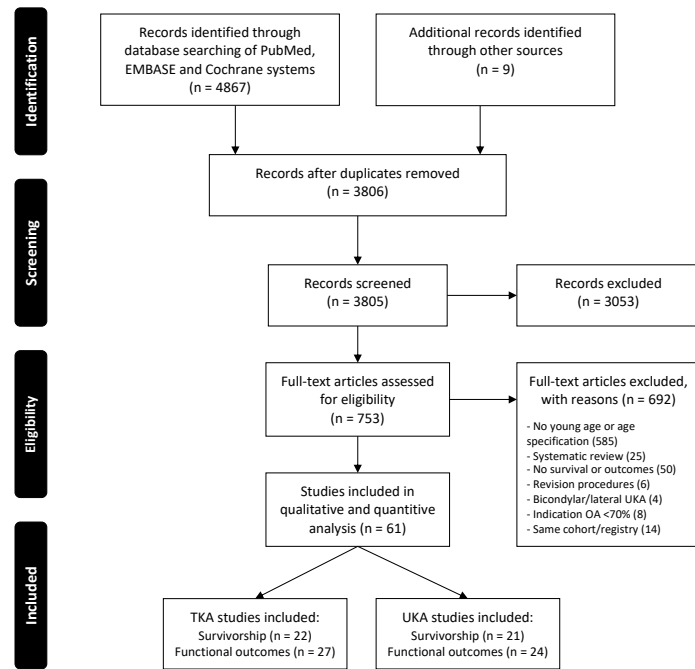
Fig. 1. Forest plot of UKA studies reporting annual revision rates in younger patients. ARR annual revision rate; 95% CI confidence. interval.

REVISION RATES OF UKA AND TKA

Twenty-one cohort studies reported data on 2224 UKAs at a mean age of 54.7 years, stating 182 revisions, yielding a revision rate of 8.18% and ARR of 1.00 (95% CI 0.77– 1.30) (Table 1; Fig. 2). This ARR corresponds to an extrapolated 5-, 10-, and 15-year survivorship of 95.0, 90.0 and 85.0%, respectively. Thirty-three cohort studies reported

data on 4737 TKAs at a mean age of 51.7 years, reporting 324 revisions, which results in a revision rate of 6.95% and ARR of 0.53 (95% CI 0.36−0.78) (Table 1; Fig. 3). This corresponds to an extrapolated 5-, 10-, and 15-year survivorship of 97.4, 94.7 and 92.1%, respectively. The revision rates and follow-up intervals of all individual cohort studies were plotted (Fig. 4).

Table 1. Revision rates of unicompartmental and total knee arthroplasty of all studies and registries.

Type of arthroplasty	No. of studies	Mean age (years)	No. of arthroplasties	No. revisions	Revision rate (%)	Mean follow-up (years)	Observed component years	Annual revision rate
UKA	21	54.7	2224	182	8.18	8.41	18,696.0	1.00
TKA	22	51.7	4737	324	6.95	9.77	46,245.9	0.53

Annual revision rate is the revision rate corrected for follow-up interval (observed years).
No. number, TKA total knee arthroplasty, UKA unicompartmental knee arthroplasty.

Fig. 2. Forest plot of UKA studies reporting annual revision rates in younger patients. ARR annual revision rate; 95% CI confidence interval.
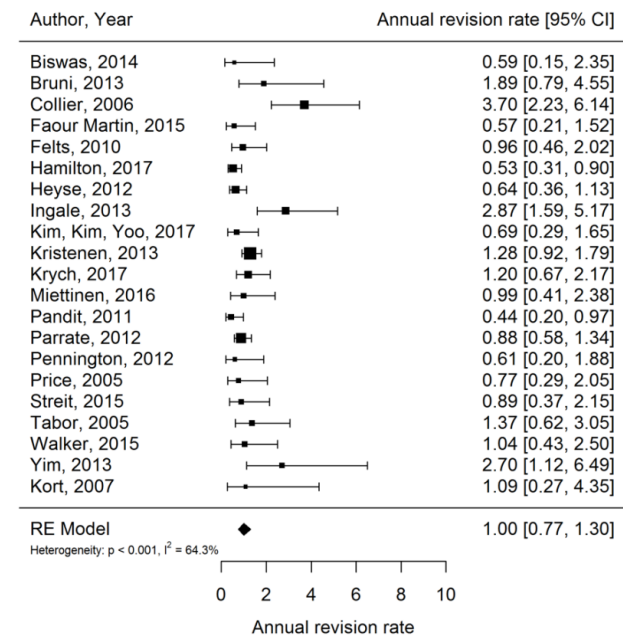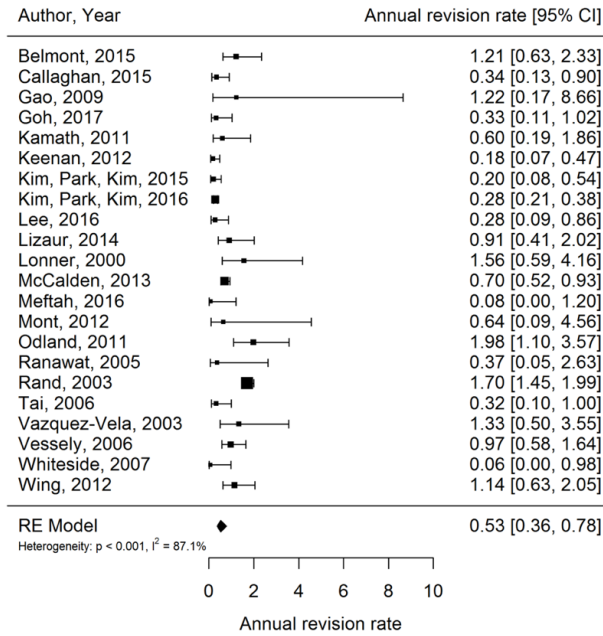
Fig. 3. Forest plot of TKA studies reporting annual revision rates in younger patients. ARR annual revision rate; 95% CI confidence interval.
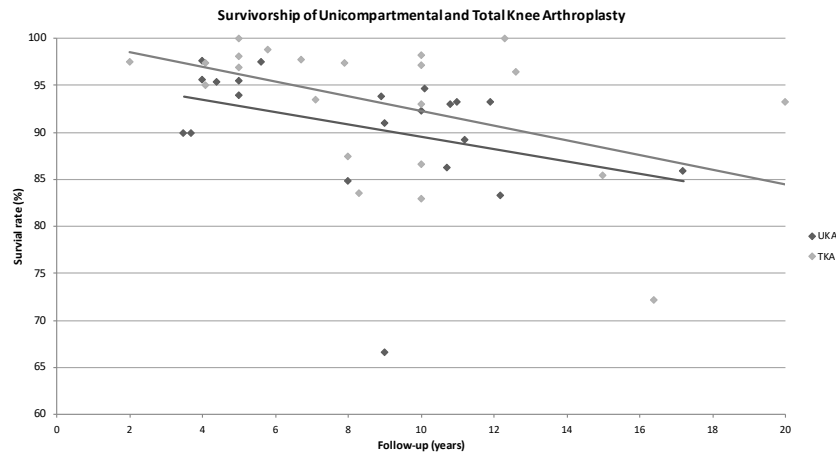
Fig. 4. All included studies reporting survivorship of UKA and TKA in young patients.

FUNCTIONAL OUTCOMES

Functional outcomes were reported by 49 cohort studies, which included scores of 2012 UKAs at mean follow-up of 7.2 years (range 2.0–17.2) and 8664 TKAs at mean follow-up of 6.7 years (2.0–25.1). Overall, no significant differences were observed in any outcome scores between UKA and TKA (Table 2; Fig. 5). At long-term follow-up (9.7 years for UKA and 11.1 years for TKA), only KSS total scores were significantly higher following UKA compared to TKA (88.1 ±4.5 and 85.8 ±5.7, respectively, *p=0.04*) (Fig. 6).

Table 2. Functional outcome scores reported by 49 cohort studies.

	UKA	TKA	p-value	References
	Mean or % of maximum (range)			
OKS	40.8 (40.0 - 41.4)	36.4 (29.0 – 42.9)	n.s.	3,7,37,39,49,50,55,67,74
HSS	94.0	89.3 (85.3 – 93.2)	n.s.	28,33,34,52,61
WOMAC	84.6% (79.6 – 89.2)	76.5% (69.5 – 83.9)	n.s.	51,53,56,60,64,74
KSS total	87.5% (77.6 – 95.5)	87.7% (74.8 – 96.5)	n.s.	3,4,7,25,28,30,31,35,38,40,41,43,51–53,56,59–61,63–67,69–71,74,77–79
Satisfaction	93.8% (83.0 - 100)	90.3% (81.0 – 95.6)	n.s.	3,29,32,33,38,39,45,46,51,53,55,59,78,79
VAS	2.1 (1.6 - 3.0)	2.3 (1.9 – 2.6)	n.s.	39,45,50,74

HSS, Hospital for Special Surgery Score KSS, Knee Society Score OKS, Oxford Knee Score VAS, visual analogue pain scale WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index Score.
Satisfaction was defined as % of patients that scored a good to excellent rate.
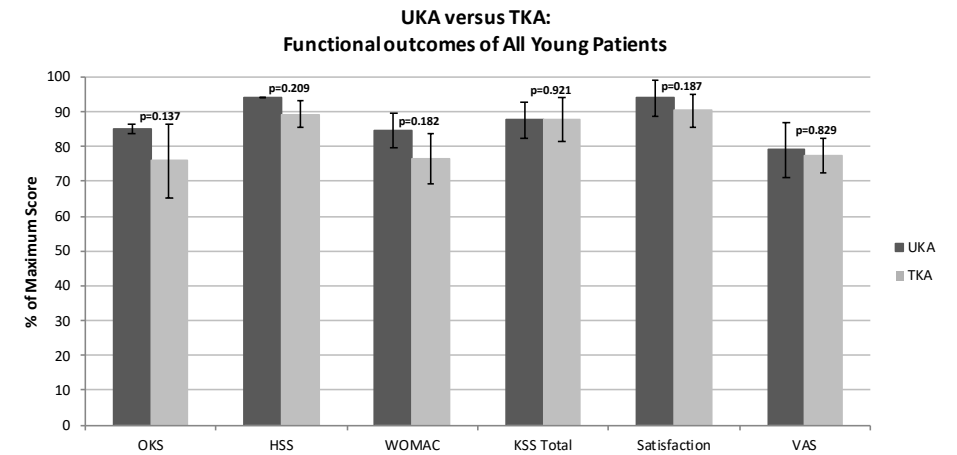
Fig. 5. Functional outcomes of all studies at mean follow-up was 7.4 years for UKA, and 6.7 years for TKA. OKS, Oxford Knee Score; HSS, Hospital for Special Surgery score, WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index score; KSS, Knee Society Score; VAS, Visual Analogue Scale.
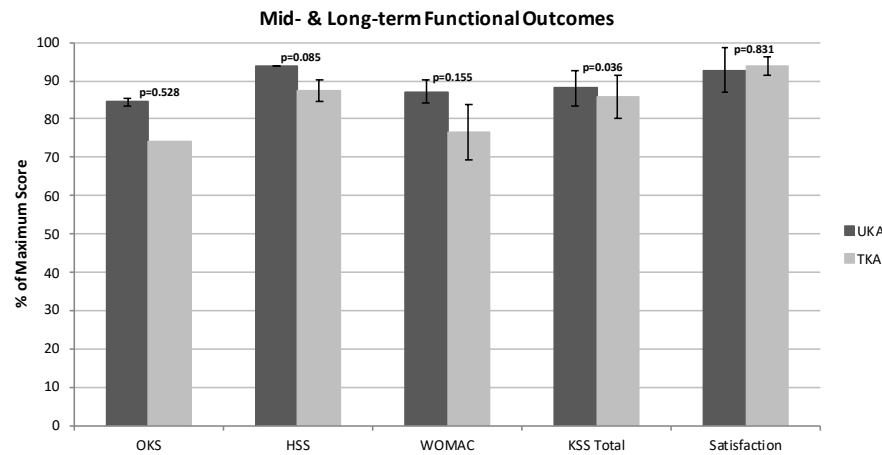
Fig. 6. Mid- to long-term functional outcomes following UKA and TKA (mean follow-up 9.7 and 11.1 years, respectively). OKS, Oxford Knee Score; HSS, Hospital for Special Surgery score, WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index score; KSS, Knee Society Score.

RANGE OF MOTION AND ACTIVITY SCORES

A total of 35 studies reported ROM and/or activity scores, including 1590 UKAs and 2487 TKAs. Eleven UKA studies[27,31,34,39,43,45,51,56,73,74,78–80], 14 TKA studies[4,28,30,35,41,45,52,53,59–61,63,64,70,77] and two comparative studies [9,45] reported larger ROM following UKA compared to TKA (125° and 114°, respectively, p=0.004). A similar trend was observed with regard to UCLA scores, six UKA studies[9,33,39,46,73,79] reported higher overall scores at each follow-up interval than five TKA studies[9,29,30,53,64] (6.9 and 6.0, respectively, n.s.). In eight studies[7,27,30,46,58,59,61,67], similar Tegner scores were observed after both arthroplasty types (Table 3).

Table 3. Activity scores following unicompartmental and total knee arthroplasty, overall and split at five-year follow-up.

Type of arthroplasty	No. of arthroplasties	Mean follow-up (years)	Range of motion	UCLA	Tegner activity scale
Overall					
UKA	1590	7.0 (2.0 – 17.2)	125° (101 – 138)	6.9 (6.4 – 7.5)	3.4 (2.6 – 4.3)
TKA	2487	8.0 (2.0 – 25.1)	114° (100 – 132)	6.0 (4.7 – 7.6)	3.2 (3.0 – 3.4)
p-value			*0.004*	*n.s.*	*n.s.*
Follow-up ≤5 yrs.					
UKA	631	3.7 (2.0 – 5.0)	122° (101 – 130)	7.1 (6.8 – 7.5)	3.6 (2.6 – 4.3)
TKA	843	3.1 (2.0 – 5.0)	113° (110 – 123)	6.2 (6.1 – 6.3)	-
p-value			*n.s.*	*0.030*	*-*
Follow-up >5 yrs.					
UKA	959	9.9 (5.6 – 17.2)	126° (115 – 138)	6.5 (6.4 – 6.5)	3.2 (3.1 – 3.2)
TKA	1644	11.1 (6.2 – 25.1)	114° (100 – 132)	6.0 (4.7 – 7.6)	3.2 (3.0 – 3.4)
p-value			*0.015*	*n.s.*	*n.s.*

No. number; n.s. non-significant; TKA, total knee arthroplasty; UCLA University of California at Los Angeles Activity Score; UKA, unicompartmental knee arthroplasty.

DISCUSSION

The most important finding of this study was that good-to-excellent outcomes can be achieved with UKA and TKA in patients less than 65 years of age. More specifically, the ARR of medial UKA was higher compared to TKA (1.00 and 0.53, respectively). On the contrary, significantly larger ROM and higher activity scores were observed following UKA at mid- to long-term follow-up. Overall functional outcomes scores were equivalent after both procedures in this patient population. This study emphasizes the importance of assessing these outcomes using a systematic approach, as the number of younger patients is often small in individual cohort studies, particularly for UKA.

Furthermore, a corresponding increase in knee OA is expected as surges in obesity and sport-related injuries are anticipated to continue.[82] Therefore, higher demand for knee arthroplasty is predicted in the younger population.[83,84] Finally, this review stresses the need for comparative clinical studies to assess outcomes of UKA and TKA, as they are currently lacking.

In this systematic review, an ARR of 1.00 following UKA and 0.53 following TKA were noted in patients less than 65 years of age, corresponding to an extrapolated 10-year survivorship of 90.0% and 94.7%, respectively. Many studies have found similar survivorship differences between UKA and TKA in the typical arthroplasty population (> 65 years), and therefore may be attributed to the following factors.[85,86] First, UKA

survival is highly sensitive to technical parameters, including lower leg alignment and component position.[87–89] However, the role of alignment in the setting of TKA is currently debated, as several authors showed good results for both kinematically and mechanically aligned knees.[90,91] The window for optimal postoperative alignment in UKA is relatively small (1−4° of varus). Since undercorrection is associated with accelerated polyethylene wear, and overcorrection induces OA progression of the contralateral compartment.[88,89,92,93] Therefore, it can be argued coronal alignment might be even more important in younger active patients, as they impart increased stresses along the knee joint for longer durations.[9,10,46] A second potential explanation for higher UKA revision rates compared to TKA relates to surgical thresholds. Several authors have suggested a lower threshold may exist for revising an UKA to a TKA, due to relative ease of the procedure.[24,94] Moreover, surgical inexperience of low-volume surgeons and the preserved bone stock after UKA surgery might contribute to the lower threshold.[86,94,95] Additionally, UKA are more often revised for unexplained pain compared to TKA (23% and 9% of all revisions, respectively).[96]

Numerous registry studies and systematic reviews have assessed survivorship in the general arthroplasty population (> 65 years).[24,97,98] Compared to the most recent Finish registry study, our extrapolated 10-year UKA survivorship was higher than their survival rate in the general population with a mean age of 63.5 years (90.0% versus 80.6%).[98] A systematic review by Rodriguez reported a survival rate at 10 years of 88% for UKA and 94% for TKA, which findings were similar to our results in a younger population (90.0% and 94.7%, respectively).[99] Another recent systematic review has compared UKA with TKA in the general OA population (mean age 67.4 and 68.6 years, respectively) using ARR. The authors found a lower ARR (0.46) for TKA, but surprisingly, an equivalent ARR for UKA (1.04) was found compared to our results.[24] In summary, TKA survivorship was higher relative to UKA, but UKA survivorship seems not to be negatively affected by age at time of surgery. More recent cohort studies by Pandit and Kristenen et al. showed comparable results between the general and younger arthroplasty population, which matches our findings as well as those of a systematic review by Chawla et al.[7,24,57] However, future studies are needed to confirm these findings.

When reviewing functional outcomes, it was found that OKS, HSS, and WOMAC scores were higher following UKA than TKA, although equivalent KSS scores were observed. At mid- and long-term follow-up, these patient-reported outcome scores continued to favor UKA (Fig. 6). This might be explained by the nature of UKA surgery including increased preservation of bone stock, larger ROM, maintenance of proprioception, and restoration of native knee kinematics.[100,101] These factors likely allow patients to 'forget'

their artificial joint more often.[102,103] This may influence postoperative satisfaction rates, as our data suggests that UKA patients were more satisfied overall (good to excellent satisfaction in 94% of UKA versus 90% of TKA).[45,46,79] Interestingly, only KSS scores were equivalent for both UKA and TKA. The sensitivity of the KSS has been questioned by authors.[104,105] According to Na et al, the KSS fails to differentiate between moderate and high functional levels, which is of special interest in younger patients as they require increased motion and strength.[105]

Additionally, this systematic review showed increased ROM and UCLA scores following UKA, indicating young patients return to high level activities compared moderate levels after TKA.[106] Several studies have similarly showed higher and often quicker return to activity following UKA.[10,11,107] Naal et al. showed a 95% return to activity rate and the majority the patients (90.3%) maintained or improved their ability to participate in sports.[11] The review by Witjes et al. found that TKA patients were also able to return to low and high-impact sports, although to a lesser extent (36−89%).[10] Finally, the comparative study by Ho et al. demonstrated a difference in timing, UKA patients were able to return to sports more quickly following surgery.[9]

This study has several limitations. First, indications for UKA and TKA differ, as both types of arthroplasty can be performed in the setting of medial OA, whereas only TKA is indicated for tricompartmental OA. Although primary diagnosis was OA in at least 70% of patients, this study was limited as most UKA studies report on solely OA patients. Furthermore, based on OA severity, preoperative outcome scores may have been different between UKA and TKA, but few studies specified which knee compartments were involved. This review has focused on cohort studies; therefore, it is likely limited to outcomes in high or moderately high-volume studies and may not reflect results from low-volume centers. Registry studies that include low-volume centers demonstrate higher revision rates (6.0−21.1%).[1,108–111] However, this difference has already been shown by many other studies.[24,95,112,113]

Nonetheless, this systematic review stresses the need for comparative studies assessing survivorship and functional outcomes in younger patients for optimal statistical comparison between UKA and TKA.[83] Most studies have used different age cutoff values to define younger patients, and therefore, mean age was calculated and found slightly higher in the UKA group (54.7 years) versus TKA (51.7 years). However, this difference was not considered clinically relevant by the authors. Finally, a possible selection bias exists as non-English articles were excluded.

This study provides an overview of the outcomes of UKA and TKA in a younger patient population, showing good-to-excellent outcomes following both procedures. Improvements in surgical design and techniques have resulted in a decreasing threshold for offering patients UKA and TKA, which in turn, has resulted in younger, more active patients accessing these surgeries. Due to the high number of patients included, this study can be used to guide surgeons, inform patients and manage their expectations with regard to risk of revision, functional outcomes and return to activity. Furthermore, this study shows that comparative studies of UKA versus TKA in younger patients are lacking in current literature.

CONCLUSION

This systematic review showed good-to-excellent outcomes are achievable with medial UKA and TKA in the young and often more active patient population. Cohort studies reported ARR of 1.00 for UKA and 0.53 for TKA in patients less than 65 years of age, corresponding to an extrapolated 10-year survivorship of 90.0 and 94.7%, respectively. Increased ROM and higher activity scores were observed following UKA compared to TKA; however, equivalent functional outcomes were reported. Despite a moderate level of evidence, this review suggests that young age may not be a contraindication for either TKA or UKA.

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Satisfaction with Return to Sports after Unicompartmental Knee Arthroplasty and What Type of Sports Are Patients Doing

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ABSTRACT

PURPOSE

The present study provides insight into patient satisfaction with return to sports after unicompartmental knee arthroplasty (UKA) and to what type of activities patients return. This is important because indications for UKA have expanded and younger and more active patients undergo surgery currently.

METHODS

Patients who received an UKA were contacted between 12 and 24 months' post-surgery, receiving a questionnaire to evaluate postoperative satisfaction with return to sports, level of return, type of activities performed pre- and postoperatively, and (activity) outcome scores (NRS, UCLA, HAAS). Descriptive statistical analysis focused on the influence of patients' sex and age and a regression model was fitted to assess the predictors for high satisfaction postoperatively.

RESULTS

One hundred and sixty-four patients (179 UKAs) with a mean age of 62.3 years responded at an average follow-up of 20.2 months. Preoperatively, 132 patients (81%) participated in sports, which increased to 147 patients (90%) after UKA. Analyzing outcomes for each knee individually, satisfaction with return to sports was recorded in 83% (149/179). Return to a higher or similar level was reported in 85.4% of the cases (117/137). Most common sports after UKA were cycling (45%), swimming (38%), and stationary cycling (27%). Overall, 93.9% of patients were able to return to low impact sports, 63.9% to intermediate and 32.7% to high impact sports. Regarding activity scores; preoperative NRS score improved from 6.40 ± 2.10 to 1.33 ± 1.73 postoperatively (p<.001). The mean preoperative UCLA score improved from 5.93 ± 2.19 to 6.78 ± 1.92 (p<.001) and HAAS score from 9.13 ± 3.55 to 11.08 ± 2.83 postoperatively (p<.001). Regression analyses showed that male sex, preoperative UCLA score and sports participation predicted high activity scores postoperatively.

CONCLUSION

The vast majority of patients undergoing medial UKA returned to sports postoperatively, of which over 80% was satisfied with their restoration of sports ability. Male patients, patients aged ≥70, and patients who participated in low-impact sports preoperatively achieved the highest satisfaction rates. Regarding type of sports, male patients and patients aged ≤55 were most likely to return to high and intermediate impact sports. This study may offer valuable information to help manage patients' expectations

regarding their ability to return to sports based on demographics and type of preoperative sporting activities.

INTRODUCTION

Patients' expectations determine their assessment of the success of joint replacement surgery, and therefore strongly influence the postoperative outcome and patient satisfaction.[1,2] Several studies have emphasized the importance of meeting patients' expectations, which have been associated with greater perceived improvement after surgery, irrespective of the preoperative level of disability caused by knee osteoarthritis.[3–6] There are a number of studies on total knee arthroplasty (TKA) reporting on postoperative activity levels and sport involvement; these studies have demonstrated variable return to sport rates (36% - 86%) with most patients returning to low-impact sports.[7–11] Furthermore, TKA patients tend to show a high degree of satisfaction with their ability to participate in sports postoperatively.[12–16] Although there is growing data on return to activity after unicompartmental knee arthroplasty (UKA), the evidence is insufficient to meaningfully inform patients and manage their expectations on their potential sport participation level after UKA.

Over the last two decades, UKA has become established as an effective treatment option for isolated compartment osteoarthritis (OA).[17–19] Due to numerous technical innovations in implant design and surgical techniques, indications for UKA have expanded, which has resulted in a younger and more active population with different preoperative expectations undergoing this procedure.[20–23] One outcome of particular importance to these patients is the expectation to return to sports after surgery. To date, several studies have reported moderate to high rates of return to sports following UKA, ranging from 53% to 91%.[9,24–28] However, the focus of prior studies has been limited to rate of return to a few sports, additionally these studies reported on small patient cohorts (26 to 131 patients), of which many were included over a decade ago when patient demands and recommendations on return to activity may have been different. The state of UKA return to sport evidence thus makes it difficult to provide modern day patients with accurate and updated recommendations to best calibrate their expectations.[8,29] Moreover, there is, to our knowledge, a lack of information with regard to satisfaction with return to sports and the maximum level of sport attained after UKA.

The goals of the present study were to 1) determine postoperative satisfaction with return to sports, 2) identify the level of sporting activity after UKA and overall activity outcome scores, and 3) report common sporting activities after surgery. Special attention was paid to the influence of patients' sex and age. We hypothesized that the vast majority of patients were satisfied and able to return to a higher or similar level compared to their preoperative level. Furthermore, it could be expected that men return to sports faster and to higher impact sports compared to women, which may potentially influence satisfaction rates.

METHODS

STUDY DESIGN AND PATIENT SELECTION

After Institutional Review Board Approval, a prospective database was queried for consecutive patients who underwent UKA surgery by one of the two authors (ADP and SMS). The primary diagnosis was isolated, either medial or lateral compartment osteoarthritis, for which all patients received a cemented fixed-bearing RESTORIS MCK Onlay tibial implant (Stryker Corp., Mahwah, NJ) using a robotic-arm-assisted surgical platform (MAKO System, Stryker Corp., Mahwah, NJ).[30] Surgical inclusion criteria for medial or lateral UKA were symptomatic unicompartmental OA, a passively correctable coronal plane deformity and a fixed flexion deformity of <15°. Surgical exclusion criteria were signs of radiographic inflammatory arthritis, the presence of Kellgren Lawrence (KL) grades 3-4 in the contralateral tibiofemoral compartment or patellofemoral (PF) joint-related symptoms (anterior knee pain with prolonged sitting with the knee flexed or pain specific to stair-climbing rather than descending stairs). Degenerative changes in the PF joint were not considered to be a contra-indication, unless there was severe bone loss or grooving of the medial or lateral facet. All patients underwent the standardized rehabilitation program, and were allowed to resume their preoperative sporting activities in consultation with their surgeon and physical therapist. Patients were not encouraged to return to high impact sports as their main cardio activity, although all activities were allowed after surgery.

Patients were eligible for inclusion if they were between 12- and 24-months post-surgery at the start of the study. Informed consent was obtained via email or postal mail. Patients received a questionnaire by email or postal mail when email address was missing. Patients were considered lost-to-follow-up after three email and/or mail shipments.

DATA COLLECTION

Clinical charts were reviewed for demographic data, preoperative diagnosis, and medical comorbidities. The authors derived a return to sport questionnaire (APPENDIX I) that was based on the work of several other prior return to sport studies for arthroplasty patients.[26,27,31–33] The questionnaire assessed the pre- and postoperative sporting activities (43 sports, walking was not considered a sport), focusing on what type of sports patients engage in and the time to return to each sport. Sports were categorized, according to the level of impact on the knee, into low, intermediate and high impact sports based on the studies by Vail[34] and Kuster[33]. Postoperative satisfaction with return to sports was recorded using a five-level Likert scale and the subjective level of return was graded as lower, similar or higher level compared to preoperative level. In addition, pre- and postoperative University of California at Los Angeles (UCLA) activity score[27,32,35], High Activity Arthroplasty Score (HAAS)[36], and Numeric Pain Rating Scale (NRS) score were collected. The UCLA activity scale has ten descriptive levels, ranging from wholly inactive, dependent on others (level 1), to regular participation in active events, such as bicycling (level 7), and regular participation in impact sports, such as jogging or tennis (level 10). The HAAS score (scored 0 to 18, worst to best) was designed to detect subtle variations in physical function of highly functioning patients.[36] In the setting of bilateral UKA, patients were asked to answer the questions separately for each knee.

STATISTICAL ANALYSIS

All statistical analyses were performed using SPSS version 24 (SPSS Inc, Armonk, NY). Descriptive analyses were performed to calculate means, standard deviations ($\pm$), frequencies, and percentages (%). Patients were divided by sex and in age groups; younger (≤55 years), middle (55-70 years), and older age (≥70 years). Mann-Whitney U and Kruskal-Wallis tests were used to compare ordinal data or when normal distribution was not followed. Furthermore, paired two-tailed t-tests were utilized to determine improvements in functional activity scores. Two ordinal regression models were fitted to assess predictors for satisfaction and high activity level postoperatively, with satisfaction and UCLA score as dependent variables.[32] These models calculate a single odds ratio (OR) and 95% confidence interval (CI) for each covariate, independent of the rank of the response category.[37] The assumptions of proportionality across threshold were tested. Summary proportional ORs and CIs were then calculated for selected independent variables, which included demographic, preoperative participation and preoperative outcome scores. Therefore, only patients who participated in sports preoperatively were included in this sub analysis. The covariates tested in all analyses included patient characteristics, such as age, sex, body mass index (BMI) and preoperative sports

participation, the type of impact of preoperative sports, preoperative UCLA score, and preoperative HAAS score. In the proportional odds model for each covariate outputs included an estimate of the regression coefficient, standard error, Wald chi-square statistic, p-value, and the corresponding OR and CI. All tests were conducted using two-sided hypothesis testing with statistical significance set at $p \leq .05$.

RESULTS

DEMOGRAPHICS

In total, 251 consecutive patients (273 knees) who had undergone robotic-arm-assisted UKA between September 2015 and October 2016 were identified. Eighty-two patients (89 knees) were lost-to-follow-up, four patients (four knees) declined participation, and one patient (one knee) was excluded for severe Parkinson's disease. Consequently, 164 patients (179 knees) remained available for inclusion (139 medial UKA, 40 lateral UKA), all 15 bilateral procedures were staged. The average age at time of surgery was 62.3 ± 8.8 years (range, 33.2 - 87.3) and mean BMI was 27.6 ± 4.4 kg/m² (range, 18.3 - 43.4). Ninety men were included with a mean age was 62.7 ± 8.7 years and average BMI was 27.8 kg/m². Seventy-four women were included with a mean age of 61.9 ± 9.0 years and BMI of 27.3 ± 5.1 kg/m². Of all included patients, 132 patients (80.5%) participated in sports within five years prior to their knee replacement. Average follow-up was 20.2 months (range 12.0 - 31.0). No revision surgeries were reported during the follow-up time period, although two arthroscopic procedures (one chondroplasty of the trochlea, resection of scarring tissue and one debridement of scar tissue both at eight months postoperatively) were registered. The average age of the excluded patients was 59.7 years (range 41.4 – 91.1), which was significantly younger than the included patients (p=.039).

RETURN TO SPORTS AND SATISFACTION

Of the 164 patients who responded to the return to sport questionnaire, 147 (89.6%) patients (161 UKAs) participated in sports after UKA and returned after 4.43 ± 3.54 months (range, 0.3 - 24.0) on average. From the initial 132 patients participating in sports preoperatively, seven patients did not return to any sports. Postoperative satisfaction of the entire cohort were scored for each individual knee, patients were either very satisfied or satisfied with their ability to participate in sports after surgery in 83.2% (n=149). Furthermore, 8.9% (n=16) was neither satisfied nor dissatisfied and 7.8% (n=14) was dissatisfied (n=14) (Table 1). Males were very satisfied or satisfied in 87.6% of the cases and females in 82.1%, which was not statistical significant (p=.068). Between

age groups, 77.8% of the younger patients ($\leq$55 years) reported being very satisfied or satisfied compared to 82.1% in patients aged 55 to 70 years and 93.1% in older patients ($\geq$70 years) (Table 2). Ranked comparison showed no significant difference between age groups (p=.123). Of the patients who preoperatively participated in sports were questioned to what level they returned to compared to their preoperative level, 42.3% of the patients reported return to a higher level and 43.1% to a similar level compared to their preoperative level. No statistically significant age- or gender-related differences were noted (Table 2). However, patients who were satisfied reported to returned to an either higher or similar level more frequently than dissatisfied patients (88% vs. 70%, p=.036).

Table 1. Overall Postoperative Satisfaction Rates After Unicompartmental Knee Arthroplasty, and by Sex and Age Groups[a].

	Overall (n=179[b])	Men (n=101[b])	Women (n=78[b])	Age ≤ 55 (n=27[b])	Age 55-70 (n=123[b])	Age ≥ 70 (n=29[b])
Very Satisfied	98 (54.7%)	63 (64.9%)	35 (44.9%)	17 (63.0%)	61 (49.6%)	20 (69.0%)
Satisfied	51 (28.5%)	22 (22.7%)	29 (37.2%)	4 (14.8%)	40 (32.5%)	7 (24.1%)
Neutral	16 (8.9%)	6 (6.2%)	10 (12.8%)	2 (7.4%)	12 (9.8%)	2 (6.9%)
Dissatisfied	10 (5.6%)	6 (6.2%)	4 (5.1%)	3 (11.1%)	7 (5.7%)	0 (0.0%)
Very Dissatisfied	4 (2.2%)	4 (4.1%)	0 (0.0%)	1 (3.7%)	3 (2.4%)	0 (0.0%)
		$p=0.068^c$			$p=0.123^d$	

[a]Percentages are of the total in the given category. [b]Number of knees within that category. [c]Mann-Whitney U test. [d]Kruskal-Wallis test.

Table 2. Level of Return to Sports After Unicompartmental Knee Arthroplasty.

	Higher Level	Similar Level	Lower Level
Overall (n=125, 137 UKAs[a])	58 (42.3%)	59 (43.1%)	20 (14.6%)
Sex			
Male (n=86[b])	37 (43.0%)	38 (44.2%)	11 (12.8%)
Female (n=51[b])	21 (41.2%)	21 (41.2%)	9 (17.6%)
p-value[c]	0.837	0.737	0.447
Age			
Younger (≤55 y) (n=20[b])	10 (50.0%)	6 (30.0%)	4 (20.0%)
Middle (55-70 y) (n=95[b])	39 (41.1%)	41 (43.2%)	15 (15.8%)
Older (≥70y) (n=22[b])	9 (40.9%)	12 (54.5%)	1 (4.5%)
p-value[c]	0.763	0.276	0.307

[a]Preoperatively, 132 patients of which 125 (137 UKAs) returned to sports postoperatively and were, therefore, eligible to answer this question for each procedure individually.
[b]Number of knees within that category. [c]Chi-square or Fisher exact tests were used to assess differences between groups per level.

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Table 3. Sporting Activities After Unicondylar Knee Arthroplasty (N=147).

Subgroup/Sport[a]	Postoperative participation N	%	Mean time to return (months)
Men (n=85[b])			
Cycling	53	62.4	3.3 (1.0 – 12.0)
Golf	35	41.2	2.9 (1.0 – 8.0)
Swimming	35	41.2	4.0 (1.0 – 12.0)
Weight lifting	28	32.9	3.4 (1.0 – 12.0)
Stationary cycling	27	31.8	2.1 (0.3 – 4.0)
Hiking	24	28.2	4.3 (1.0 – 14.0)
Downhill skiing	19	22.4	6.5 (1.0 – 12.0)
Low impact aerobics	16	18.8	3.2 (0.8 – 6.0)
Doubles tennis	12	14.1	9.2 (2.0 – 24.0)
Bowling	9	10.6	3.2 (3.0 – 4.0)
Women (n=62[b])			
Swimming	28	45.2	5.0 (2.0 – 10.0)
Cycling	21	33.9	3.7 (1.0 – 14.0)
Yoga	20	32.3	6.8 (1.0 – 16.0)
Stationary cycling	18	29.0	1.7 (0.3 – 3.0)
Hiking	15	24.2	4.9 (1.0 – 12.0)
Dancing	13	21.0	4.5 (2.0 – 7.0)
Weight lifting	11	17.7	4.6 (1.0 – 22.0)
Pilates	11	17.7	4.4 (2.0 – 12.0)
Low impact aerobics	9	14.5	6.0 (1.0 – 12.0)
Spinning	9	14.5	3.2 (1.5 – 7.0)
Younger (≤55 y) (n=23[b])			
Cycling	10	43.5	2.5 (1.0 – 5.0)
Swimming	6	26.1	3.3 (1.0 – 6.0)
Stationary cycling	6	26.1	1.8 (1.0 – 2.0)
Yoga	6	26.1	8.4 (3.0 – 12.0)
Golf	5	21.7	6.2 (3.0 – 9.0)
Middle (55-70 y) (n=101[b])			
Cycling	60	59.4	3.6 (1.0 – 14.0)
Swimming	47	46.5	3.7 (1.0 – 10.0)
Stationary cycling	33	32.7	2.0 (0.3 – 4.0)
Weight lifting	31	30.7	3.6 (1.0 – 12.0)
Hiking	30	29.7	4.7 (1.0 – 14.0)
Older (≥70 y) (n=23[b])			
Swimming	10	43.5	4.3 (1.5 – 9.0)
Golf	8	34.8	3.2 (2.0 – 6.0)
Low impact aerobics	6	26.1	1.8 (1.5 – 6.0)
Stationary cycling	6	26.1	1.9 (1.0 – 4.0)
Dancing	4	17.4	3.1 (1.5 – 4.0)

[a]Top 10 sports by sex and top 5 sports by age group. [b]Number of patients.

TYPE OF SPORTS

An increase in sports participation was noted after surgery, from 132 patients (80.5%) participating in sports preoperatively to 147 patients (89.6%) participating in at least one type of sports postoperatively (mean number of sports was 3.6 ± 3.0). The most

common sports by sex and age were displayed in Table 3. After UKA, 32.7% (n=47) of the patients participated in high impact sports, returning to singles tennis, running, and baseball most frequently (Table 4, APPENDIX II). Preoperatively, men participated in high impact sports more frequently than women (48.1% versus 30.2%, p=.040), comparable findings were reported postoperatively (38.8% vs. 24.2%, respectively, p=.062). Furthermore, men participated in intermediate impact sports more frequently after surgery than women (70.6% vs. 54.5%, respectively, p=.050). Concerning time to return, men return significantly faster to high and intermediate impact sports compared to females (p=.002 and p=.036, respectively). For age groups, preoperatively as well as postoperatively patients ≤55 years participated in more high impact sports in comparison to patients aged ≥70 years (p=.017).

Table 4. Sporting Activities by Impact Before and After Unicondylar Knee Arthroplasty.

Subgroup/Impact[a]	Preoperative participation N = 132[b]	%[c]	Postoperative participation N = 147[b]	%[c]	Mean time to return (months)[d]
Overall					
High impact	54	40.9	47	32.7	6.4 (2.0 - 22.0)
Intermediate impact	95	72.0	94	63.9	5.1 (1.0 - 24.0)
Low impact	122	92.4	138	93.9	3.8 (0.3 - 14.0)
Men					
High impact	38[e]	48.1	33[f]	38.8	5.8 (2.0 - 18.0)
Intermediate impact	53	67.1	60[f]	70.6	4.6 (1.0 - 24.0)
Low impact	73[e]	92.4	78	91.8	3.2 (0.3 - 12.0)
Women					
High impact	16[e]	30.2	15[f]	24.2	7.7 (3.0 - 22.0)
Intermediate impact	42	79.2	34[f]	54.5	6.1 (1.0 - 22.0)
Low impact	49[e]	92.5	60	96.8	4.6 (0.8 - 14.0)
Younger (≤55 y)					
High impact	13[e]	59.1	12[f]	52.2	7.3 (3.0 - 22.0)
Intermediate impact	17	77.3	15	65.2	6.4 (1.0 - 22.0)
Low impact	20	90.9	22	95.7	4.0 (1.0 - 7.5)
Middle (55-70 y)					
High impact	37[e]	41.1	32[f]	31.7	6.5 (2.5 - 18.0)
Intermediate impact	66	73.3	66	65.3	4.7 (1.0 - 10.7)
Low impact	83	92.2	96	95.0	3.9 (0.3 - 14.0)
Older (≥70 y)					
High impact	4[e]	20.0	3[f]	17.4	3.5 (3.0 - 4.0)
Intermediate impact	12	60.0	13	56.5	5.6 (1.0 - 24.0)
Low impact	19	95.0	20	87.0	3.4 (1.0 - 8.0)

[a]The top 3 sports by impact are listed in APPENDIX II.
[b]Number of patients. [c]Percentage of total in the given category.
[d]Time to return is significantly shorter in men for low and intermediate impact sports (p=0.002 and p=0.036, respectively). No differences in time to return were observed between the age groups.
[e]Significant differences in preoperative participation between the subgroups, men vs. women: high impact (p=0.040). Younger (≤55y) vs. middle (55-70) vs. older (≥70 y) age: high impact (p=0.036).
[f]Significant differences in postoperative sport participation between the specific subgroups, men vs. women: high impact (p=0.062) and intermediate impact sports (p=0.050). Younger (≤55y) vs. middle (55-70) vs. older (≥70 y) age: high impact sports (p=0.039).

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Furthermore, satisfaction by the highest impact of preoperative sports was determined. Of the patients who participated in high impact sports preoperatively, 85.2% (46/54) were satisfied with their return to sports, independent of the type they returned to. In addition, patients who participated in intermediate or low impact sports were satisfied with their postoperative sporting activity in 86.0% (49/57) and 95.2% (20/21), respectively. No statistical difference was found (p=.413).

VALIDATED OUTCOME SCORES

The mean preoperative NRS score improved from 6.40 ± 2.10 to 1.33 ± 1.73 postoperatively (p<.001). Patients who were satisfied reported a significantly lower postoperative NRS score compared to patients that were dissatisfied (mean 3.59 ± 2.85 vs. 1.13 ± 1.40, p<.001). The mean preoperative UCLA score improved from 5.93 ± 2.19 to 6.78 ± 1.92 (p<.001), indicating that patients are able to participate regularly in active activities postoperatively. Moreover, the preoperative mean total HAAS score improved from 9.13 ± 3.55 to 11.08 ± 2.83 postoperatively (p<.001), similar findings were observed in all subdomains (Table 5).

Table 5. Preoperative and Postoperative Patient Reported Outcomes[a].

	Preoperative[b]	Postoperative[b]	P-value
	Mean (± SD)		
NRS score	6.40 ± 2.10	1.33 ± 1.73	<0.001
UCLA activity score	5.93 ± 2.19	6.78 ± 1.92	<0.001
HAAS score total	9.13 ± 3.55	11.08 ± 2.83	<0.001
Walking	3.14 ± 1.36	3.83 ± 1.23	<0.001
Running	1.09 ± 1.07	1.46 ± 1.12	0.002
Stair climbing	1.67 ± 0.76	2.01 ± 0.74	<0.001
Activity level	3.27 ± 1.41	3.73 ± 1.25	0.001

[a]Statistically significant improvement was observed in Numeric Pain Rating Scale (NRS) score, University of California at Los Angeles (UCLA) activity score, and total High Activity Arthroplasty Score (HAAS) and all its subdomains, and using paired 2-tailed independent t-tests.
[b]All 164 patients (179 knees) were included.

PREDICTORS OF SATISFACTION AND HIGH ACTIVITY SCORES

Patients who participated in sports preoperatively showed an increased likelihood of satisfaction with their return to sports after surgery (OR 3.60, 95% CI 1.46-8.89, p=.005), sex and age were not found predictive. In addition, 62 patients (34.6%) patients reported preoperatively an UCLA score of 7 or more, which increased to 97 patients (54.2%) at 20.2 months' follow-up. The preoperative UCLA activity score (OR 1.16, 95% CI 1.36 - 1.87, p<.001), male sex (OR 1.95, 95% CI 1.11 - 3.41, p=.020), and

preoperative sports participation (OR 2.16, 95% CI 1.05 - 4.47, p=.037) independently predicted a postoperative UCLA score of 7 or more following UKA surgery (Table 6).

Table 6. Overall Predictors of Postoperative UCLA Activity Score of ≥7.

Predictor	Odds Ratio	95% CI	p-Value[a]
Sex[b]	1.95	1.11 – 3.41	0.020
Preoperative UCLA score	1.61	1.36 – 1.87	<0.001
Preoperative sports participation[c]	2.16	1.05 – 4.47	0.037

95% CI: confidence interval. [a]Calculated using an ordinal regression model.
[b]Female sex was baseline, male sex was a significant predictor.
[c]No preoperative sports participation was baseline; preoperative sports participation was independent of level of impact.

DISCUSSION

The aim of this study was to provide evidence based guidance for surgeons to inform their patients with regard to their ability to participate in sports after UKA surgery. It was showed that the vast majority of patients participated in sports post-operatively, of which over 80% was satisfied with their restoration of sports ability and returned to a higher or similar level of activity compared to preoperatively. Factors that were associated with high level of satisfaction were male gender, older age (≥70 years) and patients that participated in low-impact sports preoperatively. With regard to type of sports, men were more likely to return to high and intermediate impact sports after UKA surgery compared to women, and furthermore, they returned faster than women. Finally, patients aged 55 or less participated more frequently in high impact activities than older patients.

An increase in overall sports participation to 90% after surgery was noted in this cohort study, which was similar to the rates demonstrated by Naal[25] and Fisher[24]. Naal et al. studied a population of 83 patients who received an all-polyethylene tibial implant, of which 88% returned to at least one sport at 18 months' follow-up. A return to sports rate of 93% has been demonstrated by Fisher et al. after mobile-bearing Oxford UKA, however, only 64% of the 66 patients reviewed regularly participated in sports after surgery. Hopper et al[9] found that 96.5% of their 26 patients returned to sports at 22 months' follow-up, excluding all patients over the age of 75. The study by Walker et al[38] evaluated patients less than 60 years of age and found a return to sports rate of 93%, which is comparable to our results including all ages. Pietschmann et al[26] found that 80.2% of their 131 patients, with a mean age of 65.3 years, was able to return to

physical activities after surgery, which was lower than the current findings. To our knowledge, this is the largest cohort study performed, showing a high rate of return sports of 179 fixed bearing UKAs, including all ages and all levels of sporting activity.

A few prior studies have assessed overall satisfaction with UKA surgery, Naal et al[25] reported that 82% of their patients considered the overall outcome of surgery to be excellent or good. A prospective study by Presti et al[39] found that all 53 athletic patients were highly satisfied following UKA at a mean follow-up of 48 months. "Athletic" was defined as patients who participated in at least one sport before the onset of restrictive symptoms. Although these two studies were return to sport studies, satisfaction with their ability to participate in sports after surgery was not determined. Very few studies have described satisfaction level with return to sports, of which most articles reviewed patients that underwent surgery more than a decade ago when designs, surgical techniques and recommendations on return to sports may have been different.[9,13,26] An older study by Pietschmann and colleagues[26] reviewed 131 patients that underwent surgery between 1998 and 2007 and showed good-to-excellent satisfaction with their physical activity in 93%. In our study, 83.2% of the patients were satisfied with their postoperative sports participation after undergoing surgery in 2015 and 2016. This difference might be due to different techniques, but possibly more important different recommendations and patient' expectations. Due to the ongoing success and development of UKA surgery, the indications have broadened to include a younger population of patients with higher expectations which can potentially influence satisfaction.[2,6,40] A recent study showed that patients who expected some degree of pain interference with life 12 months post-surgery had a 1.3 times greater risk of not returned to desired activity compared to patients who expected no pain interference.[41] This shows the need for adequate preoperative counseling.

The goal of this study was to provide insight in to what extent satisfaction with postoperative sports participation was achieved in UKA patients, which could possibly be helpful in managing the expectations of future patients. In this study, patients were asked to subjectively rate their level of return to activity and 85.4% reported to have returned to a higher or similar level and 14.6% to a lower level. No differences were found between sexes or age groups. To our knowledge, limited data are available on subjective levels of return to sports after UKA. Walker et al[27] demonstrated that 67% of their 45 patients reported an improvement of their sports ability, while 24% stated no difference, and 9% reported impairment at a mean follow-up of three years. Ho et al[13] found that 17% of their patients did better and 56% returned to the same level compared to baseline. This was a small retrospective cohort study of 36 patients with

a follow-up of 3.8 years, which has the potential for recall bias when historical self-reported information is elicited approximately four years after surgery.

With regard to our second objective, this study evaluated the postoperative sporting endeavors after UKA surgery (Table 5). The most common sports were cycling, swimming, stationary cycling, golf, and hiking, similar activities were described by Naal[25] and Hopper[9]. Recently, a systematic review was published assessing type of activities by impact after UKA, and found a decrease in high impact activities and an increase in low impact sports postoperatively.[8] A similar trend was noted in this study, but the overall return to high impact sports was 32.7%, which was higher than the 4% reported by Witjes et al.[8] In our cohort, men were significantly more likely to return to higher impact sports sooner after surgery compared to women. Furthermore, it was found that 85% of the patients who participated in high impact sports preoperatively, were satisfied with their postoperative sporting activity independent of the type they returned to. In this study, patients were not encouraged to return to high impact sports as their main cardio activity, however, it would be interesting to evaluate the impact of preoperative instructions on the postoperative outcome, and especially how it influences satisfaction. High impact sports after UKA remain controversial, as it puts increased stress on the prosthesis and the implant-bone interface, possibly leading to failure. Therefore, it can be argued that these patients may benefit from cementless fixation, as the reported incidence of fixation failure in cementless UKA is lower than cemented UKA.[42,43] For patients who wish to return to high impact sports, cementless fixation may ultimately be the preferable fixation method as it potentially lowers the stress at the implant-bone interface.

Moreover, the results of this study showed significant improvement in pain scores after UKA surgery. Presti et al[39] demonstrated that 22.6% of the patients reported pain during physical activity, but felt that their knee was stable. Correspondingly, Hopper et al[9] found that of those 24.1% of patients that experienced pain during sport, no patients felt that their knee was unstable. UKA has proven to relieve pain successfully in daily life and creates the ability to return to physical activity, although pain during sporting activities may still be experienced.

Significant improvement in UCLA scores were observed following UKA, which is consistent with the two studies performed by Walker et al.[27,38] The authors showed that, after medial and lateral UKA, patients reported an average UCLA score of 6.8 and 6.7, respectively. Furthermore, 62% of the medial UKA patients and 66% of the lateral UKA patients were very active postoperatively, achieving UCLA scores equal

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or more than 7. In this current study, 54.2% of the patients returned to high activity levels, this difference may be explained by the younger patient population in both studies by Walker et al.[38] The authors included patients 60 years or younger in the medial UKA study and the mean age of patients in the lateral UKA study was 60 years. Age could potentially influence to what extent patients are able to reach high activity levels postoperatively. In addition, Pietschmann et al[26] found a significant difference in postoperative UCLA scores between patients who were preoperatively active and inactive. Based on these studies, predictive factors of high activity levels were assessed in our cohort, showing male sex, preoperative sports participation, and preoperative UCLA score to be predictive for postoperative UCLA score of 7 or more. These findings corresponded with the total joint literature, Williams et al[32] found that male sex and preoperative UCLA score predicted high activity scores after TKA and total hip arthroplasty. However, they identified age as a predictor as well, which was not confirmed in this study, possibly due to the age distribution, as more than 68% of our patients fitted within the age range of 55-70 years.

This study has several limitations. One of the main limitations of this study was the retrospective data collection, in addition to the concern for recall bias. Ideally, a prospective study would have improved the strength of our results. Furthermore, the number of patients that were lost to follow-up was relatively high, which potentially influences the outcomes. It could be argued that non-responders were dissatisfied with the outcome or have consulted another provider regarding their knee. Therefore, this data needs to be interpreted with caution. On the contrary, descriptive analysis showed that these patients were younger than the included patients, which could suggest that they are possibly more active. Based on the study by Walker et al[38], which included patients 60 years or younger, our rate of return might have been higher. Subsequently, this is, to our knowledge, the largest UKA return to sports study performed with modern implants, including 164 patients. Another limitation was that the follow-up period was too short to report on possible risks regarding the longevity of the implant dependent on the activity. Future studies, using current UKA designs, surgical techniques, and sport recommendations, with longer follow-up are necessary to assess these risks.[44] The results of this study allow surgeons to inform UKA patients preoperatively with regard to their ability to participate in sports postoperatively, which could assist in managing patients' expectations.

CONCLUSION

The vast majority of patients undergoing medial UKA returned to one or more sports postoperatively, of which over 80% was satisfied with their restoration of sports ability and returned to a higher or similar level of activity compared to preoperatively. Male patients, patients aged 70 or above, and patients who participated in low-impact sports preoperatively achieved the highest level of satisfaction. With regard to type of sports, male patients and patients aged 55 or less were most likely to return to high and intermediate impact sports after UKA surgery. This present study may offer valuable information to help manage patients' expectations regarding their ability to return to sports postoperatively based on patient characteristics and type of preoperative sporting activities.

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APPENDIX I. Questionnaire

QUESTIONNAIRE FOR RETURN TO SPORTS AFTER PARTIAL KNEE REPLACEMENT

1. Today's Date:

2. Patient name:

3. Date of birth:

4. Gender: Female / Male

5. What is your height?

6. What is your current weight?

7. Date of Surgery:

8. Which knee did you have surgery on? Left / Right / Both

9. Did you participate in any physical activity or sports 5 years prior to your knee replacement? YES/NO
   If Yes, please proceed to question 10.
   If No, please proceed to page 3, level of function

10. Have you ever had surgery on that/those knee(s) before the replacement?
    If Yes, what type(s) of surgery and when? Please specify

11. Have you ever had surgery on that/those knee(s) after the replacement?
    I Yes, what type(s) of surgery and when? Please specify

QUESTIONNAIRE 1 – SPORTS BEFORE SURGERY

Please define the type of sports you were able to perform within 5 years before surgery.

Type of sports (select all that apply)		
☐ Barre	☐ Doubles tennis	☐ Baseball / softball
☐ Bicycling	☐ Downhill skiing	☐ Basketball
☐ Bowling	☐ Free weight lifting	☐ Boot camp
☐ Cross-country skiing	☐ Hiking	☐ Cross fit
☐ Dancing	☐ Horseback riding	☐ Football
☐ Golf	☐ Ice skating	☐ Handball
☐ Isokinetic weight lifting	☐ Low-impact aerobics	☐ High Intensity Interval Training (HIIT) classes
☐ Pilates	☐ Rock climbing	
☐ Rowing	☐ Spinning	☐ Hockey
☐ Sailing	☐ Zumba	☐ Jogging/ running
☐ Speed walking		☐ Karate
☐ Stationary cycling		☐ Kickboxing
☐ Swimming		☐ Lacrosse
☐ Table tennis		☐ Racquetball
☐ Water aerobics		☐ Singles tennis
☐ Yoga		☐ Soccer
		☐ Volleyball
		☐ Water skiing
		☐ Other:_____

Please report the average duration and frequency of every sport.

Sport 1:		
Duration:	minutes / hours	(please select)
Frequency:	per week / month	(please select)

Sport 2:		
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 3:		
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 4:		
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 5:		
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 6:		
Duration:	minutes / hours	
Frequency:	per week / month	

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Select your highest level of function in each of the four categories BEFORE SURGERY.

1. Walking
☐ Over rough ground >1 hour
☐ Unlimited on flat, rough ground with difficulty
☐ Unlimited on flat, no rough ground
☐ On flat at least 30 minutes
☐ Short distances unassisted (up to 20 meters or 22 yards)
☐ Using walking aids for short distances or worse

2. Running
☐ More than 5 kilometers or 3.11 miles
☐ Jog slowly up to 5 kilometers or 3.11 miles
☐ Run easily across the road
☐ Run a few steps to avoid traffic if necessary
☐ Cannot run

3. Stair climbing
☐ Climb stairs 2 at a time
☐ Climb without hand rail
☐ Climb with hand rail or stick
☐ Cannot climb stairs

4. Activity level
☐ Competitive sports (e.g. singles tennis, running > 10km or 6.21mi, cycling > 80km or 49mi)
☐ Social sports (e.g. doubles tennis, skiing, jogging < 10km or 6.21mi, high impact aerobics)
☐ Vigorous recreational activities (e.g. hill-walking, low impact aerobics, heavy gardening or manual work/farming)
☐ Moderate recreational activities (e.g. golf, light gardening, light working activities)
☐ Light recreational activities (e.g. short walks, lawn bowls)
☐ Required outdoor activities only (e.g. walk short distance to shop)
☐ Housebound without assistance

Check one box that best describes your activity level BEFORE SURGERY.

☐ 1: Wholly Inactive, dependent on others, and cannot leave residence
☐ 2: Mostly Inactive or restricted to minimum activities of daily living
☐ 3: Sometimes participates in mild activities, such as walking, limited housework and limited shopping
☐ 4: Regularly Participates in mild activities
☐ 5: Sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping
☐ 6: Regularly participates in moderate activities
☐ 7: Regularly participates in active events such as bicycling
☐ 8: Regularly participates in active events, such as golf or bowling
☐ 9: Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor or backpacking
☐ 10: Regularly participates in impact sports

Please define your pain BEFORE SURGERY on a scale of 1 to 10.


```
    |   |   |   |   |   |   |   |   |   |
    0   1   2   3   4   5   6   7   8   9   10
   No                  Moderate             Worst
  Pain                   Pain                Pain
                                           Possible
```

Pain level:

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QUESTIONNAIRE 2 – RETURN TO SPORTS AFTER SURGERY

1. To what level of sports were you able to return to after surgery?
☐ Lower level/intensity
☐ Similar level/intensity
☐ Higher level/intensity

2. How satisfied are you with the return to sports?

Very satisfied/ Satisfied/ Neutral/ Dissatisfied/ Very dissatisfied

Please define the type of sports you were able to return to AFTER SURGERY.

Type of sports (select all that apply)		
☐ Barre	☐ Doubles tennis	☐ Baseball / softball
☐ Bicycling	☐ Downhill skiing	☐ Basketball
☐ Bowling	☐ Free weight lifting	☐ Boot camp
☐ Cross-country skiing	☐ Hiking	☐ Cross fit
☐ Dancing	☐ Horseback riding	☐ Football
☐ Golf	☐ Ice skating	☐ Handball
☐ Isokinetic weight lifting	☐ Low-impact aerobics	☐ High Intensity Interval Training (HIIT)
☐ Pilates	☐ Rock climbing	classes
☐ Rowing	☐ Spinning	☐ Hockey
☐ Sailing	☐ Zumba	☐ Jogging/ running
☐ Speed walking		☐ Karate
☐ Stationary cycling		☐ Kickboxing
☐ Swimming		☐ Lacrosse
☐ Table tennis		☐ Racquetball
☐ Water aerobics		☐ Singles tennis
☐ Yoga		☐ Soccer
		☐ Volleyball
		☐ Water skiing
		☐ Other:_____

Please report when you were able to return to the sport AFTER SURGERY, the average duration, and frequency of every sport.

Sport 1:		
Return after surgery:	after .... months or	...... years
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 2:		
Return after surgery:	after .... months or	...... years
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 3:		
Return after surgery:	after .... months or	...... years
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 4:		
Return after surgery:	after .... months or	...... years
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 5:		
Return after surgery:	after .... months or	...... years
Duration:	minutes / hours	
Frequency:	per week / month	

Sport 6:		
Return after surgery:	after .... months or	...... years
Duration:	minutes / hours	
Frequency:	per week / month	

Select your highest level of function in each of the four categories AFTER SURGERY.

1. Walking
   - ☐ Over rough ground >1 hour
   - ☐ Unlimited on flat, rough ground with difficulty
   - ☐ Unlimited on flat, no rough ground
   - ☐ On flat at least 30 minutes
   - ☐ Short distances unassisted (up to 20 meters or 22 yards)
   - ☐ Using walking aids for short distances or worse

2. Running
   - ☐ More than 5 kilometers or 3.11 miles
   - ☐ Jog slowly up to 5 kilometers or 3.11 miles
   - ☐ Run easily across the road
   - ☐ Run a few steps to avoid traffic if necessary
   - ☐ Cannot run

3. Stair climbing
   - ☐ Climb stairs 2 at a time
   - ☐ Climb without hand rail
   - ☐ Climb with hand rail or stick
   - ☐ Cannot climb stairs

4. Activity level
   - ☐ Competitive sports (e.g. singles tennis, running > 10km or 6.21mi, cycling > 80km or 49mi)
   - ☐ Social sports (e.g. doubles tennis, skiing, jogging < 10km or 6.21mi, high impact aerobics)
   - ☐ Vigorous recreational activities (e.g. hill-walking, low impact aerobics, heavy gardening or manual work/farming)
   - ☐ Moderate recreational activities (e.g. golf, light gardening, light working activities)
   - ☐ Light recreational activities (e.g. short walks, lawn bowls)
   - ☐ Required outdoor activities only (e.g. walk short distance to shop)
   - ☐ Housebound without assistance

Check one box that best describes your current level of activity AFTER SURGERY.
- ☐ 1: Wholly Inactive, dependent on others, and cannot leave residence
- ☐ 2: Mostly Inactive or restricted to minimum activities of daily living
- ☐ 3: Sometimes participates in mild activities, such as walking, limited housework and limited shopping
- ☐ 4: Regularly Participates in mild activities
- ☐ 5: Sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping
- ☐ 6: Regularly participates in moderate activities
- ☐ 7: Regularly participates in active events such as bicycling
- ☐ 8: Regularly participates in active events, such as golf or bowling
- ☐ 9: Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor or backpacking
- ☐ 10: Regularly participates in impact sports

Please define your pain AFTER SURGERY on a scale of 1 to 10.

0	1	2	3	4	5	6	7	8	9	10
No Pain					Moderate Pain					Worst Pain Possible

APPENDIX II

Top 3 Preoperative and Postoperative Sporting Activities Within Each Category

	Preoperative sports (N = 139)	Postoperative sports (N = 147)
Overall		
High impact	Running, baseball, singles tennis	Singles tennis, running, baseball
Intermediate impact	Weight lifting, downhill skiing, hiking	Weight lifting, hiking, downhill skiing
Low impact	Bicycling, swimming, golf	Bicycling, swimming, stationary cycling
Men		
High impact	Running, baseball, singles tennis	Running, singles tennis, baseball
Intermediate impact	Weight lifting, downhill skiing, hiking	Weight lifting, hiking, downhill skiing
Low impact	Bicycling, swimming, golf	Bicycling, swimming, golf
Women		
High impact	Running, singles tennis, high intensity interval training	Singles tennis, running, high intensity interval training
Intermediate impact	Hiking, low-impact aerobics, weight lifting	Hiking, weight lifting, low-impact aerobics
Low impact	Yoga, bicycling, swimming	Swimming, bicycling, yoga
Younger (≤55 y)		
High impact	Running, baseball, singles tennis	Singles tennis, running, hockey
Intermediate impact	Downhill skiing, weight lifting, hiking	Weight lifting, downhill skiing, hiking
Low impact	Bicycling, swimming, golf	Bicycling, swimming, golf
Middle (55-70 y)		
High impact	Running, baseball, singles tennis	Running, singles tennis, cross fit
Intermediate impact	Weight lifting, hiking, downhill skiing	Weight lifting, hiking, downhill skiing
Low impact	Bicycling, swimming, golf	Bicycling, swimming, stationary cycling
Older (≥70 y)		
High impact	Running, baseball, singles tennis	Singles tennis, running, baseball
Intermediate impact	Doubles tennis, downhill skiing, hiking	Low-impact aerobics, hiking, doubles tennis
Low impact	Swimming, golf, stationary cycling	Swimming, golf, stationary cycling

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General discussion

DISCUSSION

In many industries, from aviation to manufacturing to financial services, technology is emerging. According to experts, development consists of five phases; (1) consideration of the industry as an 'art' by experts in the field, (2) development of 'rules plus instruments', (3) development of 'standardized procedures and templates', (4) automation, and (5) computer integration. Aircraft autopilot systems, for example, have shown that outcomes improve as intuition is replaced by accurate real-time data.[1] Currently, the health care industry seems to be hovering in and around stage '3', although progression through the stages is to be expected. The timing, however, of when automation and computer integration will become widely adopted in our healthcare system is never prospectively clear.[1,2] The use of robot technology in the field of joint arthroplasty has grown exponentially over the last decade, with currently over 15% of unicompartmental knee arthroplasties (UKAs) being performed with robotic assistance in the United States.[3,4] While robotic systems have proven to be effective in increasing the accuracy and consistency of component positioning, re-tensioning the soft tissues and restoration of the mechanical axis, the clinical impact of their use remains unclear.[5–7] Therefore, this thesis focused on the different aspects of robotic-assisted UKA surgery, in which patient selection criteria, radiographic and clinical outcomes were evaluated. The aim was to answer the following questions:

1. Is it possible to predict the feasibility of correcting the mechanical axis with medial unicompartmental knee arthroplasty of patients with large preoperative varus deformities?
2. What is the incidence of radiolucency in cemented fixed-bearing medial UKA and does it affect functional outcomes?
3. Could magnetic resonance imaging be a complementary tool for assessing symptomatic UKA by quantifying appearances at the bone-component interface?
4. What are the clinical outcomes of robotic-assisted medial fixed-bearing UKA compared to all-polyethylene UKA and TKA at mid-term follow-up?
5. Do young patients report better outcomes after UKA compared to TKA when systematically reviewing the literature?
6. Are patients satisfied with their postoperative sports participation and what type of activities are they engaging in after UKA surgery?

1. *Is it possible to predict the feasibility of correcting the mechanical axis with medial unicompartmental knee arthroplasty of patients with large preoperative varus deformities?*

Proper restoration of limb alignment and appropriate positioning of the components are major contributors to successful UKA. The aim during UKA surgery is to restore knee kinematics by re-tensioning the ligaments, especially the medial collateral ligament. In UKA, correct ligament balance is restored by positioning the components accurately and inserting an appropriate bearing thickness.[6,8] As the tension is restored to normal, the intra-articular deformity secondary to arthritis is corrected. Many patients have a varus deformity before developing medial osteoarthritis due to an extra-articular deformity, which potentially influences postoperative alignment.[9] Currently, most surgeons estimate the correctability of a patients' mechanical axis by physical examination or obtain stress views preoperatively. Based on the recommendations by Kozinn and Scott, medial UKA patients should have a preoperative varus deformity of 15° or less that is correctable to neutral.[10] The goal during surgery is to correct the mechanical axis to 7° of varus or less, since excessive residual varus alignment leads to increased forces in the medial compartment.[11,12] Overloading the medial compartment is associated with increased risk for failure due to polyethylene wear and aseptic loosening.[12–15] With regard to functional outcomes, authors have noted significantly better patient-reported outcomes (International Knee Society and Western Ontario and McMaster Universities Osteoarthritis Index, respectively) in patients with postoperative minor varus alignment (≤4°) compared to neutral alignment.[12,16] Whilst the importance of coronal alignment has been widely discussed in literature, objective measures to predict the correctability of the mechanical axis are lacking. In chapter three, the predictive role of several radiographic deformity measurements was evaluated using weight bearing long leg radiographs.[17] In this study, the correctability of the mechanical axis in medial UKA patients with large preoperative varus deformities was assessed, and secondly, the feasibility of optimal postoperative alignment based on the estimated mechanical axis was evaluated. It was found that optimal (≤4°) or acceptable (5°-7°) alignment was achieved in 98% of the patients with a preoperative varus deformity of 7° or greater undergoing robotic-assisted medial UKA. Furthermore, the estimated mechanical axis based on preoperative mechanical axis minus the joint line convergence angle was a significant predictor to evaluate the feasibility of achieving optimal postoperative alignment. This was based on the rational that lower limb realignment is primarily driven by the correction of the joint line deformity, as medial UKA restores joint height and improves joint congruence, as was shown by Chatellard et al[18] and Khamaisy et al.[19] The use of robot assistance might contribute

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favorably to the feasibility of achieving optimal or acceptable alignment during medial UKA, due to the high degree of accuracy and consistency provided by the robotic system.[7,20] Although this study showed that it is technically possible, attention must also be paid to functional outcomes. The knowledge that patients with large preoperative deformities can be corrected to minor varus alignment, might allow broadening of the indications for surgery and offering UKA to a greater proportion of patients.

2. *What is the incidence of radiolucency in cemented fixed-bearing medial UKA and does it affect functional outcomes?*

There are two types of radiolucent lines (RLL) as described by Goodfellow et al, physiological (1-2 mm and well-defined) and pathological (>2 mm, poorly defined, and often related to aseptic loosening) RLL.[21] In chapter four, the different aspects of radiolucency were highlighted after analyzing 351 medial UKAs.[22] The incidence of femoral and tibial physiological RLL was 10.2% and 25.3%, respectively, of which 6.8% concerned both components. Several previous studies have showed a higher incidence of tibial radiolucency using cemented implants, this discrepancy might be due to different implant designs with altered stabilizing mechanisms (one peg, two pegs, vertical stabilizer), surgical techniques and radiographic assessment methods.[23–26] This was the first study to describe a difference in time of onset of physiological femoral and tibial RLL (1.36 and 1.00 years, respectively). Although the etiology of radiolucency remains unclear, many hypothesis have been proposed in literature. Authors have suggested that the mechanism leading to RLL may be different for the femoral and tibial component. A cadaveric study showed that femoral RLL develop through a rocking mechanism around the stabilizing pegs, while tibial RLL occur by compressive loading of the component. Mechanical stress at the bone-component interface is associated with formation of fibrocartilage.[23,27,28] Another finding was that tibial and femoral radiolucencies were not correlated with inferior functional outcomes when compared to matched controls. This corresponds to the results published by the Oxford group, although they reported a significantly lower incidence of radiolucency using cementless implants.[29,30] Therefore, at the longer term, improved fixation using cementless designs may lower the risk of aseptic loosening, which is one of the major reasons for revision of cemented medial UKA.[31,32] Another factor that may contribute to a lower revision rate when using cementless designs is the threshold for revision, as physiological RLL may be interpreted as prosthetic loosening, especially by low-volume surgeons.[33]

3. *Could magnetic resonance imaging be a complementary tool for assessing symptomatic UKA by quantifying appearances at the bone-component interface?*

Stable implant fixation is essential to prevent loosening. Components are prone to fixation failure due to shear forces at the bone-cement interface, and to rocking when eccentrically loaded, which leads to tension on the unloaded side of the interface.[34] Sequential radiography is typically used to monitor arthroplasties over time, but assessment of periprosthetic bone and soft tissues remains challenging, especially in symptomatic patients. There are various diagnostic imaging modalities available to assess symptomatic arthroplasty patients, including combinations of radiographic views, computed tomography (CT), magnetic resonance imaging (MRI); and several nuclear imaging techniques, such as planar bone scintigraphy with or without single photon emission computed tomography (SPECT), and fluorodeoxyglucose (FDG)-positron emission tomography (PET)/CT.[35–37] The principal advantage of using nuclear modalities is the elimination of metal artefact that compromises CT imaging and, to a lesser extent, MRI due to the use of metal artefact suppression techniques. According to a recent systematic review, the SPECT/CT is the most accurate nuclear imaging technique to diagnose loosening of total knee arthroplasty (TKA) when compared to operative findings.[35] However, it is commonly agreed that diffuse uptake around a prosthesis does not differentiate between loosening, infection, mechanical malalignment or progression of OA.[38] Nevertheless, the negative predictive value of detecting loosening using SPECT/CT, meaning no tracer uptake around the prosthesis, is close to a 100%.[35,38,39] Although in the setting of UKA, when only one compartment is replaced, SPECT/CT may not be suitable as changes in the unreplaced knee compartments could cause difficulty interpreting the SPECT tracer uptake. To our knowledge, no studies have assessed the diagnostic accuracy of SPECT/CT for UKA specifically. Most of these nuclear imaging modalities allow for assessment of aseptic loosening, however, are unable to detect subtle abnormalities at the bone-component interface or soft tissue changes, such as wear-induced synovitis.[40,41] In recent decades, MRI has become the standard for the evaluation of joints and soft tissues in the native knee. However, MRI was considered to have limited diagnostic properties for knee arthroplasty patients, due to artifacts caused by the prosthetic components.[42] The use of multiacquisition variable-resonance image combination (MAVRIC) technique has been found to substantially reduce susceptibility artifacts near metallic components. MAVRIC minimizes image distortion, attained with existing clinical MRI hardware.[43,44] The clinical viability of this technique in the setting of total joint arthroplasty has been assessed by several studies.[44–47] In chapter five, the diagnostic properties of MRI with the MAVRIC sequence were evaluated for symptomatic medial UKA patients.[48]

It was noted that MRI with the addition of MAVRIC could be a valuable complement to radiographic evaluation of symptomatic UKA patients, as is allows for reliable quantification of appearances at the bone-implant interface at the tibial and femoral side. When compared to conventional radiographs, MRI findings and radiolucent lines observed on radiographs were poorly correlated. The indication for MRI was unexplained pain in 67% of the patients, which is one the leading causes for revision in UKA.[31,49] Of all 55 patients included, 13 patients underwent re-operations subsequent to MRI, however, only one patient was revised. It could be argued that MRI with the addition of MAVRIC may influence the threshold for revision surgery, as reliable assessment of painful UKA can be performed, especially in cases of unremarkable radiographic findings. Future studies could be focusing on the distinction between the bone-component interface of symptomatic and asymptomatic patients, and secondly, evaluate differences between cemented and cementless UKA designs.

4. *What are the clinical outcomes of robotic-assisted medial fixed-bearing UKA compared to all-polyethylene UKA and TKA at mid-term follow-up?*

Despite the potential advantages of UKA over TKA, in terms of restoration of normal knee kinematics, less blood loss, accelerated recovery, and increased range of motion, UKA survivorship is recorded lower than TKA.[50–53] Longevity of UKA is determined by lower leg alignment, soft tissue balance, component position and alignment. In order to improve the outcomes of UKA and potentially match those of TKA, robotic systems have been introduced, which creates the ability to not only control but also optimize these surgical variables. Studies have showed that these systems are more accurate and consistent in controlling these variables when compared to conventional methods. While these systems have proven to be more precise, they add significant cost and its clinical impact is still debated. Therefore, in chapter six the results of a large multicenter study evaluating mid-term survivorship and satisfaction following robotic-arm-assisted medial UKA were described.[54] High survivorship (97%) was found and 92% of the patients were satisfied with the current knee function at a mean follow-up of 5.7 years. Aseptic loosening was the most common mode of failure despite the use of robotics, therefore, it is believed that survival of medial UKA can benefit from cementless fixation.[32] In chapter seven, the functional outcomes of two different UKA tibial designs (metal-backed/onlay and all-polyethylene/inlay) and TKA were compared at mid-term follow-up.[55] Functional outcomes following metal-backed medial UKA were significantly better compared to all-polyethylene medial UKA and TKA. The first studies comparing robotic-arm-assisted to conventional implanted UKA have been published recently, all reporting outcomes at short-term follow-up, therefore difficult to relate to the aforementioned studies.[56–58]

Though Gilmour et al showed improved survivorship (100%) and lower post-operative pain in patients undergoing robotic-arm-assisted surgery compared to conventional surgery, which reported a survivorship of 97% at two-year follow-up. Equivalent functional outcome scores have been recorded, possibly due to the ceiling effects observed.[57] Another study noted that robotic UKA had a lower rate of postoperative limb alignment outliers, as well as a lower revision rate, compared to conventional technique at 20 months follow-up using the Navio robotic system.[58] Although these results may seem promising, long-term survivorship data is needed to compare the robotic and conventional surgical technique, as revision rates may have major implications for the cost-effectiveness of robotic technology.[59]

5. *Do young patients report better outcomes after UKA compared to TKA when systematically reviewing the literature?*

According to the indications proposed by Kozinn and Scott, the best candidates for UKA are more than 60 years old and have a low demand for activity.[10] Therefore, many surgeons did consider young age a contraindication to UKA initially, as the longevity of the implant may be impaired by the high demands of young patients with an increased risk for multiple revisions due to longer life expectancy. However, UKA has distinct features which are of special interest to younger and frequently more active patients, such as increased range of motion, preservation of more bone stock during primary surgery and fast recovery. Moreover, they tend to forget their artificial joint more often after UKA than TKA.[60–62] In chapter eight, a systematic review was conducted to gain insight in survivorship, functional outcomes and activity levels of medial UKA and TKA patients less than 65 years of age.[63] The annual revision rate (ARR) of UKA was higher than TKA (1.00 and 0.53, corresponding to an extrapolated 10-year survivorship of 90% and 94.7%, respectively). On the contrary, significantly larger range of motion and higher activity scores were observed following UKA at mid- to long-term follow-up. Overall functional outcome scores were equivalent after both UKA and TKA. A recent meta-analysis assessing survivorship of medial UKA and TKA of the general OA population (mean age 67.4 and 68.6 years, respectively), found a lower ARR (0.46) for TKA, but an equivalent ARR for UKA (1.04) compared to our findings.[64] Both studies showed that TKA was associated with a lower revision rate than UKA, however, UKA survivorship seems not to be negatively affected by age at the time of surgery. All the included UKA studies in this systematic review used conventional surgical techniques. The ARR found in this study was similar to the results reported in the multicenter robotic-assisted medial UKA study in chapter seven when focussing on the age group <60 years of age. When evaluating the age group 60 - 69 years, the ARR reported in

the multicenter study was 0.30.[54] Therefore, the question remains if younger patients would benefit from the use of robot technology based on survival analysis.

6. Are patients satisfied with their postoperative sports participation and what type of activities are they engaging in after UKA surgery?

Most previous work has focused on tangible factors that drive patient satisfaction, such as the effect of different prosthesis and surgical factors. There is growing evidence that suggest that factors intrinsic to the patient may significantly affect outcome as well. Patients' expectations are linked to their assessments of outcome and satisfaction. Therefore, the goal of the study presented in chapter nine was to assess the level of satisfaction with postoperative sports participation and the type of sports patients are doing after surgery, in order to provide modern day patients with accurate and updated recommendations to best calibrate their expectations. This study showed that the vast majority of patients participated in sports after UKA surgery, of which over 83% was satisfied with their restoration of sports ability. Male patients, patients aged 70 or above, and patients who participated in low-impact sports preoperatively achieved the highest level of satisfaction postoperatively. With regard to type of sports, male patients and patients aged 55 or less were most likely to return to high and intermediate impact sports after surgery. These patients are often high demanding, though 85% of patients performing high impact sports was satisfied. Future studies are needed to assess the possible activity related risks in relation to the longevity of the implant. A sub analysis of the present study showed that a high preoperative UCLA activity score, male sex, and preoperative sports participation were predictors for a high level of activity postoperatively (UCLA score ≥7). Similar findings were reported by Williams et al, though in their study, age and BMI were also predictive of high postoperative UCLA scores.[65] This discrepancy may possibly be due to a different patient population, as they included total hip and knee arthroplasty patients with a higher mean age (>5 years). On the other hand, earlier studies found BMI did not predict the need for revision surgery, postoperative knee pain, function, or satisfaction following UKA.[16,66,67] In the current study, all surgeries were performed using the MAKO robotic system, therefore, the additional value of using robotics cannot be determined. A comparative study by Gilmour et al. suggested that, despite the small group size, patients who were more active preoperatively (UCLA score >5), achieved significantly better outcomes following robotic-assisted surgery than conventional surgical techniques.[57] The study presented in chapter nine may offer valuable information to help manage patients' expectations regarding their ability to return to sports postoperatively based on patient characteristics and type of preoperative sporting activities.

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Appendices

SUMMARY

The Role of Robotics in Unicompartmental Knee Arthroplasty – Imaging, Survival and Outcomes

This thesis focusses on patient selection, the role of imaging and clinical outcomes in the setting robotic-assisted unicompartmental knee arthroplasty (UKA) using the MAKO system. A general introduction is provided in **Chapter 1**.

Motivated by a desire to improve clinical outcomes and reduce complications of UKA, strict selection criteria as well as many technological advances have been implemented. In **Chapter 2**, a literature review was conducted to provide an overview of different aspects of UKA in terms of indications and contraindications for surgery; the role of age, body mass index, patellofemoral osteoarthritis, anterior cruciate ligament integrity and chondrocalcinosis was highlighted. Moreover, different fixation techniques (cemented and cementless) and UKA designs (fixed and mobile bearing) were reviewed. Besides new fixation strategies and UKA designs, surgical techniques have developed over the years. Most orthopedic surgeons still use conventional methods to implant UKA, nonetheless, the use of robotics is emerging. The literature on modes of failure after UKA has also been studied; aseptic loosening, progression of osteoarthritis, polyethylene wear and unexplained pain were the most common. Regarding the geographical differences, in Asia and Europe, there is skepticism about the use of robotics due to the indistinct importance of optimizing precision in UKA, expenses, learning curve, increased OR time and risks associated with preoperative imaging with robot technology. In the USA, three robotic systems are FDA-approved for UKA currently, of which the MAKO robotic system (Stryker Corp, Mahwah, NJ, USA) has the largest market share.

One of the proposed patient selection criteria for medial UKA is a preoperative varus deformity of 15° or less that is correctable to neutral during physical examination. This is based on the rationale that it is less feasible to restore the mechanical axis to neutral or close to neutral during surgery in patients who have not fulfilled this criterium. A consequence of excessive residual varus alignment is increased compartment forces by overloading medially, which can ultimately lead to UKA failure. In **Chapter 3**, the feasibility of correcting large preoperative varus deformities with UKA surgery has been evaluated based on radiographic parameters. In 200 consecutive robotic-arm-assisted medial UKA patients with large preoperative varus deformities (≥7°), the mechanical axis angle (MAA) and joint line convergence angle (JLCA) were measured on hip-knee-

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ankle radiographs. It was assessed what number of patients were corrected to optimal (≤4° of varus) and acceptable (5°-7° of varus) alignment, and whether the feasibility of this correction could be predicted using an estimated MAA (eMAA, preoperative MAA–JLCA). In this study, in 98% of the patients, the mechanical axis was restored to either optimal (62%) or acceptable (36%) postoperative alignment with the use of robotic assistance. It has been argued that the preoperative varus alignment, in the setting of isolated medial OA, originates mostly from a progressing intra-articular deformity. By correcting joint line obliquity through medial UKA, the mechanical axis can be restored to 7° of varus or less. The eMAA was found to be a significant predictor to evaluate the feasibility of achieving optimal postoperative alignment (≤4°), in our cohort 78% of the patients with an eMAA of 4° of varus or less had a postoperative alignment within similar range. Furthermore when the eMAA exceeded 4° of varus, a higher frequency of extra-articular deformities was noted, measured as mechanical lateral distal femoral angle and medial proximal tibial angle. In our cohort, more tibial deformities were observed in the eMAA >4° group compared to the ≤4° group (70% and 31%, respectively). Moreover, when combining these findings with the significantly lower predicted probability of achieving optimal postoperative alignment, other treatments, such as high tibial osteotomy and distal femoral osteotomy, should be considered in this subgroup of patients.

The importance of preoperative imaging has been discussed, however, radiography also plays a significant role during the follow-up of arthroplasty patients. Anteroposterior and lateral radiographs are obtained frequently after surgery on which different features can be objectified. In **Chapter 4**, the incidence of physiological femoral and tibial radiolucency in cemented UKA was evaluated. Furthermore, the time of onset of radiolucency and its correlation with short-term patient-reported functional outcomes was assessed. In this cohort study of 352 patients, the incidence of femoral and tibial physiological radiolucent lines was 10.2% and 25.3%, respectively, of which 6.8% concerned both components. Our data suggested that the time of onset of femoral radiolucency was significantly later (1.36 years) than tibial radiolucency (1.00 years). Patients with radiolucent lines around their prosthesis reported similar functional outcomes as the matched cohort group without radiolucency.

Evaluation of symptoms that arise after joint replacement can be challenging, earlier studies have showed the diagnostic value of supplemental magnetic resonance imaging (MRI). However, susceptibility artifacts can still limit the assessment of bone and soft tissues, with the use of multiacquisition variable-resonance image combination (MAVRIC) MR sequence, these artifacts can be reduced substantially near metallic

implants. The retrospective observational study in **Chapter 5** included 55 consecutive patients with symptomatic cemented UKA, of which the vast majority demonstrated a bone marrow edema pattern (71% and 75%, respectively) and fibrous membrane (69% and 89%, respectively) at the femoral and tibial interface. Second, no correlation was found between MRI findings and radiolucent lines on radiographs. MRI with the addition of a MAVRIC sequence can be a complementary tool for assessing symptomatic UKA as it quantifies appearances at the bone-component interface, especially in cases of unremarkable radiographic findings. Despite good reproducibility of analysis of the bone-component interface after cemented UKA, future studies are necessary to define the bone-component interface of symptomatic and asymptomatic patients.

Over the last two decades, many technological advances have aimed for control and improvement of surgical variables in order to 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. In **Chapter 6**, the results of our prospective, multicenter study were shown, focusing on midterm survivorship, modes of failure, and satisfaction with robotic-assisted medial UKA. In total, 384 patients (432 knees) were included at a mean follow-up of 5.7 years (range 5.0-7.7). Thirteen revisions were performed, resulting in 97% survivorship at midterm follow-up. The most common mode of failure was aseptic loosening. Of all unrevised patients, 91% was either very satisfied or satisfied with their current knee function. However, in spite of the use of robotic-assisted surgery, fixation failure remains a problematic issue with cemented implants, particularly in the younger as well as the obese population. These early survival results look promising and may be comparable to total knee arthroplasty (TKA) outcomes, but comparative studies with longer follow-up are needed.

In current orthopaedic practice, there are two different tibial designs available, all-polyethylene 'inlay' and metal-backed 'onlay' components with each distinct features. In **Chapter 7**, the functional outcomes of these two tibial UKA designs were assessed and compared to the outcomes of TKA at midterm follow-up. In this study, it was found that patients with a medial onlay UKA reported significant better overall functional outcomes when compared to those of medial inlay UKA. Similarly, patients with an medial onlay UKA obtained higher functional outcome scores than the TKA patients, while no differences were noted between patients receiving medial inlay UKA and TKA.

The young patient with end-stage osteoarthritis is difficult to treat, after failing conservative treatment, the most suitable surgical option remains controversial.

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Surgical concerns include accelerated wear due to higher activity levels as well as increased likelihood of need for multiple subsequent revision surgeries, though UKA has specific benefits over TKA, which may be of special interest for the young patients. To gain more insight in the younger population after knee replacement, a systematic review was conducted in **Chapter 8** to assess survivorship, functional outcomes and activity levels of medial UKA and TKA in patients less than 65 years of age. The main finding of this study was that good-to-excellent outcomes can be achieved with UKA and TKA in younger patients. The annual revision rate of medial UKA was higher compared to TKA (1.00 and 0.53, respectively), corresponding to an extrapolated 10-year survivorship of 90% and 94.7%, respectively. On the contrary, significantly larger range of motion and higher activity scores were observed following UKA than TKA at mid- to long-term follow-up. Overall functional outcome scores were equivalent after both procedures. Despite a moderate level of evidence, this review suggests that young age may not be a contraindication for either UKA or TKA.

In the previous chapters satisfaction with current knee function was obtained as an outcome measurement. **Chapter 9** provides insight into patient satisfaction with return to sports after UKA and to what type of activities patients return. This is important because indications for UKA have expanded and younger and more active patients undergo surgery currently. One hundred and sixty-four patients (179 UKAs) were included of which 81% participated in sports preoperatively, that increased to 90% after UKA. Eighty-three percent of the patients was satisfied with their ability to participate in sports postoperatively. The most common sports recorded after UKA were cycling (45%), swimming (38%), and stationary cycling (27%). Overall, 93.9% of patients was able to return to low impact sports, 63.9% to intermediate, and 32.7% to high impact sports. Moreover, satisfaction by the highest impact of preoperative sports was determined. Of the patients who participated in high impact sports preoperatively, 85.2% was satisfied with their restoration of sports ability, independent of the type they returned to. In addition, patients who participated in intermediate or low impact sports were satisfied in 86.0% and 95.2%, respectively. This study may offer valuable information to help manage patients' expectations regarding their ability to return to sports preoperatively based on demographics and type of preoperative sporting activities.

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NEDERLANDSE SAMENVATTING

The Role of Robotics in Unicompartmental Knee Arthroplasty – Imaging, Survival and Outcomes

In dit proefschrift worden verschillende aspecten besproken ten aanzien van de robot geassisteerde unicondylaire knieprothese (UKP), waarbij de focus ligt op patiënt selectie, de rol van beeldvorming en de klinische uitkomsten na operatie. In **Hoofdstuk 1** wordt er een algemene inleiding gegeven.

Om de klinische resultaten te verbeteren en het aantal complicaties van UKP te reduceren, zijn er strikte indicaties opgesteld evenals nieuwe technologieën geïmplementeerd. **Hoofdstuk 2** bevat een literatuuronderzoek dat verschillende facetten van de UKP belicht, onder andere worden de indicaties en contra-indicaties voor operatie besproken waarbij er specifiek aandacht is voor de leeftijd van de patiënt, body mass index, aanwezigheid van patellofemorale artrose, integriteit van de voorste kruisband en chondrocalcinosis. Ten tweede is er aandacht voor de verschillende fixatietechnieken (gecementeerd en ongecementeerd) en diverse UKP ontwerpen, fixed en mobile-bearing. Naast nieuwe fixatiestrategieën en UKP ontwerpen, zijn er tevens ontwikkelingen geweest op het gebied van chirurgische technieken de afgelopen jaren, waarbij het gebruik van de robot in opkomst is. Daarnaast is de literatuur ten aanzien van de redenen waarom UKP falen geanalyseerd; aseptische loslating, progressie van artrose, polyethyleen slijtage en onverklaarbare pijn zijn de meest voorkomende redenen. Wat betreft de geografische verschillen, in Azië en Europa, is er scepsis over het gebruik van robotica vanwege het onduidelijke belang van het optimaliseren van precisie in UKP, kosten, leercurve, verlengde operatietijd en risico's geassocieerd met preoperatieve beeldvorming met robottechnologie. In de Verenigde Staten zijn drie robotsystemen door de FDA goedgekeurd voor UKP, waarvan het MAKO-robotsysteem (Stryker Corp, Mahwah, NJ, VS) het grootste marktaandeel heeft.

Een van de selectiecriteria voor patiënten voor mediale UKP is een preoperatieve varusdeformatie van 15° of minder die gecorrigeerd kan worden naar neutraal tijdens lichamelijk onderzoek. Dit is gebaseerd op het feit dat het minder haalbaar wordt geacht om de mechanische beenas naar neutraal of bijna neutraal te herstellen gedurende de operatie als patiënten niet voldoen aan dit criterium. Een gevolg van een excessieve resterende varusdeformatie is een verhoogde druk in het mediale compartiment van de knie, wat uiteindelijk kan leiden tot falen van de UKP. In **Hoofdstuk 3** is de haalbaarheid van de beenas correctie getoetst bij UKP patiënten met grote preoperatieve

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varusdeformaties op basis van radiografische parameters. Bij 200 opeenvolgende robot geassisteerde mediale UKP patiënten met grote preoperatieve varus deviaties (≥7°), is de mechanische as (MAA) en convergentiehoek van de gewrichtsspleet (JLCA) gemeten op heup-knie-enkel röntgenfoto's. Het aantal patiënten dat postoperatief een optimale (≤4°) en acceptabele (5°-7°) mechanische beenas is berekend, daarnaast is er gekeken of de mate van correctie voorspelt kan worden met behulp van een geschatte MAA (eMAA, preoperatieve MAA–JLCA). In deze studie werd bij 98% van de patiënten de mechanische as hersteld naar een optimale (62%) of acceptabele (36%) postoperatieve beenas met het gebruik van robot assistentie. Er zijn studies die betogen dat een preoperatieve varusdeformatie bij geïsoleerde mediale OA voornamelijk afkomstig is van een voortschrijdende intra-articulaire deformatie. Bij de implantatie van de UKP wordt de intra-articulaire discongruentie opgeheven, waardoor de postoperatieve mechanische as verbetert. De geschatte mechanische as bleek een significante voorspeller te zijn om de haalbaarheid te evalueren van het bereiken van een optimale postoperatieve uitlijning (≤4°). In ons cohort had 78% van de patiënten met een geschatte mechanische as ≤4° varus een postoperatieve uitlijning binnen een vergelijkbaar bereik. Als de geschatte mechanische as 4° varus overschreed, werd een hogere frequentie van extra-articulaire deformaties opgemerkt, gemeten als mechanische laterale distale femorale hoek en mediale proximale tibiale hoek. In ons cohort werden meer tibiale deformaties waargenomen in de geschatte mechanische as >4° groep vergeleken met de ≤4° groep (respectievelijk 70% en 31%). Wanneer deze bevindingen worden gecombineerd met de significant lagere voorspelde kans op het bereiken van een optimale postoperatieve mechanische as, kan worden geconcludeerd dat in deze subgroep van patiënten andere behandelingen sterk overwogen moeten worden, zoals een valgiserende tibiakop osteotomie of distale femur osteotomie.

Het belang van preoperatieve beeldvorming is hiervoor besproken, daarnaast speelt radiologie een belangrijke rol in de follow-up van protheses. Anteroposterieure en laterale röntgenfoto's worden frequent verkregen na een operatie, waarbij verschillende kenmerken worden geobjectiveerd. **Hoofdstuk 4** beschrijft de incidentie van fysiologische femorale en tibiale radiolucencies na een gecementeerde UKP. Tevens is er onderzocht op welk tijdstip radiolucencies ontstaan en of er een correlatie bestaat met patiënt gerapporteerde functionele uitkomsten op korte termijn. Deze cohortstudie met 352 patiënten beschrijft een incidentie van femorale en tibiale fysiologische radiolucencies van respectievelijk 10,2% en 25,3%, waarvan 6,8% beide componenten betrof. Onze gegevens suggereren dat het tijdstip van het ontstaan van femorale radiolucencies (1,36 jaar) significant later is dan de tibiale radiolucencies (1,00 jaar). Patiënten met radiolucente lijnen rond de prothese rapporteerden vergelijkbare

functionele resultaten als de bijpassende cohortgroep zonder radiolucencies.

Eerdere studies hebben de diagnostische waarde van beeldvorming door magnetische resonantie (MRI) aangetoond voor het evalueren van patiënten die klachten houden na een gewrichtsvervangende operatie. Beeldartefacten kunnen echter nog steeds de beoordeling van bot- en omliggende weefsels beperken, met gebruik van een MR-sequentie met een variabele multi-acquisitie beeldcombinatie (MAVRIC) kunnen deze artefacten aanzienlijk worden gereduceerd bij metalen implantaten. De retrospectieve observationele studie in **Hoofdstuk 5** bevatte 55 opeenvolgende patiënten met symptomatische gecementeerde UKP, waarvan de overgrote meerderheid een beenmerg oedeempatroon (respectievelijk 71% en 75%) en fibreusmembraan (respectievelijk 69% en 89%) vertoonde ter plaatse van de femorale en tibiale interface. Ten tweede werd er geen verband gevonden tussen MRI-bevindingen en radiolucente lijnen op röntgenfoto's. MRI met de additie van de MAVRIC-sequentie kan een complementair hulpmiddel zijn voor het beoordelen van symptomatische UKPs, onder andere door het kwantificeren van afwijkingen op de bot-component interface, vooral in patiënten met röntgenfoto's zonder afwijkingen. Ondanks een goede reproduceerbaarheid van de analyse van de bot-component interface na gecementeerde UKP, zijn toekomstige studies nodig om de interface van symptomatische en asymptomatische patiënten te definiëren.

In de laatste twee decennia hebben veel technologische ontwikkelingen zich gericht op het controleren en optimaliseren van chirurgische variabelen om de overleving van UKP te verbeteren. Om die reden is robot geassisteerde chirurgie geïmplementeerd, dit maakt het mogelijk om een anatomische restauratie na te streven met een verbeterde weke delen balans, reproduceerbare uitlijning van de mechanische beenas, nauwkeurige implantaatpositie en herstel van natieve kniekinematica met UKP. In **Hoofdstuk 6** worden de resultaten van ons prospectieve, multicenteronderzoek getoond, gericht op de overleving op middellange termijn, redenen van revisie en patiënt tevredenheid na robot geassisteerde mediale UKP. In totaal werden 384 patiënten (432 knieën) geïncludeerd met een gemiddelde follow-up van 5,7 jaar (spreiding 5,0-7,7). Dertien patiënten zijn gereviseerd, wat resulteerde in een overleving van 97%. De meest voorkomende reden voor revisie was aspectische loslating. Van alle niet-gereviseerde patiënten was 91% (zeer) tevreden met de huidige kniefunctie. Ondanks het gebruik van robot gestuurde chirurgie blijft aseptische loslating een reëel probleem bij gecementeerde implantaten, met name bij de jongere en zwaarlijvige patiënt. Deze vroege overlevingsresultaten ogen veelbelovend en evenaren de resultaten van totale knieprotheses (TKP), maar vergelijkende studies met langere follow-up zijn noodzakelijk.

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In de huidige orthopedische praktijk zijn er twee verschillende tibiale componenten beschikbaar met elk afzonderlijke kenmerken; een volledig polyethyleen tibiale component oftewel 'inlay' en een tibiale component met een metalen basisplaat genaamd 'onlay'. In **Hoofdstuk 7** zijn de functionele uitkomsten van deze twee tibiale UKP componenten beoordeeld en vergeleken met de uitkomsten van TKP na middellange follow-up. De resultaten van deze studie lieten zien dat patiënten met een mediale onlay UKP significant betere functionele uitkomsten rapporteerden in vergelijking met mediale inlay UKP patiënten. Tevens scoorden patiënten met een mediale onlay UKP hogere functionele resultaten dan de TKP patiënten, terwijl geen verschillen werden waargenomen tussen de uitkomsten van mediale inlay UKP en TKP patiënten.

Het behandelen van een jonge patiënt met gevorderde gonartrose is vaak lastig, na gefaalde conservatieve therapie, blijft de keuze voor de meest geschikte chirurgische optie omstreden. Vanwege het hogere activiteitenniveau zal er mogelijk versnelde slijtage van de prothese optreden, evenals de noodzaak tot meerdere revisieoperaties gedurende het leven, daartegenover staat dat UKP specifieke voordelen heeft ten opzichte van TKP die van bijzonder belang kunnen zijn voor de jongere patiënt. Om meer inzicht in de jongere artrose populatie te krijgen, is in **Hoofdstuk 8** een systematisch literatuuronderzoek uitgevoerd om de overleving, functionele uitkomsten en activiteitenniveaus te beoordelen van mediale UKP en TKP patiënten jonger dan 65 jaar. De belangrijkste bevinding van deze studie was dat met zowel UKP als TKP goede tot uitstekende resultaten worden bereikt bij jongere patiënten. Het jaarlijkse revisiepercentage van mediale UKP was hoger dan TKP (respectievelijk 1,00 en 0,53), wat overeenkomt met een geëxtrapoleerde 10-jaars overleving van respectievelijk 90% en 94,7%. Anderzijds worden er significant grotere bewegingsuitslagen en hogere activiteitscores geobserveerd na UKP dan TKP tijdens middellange tot lange follow-up. De functionele uitkomsten waren na beide procedures gelijk bij patiënten jonger dan 65 jaar. Ondanks een matig niveau van bewijs suggereert deze review dat een jonge leeftijd geen contra-indicatie is voor een UKP of TKP.

In eerdere hoofdstukken van dit proefschrift is de tevredenheid met de huidige kniefunctie gebruikt als een uitkomstmaat. **Hoofdstuk 9** geeft inzicht in de patiënt tevredenheid met de postoperatieve sportparticipatie na een UKP, alsmede het type activiteiten welke worden uitgeoefend. Dit is belangrijk omdat de indicaties voor UKP zijn uitgebreid en steeds meer jongere en actievere patiënten een operatie ondergaan. Honderdvierenzestig patiënten (179 UKPs) werden geïncludeerd, waarvan 81% preoperatief een sport beoefende, dit percentage nam tot 90% postoperatief.

Drieëntachtig procent van de patiënten was tevreden met hun vermogen om postoperatief aan sport deel te nemen. De meest voorkomende sporten die na een UKP werden geregistreerd, waren fietsen (45%), zwemmen (38%) en stationair fietsen (27%). In totaal kon 93,9% van de patiënten terugkeren naar sporten met een lage impact, 63,9% naar gemiddelde impact en 32,7% naar hoge impact. Van de patiënten die preoperatief aan high impact sporten deelnamen, was 85,2% tevreden met hun herstel van sportvermogen, ongeacht het type waar men naar terugkeerde. Patiënten die sporten van gemiddelde of lage impact beoefenen waren tevreden in respectievelijk 86,0% en 95,2%. Deze studie kan waardevolle informatie bieden om reële verwachtingen te creëren met betrekking tot het vermogen om terug te keren naar sport op basis van demografie en het type preoperatieve sportactiviteiten.

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PhD PORTFOLIO

Name PhD student: Laura Jill Kleeblad

PhD period: 2016 – 2020

Name PhD Supervisor: Prof. dr. G.M.M.J. Kerkhoffs

1. PhD training		
	Year	Workload (Hours/ECTS)
Courses		
- Medical Statistics, Basic and Advanced	2015	1.0
- Good Clinical Practice	2015	0.75
Presentations		
- Feasibility of correcting mechanical axis in large varus deformities with unicompartmental knee arthroplasty.	2017	0.5
- Poster, Eastern Orthopaedic Association Annual Meeting, Miami, FL, United States of America		
- Mid-term Survivorship and Patient Satisfaction of Robotic-Assisted Medial Unicompartmental Knee Arthroplasty: A Multicenter Study.		
- Poster, European Knee Society, London, United Kingdom	2017	0.5
- Poster, American Academy of Orthopaedic Surgeons Annual Meeting, New Orleans, LA, United States of America	2018	0.5
- Poster, European Federation of National Associations of Orthopaedics and Traumatology, Barcelona, Spain	2018	0.5
- Long-term survivorship, radiologic and functional outcomes of operatively treated unicondylar tibial plateau fractures.		
- Presentation, American Academy of Orthopaedic Surgeons Annual Meeting, New Orleans, LA, United States of America	2018	0.5
- Do Preoperative Radiographic Patellofemoral Degenerative Changes and Malalignment Compromise Patellofemoral-Specific Outcome Scores following Fixed-Bearing Medial Unicompartmental Knee Arthroplasty?	2019	0.5
- Presentation, American Academy of Orthopaedic Surgeons Annual Meeting, Las Vegas, NV, United States of America		

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1. PhD training (continued)		
	Year	**Workload (Hours/ECTS)**
Presentations		
- Satisfaction with Return to Sports after Unicompartmental Knee Arthroplasty and What Type of Sports Are Patients Doing?	2019	0.5
- Presentation, American Academy of Orthopaedic Surgeons Annual Meeting, Las Vegas, NV, United States of America		
- Mid-term Survivorship and Patient-Reported Outcomes of Robotic-Arm-Assisted Partial Knee Arthroplasty: A Single-Surgeon Study of 1018 Knees	2019	0.5
– Presentation, American Academy of Orthopaedic Surgeons Annual Meeting, Las Vegas, NV, United States of America		
(Inter)national conferences		
- Nederlandse Orthopaedische Vereniging Jaarcongres, Den Bosch, The Netherlands	2016, 2020	2.0
- European Knee Society, London, United Kingdom	2017	0.75
- Eastern Orthopaedic Association Annual Meeting, Miami, FL, United States of America	2017	0.50
- American Academy of Orthopaedic Surgeons Annual Meeting 2018, New Orleans, LA, United States of America	2018	1.0
- American Academy of Orthopaedic Surgeons Annual Meeting 2019, Las Vegas, NV, United States of America	2019	1.0

2. Teaching		
	Year	**Workload (Hours/ECTS)**
Tutoring, Mentoring		
- Master thesis: Niels Laas; Computer Assisted Surgery, Hospital for Special Surgery, New York, NY, United States of America	2018	1.0
- Master thesis: Joost Burger; Orthopaedic Surgery, Spaarne Gasthuis, Hoofddorp, The Netherlands	2018	1.0
Other	2017	
- Reviewer for Journal of Arthroplasty, The Knee	– 2020	2.0

3. Parameters of Esteem	
	Year
Grants	
- Stryker Research Grant	2018
- Anna Fonds	2016
Awards and Prizes	
- Feasibility of correcting mechanical axis in large varus deformities with unicompartmental knee arthroplasty.	2017
- Awarded as Best Conference Paper at Limb Lengthening and Reconstruction Society Conference, Park City, UT, United States of America.	

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'Happiness does not come from doing easy work, but from the afterglow of satisfaction that comes after the achievement of a difficult task that demanded our best' – Theodore Isaac Rubin. This achievement is only made possible by the help of many others, and therefore, I would like to thank several people who helped me during my PhD.

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again in the future.

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Dear Jelle, what a great time we had in New York. You showed me the principles of research, from writing a study proposal, performing statistical analysis, to writing a manuscript. Thank you for all the guidance you have provided me, which has eventually led to this thesis. Besides work, we played field hockey in New York, where we met a lot of fun people, including Rhian. I am happy I can still call you my colleague, both pursuing our goal of becoming an orthopaedic surgeon.

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To all the orthopaedic surgeons and (former) residents of the Alrijne ziekenhuis, thank you for the educational, but also very fun time. I have enjoyed working with you all a lot, spending many hours in the OR.

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To all the orthopaedic surgeons and (former) residents of the ROGO NoordWest, thank you for the support over the last few years. I started as a medical student, who has the honor to return as a resident within this ROGO, and I am very excited for the upcoming years. The skiing trip last March was awesome, even with a broken clavicle, I cannot wait for next year.

To all the surgeons and (former) residents of the Noordwest Ziekenhuisgroep, you have been an amazing group of people with an extraordinary attitude. I have felt very welcome as an orthopaedic resident, which had to learn a lot about general surgery. You have provided me the best groundwork for the rest of my surgical career, thank you. The team weekend in Scheveningen was so much fun with all of you. Moreover, Hermien, Kees-Jan and Alexander, I greatly appreciate you supporting me to finalize my thesis during my time in Alkmaar.

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Dear Pieter, almost five years ago we started our orthopaedic career in a research office at the Spaarne Gasthuis. Each following our own path, both resulting in a residency spot within the ROGO-NW. We started our residency in Alkmaar, which was incredible, so many amazing experiences in and outside of the hospital. Thank you for teaching me to sometimes take a step back and enjoy. I cannot wait for the upcoming years, as we get to continue our career in orthopaedic surgery.

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CURRICULUM VITAE

Laura Jill Kleeblad was born on September 19th 1990 In Naarden, the Netherlands. After graduating from 't Willem de Zwijger College Bussum, she moved to the United States of America to study pre-medicine and play field hockey at the University of Connecticut. During this year, both academic as well as sporting achievements were obtained, resulting in the BIG EAST championship and finishing the season 8th of the country with her team. Following this year, she got accepted to medical school at the Vrije Universiteit of Amsterdam and continued playing field hockey at Hurley Dames 2.

Her interest in Orthopedic Surgery started during her senior internship at the Spaarne Gasthuis Hoofddorp, which was followed by a research internship in which she performed a validity study of an ankle measuring device under the supervision of Dr. D.A. Vergroesen. During her internships, she was offered a position as a research fellow at Hospital for Special Surgery in New York by Dr. A. van Noort and Dr. H.A. Zuiderbaan. In 2015, she obtained her medical degree after which she started working as an orthopaedic resident not in training at the Alrijne Ziekenhuis Leiderdorp. After eight months, she moved to New York City and started as a research fellow in Orthopaedic Surgery at the Computer Assisted Surgery Department at the Hospital for Special Surgery under the supervision of Dr. A.D. Pearle. Her research focused mostly on radiographic and patient-reported outcomes after robotic-assisted medial unicompartmental knee arthroplasty. In 2018, she managed to obtain a large industry grant to enable future fellows to continue research in the field of robotic-assisted surgery.

In June 2018, she returned to Amsterdam to start her orthopaedic residency training. She started her training as a resident in general surgery at the Noordwest Ziekenhuisgroep Alkmaar under the supervision of Dr. W.H. Schreurs and Dr. K.J. Ponsen. Since January 2020, she has continued her training as a resident in orthopaedic training at the Spaarne Gasthuis Hoofddorp under the supervision of Dr. A. van Noort.