# UKA

**BREAKING THE MOLD OF THE ONE-SIZE-FITS-ALL PARADIGM**

Gaby V. ten Noever de Brauw

# UNICOMPARTMENTAL KNEE ARTHROPLASTY

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# UNICOMPARTMENTAL KNEE ARTHROPLASTY

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# GENERAL INTRODUCTION

# Chapter 1

## Introduction and thesis outline

## Knee osteoarthritis

The knee, which is the largest and arguably one of the most mechanically complex joints in the human body, consists of two main articulations: the medial and lateral tibiofemoral joint and the patellofemoral joint. Owing to its complex anatomical structure and the demands of bearing substantial loads, the knee is susceptible to both traumatic injuries and degenerative changes. Knee osteoarthritis (OA) is a prevalent degenerative disease characterized by the progressive deterioration of articular cartilage and subchondral bone within the tibiofemoral compartment, the patellofemoral compartment, or both. In its advanced stages, this degenerative process typically manifests as (chronic) pain, joint stiffness, mechanical instability, and a reduced range of motion, all of which contribute to significant functional impairment and an overall reduced quality of life.

Isolated OA, in which the damage is predominantly confined to a single compartment (Figure 1, p. 19), is relatively rare compared to generalized OA, which involves the extensive deterioration of cartilage in multiple compartments of the knee joint. Medial OA represents the predominant form of isolated compartment OA, typically associated with varus alignment and a characteristic anteromedial wear pattern of the tibial plateau, affecting approximately 27% of the osteoarthritic population[1]. In contrast, isolated lateral compartment OA, generally associated with valgus alignment, represents only 5% of cases. The prevalence of these conditions can increase up to 50% and 10%, respectively, when concomitant involvement of the patellofemoral compartment is not accounted for.

Considering the rising global prevalence and economic burden of symptomatic knee OA, driven by increasing life expectancy and escalating obesity rates, there is an imperative need for efficacious therapeutic interventions[2]. Additionally, emerging evidence indicates that younger individuals, particularly those with a history of previous joint injuries, are increasingly susceptible to knee OA[3, 4]. These younger individuals, who often have higher functional demands, require interventions that provide both durable outcomes and support a return to high levels of physical activity, driving a continuous need for innovation. In the setting of isolated compartment knee OA, where conservative treatments have proven insufficient, several well-established surgical interventions are available. Compared to generalized OA, where total knee arthroplasty (TKA) is often deemed the most suitable intervention, isolated compartment OA allows for the consideration of less invasive alternatives, including unicompartmental knee arthroplasty (UKA). A procedure indicated for individuals presenting with localized articular pathology confined to a single compartment of the knee joint.

**Historical development of unicompartmental knee arthroplasty**

The concept of selectively resurfacing the affected compartment to address isolated compartment OA, as opposed to the entire knee joint, originated in the early 1950s[5]. Proponents argued that preserving the unaffected compartment and cruciate ligaments allows UKA to replicate the physiological knee kinematics and proprioceptive function more accurately, thereby providing a more natural sensation of the knee. However, despite the promising theoretical advantages of UKA, initial results were disappointing, which temporarily hindered its development and application[6-8]. A significant factor contributing to these suboptimal outcomes and high failure rates was the inappropriate selection of patients. In an effort to increase survivorship and improve outcomes, Kozinn and Scott proposed a set of highly restrictive criteria for patient selection, which became fundamental in refining the indications for UKA and its efficacy as a treatment for isolated compartment OA[9].

Initial 1989 Kozinn and Scott criteria for unicompartmental knee arthroplasty[9]

- Isolated medial or lateral compartmental disease (no patellofemoral OA)
- Low to medium physical activity levels and not performing heavy labor
- Preoperative pain in rest should be minimal
- Age >60 years and weight <82 kg (180lb)
- Intact ACL
- Noninflammatory osteoarthritis
- Angular deformity not exceeding 10° of varus or 15° of valgus
- Correctable (varus) deformity (<5°) and flexion contracture <5°
- Preoperative range of motion >90°

Over the past decades, UKA has continued to evolve. Improvements in surgical techniques, implant designs, and technological innovations have collectively improved both the efficacy and reliability of the procedure. Modern UKA now features a variety of options, including both mobile and fixed bearing designs, as well as cemented and cementless fixation methods. Moreover, while their clinical efficacy and cost-effectiveness have yet to be fully validated, the integration of robotic-assisted and computer-navigated systems has demonstrated potential to improve functional outcomes while simultaneously enhancing precision and accuracy of implant placement during UKA[10-13]. Consequently, traditional indications have been thoroughly reevaluated, resulting in the retraction of several formerly accepted contraindications for UKA[14]. Currently, patient characteristics such as age, body mass index, level of physical activity, chondrocalcinosis, and the presence of patellofemoral osteoarthritis are no longer considered as absolute contraindications for UKA[14, 15]. This reappraisal has expanded the eligibility for UKA, now considered appropriate for approximately 20% to 50% of patients requiring knee arthroplasty[16, 17]. Nonetheless, while UKA has evolved as a highly effective minimally invasive alternative to TKA and corrective osteotomies, it continues to be underutilized, with adoption rates varying significantly across Western countries, currently ranging from a mere 4% to 20% of all primary knee arthroplasties[18-23].

The underutilization of UKA in appropriately indicated cases is attributable to several factors, including persistent concerns regarding its higher reported all-cause revision rates, the lack of familiarity and knowledge among surgeons regarding the optimal criteria for patient selection, and the procedure's inherently complex technical demands. While revision rates are universally recognized as a critical metric for evaluating the success of joint replacement surgeries, their application as an objective metric to directly compare TKA and UKA may be inherently misleading, given that UKA is generally more amenable to revision in response to equivalent clinical outcomes[24]. Despite these nuances, these challenges continue to impede the broader acceptance and implementation of UKA in the management of symptomatic isolated compartment OA, which is regrettable considering the substantial advantages of UKA when utilized in appropriately selected patients.

## Advantages and pitfalls associated with unicompartmental knee arthroplasty versus total knee arthroplasty

+ Ligament preserving procedure: UKA preserves the cruciate ligaments, thereby restoring normal ligament-driven knee kinematics and providing a more physiologically, natural sensation of the knee[25]
+ Reduced perioperative blood loss and surgical time: UKA results in significantly lower perioperative blood loss and reduced operation time compared to TKA[26, 27]
+ Superior postoperative range of motion: UKA is associated with a greater postoperative range of motion relative to TKA[28]
+ Fewer postoperative complications: UKA is associated with a lower incidence of postoperative complications compared to TKA, including thromboembolism, myocardial infarction, stroke, infection and mortality[29, 30]
+ Shorter hospital stays and fewer readmissions: UKA is associated with a reduced length of hospital stay and fewer readmissions compared to TKA[29, 31, 32]
+ Lower postoperative pain scores: UKA is associated with less postoperative pain and a reduced requirement for opioid analgesics in comparison to TKA[33, 34]
+ Lower risk of revision for periprosthetic joint infections: TKA has a higher periprosthetic joint infection revision risk[35]
+ Minimally invasive: the minimally invasive nature of UKA requires a smaller incision compared to TKA, while simultaneously minimizing extensive releases of soft tissues
+ Bone stock preservation: UKA allows for more bone stock preservation, enhancing the feasibility of potential future revision surgery, while preserving a greater extent of the anatomical and native integrity of the knee
+ Improved functional outcomes: UKA is associated with higher activity scores, as well as higher return to sport (range 74% to 100% for UKA vs 36% to 89% for TKA) and return to work (73% vs 48% within 3 months) rates compared to TKA[36-38]
+ Kneeling ability: UKA shows higher postoperative kneeling ability compared to TKA[39]
+ Ease of revision surgery: UKA is usually easier to revise than TKA

- Higher revision rates: UKA is associated with higher revision rates compared to TKA[29, 40, 41]
- Technical demands and learning curve: UKA is technically more demanding compared to TKA and presents a more pronounced learning curve[42, 43]
- Optimal usage rate requirement (i.e., the proportion of unicompartmental knee arthroplasty procedures performed relative to the total number of knee arthroplasty procedures): the clinical outcomes of UKA are inherently correlated with its usage rate, with the most favorable results observed at a UKA usage rate between 40% and 60%. It is recommended to maintain a usage rate of at least 20%, as lower rates are associated with higher revision rates[44-46]

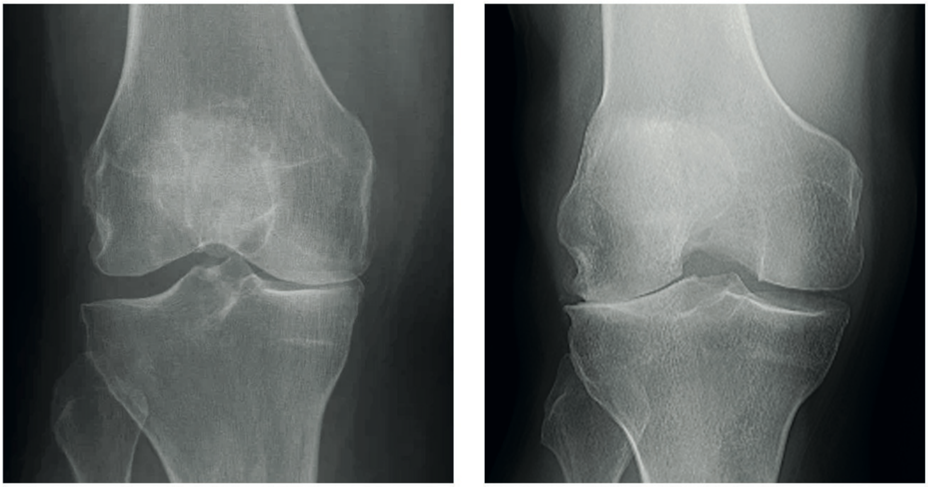

**Figure 1:** On the left, an example of isolated medial compartment osteoarthritis with significant medial joint space narrowing ("bone-on-bone" osteoarthritis) and subchondral sclerosis. On the right, an example of end-stage isolated lateral compartment osteoarthritis on a Rosenberg view radiograph, with pronounced narrowing of the lateral joint space and mild osteophyte formation confined exclusively to the lateral compartment.

## Thesis outline

This thesis aims to refine the prevailing perspectives on UKA by elucidating various determinants that influence patient suitability and by providing novel insights into the diverse manifestations of isolated compartment OA. Through these objectives, this work aspires to facilitate the wider adoption and acceptance of UKA, while simultaneously contributing to the ongoing transition from generalized approaches to patient selection and OA management to more nuanced, tailored frameworks that account for the unique individual characteristics of patients with symptomatic isolated compartment knee OA.

*Patient suitability and implant selection*

The success of UKA is dependent on both patient-related and surgical factors, each of which play a fundamental role in ensuring optimal outcomes and long-term durability of the procedure. Recognized key factors contributing to successful UKA include, but are not limited to, appropriate patient selection, comprehensive preoperative planning, the use of a well-designed implant with the appropriate fixation technique, and the surgeon's experience. Within this context, the prerequisites for achieving successful outcomes following UKA are heavily influenced by the distinctive, patient-specific characteristics of individuals. Therefore, the overarching aim of the first part of this thesis specifically centers around the objective to identify patient-related factors that influence patient eligibility and predict successful outcomes in UKA.

A critical consideration during preoperative planning involves the choice of fixation, which is significantly influenced by both the surgeon's preferences and individual patient characteristics. Cemented fixation has traditionally been considered the gold standard in UKA, praised for its immediate stabilization and reliable long-term outcomes[15]. Nevertheless, cementless fixation offers several proposed advantages over cemented designs, provided it is utilized in carefully selected patients[47]. **Chapter 2** of this thesis provides a comprehensive evaluation of the suitability of both fixation techniques across diverse age groups using data from the Dutch Arthroplasty Register. This chapter specifically examines the impact of age on the implant survival and modes of failure of both cemented and cementless UKA, aiming to provide a nuanced perspective on whether age-related factors should be a determining factor in selecting the most suitable fixation technique for individual patients.

Patient selection in clinical practice predominantly focuses on physical and anatomical criteria, frequently marginalizing the significant impact of psychological and emotional factors on a patient's surgical readiness. Effective postoperative recovery extends beyond mere physical rehabilitation, necessitating the establishment of realistic patient expectations and psychological resilience, elements that are pivotal for achieving favorable clinical outcomes. **Chapter 3** of this thesis evaluates how psychological factors, including pain catastrophizing, anxiety, and depression, impact subjective outcomes following UKA. This chapter aims to elucidate the extent to which these psychological factors may predispose patients to suboptimal postoperative outcomes, thereby facilitating the early identification and potential management of those at elevated risk.

Extra-articular deformities, whether arising from post-traumatic events or developmental origins, are frequently observed in patients being considered for UKA. Since knee OA primarily manifests as an intra-articular disease, the coexistence of extra-articular deformities has provoked ongoing discussions regarding their potential influence on the surgical outcomes of UKA. In the absence of definitive consensus regarding their clinical relevance, many surgeons adopt a cautious and often conservative stance when assessing the suitability of UKA in patients with advanced knee OA and pronounced extra-articular bony deformities. This cautionary approach may inadvertently contribute to the unjustified exclusion of a substantial proportion of patients who might otherwise derive considerable benefit from UKA. **Chapter 4** of this thesis specifically evaluates the suitability of UKA in patients presenting with extra-articular proximal tibial varus deformities. This chapter endeavors to enhance awareness among surgeons regarding the implications of these deformities on the efficacy of UKA, thereby aiming to improve the quality of clinical decision-making in complex clinical cases.

*Return to sport and physical function*

As surgical indications are expanding to younger and more physically active patients, there is a growing demand for interventions that facilitate a return to optimal or “pre-disease” levels of physical function. While UKA has been shown to outperform TKA in terms of return to sport[38, 48, 49], the relative efficacy of these procedures in facilitating a return to sport across varying levels of physical impact remains unclear. **Chapter 5** of this thesis provides an in-depth review of the return to sport outcomes following TKA, UKA and patellofemoral arthroplasty, with a particular emphasis on differentiating the outcomes for low-, moderate- and high-impact sports. In doing so, this chapter aims to build upon the existing body of knowledge by providing a more refined comparison of these procedures in the context of various levels of physical demands.

The lateral manifestation of unicompartmental knee OA is relatively rare and often assessed within the broader context of medial unicompartmental knee OA. Consequently, there exists a notable underrepresentation of literature specifically addressing isolated lateral OA, the unique surgical interventions used to address it, and their effectiveness in restoring athletic performance following surgery. **Chapter 6** of this thesis systematically reviews the best available evidence on the return to sport outcomes following lateral UKA, with a particular emphasis on comparing these outcomes with those achieved with distal femoral osteotomy as treatment for lateral OA. Collectively, these chapters aim to guide the establishment of informed and realistic expectations among both surgeons and patients regarding the anticipated return to physical function following the diverse range of surgical interventions available for managing isolated compartment knee OA.

*Phenotypic manifestations of isolated compartment knee osteoarthritis*

The achievement of optimal lower limb alignment has historically been considered as one of the primary and most fundamental objectives in knee arthroplasty. Since its early development, aligning the knee in a mechanically neutral position has been standard practice, reflecting the prevailing assumption that a standardized, one-size-fits-all approach would yield the most predictable and favorable outcomes. However, recent evidence has challenged the universal applicability of the widespread implementation of these generalized approaches. Critics highlight the potential shortcomings of these uniform strategies, arguing that the rigid adherence to standardized protocols may overlook the significant individual anatomic variations among patients. In response to these concerns, there has been a burgeoning interest in developing more nuanced, patient-specific alignment strategies, which aim to better accommodate the unique anatomical features of patients by striving to restore the knee to its pre-arthritic state and its inherent soft tissue balance[50, 51].

Over the past decade, substantial progress has been made in the field of personalized knee arthroplasty, with researchers having devoted considerable attention towards examining the phenotypic osteoarthritic expressions in patients with generalized knee OA[52-54]. These efforts have focused on characterizing the inter-patient variability and phenotypic manifestations in both healthy and osteoarthritic knees, with the ultimate aim of determining whether individualized alignment strategies tailored to specific phenotypes offer superior clinical outcomes compared to conventional, standardized approaches. Preliminary findings from subsequent research indicate that restoring the patient's specific knee phenotype may indeed yield improved outcomes[55, 56]. Nevertheless, despite the theoretical allure of these so-called "personalized approaches", their clinical advantages have yet to be conclusively demonstrated in empirical evidence.

The overarching aim of the final part of this thesis seeks to extend this line of research to patients affected by isolated compartment OA - an area that has not been previously investigated - thereby serving as foundation for the exploration of novel innovative approaches aimed at delivering personalized care. **Chapter 7** and **Chapter 8** of this thesis are aimed to evaluate the phenotypic manifestations of isolated anteromedial OA using both the Coronal Plane Alignment of the Knee (CPAK) classification and the functional knee phenotype system[53, 54]. In these chapters, particular attention is devoted to gender-specific and age-related differences in the phenotypic manifestations and anatomical locations of deformities, while also investigating whether phenotypic diversity holds significant relevance when aiming to restore pre-arthritic alignment. As a continuation of the preceding chapters, **Chapter 9** and **Chapter 10** extend this evaluation to patients with isolated lateral compartment OA. In Chapter 10 the first preliminary attempt was made to investigate whether phenotypic restoration is associated with improved outcomes following lateral UKA, seeking to establish the groundwork for further research into the clinical significance of phenotype-based approaches.

Finally, a general discussion including conclusions and future perspectives, followed by a succinct summary that provides answers to the guiding questions of this thesis, are presented in **Chapter 11** and **12**.

## Guiding questions outlined in this thesis

The forthcoming chapters of this thesis are designed to provide answers to the following questions:

- Chapter 2: *"How do survival rates and failure patterns compare between cemented and cementless medial UKA across different age demographics, and should age be a determinative factor in selecting the most suitable fixation technique for individual patients?"*
- Chapter 3: *"How do psychological factors influence subjective outcomes following UKA, and should preoperative psychological status be a critical factor in the decision to proceed with UKA?"*
- Chapter 4: *"Does the presence of an extra-articular tibial varus deformity adversely affect outcomes following fixed-bearing medial UKA, and should caution be exercised when considering UKA in patient with excessive preoperative deformities?"*
- Chapter 5: *"What are the anticipated outcomes regarding return to sport and physical function following TKA, UKA and patellofemoral arthroplasty, and does one procedure demonstrate superior efficacy in achieving postoperative physical function over the other?"*
- Chapter 6: *"What outcomes can be expected in terms of physical performance and return to sport following lateral UKA and distal femoral osteotomy?"*
- Chapter 7: *"To what extent do knees affected by anteromedial OA display uniform characteristics, and how are phenotypic expressions differentiated by gender and age?"*
- Chapter 8: *"Which functional knee phenotypes are observed in knees with anteromedial OA, and is consideration of phenotypic variation of importance when aiming to restore pre-arthritic alignment?"*
- Chapter 9: *"What is the extent of phenotypic diversity among patients with isolated lateral compartment OA, and how are the specific anatomical locations of extra-articular deformities within these knees distributed in relation to gender and age?"*
- Chapter 10: *"In the context of isolated lateral compartment OA, is there a particular preoperative knee phenotype associated with superior outcomes, and does phenotypic restoration following lateral UKA yield superior postoperative outcomes?"*

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# PATIENT SUITABILITY AND IMPLANT SELECTION

# Chapter 2

# Distinct age-related modes of failure in cemented and cementless Oxford medial unicompartmental knee arthroplasty

## Results from 25,762 patients in the Dutch Arthroplasty Register

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**Abstract**

**Aims:** the primary objective of this study was to compare short-term implant survival between cemented and cementless fixation for the mobile-bearing Oxford medial unicompartmental knee arthroplasty (UKA) across various age groups. The secondary objectives were to compare modes of failure and to evaluate patient-reported outcomes.

**Methods:** a total of 25,762 patients, comprising 8,022 cemented (31.1%) and 17,740 cementless (68.9%) medial UKA cases, were included from the Dutch Arthroplasty Register. Patient stratification was performed based on age: < 50 years, 50 to 59 years, 60 to 69 years, and ≥ 70 years. Survival rates and hazard ratios were calculated. Modes of failure were described and postoperative change in baseline for the Oxford Knee Score and numerical rating scale for pain at 6 and 12 months' follow-up were compared.

**Results:** the 2.5-year implant survival rate of cementless UKA was significantly higher compared to cemented UKA in patients aged younger than 60 years (age < 50 years: 95.9% (95% CI 93.8 to 97.3) vs 90.9% (95% CI 87.0 to 93.7); p = 0.007; and 50 to 59 years: 95.6% (95% CI 94.9 to 96.3) vs 94.0% (95% CI 92.8 to 95.0); p = 0.009). Cemented UKA exhibited significantly higher revision rates for tibial loosening (age < 50 and 60 to 69 years), while cementless UKA was associated with higher revision rates for periprosthetic fractures (age ≥ 60 years). Patient-reported outcomes were similar between both fixation techniques, irrespective of age.

**Conclusion:** cementless fixation resulted in superior short-term implant survival compared to cemented fixation among younger patients undergoing Oxford mobile-bearing medial UKA. Distinct failure patterns between fixation techniques emerged across various age groups, with revisions for tibial loosening being associated with cemented UKA in younger patients, while revisions for periprosthetic fractures were specifically identified among elderly patients undergoing cementless UKA.

## Introduction

The continuous refinement of surgical techniques, the introduction of new implant designs, enhanced instrumentation, and careful patient selection, collectively contribute to the numerous advantages that unicompartmental knee arthroplasty (UKA) offers over total knee arthroplasty (TKA) for managing isolated compartment knee osteoarthritis (OA).[1, 2]

Accurate implantation is critical in UKA.[3] While UKA components have traditionally been fixated using cement, cementless UKA systems have become increasingly popular due to their potential for superior durability, which relies on biological fixation through osseointegration rather than cemented fixation.[4-7] Potential benefits of cementless fixation in mobile-bearing UKA include the avoidance of cement-related complications, reduction of radiolucencies, reduced surgical time and lower associated costs.[4, 8, 9]

In recent decades, the number of young and active patients undergoing UKA, who require firm long-lasting fixation, has increased. The success of osseointegration and subsequent bone-implant fixation in cementless UKA depends on good bone quality, which is influenced by factors such as age.[10-13] As a result, cementless implants were generally reserved for younger patients with adequate bone quality. Conversely, older patients often exhibit inferior bone quality characterized by lower bone mass density, making the use of cemented UKA systems potentially preferable within this group.[10, 11, 14] However, the effect of age on the survival of both cemented and cementless UKA and the choice between both fixation techniques in different age groups remains an underexplored subject.

The primary objective of this study was to compare the short-term implant survival between cemented and cementless fixation for the mobile-bearing Oxford medial UKA across various age groups. The secondary objectives were to compare modes of failure and patient-reported outcomes (PROMs) between both fixation techniques across various age groups. Working on the premise that sufficient bone quality is required for effective biological fixation, we hypothesized that implant survival is influenced by fixation type, with age potentially acting as a modifying factor.

## Methods

*Study design*

This is a retrospective cohort study of prospectively collected data. Data were obtained from the national Dutch Arthroplasty Register (LROI), which was established by the Dutch Orthopaedic Association. This registry contains a comprehensive national repository of information pertaining to arthroplasty procedures performed within the Netherlands, encompassing patient demographic details, implant specifications, surgical techniques, and pre-, intra- and postoperative variables. Informed consent of patients is obtained through the use of an opt-out system. The LROI achieves complete coverage of all hospitals in the Netherlands, with data completeness reaching 99% for primary knee arthroplasties and 98% for knee revision arthroplasties in the year 2022.[15]

*Study sample*

The Oxford medial UKA is prominently recognized as one of the most frequently utilized UKA implants worldwide, as evidenced by data from National Joint Registries.[15-19] Alongside the decision between cementless and cemented implants, consideration must be given to the type of bearing system employed, with cementless implants predominantly involving mobile-bearing systems, whereas cemented implants offer both mobile-bearing and fixed-bearing systems. To maintain consistency and minimize confounding variables related to distinct implant designs and bearing types, this study focused exclusively on the Oxford mobile-bearing UKA system. Thus, the current study retrieved data on all primary cemented and cementless Oxford medial UKA procedures performed for the indication of OA between January 2014 and December 2022 from the LROI. All patients received the same cementless mobile-bearing UKA implant or cemented mobile-bearing UKA implant (Oxford, Zimmer Biomet, Bridgend, United Kingdom). During the study period, there were no significant modifications in the instrumentation used for the implantation of both systems. Patient characteristics including age, sex, body mass index (BMI) and smoking status were obtained. Additionally, for each surgical procedure, data were collected on the American Society for Anesthesiologist (ASA) grade, Charnley score, previous surgery status (i.e., any previous surgical procedure to the operative knee), revision status, and reason(s) for revision.

*Age groups*

Patients were classified into the following distinct age groups: < 50 years, 50 to 59 years, 60 to 69 years, and >70 years. Due to a significant interaction between fixation and age ($p$ = <0.001), the analysis was stratified by age.

*Implant survival and modes of failure*

This study predominantly concentrated on the 2.5-year implant survival and revisions that occurred during the first 2.5-year follow-up as the primary outcome of interest, given the prevailing understanding that the migration of cementless components typically occurs within the initial months following surgery.[6] Implant survival was defined as the duration from initial implantation to the first implant revision procedure for any cause. Revision surgery, defined as any procedure involving exchange, removal, and/or addition of one or more primary medial UKA components, is reported in the LROI database through revision forms completed by surgeons. Patients who died during the study period, and therefore did not complete the full 2.5-year follow-up were treated as censored in the survival analyses. Data including information about the patient, date of revision, predefined reasons for revision, and type of revision were obtained from the LROI.

*Patient-reported outcomes*

To evaluate the association between fixation technique and patient-reported outcomes within distinct age groups, PROMs collected at baseline and at six and 12-months' follow-up, were compared. PROMs included the Oxford Knee Score (OKS) and the Numeric Rating Scale (NRS) for pain during both rest and activity. The OKS is scaled from 0 (indicating the worst possible knee-related function and pain) to 48 (representing excellent knee function and absence of pain). The NRS for pain during rest and activity is scaled from 0 (no pain) to 100 (worst imaginable pain).

*Statistical analyses*

Descriptive statistics were used to summarize demographics and PROMs by fixation technique within different age groups. Kaplan-Meier survival rates with 95% confidence intervals (95% CIs) were calculated to assess the implant survivorship of both cemented and cementless medial UKA across different age groups, generating Kaplan-Meier curves with 95% CIs. Log-rank tests were used to compare the 2.5-year implant survival between fixation techniques across different age groups. Univariate and multivariable Cox proportional hazard models were conducted to crude and assess adjusted hazard ratios (HRs) for the risk of revision between fixation techniques. Adjustments were made for sex, ASA grade, BMI, and Charnley score. Proportional hazard assumptions were assessed using Schoenfeld's tests. Modes of failure were described by fixation technique and stratified by age, with comparative analyses conducted using either a chi-square test or Fisher's exact test, as appropriate.

Pre- to postoperative change in PROMs during the first 12 months postoperatively were compared between fixation technique and stratified by age using linear mixed model (LMM) analyses. Adjusted differences were calculated, with adjustments made for sex, ASA grade, BMI, Charnley score, and previous surgery. The level of significance was set at 0.05 for all analyses, and statistical analyses were performed using SPSS v. 26 (IBM, USA) and R v. 4.2.2 (R Foundation for Statistical Computing, Austria).

## Results

A total of 25,762 primary cemented and cementless Oxford mobile-bearing medial UKAs performed between 2014 and 2022 were included in this study, comprising 8,022 cemented (31.1%) and 17,740 cementless (68.9%) UKA cases. Patients aged younger than 60 years comprised 7,423 cases (28.8%), whereas those aged 60 years and above accounted for 18,339 of cases (71.2%). The mean age was 64.7 ± 8.7 years, the mean BMI was 29.2 ± 4.5 kg/m$^2$, and the minority of patients were male (n = 11,632; 45.0%). The demographics of all patients per age group are presented in Table 1.

**Table 1.** Pre- and intraoperative patient demographic details

| Variable | Total | < 50 years | | 50 to 59 years | | 60 to 69 years | | ≥ 70 years | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cemented | Cementless | Cemented | Cementless | Cemented | Cementless | Cemented | Cementless |
| No. knees | 25,762 (100%) | 311 (33.1%) | 628 (66.9%) | 2,073 (32.0%) | 4,411 (68%) | 3,299 (31.7%) | 7,113 (68.3%) | 2,339 (29.5%) | 5,588 (70.5%) |
| Age (y) | 64.7 ± 8.7 | 46.7 ± 2.4 | 46.8 ± 2.4 | 55.4 ± 2.8 | 55.4 ± 2.7 | 64.4 ± 2.8 | 64.5 ± 2.8 | 74.9 ± 4.2 | 74.8 ± 4.0 |
| Gender, males | 11,632 (45.0%) | 108 (34.7%) | 200 (31.8%) | 869 (41.9%) | 1,914 (43.4%) | 1,519 (46.0%) | 3,414 (48.0%) | 1,044 (44.6%) | 2,564 (45.9%) |
| BMI (kg/m$^2$) | 29.2 ± 4.5 | 30.8 ± 5.0 | 30.8 ± 5.0 | 30.4 ± 4.9 | 30.3 ± 4.7 | 29.2 ± 4.3 | 29.1 ± 4.5 | 28.3 ± 4.1 | 28.1 ± 4.1 |
| Smoking | 2,262 (8.8%) | 45 (14.5%) | 91 (14.5%) | 285 (13.7%) | 583 (13.2%) | 320 (9.7%) | 614 (8.6%) | 99 (4.2%) | 225 (4.0%) |
| ASA | | | | | | | | | |
| I | 4,642 (18.0%) | 97 (31.2%) | 206 (32.8%) | 449 (24.1%) | 1,074 (24.4%) | 568 (17.2%) | 1411 (19.9%) | 225 (9.6%) | 560 (10.0%) |
| II | 17,308 (67.2%) | 192 (61.7%) | 384 (61.6%) | 1,332 (64.3%) | 2,934 (66.6%) | 2257 (68.5%) | 4824 (67.9) | 1,530 (65.4%) | 3,852 (68.9%) |
| III to IV | 2,804 (14.8%) | 22 (7.1%) | 22 (7.1%) | 241 (11.6%) | 400 (9.1%) | 471 (14.3%) | 870 (12.2%) | 584 (25.0%) | 1,175 (21.0%) |
| Charnley | | | | | | | | | |
| A | 12,585 (48.8%) | 192 (63.2%) | 336 (53.8%) | 1,183 (58.1%) | 2,137 (48.9%) | 1,738 (53.4%) | 3,306 (46.9%) | 1,211 (52.5%) | 2,479 (44.8%) |
| B1 | 8,139 (31.6%) | 78 (25.7%) | 200 (32.1%) | 564 (27.7%) | 1,484 (34.0%) | 984 (28.7%) | 2,369 (33.6%) | 622 (26.9%) | 1,870 (33.8%) |
| B2/C | 4,763 (18.5%) | 34 (11.2%) | 88 (14.1%) | 290 (14.2%) | 745 (17.1%) | 569 (17.5%) | 1,381 (19.6%) | 475 (20.6%) | 1,180 (21.3%) |
| Previous surgery † | 5,998 (23.0%) | 162 (52.1%) | 226 (36.0%) | 733 (35.4%) | 1,209 (27.4%) | 854 (25.9%) | 1,624 (22.8%) | 372 (15.9%) | 817 (14.6%) |

Patient demographics are given in mean ± SD, or numbers and frequencies (%) for the entire cohort and stratified by age and fixation technique. *ASA,* American Society of Anesthesiologists; *BMI,* Body Mass Index.
† Previous surgery indicates any previous surgical procedure to the operative knee.

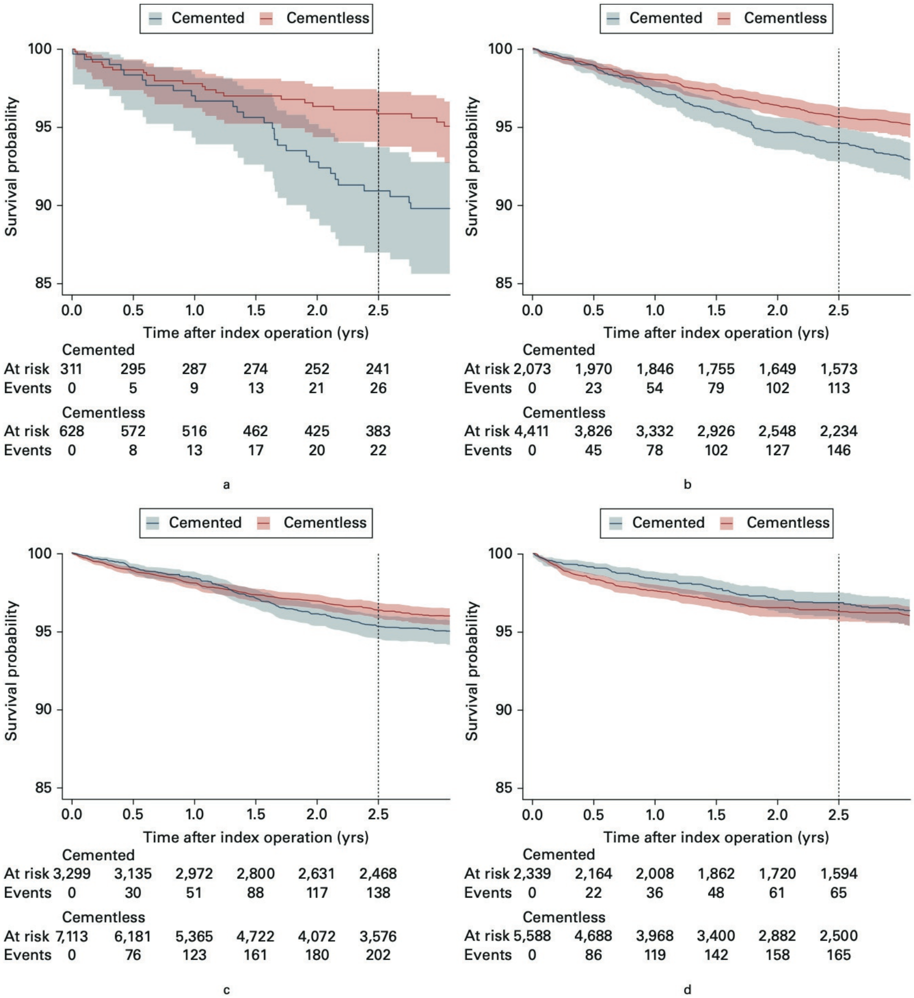


**Figure 1.** Kaplan-Meier survival curves for cemented and cementless Oxford medial unicompartmental knee arthroplasty across the (a) < 50 years, (b) 50 to 59 years, (c) 60 to 69 years, and (d) ≥ 70 years age groups. The 95% CIs are represented by the shaded area in the graphs.

*Implant survival*

The 2.5-year implant survival rate of cementless fixation was significantly higher compared to cemented medial UKA in patients younger than 50 years and those aged between 50 and 59 years (95.9% [95% CI 93.8 to 97.3] vs. 90.9% [95% CI 87.0 to 93.7]; $p$ = 0.007; and 95.6% [95% CI 94.9 to 96.3] vs. 94.0% [95% CI 92.8 to 95.0]; $p$ = 0.009, respectively; Table 2), with adjusted crude HRs of 0.46 (95% CI

0.26 to 0.82; $p = 0.008$) and 0.73 (CI 95% 0.57 to 0.94; $p = 0.009$), respectively. For patients aged between 60 and 69 years and those over 69 years, implant survival rates were not significantly different in both fixation groups. However, despite not reaching statistical significance, the adjusted HR for patients older than 69 years was 1.22 (95% CI 0.91 to 1.64; $p = 0.174$; Table 2). Kaplan-Meier survival curves for cemented and cementless medial UKA across different age groups are presented in Figure 1.

**Table 2.** Kaplan-Meier survival rates and adjusted hazard ratios for implant survival of cementless versus cemented (reference) medial unicompartmental knee arthroplasty.

| Age groups | Survival rate (95% CI) | | Adjusted HR (95% CI) † | *p* value |
|---|---|---|---|---|
| | Cemented | Cementless | | |
| < 50 years | 90.9 (87.0 to 93.7) | 95.9 (93.8 to 97.3) | 0.46 (0.26 to 0.82) | 0.008* |
| 50 to 59 years | 94.0 (92.8 to 95.0) | 95.6 (94.9 to 96.3) | 0.73 (0.57 to 0.94) | 0.009* |
| 60 to 69 years | 95.3 (94.5 to 96.0) | 96.4 (95.8 to 96.8) | 0.81 (0.66 to 1.02) | 0.075 |
| ≥ 70 years | 96.8 (96.0 to 97.5) | 96.3 (95.7 to 96.8) | 1.22 (0.91 to 1.64) | 0.174 |

Kaplan-Meier survival rates of cemented and cementless medial unicompartmental knee arthroplasty presented as (95% CI) and range. Adjusted HR for implant survival of cementless versus cemented medial unicompartmental knee arthroplasty were calculated using Cox proportional hazard regression models.
*CI,* Confidence interval; *KM,* Kaplan-Meier; *HR,* Hazard ratio.
† Adjusted for gender, BMI, Charnley and ASA score.
* Indicates statistical significance

*Modes of failure*

Instability was the predominant cause for revision during the first 2.5-year follow-up across all age groups, irrespective of fixation technique (Table 3). The incidence of revision for tibial loosening was significantly higher in cemented UKA compared to cementless UKA in patients under the age of 50, as well as in patients aged between 60 and 69 years (30.8% vs. 0.0%; $p = 0.005$; and 22.5% vs. 9.9%; $p = \leq 0.001$, respectively). Conversely, cementless UKA resulted in higher revision rates due to periprosthetic fractures in patients aged between 60 and 69 years and beyond 69 years (6.9% vs. 0%; $p = 0.002$; and 26.7% vs. 7.7%; $p = 0.002$, respectively).

**Table 3**. Reasons for revision of cemented and cementless medial unicompartmental knee arthroplasty across different age groups.

| Reasons for revision | < 50 years | | | 50 to 59 years | | | 60 to 69 years | | | ≥ 70 years | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cemented *n* = 26 | Cementless *n* = 22 | *p* value | Cemented *n* = 113 | Cementless *n* = 146 | *p* value | Cemented *n* = 138 | Cementless *n* = 202 | *p* value | Cemented *n* = 65 | Cementless *n* = 144 | *p* value |
| Instability | 8 (30.8%) | 12 (54.4%) | 0.096 | 27 (23.9%) | 48 (32.9%) | 0.114 | 22 (15.9%) | 50 (24.8%) | .05 | 16 (24.6%) | 33 (20.0%) | .44 |
| Tibial loosening | 8 (30.8%) | 0 (0.0%) | 0.005* | 15 (13.3%) | 12 (8.2%) | 0.187 | 31 (22.5%) | 20 (9.9%) | <.01* | 13 (20.0%) | 22 (13.3%) | .21 |
| Malalignment | 6 (23.1%) | 2 (9.1%) | 0.026 | 12 (10.6%) | 15 (10.3%) | 0.928 | 12 (8.7%) | 22 (10.9%) | .51 | 8 (12.3%) | 9 (5.5%) | .09 |
| Infection | 1 (3.8%) | 3 (13.6%) | 0.320 | 16 (14.2%) | 16 (11.0%) | .44 | 16 (11.6%) | 26 (12.9%) | .73 | 10 (15.4%) | 21 (12.7%) | .60 |
| Fractures | 0 (0.0%) | 0 (0.0%) | n.a. | 2 (1.8%) | 3 (2.1%) | 1.00 | 0 (0.0%) | 14 (6.9%) | <.01* | 5 (7.7%) | 44 (26.7%) | <.01* |
| Progression OA | 5 (19.2%) | 1 (4.5%) | 0.199 | 22 (19.5%) | 25 (17.1%) | .63 | 23 (16.7%) | 24 (11.9%) | .21 | 8 (12.3%) | 19 (11.5%) | .87 |
| Pain | 1 (3.8%) | 0 (0.0%) | > 0.99 | 11 (9.7%) | 14 (9.6%) | .97 | 9 (6.5%) | 16 (7.9%) | .68 | 3 (4.6%) | 6 (3.6%) | .72 |
| Patella dislocation | 0 (0.0%) | 0 (0.0%) | n.a. | 0 (0.0%) | 2 (1.4%) | .51 | 1 (0.7%) | 1 (0.5%) | 1.00 | 1 (1.5%) | 0 (0.0%) | .28 |
| Polyethylene wear | 0 (0.0%) | 1 (4.5%) | 0.458 | 3 (2.7%) | 3 (2.1%) | 1.00 | 4 (2.9%) | 10 (5.0%) | .35 | 2 (3.1%) | 3 (1.8%) | .62 |
| Femoral loosening | 1 (3.8%) | 0 (0.0%) | > 0.99 | 4 (3.5%) | 5 (3.4%) | 1.00 | 4 (2.9%) | 1 (0.5%) | .16 | 3 (4.6%) | 3 (1.8%) | .34 |
| Patellar loosening | 0 (0.0%) | 0 (0.0%) | n.a. | 0 (0.0%) | 1 (0.7%) | 1.00 | 0 (0.0%) | 0 (0.0%) | n.a. | 0 (0.0%) | 2 (1.2%) | 1.00 |
| Revision removal | 0 (0.0%) | 0 (0.0%) | n.a. | 1 (0.9%) | 3 (2.1%) | 1.00 | 1 (0.7%) | 3 (1.5%) | .65 | 2 (3.1%) | 4 (2.4%) | .68 |
| Arthrofibrosis | 2 (7.7%) | 0 (0.0%) | 0.493 | 1 (0.9%) | 2 (1.4%) | 1.00 | 2 (1.4%) | 2 (1.0%) | 1.00 | 1 (1.5%) | 3 (1.8%) | 1.00 |
| Unspecified | 5 (19.2%) | 5 (22.7%) | > 0.99 | 31 (27.4%) | 34 (23.3%) | .45 | 46 (33.3%) | 59 (29.2%) | .42 | 16 (24.6%) | 37 (22.4%) | .72 |

Reasons for revisions of cemented and cementless medial unicompartmental knee arthroplasty are given in numbers and frequencies (%) and stratified by age. *OA*, osteoarthritis.

*Patient-reported outcomes*

PROMs were obtained at baseline and at six and 12 months' follow-up, with complete data available for 9,871 (38.3%), 6,480 (25.2%), and 5,814 (22.6%) procedures, respectively. No significant differences in patient characteristics were observed between responders and non-responders. Adjusted differences in change from baseline during the first 12 months postoperatively did not reveal any significant differences between cemented and cementless medial UKA for both the OKS and NRS for pain (Table 4). The overall mean scores of PROMs of cemented and cementless medial UKA stratified by age is presented in Table 5.

**Table 4.** Adjusted differences between cemented versus cementless (reference) medial UKA in change from baseline of patient-reported outcome measures.

| | Adjusted β (95% CI) † | *p* value |
|---|---|---|
| **OKS** | | |
| < 50 years | -1.18 (-2.67 to 0.31) | 0.120 |
| 50 to 59 years | -0.26 (-0.84 to 0.32) | 0.377 |
| 60 to 69 years | 0.12 (-0.32 to 0.56) | 0.579 |
| ≥ 70 years | -0.24 (-0.73 to 0.25) | 0.333 |
| **NRS Pain at rest** | | |
| < 50 years | 0.19 (-0.27 to 0.64) | 0.419 |
| 50 to 59 years | -0.07 (-0.25 to 0.11) | 0.461 |
| 60 to 69 years | -0.13 (-0.27 to 0.01) | 0.068 |
| ≥ 70 years | 0.03 (-0.14 to 0.20) | 0.370 |
| **NRS Pain during activity** | | |
| < 50 years | 0.27 (-0.22 to 0.75) | 0.278 |
| 50 to 59 years | 0.01 (-0.17 to 0.19) | 0.936 |
| 60 to 69 years | 0.02 (-0.12 to 0.16) | 0.816 |
| ≥ 70 years | 0.03 (-0.13 to 0.19) | 0.704 |

Adjusted differences in change from baseline of patient-reported outcomes. *NRS,* Numeric rating scale; *OKS,* Oxford knee score; *UKA,* Unicompartmental knee arthroplasty.
† Adjusted for gender, BMI, ASA, Charnley, previous surgery.

**Discussion**

The main finding of the present study, using data from the LROI, was that implant survival of cemented and cementless Oxford mobile-bearing medial UKA is influenced by age. Cementless fixation led to higher short-term implant survival rates compared to cemented fixation in patients under the age of 60, whereas no significant differences in survival rates were observed between fixation techniques in patients aged over 59 years. Although implant survival rates did not differ among older patients, distinctive modes of failure patterns were evident between both fixation techniques within this group. Cementless UKA demonstrated higher rates of periprosthetic fractures in patients over 59 years, while cemented UKA resulted in higher revision rates for tibial loosening in specifically younger patients. Nonetheless, this study did not identify substantial differences in the improvement of physical function or pain between cemented and cementless UKA, irrespective of a patient's age.

Despite the well-studied mid- and long-term outcomes of both fixation techniques, this study represents one of the first large-scale studies comparing implant survival- and revision rates across various age groups during the initial 2.5-year postoperative period of both cemented and cementless UKA. Evaluation of implant survival revealed higher 2.5-year implant survival rates among younger patients undergoing cementless UKA, with cementless UKA associated with a 54% lower risk of revision in patients aged under 50 years and a 27% lower risk of revision in those aged between 50 and 59 years compared to cemented fixation. Considering the increasing prevalence of younger patients requiring knee arthroplasty and the potential for improved longevity and success with cementless fixation in these specific patients, these findings have important implications for clinical decision-making and implant selection. Findings from the present study align with previous findings from a National Joint Registry study, associating cementless fixation with reduced ten-year revision rates (HR 0.73 [95% CI 0.56 to 0.94]; $p = 0.02$), accompanied by significantly fewer revisions for aseptic loosening (0.5% vs. 1.6%) compared to cemented fixation in patients aged younger than 60 years.[20] Hence, depending on bone quality, caution is advised regarding the use of cemented fixation in younger patients.

There is an identified shift in failure patterns of cementless UKA among older patients. In contrast to the relatively low revision rate for periprosthetic fractures in patient younger than 70 years for both cemented and cementless UKA, periprosthetic fractures have emerged as the predominant cause for revision in patients over 69 years undergoing cementless UKA, demonstrating a significantly higher incidence compared to cemented UKA (26.7% vs. 7.7%).

While previous studies have highlighted the elevated risk of periprosthetic fractures in cementless UKA compared to cemented UKA, none of these studies have accounted for age as a variable.[13, 21, 22] Given our specific observation of higher revision rates for periprosthetic fractures predominantly in elderly patients, previous findings of increased periprosthetic risk in cementless UKA may not apply to the younger population. Periprosthetic fractures are a multifactorial complication influenced by a variety of factors, all of which are closely linked to surgical technique and surgeon experience.[23] Poor bone quality alongside the increased impact forces exerted on the tibial plateau during the hammering phase of cementless procedures likely constitute the primary risk factors associated with periprosthetic fractures following cementless UKA.[11, 13, 24] Advocating for a more nuanced approach, considering factors such as bone quality alongside age, is recommended when assessing the feasibility of performing cementless UKA in older patients, an approach endorsed by previous authors.[11]

Tibial loosening occurred more frequently in cemented UKA compared to cementless UKA across all age groups, thereby aligning with the initial objective behind the introduction of cementless fixation techniques, aimed at reducing the incidence of aseptic loosening. Cemented UKA resulted in significantly higher revision rates for tibial loosening compared to cementless UKA in patients aged below 50 years (30.8% vs. 0.0%) and between 60 and 69 years (22.5% vs. 9.9%). These findings align with previous studies using data from national joint registries in Finland, Denmark, and the UK, demonstrating a higher frequency of tibial loosening in cemented implant designs.[21, 22, 25]

The higher incidence of tibial loosening in younger patients undergoing cemented UKA may be attributable to the heightened activity levels inherent to this specific patient group. As the cement mantle lacks the same remodeling capacities as biologically osseointegrated components, increased activity levels expose the cement mantle to repetitive stress and loading, potentially resulting in greater incidences of tibial loosening.[26, 27] Additionally, younger patients generally have denser bone in comparison to older patients, which is associated with significantly reduced cement penetration and increased areas without cement infiltration at the bone-cement interface.[28, 29] Achieving biomechanical stability in cemented fixation relies on adequate cement penetration in trabecular bone, which potentially contributes to the higher instances of tibial loosening observed specifically in patients younger than 50 years, as well as patients aged between 60 and 69 years.[30, 31] An alternative explanation lies in the increased risk of radiolucent lines surrounding the tibial bone-cement interface, a phenomenon more prevalent following cemented UKA.[8, 9] Despite the absence of a definitive consensus regarding their clinical significance, radiolucencies have conventionally been interpreted as a sign of implant loosening. However, many of these radiolucencies do not necessarily have pathological consequences and do not indicate implant failure or the need for revision surgery.[32] Consequently, this misinterpretation may have resulted in unnecessary revisions within this group, as revisions may have been performed based on radiological findings rather than actual implant loosening. This highlights the importance of reconsidering the clinical significance of radiolucencies and adopting a more nuanced approach to interpreting them.

A key strength of this nationwide study lies in its large-scale comparison of outcomes between both cemented and cementless fixation for the same implant across various age groups, utilizing one of the largest patient datasets to date for this purpose. Nevertheless, this study is not devoid of limitations. Despite the LROI registry's impressive data completeness, exceeding more than 99% for primary knee arthroplasties, outcome measures remain underreported. While the primary emphasis of this study revolves around survival data, data incompleteness for PROMs may have introduced bias. Furthermore, this study did not incorporate activity scores in its analyses, which would have been insightful since age alone does not always fully reflect patient activity levels. Second, to mitigate variability associated with different implants and bearing types, this study specifically focused on the Oxford mobile-bearing UKA system. Consequently, caution should be exercised when generalizing the findings to other implants and bearing types. Third, this is a retrospective study of prospectively collected data, emphasizing that observed associations do not necessarily indicate causality. Finally, it is noteworthy that bearing dislocation, a commonly reported mode of failure in UKA, was not classified as a predefined reason for revision in the LROI. Instead, it was classified under the broader term “instability”, which limits adequate evaluations of distinct subtypes of instability.

**Conclusion**

Cementless fixation resulted in superior short-term implant survival compared to cemented fixation among younger patients undergoing Oxford mobile-bearing medial UKA. Distinct failure patterns between fixation techniques emerged across various age groups, with revision for tibial loosening being associated with cemented UKA, while elevated rates of periprosthetic fractures were specifically identified among elderly patients undergoing cementless UKA. No differences were observed regarding improvements in physical function and knee-related pain between both fixation techniques. Understanding these distinctive failure patterns associated with each fixation technique across varying age groups is crucial for informing shared decision-making and optimizing patient outcomes.

**Table 5.** Patient-reported outcomes of cemented and cementless medial unicompartmental knee arthroplasty.

| | Cemented medial UKA | | | | Cementless medial UKA | | | |
|---|---|---|---|---|---|---|---|---|
| | < 50 years | 50 to 59 years | 60 to 69 years | ≥ 70 years | < 50 years | 50 to 59 years | 60 to 69 years | ≥ 70 years |
| **OKS** | | | | | | | | |
| Baseline | 21.0 ± 7.2 | 22.7 ± 6.7 | 23.9 ± 7.1 | 24.9 ± 7.4 | 21.0 ± 6.8 | 23.1 ± 7.3 | 24.9 ± 7.2 | 25.6 ± 7.6 |
| 6 months | 36.5 ± 9.7 | 38.1 ± 7.9 | 39.4 ± 7.6 | 40.2 ± 7.0 | 38.7 ± 8.3 | 38.9 ± 7.8 | 40.2 ± 7.3 | 40.6 ± 5.6 |
| 12 months | 38.2 ± 7.8 | 39.3 ± 7.3 | 40.9 ± 6.9 | 40.8 ± 7.0 | 40.6 ± 8.1 | 39.7 ± 8.1 | 41.1 ± 7.0 | 41.8 ± 6.3 |
| **NRS pain at rest** | | | | | | | | |
| Baseline | 6.3 ± 1.8 | 5.8 ± 2.2 | 5.4 ± 2.4 | 4.9 ± 2.6 | 6.0 ± 2.2 | 5.4 ± 2.5 | 5.1 ± 2.5 | 4.6 ± 2.6 |
| 6 months | 2.0 ± 2.3 | 1.8 ± 2.2 | 1.5 ± 2.0 | 1.6 ± 2.1 | 1.6 ± 2.1 | 1.5 ± 2.0 | 1.4 ± 2.1 | 1.4 ± 2.0 |
| 12 months | 1.9 ± 2.1 | 1.6 ± 2.0 | 1.4 ± 2.0 | 1.3 ± 2.1 | 1.0 ± 1.7 | 1.4 ± 2.1 | 1.2 ± 2.0 | 1.2 ± 2.0 |
| **NRS pain during activity** | | | | | | | | |
| Baseline | 8.3 ± 1.5 | 7.9 ± 1.5 | 7.6 ± 1.7 | 7.4 ± 1.7 | 8.0 ± 1.8 | 7.6 ± 1.7 | 7.3 ± 1.8 | 7.1 ± 1.9 |
| 6 months | 3.2 ± 2.8 | 3.0 ± 2.5 | 2.5 ± 2.3 | 2.4 ± 2.4 | 2.9 ± 2.6 | 2.7 ± 2.4 | 2.4 ± 2.4 | 2.1 ± 2.3 |
| 12 months | 3.2 ± 2.5 | 2.6 ± 2.5 | 2.3 ± 2.4 | 2.1 ± 2.4 | 2.0 ± 2.4 | 2.4 ± 2.6 | 2.0 ± 2.3 | 1.8 ± 2.3 |

Patient-reported outcomes of cemented and cementless medial unicompartmental knee arthroplasty at baseline, and at 6- and 12-months follow-up are given in mean ± SD. *NRS,* Numeric rating scale; *OKS,* Oxford knee score; *UKA,* Unicompartmental knee arthroplasty.

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# Chapter 3

# The mind matters: psychological factors influence subjective outcomes following unicompartmental knee arthroplasty

a prospective study

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**Abstract**

**Purpose:** this study aimed to investigate how psychological factors, including pain catastrophizing (PC), anxiety, and depression affect preoperative and postoperative subjective outcomes in patients undergoing unicompartmental knee arthroplasty (UKA).

**Methods:** a prospective comparative study was performed among 150 patients undergoing medial or lateral UKA for isolated unicompartmental osteoarthritis. Patients were categorized based on their preoperative PC and Hospital Anxiety and Depression Scale, stratifying them into groups with PC, anxiety or depression, and those without these psychological factors.

**Results:** at 24 months, PC patients had inferior outcomes in KOOS-PS (66.9 ± 16.5 vs. 77.6 ± 14.7, $p$ = .008), EQ5D-VAS (63.5 ± 19.9 vs. 78.9 ± 20.1, $p$= .003), and FJS (73.7 ± 14.3 vs. 84.6 ± 13.8, $p$ = .003). Anxiety was associated with inferior KOOS-PS (65.4 ± 15.2 vs. 78.2 ± 14.5, $p$ = <.001), EQ5D-VAS (64.2 ± 23.2 vs. 79.3 ± 19.4, $p$ = .002), FJS (75.7 ± 16.8 vs. 84.6 ± 13.4, $p$ = .008), and NRS-pain (27.4 ± 24.6 vs. 13.7 ± 19.3, $p$ = .023) at 24 months. Depression consistently resulted in inferior outcomes in KOOS-PS, EQ5D-VAS, FJS, and NRS-pain across all follow-up assessments ($p$ = <.05). Additionally, patients with anxiety and depression experienced longer length of hospital stay compared to those without these psychological factors (anxiety: 2.3 ± 2.3 vs. 0.8 ± 0.8 days, $p$ = .006; depression: 2.3 ± 2.4 vs. 0.8 ± 0.8 days, $p$ = .017).

**Conclusions:** preoperative PC, anxiety and depression are associated with inferior subjective outcomes both prior to and following UKA. Among these factors, depression seemed to exert the most substantial adverse impact on outcomes following UKA. Patients with anxiety and depression had an extended duration of hospitalization lasting over twice as long as patients without these psychological factors. It seems that inferior outcomes primarily stem from the suboptimal preoperative condition rather than an inherent inability to benefit from UKA.

## Introduction

Emotional well-being and pre-existing psychological factors, such as the phenomenon of pain catastrophizing (PC), anxiety, and depression consistently emerge as crucial determinants influencing the overall success of total knee arthroplasty (TKA) and other orthopedic surgical interventions[1-3]. PC, characterized by an exaggerated adverse response to actual or anticipated pain, anxiety, and depression have been associated with less satisfactory outcomes in subjective function, increased postoperative pain, and extended hospitalization following TKA[4-6].

However, while extensively studied in the context of TKA, there remains a lack of sufficient evidence regarding the extent to which psychological factors influence surgical outcomes of unicompartmental knee arthroplasty (UKA). Recognizing the substantial impact of pre-surgical psychological factors on surgical outcomes and identifying predictors for dissatisfaction and suboptimal patient-reported outcomes can refine preoperative risk assessments. This, in turn, could lead to more targeted and effective psychological interventions tailored to specific individual needs, potentially improving outcomes of UKA.

Therefore, this study aimed to assess how psychological factors, including PC, anxiety, and depression affect subjective function, quality of life, joint awareness, and pain both prior to and following UKA. We hypothesized that preoperative PC, anxiety, and depression, may be associated with inferior patient-reported outcomes prior to and following UKA.

## Methods

This prospective cohort study was conducted in a Dutch high-volume university hospital between November 2020 and December 2021. Institutional Review Board (#L019-075) approval and written informed consent of all patients were obtained prior to data collection. Patients were eligible for inclusion in this study if they underwent medial or lateral UKA for isolated compartment knee OA, had complete preoperative anteroposterior knee radiographs, were proficient in Dutch to complete questionnaires, and had at least two-year follow-up. Patients were excluded if they had incomplete or poor-quality radiographic records, or incomprehensive or insufficient PROMs. Within the specified timeframe, a total of 215 patients underwent medial or lateral UKA for isolated compartment osteoarthritis (OA). Of these, 64 were considered lost to follow-up, and one individual did not complete the Pain Catastrophizing Scale (PCS) preoperatively, resulting in a final cohort of 150 patients. A detailed flowchart of patient selection and lost to follow-up is provided in Figure 1.

*Surgical procedure*

All patients received the same mobile bearing medial UKA implant (Oxford, Zimmer Biomet, Bridgend, United Kingdom) and fixed bearing lateral UKA implant (Oxford, Zimmer Biomet, Bridgend, United Kingdom). Surgical procedures were performed employing conventional manual techniques by a team comprising of four highly experienced senior orthopedic surgeons. Procedures involved either the medial parapatellar or subvastus approach. Postoperative care followed a standardized protocol, which included antithrombotic prophylaxis (low molecular weight heparin) administered for a duration of four weeks postoperatively, alongside mobilization and physical therapy. Patients were considered eligible for discharge if they were able to ambulate independently, with assistance of crutches or a walker if necessary, exhibited an absence of any wound-related problems or signs of infection, and if their pain was under control, as indicated by a Numeric Rating Scale (NRS) for pain score of less than 4.

*Radiographic evaluation*

The Kellgren-Lawrence (KL) grading system[7] was used to describe the OA severity on preoperative radiographs. The operative compartment of the joint was assigned a KL grade from 0 to 4, classifying the severity of OA from absence of OA (grade 0) to severe OA (grade 4).

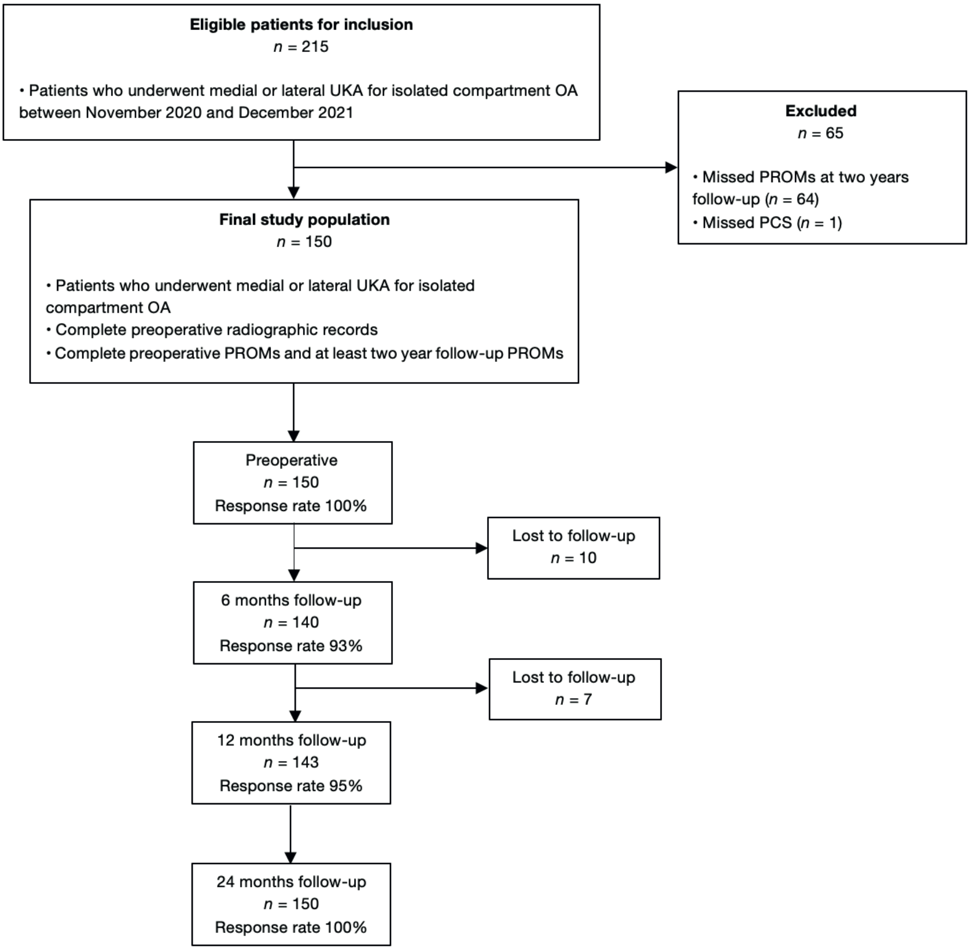


**Figure 1.** Flowchart of patient selection and lost to follow-up. *OA,* Osteoarthritis; *PCS;* Pain Catastrophizing Score; *PROMs,* Patient-reported outcome measures; *UKA,* Unicompartmental Knee Arthroplasty.

*Pain catastrophizing*

Preoperatively, all patients completed the validated PCS[8]. This scale evaluates how individuals respond mentally and emotionally when experiencing pain, covering elements such as magnification, rumination, and feelings of helplessness[9]. It comprises of 13 specific items rated on a five-point Likert scale, with 0 representing no engagement in catastrophizing behavior, and 4 indicating consistent engagement. A total score of ≥ 30 (range 0-52) indicates a clinically relevant level of PC[8]. Therefore, patients were classified into a PC group (PCS ≥ 30) and a non-PC group (PCS < 30) based on their preoperative PCS.

*Anxiety and depression*

The Hospital Anxiety and Depression Scale (HADS)[10] was used to evaluate preoperative anxiety and depression through two distinct subscales, each consisting of seven questions rated on a four-point Likert scale. The two scales were evaluated separately. Higher scores indicate an increased probability or severity of anxiety or depression. Scores ranging from 0 to 7 are considered normal, scores of 8 to 10 suggest mild manifestations, scores between 11 to 14 moderate levels, and scores ranging from 15 to 21 severe manifestations of either anxiety or depression[10]. Patients were classified into anxiety or non-anxiety groups (HADS ≥ 8 or HADS < 8, respectively) based on their preoperative HADS scores for depression. The same methodology was used for the classification of depression. PCS and HADS questionnaires were assessed approximately three weeks before the procedure, with an average of 20.8 days preceding the surgical intervention.

*Patient-reported outcomes*

Patient-reported outcomes were assessed preoperatively and at 6-, 12- and 24 months postoperatively using standardized questionnaires through email, accompanied by two automated reminders to prompt questionnaire completion. These comprised of the Knee Injury and Osteoarthritis Outcome Score-Physical function Short form (KOOS-PS), 5-level EQ5D Visual Analog Scale (EQ5D-VAS), Forgotten Joint Score (FJS), and Numeric Rating Scale for pain (NRS-pain). The KOOS-PS assesses the physical function of patients experiencing knee problems on a scale from 0 (indicating extreme difficulty in physical function) to 100 (representing no difficulty in physical function)[11]. The EQ5D-VAS assesses the overall self-rated quality of life on a scale from 0 ('the worst health you can imagine') to 100 ('the best health you can imagine')[12]. The FJS assesses the ability of patients to mentally "forget" about their joint following knee arthroplasty, ranging from 0 (high joint awareness) to 100 (no joint awareness) [13]. The NRS-pain, quantifying pain intensity on a scale from 0 (no pain) to 100 (worst imaginable pain), was separately assessed during physical activity and rest[14]. Subsequently, the collective average of these scores was utilized to present the overall pain experience among patients undergoing UKA. Utilization of these specific outcome measures collectively contributes to a comprehensive understanding of various facets of a patient's status, offering insights into pre- and postoperative subjective functionality, quality of life, the extent of joint awareness and pain levels.

*Minimal Clinically Important Differences*

To evaluate the clinical significance of improvement following UKA, incidence rates of patients who exceeded the Minimal Clinically Important Differences (MCIDs) for knee OA were calculated based on delta scores (**Δ**; i.e., the difference between initial and follow-up evaluations). The MCID values were 10 for the KOOS-PS[15-17], 6.4 for the EQ5D-VAS[18], and 18 for the NRS-pain[17, 19].

*Statistical analyses*

All analyses were performed in IBM SPSS Statistics for Macintosh (Version 28.0.1.1, IBM Corp., Armonk, NY), with a predetermined significance level set at 0.05. Patient and pre-, intra-, and postoperative demographics, and PROMs were presented using descriptive statistics across the entire patient cohort and stratified by PCS and HADS subgroups. Normality of continuous variables was assessed using the Shapiro-Wilk test. Comparisons of means between two independent samples were carried out using either the Mann-Whitney *U* test or independent *t*-test, depending on the distribution. Comparison of discrete variables and the proportion of patients exceeding the MCID were performed using the Chi-squared test or Fisher's exact test as appropriate.

## Results

The demographic data of the 150 included patients stratified by PCS and HADS subgroups is presented in Tables 1 and 2, respectively. Preoperative PC, anxiety and depression were observed in 17 (11.3%), 21 (14.0%), and 20 patients (13.3%), respectively. The overall two-year implant survival rate following UKA was 98.7% (148 patients). Two patients (1.3%), both without pre-existing conditions of PC, anxiety, or depression underwent partial revision surgery within the initial six months following surgery. Both revisions involved an exchange of the polyethylene insert due to complications related to infection and pain.

**Table 1.** Pre-, intra-, and postoperative patient demographics stratified by Pain Catastrophizing Score

| Demographics | Total ($n$ =150) | PCS <30 ($n$ = 133) | PCS ≥ 30 ($n$ = 17) | $p$ value[§] |
|---|---|---|---|---|
| Age (y) | 66.6 ± 8.9 | 67.1 ± 8.9 | 62.6 ± 8.8 | n.s. |
| Females | 77 (51.3%) | 70 (52.6%) | 7 (41.2%) | n.s. |
| BMI (kg/m$^2$) | 29.0 ± 4.7 | 28.7 ± 4.5 | 31.1 ± 5.9 | n.s. |
| Smoking | 7 (4.7%) | 5 (3.8%) | 2 (11.8%) | n.s. |
| KL-grade IV | 118 (78.7%) | 104 (78.2%) | 14 (82.4%) | n.s. |
| Medial UKA | 145 (96.7%) | 130 (97.7%) | 15 (88.2%) | n.s. |
| ASA I/II | 114 (76.0%) | 101(75.9%) | 13 (76.5%) | n.s. |
| Length of stay (days) | 1.0 ± 1.2 | 0.9 ± 1.0 | 1.7 ± 2.2 | n.s. |
| All cause revision | 2 (1.3%) | 2 (1.5%) | 0 (0.0%) | n.a. |

Patient demographics are given in mean ± SD or numbers and frequencies (%) for the entire cohort and stratified by PCS. *BMI,* Body Mass Index; *KL,* Kellgren-Lawrence; *PCS,* Pain Catastrophizing Score; *UKA;* Unicompartmental Knee Arthroplasty.

§ Comparison of patient demographics by PCS

* Indicates statistical significance

*Pain catastrophizing*

Preoperatively, PC patients had significantly inferior outcomes in subjective function, quality of life, and pain levels compared to those without PC (KOOS-PS: 39.2 ± 13.9 vs. 55.8 ± 13.5, $p$ = <.001; EQ5D-VAS: 56.4 ± 19.1 vs. 75.7 ± 17.3, $p$ = <.001; NRS-pain: 71.8 ± 15.5 vs. 57.1 ± 18.1, $p$ = .002). Postoperatively, PC patients demonstrated inferior outcomes in subjective function at 12- and 24 months follow-up (12 months: 66.7 ± 15.4 vs. 76.6 ± 14.9, $p$ = .016; 24 months: 66.9 ± 16.5 vs. 77.6 ± 14.7, $p$ = .008) and joint awareness at 24 months (73.7 ± 14.3 vs. 84.6 ± 13.8,

**Table 2.** Pre-, intra-, and postoperative patient demographics stratified by Hospital Anxiety and Depression Scale

| | **Non anxiety** | **Anxiety** | | **Non depression** | **Depression** | |
|---|---|---|---|---|---|---|
| Demographics | HADS <8 (*n* = 129) | HADS ≥ 8 (*n* = 21) | *p* value§ | HADS <8 (*n* = 130) | HADS ≥ 8 (*n* = 20) | *p* value§ |
| Age (years) | 66.6 ± 8.9 | 66.4 ± 9.2 | n.s. | 66.8 ± 8.8 | 65.0 ± 9.6 | n.s. |
| Females | 65 (50.4%) | 12 (57.1%) | n.s. | 67 (51.5%) | 10 (50.0%) | n.s. |
| BMI (kg/m$^2$) | 28.9 ± 4.8 | 29.5 ± 4.1 | n.s. | 28.7 ± 4.7 | 30.5 ± 4.4 | n.s. |
| Smoking | 4 (3.1%) | 3 (14.3%) | n.s. | 3 (2.3%) | 4 (20.0%) | .006* |
| KL-grade IV | 101 (78.3%) | 17 (81.0%) | n.s. | 102 (78.5%) | 16 (80.0%) | n.s. |
| Medial UKA | 126 (97.7%) | 19 (90.5%) | n.s. | 127 (97.7%) | 18 (90.0%) | n.s. |
| ASA I/II | 99 (76.7%) | 15 (71.4%) | n.s. | 98 (75.4%) | 16 (80.0%) | n.s. |
| Length of stay (days) | 0.8 ± 0.8 | 2.3 ± 2.3 | .006* | 0.8 ± 0.8 | 2.3 ± 2.4 | .017* |
| All cause revision | 2 (1.6%) | 0 (0.0%) | n.a. | 2 (1.5%) | 0 (0.0%) | n.a. |

Patient demographics are given in mean ± SD or numbers and frequencies (%) and stratified by HADS. *BMI,* Body Mass Index; *HADS,* Hospital Anxiety and Depression Scale; *KL,* Kellgren-Lawrence; *UKA;* Unicompartmental Knee Arthroplasty.

§ Comparison of patient demographics by HADS

* Indicates statistical significance

$p$ = .003) compared to non-PC patients. Additionally, patients with PC reported lower quality of life at 6- and 24 months follow-up, while at 12 months, their reported quality of life was comparable to non-PC patients (Table 3). Pain levels were comparable between PC and non-PC patients following UKA. Moreover, PC patients had significantly more clinical improvement in the KOOS-PS from baseline to 6 months compared to non-PC patients (Table 4). Nonetheless, both groups exhibited comparable proportions of patients reaching the MCID across all time intervals. A detailed overview of the progression of patient-reported outcomes among patients with and without PC tendencies is presented in Figure 2.

**Table 3.** Patient-reported outcomes stratified by Pain Catastrophizing Score

| Outcome variable | Total ($n$ = 150) | PCS <30 ($n$ = 133) | PCS ≥ 30 ($n$ = 17) | $p$ value[§] |
|---|---|---|---|---|
| **KOOS-PS** | | | | |
| Preoperative | 53.9 ± 14.5 | 55.8 ± 13.5 | 39.2 ± 13.9 | <.001* |
| 6 months | 74.3 ± 14.9 | 74.7 ± 15.0 | 70.7 ± 14.6 | n.s. |
| 12 months | 75.6 ± 15.2 | 76.6 ± 14.9 | 66.7 ± 15.4 | .016* |
| 24 months | 76.4 ± 15.2 | 77.6 ± 14.7 | 66.9 ± 16.5 | .008* |
| **EQ5D-VAS** | | | | |
| Preoperative | 73.7 ± 18.4 | 75.7 ± 17.3 | 56.4 ± 19.1 | <.001* |
| 6 months | 76.9 ± 21.1 | 79.0 ± 19.0 | 56.8 ± 30.1 | .022* |
| 12 months | 77.1 ± 20.1 | 77.8 ± 20.5 | 72.1 ± 15.5 | n.s. |
| 24 months | 77.1 ± 20.6 | 78.9 ± 20.1 | 63.5 ± 19.9 | .003* |
| **FJS** | | | | |
| 6 months | 80.3 ± 13.3 | 80.9 ± 13.1 | 75.1 ± 14.2 | n.s. |
| 12 months | 82.2 ± 13.4 | 83.0 ± 13.4 | 76.0 ± 12.7 | n.s. |
| 24 months | 83.3 ± 14.2 | 84.6 ± 13.8 | 73.7 ± 14.3 | .003* |
| **NRS-Pain** | | | | |
| Preoperative | 58.8 ± 18.4 | 57.1 ± 18.1 | 71.8 ± 15.5 | .002* |
| 6 months | 18.3 ± 20.5 | 17.9 ± 20.7 | 21.8 ± 19.1 | n.s. |
| 12 months | 14.9 ± 20.4 | 13.8 ± 19.5 | 24.3 ± 25.9 | n.s. |
| 24 months | 15.6 ± 20.6 | 14.6 ± 20.2 | 24.1 ± 22.0 | n.s. |

Patient-reported outcomes are given in mean ± SD for the entire cohort and stratified by PCS. The NRS-pain represents the average pain experienced during both physical activity and rest. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *KOOS,* Knee Injury and Osteoarthritis Outcome Score; *NRS,* Numeric Rating Scale; *PCS,* Pain Catastrophizing Score.

[§] Comparison of patient demographics by PCS

* Indicates statistical significance

*Anxiety*

Patients with anxiety exhibited significantly inferior outcomes in subjective function and quality of life before surgery in contrast to patients without anxiety (KOOS-PS: 43.5 ± 16.9 vs. 55.6 ± 13.3, $p$ = <.001; EQ5D-VAS: 59.6 ± 18.0 vs. 76.0 ± 17.5, $p$ = .001). Quality of life remained consistently lower in patients with anxiety following UKA, while subjective function solely remained lower at 12- and 24 months follow-up (Table 5). Additionally, patients with anxiety reported to have higher pain levels at 24 months follow-up (27.4 ± 24.6 vs. 13.7 ± 19.3, $p$ = .023) and lower FJS compared to patients without anxiety at all follow-up assessments ($p$ <.05). Moreover, patients with anxiety experienced longer length of hospital stay compared to patients without anxiety (2.3 ± 2.3 days vs. 0.8 ± 0.8 days, $p$ = .006). There were no differences in clinical improvement and MCID across all time intervals between anxiety and non-anxiety patients (n.s.; Table 6). A detailed overview of the progression of patient-reported outcomes among patients with and without anxiety is presented in Figure 3.

*Depression*

Before surgery, patients with depression demonstrated significantly inferior outcomes in subjective function, quality of life, and pain levels compared to patients without depression (KOOS-PS: 42.4 ± 16.0 vs. 55.7 ± 13.4, $p$ = <.001; EQ5D-VAS: 57.1 ± 15.6 vs. 76.0 ± 17.6, $p$ = <.001; NRS-pain: 65.5 ± 15.2 vs. 57.7 ± 18.6, $p$ = .049). Patients with depression consistently sustained these inferior outcomes and experienced more joint awareness compared to patients without depression throughout all subsequent postoperative follow-up assessments (Table 5). Moreover, patients with depression had an extended duration of hospitalization compared to patients without depression (2.3 ± 2.4 days vs. 0.8 ± 0.8 days, $p$ = .017). Patients without depression experienced significantly more clinical improvement in pain (-44.8 ± 23.5 vs. -32.3 ± 25.4, $p$ = .029) and a higher proportion reached the MCID (87.7% vs 65.0%, $p$ = .016) from baseline to 24 months compared to patients with depression. Conversely, significantly more patients in the depression group reached the MCID for EQ5D-VAS from baseline to 6 months compared to patients without depression (Table 6). A detailed overview of the progression of patient-reported outcomes among patients with and without depression is presented in Figure 4.

**Table 4.** Clinical improvement in patient-reported outcomes stratified by Pain Catastrophizing Score

| Outcome variable | Total (*n* = 150) | PCS <30 (*n* = 133) | PCS ≥ 30 (*n* = 17) | *p* value§ |
|---|---|---|---|---|
| **KOOS-PS** | | | | |
| Δ 0-6 mos | 19.9 ± 17.2 | 18.9 ± 16.9 | 28.7 ± 18.1 | .043* |
| Δ 0-12 mos | 21.4 ± 16.0 | 20.7 ± 15.6 | 27.5 ± 18.5 | n.s. |
| Δ 0-24 mos | 22.6 ± 15.6 | 21.9 ± 15.4 | 28.5 ± 15.9 | n.s. |
| MCID Δ 0-6 mos | 108 (76.6%) | 95 (74.8%) | 13 (92.9%) | n.s. |
| MCID Δ 0-12 mos | 109 (76.2%) | 96 (75.0%) | 13 (86.7%) | n.s. |
| MCID Δ 0-24 mos | 116 (78.4%) | 102 (77.3%) | 14 (87.5%) | n.s. |
| **EQ5D-VAS** | | | | |
| Δ 0-6 mos | 3.5 ± 21.7 | 3.3 ± 19.9 | 5.6 ± 38.9 | n.s. |
| Δ 0-12 mos | 2.9 ± 22.5 | 1.7 ± 22.0 | 15.2 ± 25.4 | n.s. |
| Δ 0-24 mos | 3.5 ± 22.9 | 3.4 ± 21.5 | 3.8 ± 33.7 | n.s. |
| MCID Δ 0-6 mos | 42 (43.3%) | 36 (40.4%) | 6 (75.0%) | n.s. |
| MCID Δ 0-12 mos | 40 (40.0%) | 34 (37.4%) | 6 (66.7%) | n.s. |
| MCID Δ 0-24 mos | 35 (34.3%) | 32 (35.2%) | 3 (27.3%) | n.s. |
| **NRS-Pain** | | | | |
| Δ 0-6 mos | -40.1 ± 24.9 | -39.1 ± 25.1 | -49.3 ± 20.9 | n.s. |
| Δ 0-12 mos | -43.6 ± 24.4 | -43.1 ± 24.1 | -48.0 ± 27.7 | n.s. |
| Δ 0-24 mos | -43.1 ± 24.0 | -42.6 ± 24.2 | -47.7 ± 22.6 | n.s. |
| MCID Δ 0-6 mos | 117 (83.6%) | 104 (82.5%) | 13 (92.9%) | n.s. |
| MCID Δ 0-12 mos | 122 (85.3%) | 109 (85.2%) | 13 (86.7%) | n.s. |
| MCID Δ 0-24 mos | 127 (84.7%) | 112 (84.2%) | 15 (88.2%) | n.s. |

Outcomes are given in mean ± SD or numbers and frequencies (%) for the entire cohort and stratified by pain catastrophizing score. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *KOOS,* Knee Injury and Osteoarthritis Outcome Score; *MCID;* Minimal Clinically Important Difference; *PCS,* Pain Catastrophizing Score.

§ Comparison of patient demographics by PCS

* Indicates statistical significance

## Discussion

The main findings of the present study reveal that pre-existing psychological factors such as PC, anxiety, and depression negatively influence subjective outcomes both prior to and following UKA. Depression appeared to exert the most substantial influence on postoperative outcomes, consistently correlating with inferior outcomes in subjective function, quality of life, joint awareness, and pain across all follow-up assessments. Additionally, patients with anxiety and depression had an extended duration of hospitalization compared to patients without these psychological factors. Nonetheless, despite experiencing inferior subjective outcomes both prior to and following UKA, patients with pre-existing psychological factors demonstrated comparable improvements in subjective outcomes compared to patients without these psychological factors. Hence, it seems that inferior outcomes primarily stem from the suboptimal preoperative condition rather than an inherent inability to benefit from UKA.

Over the past decade, considerable attention has been directed towards understanding the influence of psychological factors on the outcomes of TKA. To the best of the authors' knowledge, this study represents the first and largest cohort study with a minimum of two-year follow-up assessing the relatively underexplored impact of PC, anxiety, and depression on various patient-reported outcomes both prior to and following UKA.

PC has gained prominence as a pivotal determinant influencing the severity and persisting nature of chronic pain, potentially serving as an independent prognostic factor for unfavorable surgical outcomes[20-22]. This study identified that 11% of patients met the criteria for PC, representing a comparatively lower prevalence in contrast to similar studies on TKA, which ranged from 15 to 27.5%[17, 23]. The present study demonstrated that patients with a high degree of preoperative PC tendencies had inferior outcomes in subjective function, quality of life, and pain levels prior to undergoing UKA. These findings are in accordance with the existing literature on TKA, which indicate that patients with preoperative PC tend to experience worse function and pain preceding their TKA[17, 23]. In a study pertaining to TKA, Van der List et al.[17] reported a mean preoperative NRS-pain level of 72.2 ± 15.4, which was similar to the mean preoperative pain level of 71.8 ± 15.5 observed among UKA patients with PC in the present study. While PC was associated with inferior outcomes in subjective function, quality of life, and joint awareness 24 months following UKA, pain levels were comparable to those of non-PC patients throughout all follow-up assessments. This contradicts studies suggesting a long-term effect of PC on elevated postoperative pain[17, 23, 24].

**Table 5.** Patient-reported outcomes stratified by Hospital Anxiety and Depression Scale

| Outcome variable | **Non anxiety** HADS <8 (*n* = 129) | **Anxiety** HADS ≥ 8 (*n* = 21) | *p* value§ | **Non depression** HADS <8 (*n* = 130) | **Depression** HADS ≥ 8 (*n* = 20) | *p* value§ |
|---|---|---|---|---|---|---|
| **KOOS-PS** | | | | | | |
| Preoperative | 55.6 ± 13.3 | 43.5 ± 16.9 | <.001* | 55.7 ± 13.4 | 42.4 ± 16.0 | <.001* |
| 6 months | 74.6 ± 14.9 | 71.8 ± 15.7 | n.s. | 75.1 ± 14.6 | 67.9 ± 16.8 | .044* |
| 12 months | 76.6 ± 14.6 | 68.4 ± 17.3 | .033* | 76.7 ± 14.0 | 66.9 ± 20.4 | .011* |
| 24 months | 78.2 ± 14.5 | 65.4 ± 15.2 | <.001* | 78.3 ± 14.1 | 63.7 ± 16.9 | <.001* |
| **EQ5D-VAS** | | | | | | |
| Preoperative | 76.0 ± 17.5 | 59.6 ± 18.0 | .001* | 76.0 ± 17.6 | 57.1 ± 15.6 | <.001* |
| 6 months | 78.8 ± 19.4 | 63.1 ± 28.0 | .038* | 78.1 ± 21.4 | 67.9 ± 16.4 | .049* |
| 12 months | 78.7 ± 20.2 | 66.5 ± 16.0 | .015* | 78.9 ± 19.9 | 64.2 ± 16.7 | .004* |
| 24 months | 79.3 ± 19.4 | 64.2 ± 23.2 | .002* | 78.7 ± 20.6 | 67.3 ± 18.4 | .020* |
| **FJS** | | | | | | |
| 6 months | 81.2 ± 12.7 | 73.6 ± 15.6 | .026* | 81.5 ± 12.5 | 70.9 ± 15.7 | .002* |
| 12 months | 83.1 ± 12.9 | 76.4 ± 15.9 | .048* | 83.5 ± 12.5 | 72.6 ± 16.2 | .001* |
| 24 months | 84.6 ± 13.4 | 75.7 ± 16.8 | .008* | 84.9 ± 13.1 | 73.3 ± 17.3 | <.001* |
| **NRS-Pain** | | | | | | |
| Preoperative | 58.1 ± 17.9 | 62.9 ± 21.0 | n.s. | 57.7 ± 18.6 | 65.5 ± 15.2 | .049* |
| 6 months | 17.6 ± 20.1 | 23.8 ± 23.4 | n.s. | 16.9 ± 19.7 | 29.7 ± 24.0 | .018* |
| 12 months | 13.5 ± 18.7 | 24.4 ± 28.7 | n.s. | 13.1 ± 18.3 | 28.2 ± 29.5 | .004* |
| 24 months | 13.7 ± 19.3 | 27.4 ± 24.6 | .023* | 12.9 ± 18.4 | 33.3 ± 25.1 | .002* |

Patient-reported outcomes are given in mean ± SD and stratified by HADS. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *HADS,* Hospital Anxiety and Depression Scale; *KOOS,* Knee Injury and Osteoarthritis Outcome Score.

§ Comparison of patient demographics by HADS

* Indicates statistical significance

The present findings show that depression appeared to have the most substantial impact on inferior outcomes following UKA. There is only one other study investigating the influence of mental health on outcomes following UKA, associating preoperative psychological distress with relatively higher pain levels, reduced fulfillment of expectations, and suboptimal functional outcomes both prior to and at 2- and 10 years postoperatively[25]. The present study significantly contributes to the existing gap in literature by specifically focusing on anxiety and depression, demonstrating their association with inferior subjective functionality, reduced quality of life, more joint awareness, and higher pain levels both prior to and following UKA. Moreover, fewer patients with depression experienced a meaningful clinical improvement in pain from baseline to 24 months. These findings align with previous studies emphasizing the adverse prognostic characteristics of anxiety and depression on TKA, consistently associating these factors with suboptimal outcomes in subjective function, pain perception, and postoperative patient satisfaction[1, 26, 27]. Moreover, anxiety and depression have been associated with inferior functional status at baseline in patients undergoing total hip arthroplasty[28]. Several studies have also suggested that depression serves as a risk factor for higher hospitalizations cost and postoperative complications following TKA[29-32]. This aligns with the findings of the present study, demonstrating that patients with anxiety and depression experienced hospitalizations lasting over twice as long as those without these psychological conditions. Additionally, a recent systematic review demonstrated that preoperative depression increased the risk of persistent pain, dissatisfaction and complications in patients undergoing total joint arthroplasty[3]. Nevertheless, despite the unfavorable outcomes associated with anxiety and depression, UKA resulted in an overall improvement in knee joint function, reduced joint pain, and increased quality of life. Prior studies have indicated that the advantages and reduced pain associated with arthroplasty have the potential to alleviate symptoms and reduce the incidence of mental health problems postoperatively[2, 33]. Thus, even within the context of influential psychological risk factors such as anxiety and depression, UKA presents as a promising surgical intervention for addressing isolated compartment knee OA.

Recognizing pain as a primary determinant of dissatisfaction and failure following UKA, it is important to acknowledge the negative prognostic characteristics attributed to PC, anxiety, and depression on subjective outcomes following UKA[34]. While several studies highlight that PC, anxiety, and depression are modifiable factors, the efficacy of treatments such as cognitive-behavioral therapy and antidepressants in improving outcomes of arthroplasty procedures remains controversial[35-37]. Nonetheless, recognizing pre-surgical psychological risk factors and raising awareness may allow surgeons to refine preoperative risk assessments and more accurately tailor expectations, thereby potentially enhancing outcomes following UKA.

The present study has several limitations. First, patients were lost to follow-up at 6- and 12 months (7% and 5%, respectively). Nevertheless, the remaining cohort with available data at 6- and 12 months was still considerable in size, making it the largest study cohort examining the influence of psychological risk factors among patients undergoing UKA. Second, the prevalence of patients meeting the criteria for PC (11.3%), anxiety (14.0%), and depression (13.3%) were low. Yet, these percentages align reasonably with reported findings in similar studies examining the influence of these psychological factors on outcomes following TKA[2, 17]. Third, this was a single-center study which potentially influences the generalizability of the result. Last, this study lacks multivariate analyses.

## Conclusion

Preoperative PC, anxiety and depression are associated with inferior subjective outcomes both prior to and following UKA. Among these factors, depression seemed to exert the most substantial adverse impact on outcomes following UKA. Patients with anxiety and depression had an extended duration of hospitalization lasting over twice as long as patients without these psychological factors. Nonetheless, despite experiencing inferior subjective outcomes both prior to and following UKA, patients with pre-existing psychological factors demonstrated comparable improvements in subjective outcomes. Hence, it seems that inferior outcomes primarily stem from the suboptimal preoperative condition rather than an inherent inability to benefit from UKA.

**Table 6.** Clinical improvement in patient-reported outcomes stratified by Hospital Anxiety and Depression Scale

| Outcome variable | Non anxiety HADS <8 (*n* = 129) | Anxiety HADS ≥ 8 (*n* = 21) | *p* value§ | Non depression HADS <8 (*n* = 130) | Depression HADS ≥ 8 (*n* = 20) | *p* value§ |
|---|---|---|---|---|---|---|
| **KOOS-PS** | | | | | | |
| Δ 0-6 mos | 19.1 ± 16.8 | 25.5 ± 19.9 | n.s. | 19.5 ± 17.3 | 22.8 ± 16.7 | n.s. |
| Δ 0-12 mos | 21.0 ± 15.1 | 24.7 ± 21.4 | n.s. | 21.0 ± 15.8 | 24.4 ± 17.0 | n.s. |
| Δ 0-24 mos | 22.6 ± 15.2 | 22.3 ± 18.1 | n.s. | 22.7 ± 15.7 | 21.9 ± 15.3 | n.s. |
| MCID Δ 0-6 mos | 93 (75.0%) | 15 (88.2%) | n.s. | 94 (75.2%) | 14 (87.5%) | n.s. |
| MCID Δ 0-12 mos | 96 (76.8%) | 13 (72.2%) | n.s. | 96 (76.2%) | 13 (76.5%) | n.s. |
| MCID Δ 0-24 mos | 102 (79.7%) | 14 (70.0%) | n.s. | 101 (78.3%) | 15 (78.9%) | n.s. |
| **EQ5D-VAS** | | | | | | |
| Δ 0-6 mos | 3.9 ± 21.3 | 0.3 ± 25.6 | n.s. | 2.6 ± 22.2 | 12.3 ± 14.6 | n.s. |
| Δ 0-12 mos | 2.7 ± 23.1 | 4.8 ± 18.1 | n.s. | 3.1 ± 23.2 | 1.2 ± 15.3 | n.s. |
| Δ 0-24 mos | 4.0 ± 21.8 | 0.1 ± 29.4 | n.s. | 2.8 ± 22.7 | 7.8 ± 25.3 | n.s. |
| MCID Δ 0-6 mos | 37 (43.0%) | 5 (45.5%) | n.s. | 35 (39.8%) | 7 (77.8%) | .037* |
| MCID Δ 0-12 mos | 33 (37.5%) | 7 (58.3%) | n.s. | 35 (38.9%) | 5 (50.0%) | n.s. |
| MCID Δ 0-24 mos | 30 (34.5%) | 5 (33.3%) | n.s. | 28 (31.5%) | 7 (53.8%) | n.s. |
| **NRS-Pain** | | | | | | |
| Δ 0-6 mos | -40.4 ± 24.1 | -38.2 ± 30.6 | n.s. | -40.7 ± 24.5 | -35.6 ± 28.1 | n.s. |
| Δ 0-12 mos | -44.2 ± 22.8 | -39.2 ± 34.5 | n.s. | -44.3 ± 23.4 | -38.5 ± 31.5 | n.s. |
| Δ 0-24 mos | -44.4 ± 23.3 | -35.5 ± 27.5 | n.s. | -44.8 ± 23.5 | -32.3 ± 25.4 | .029* |
| MCID Δ 0-6 mos | 104 (84.6%) | 13 (76.5%) | n.s. | 105 (84.7%) | 12 (75.0%) | n.s. |
| MCID Δ 0-12 mos | 109 (87.2%) | 13 (72.2%) | n.s. | 110 (87.3%) | 12 (70.6%) | n.s. |
| MCID Δ 0-24 mos | 112 (86.8%) | 15 (71.4%) | n.s. | 114 (87.7%) | 13 (65.0%) | .016* |

Outcomes are given in mean ± SD or numbers and frequencies (%) and stratified by HADS. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *HADS,* Hospital Anxiety and Depression Scale; *KOOS,* Knee Injury and Osteoarthritis Outcome Score; *MCID;* Minimal Clinically Important Difference.

§ Comparison of patient demographics by HADS

* Indicates statistical significance

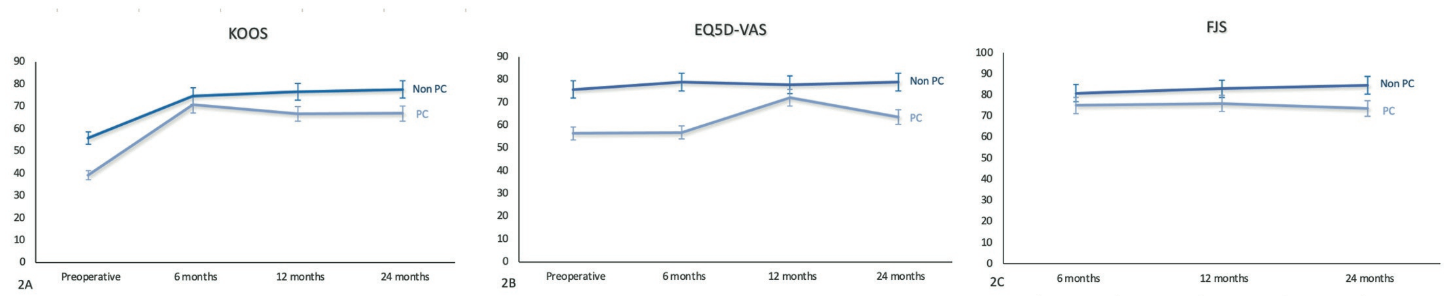


**Figure 2.** Progression of patient-reported outcomes among patients with pain catastrophizing tendencies (PCS ≥ 30) and patients without pain catastrophizing tendencies (PCS <30). **2A,** KOOS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by PCS. **2B,** EQ5D-VAS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by PCS. **2C,** FJS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by PCS. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *KOOS,* Knee Injury and Osteoarthritis Outcome Score; *PCS,* Pain Catastrophizing Score.

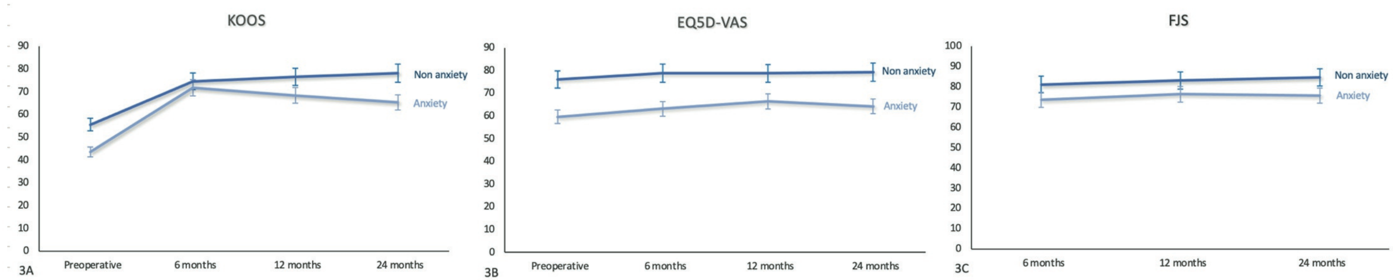


**Figure 3.** Progression of patient-reported outcomes among patients with anxiety (HADS ≥ 8) and patients without anxiety (HADS <8). **3A,** KOOS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by HADS. **3B,** EQ5D-VAS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by HADS. **3C,** FJS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by HADS. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *HADS,* Hospital Anxiety and Depression Scale; *KOOS,* Knee Injury and Osteoarthritis Outcome Score.

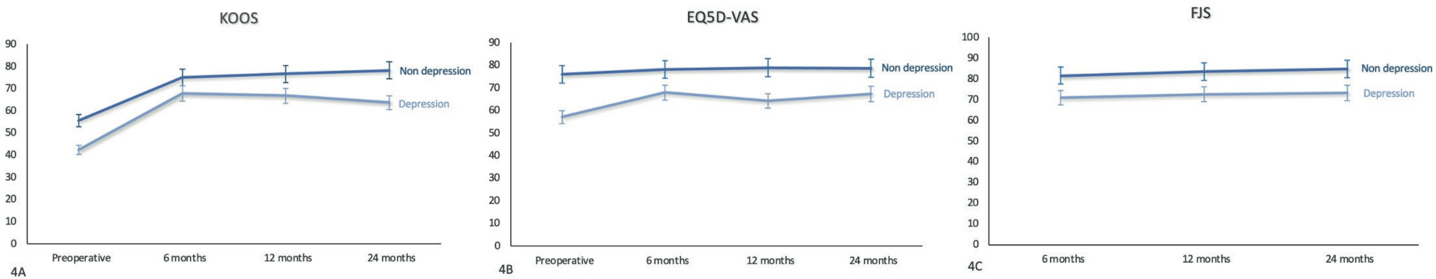


**Figure 4.** Progression of patient-reported outcomes among patients with depression (HADS ≥ 8) and patients without depression (HADS <8). **4A,** KOOS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by HADS. **4B,** EQ5D-VAS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by HADS. **4C,** FJS preoperatively and 6-, 12-, and 24 months following unicompartmental knee arthroplasty stratified by HADS. *EQ5D-VAS,* 5-level EQ5D Visual Analog Scale; *FJS,* Forgotten Joint Score; *HADS,* Hospital Anxiety and Depression Scale; *KOOS,* Knee Injury and Osteoarthritis Outcome Score.

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# Chapter 4

# Preoperative extra-articular proximal tibial varus deformities do not contribute to inferior subjective outcomes following fixed-bearing medial unicompartmental knee arthroplasty

a prospective study comprising 104 knees

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The Knee

## Abstract

**Purpose:** this study aimed to evaluate the impact of preoperative extra-articular proximal tibial varus deformities on preoperative and postoperative subjective outcomes in patients undergoing medial UKA.

**Methods:** a prospective study was performed among 104 patients undergoing robotic-arm assisted fixed-bearing medial UKA for isolated anteromedial compartment osteoarthritis. Patients were categorized based on their preoperative medial proximal tibial angle (MPTA), stratifying them into patients with tibial varus (MPTA <85°) and those without (MPTA ≥ 85°). Radiographic outcomes were assessed and patient-reported outcomes, including the UCLA activity score, OKS, VAS-pain, KOOS-JR, and patient satisfaction were compared between groups preoperatively and at 12- and 24 months follow-up.

**Results:** postoperatively, patients with tibial varus exhibited more pronounced residual varus alignment (3.8° vs. 0.7°, $p$ = <.001), as well as lower MPTA and joint line obliquity (JLO) values compared to patients without tibial varus. Patients with tibial varus deformities expressed significantly higher satisfaction levels following their surgery (93.4% vs. 77.6%, $p$ = .026) and reported higher UCLA activity scores both at baseline (6.4 vs. 5.1, $p$ = .006) and one-year follow-up (7.6 vs. 6.6, $p$ = .018) compared to those without tibial varus. However, at 24 months, no significant differences were observed in PROMs or clinical improvement in PROMs between groups.

**Conclusions:** this study supports the safe utilization of fixed-bearing medial UKA as an effective surgical intervention for managing isolated anteromedial OA, even in the presence of preoperative tibial varus deformities. While preoperative tibial varus may predispose patients to a more pronounced residual varus following medial UKA, subjective outcomes appear to remain unaffected.

## Introduction

Unicompartmental knee arthroplasty (UKA) is a highly effective, minimally invasive surgical approach for managing isolated anteromedial compartment knee osteoarthritis (OA). Nevertheless, surgeons are still reluctant to use this procedure, perceiving it as less reliable and surgically more challenging compared to total knee arthroplasty (TKA)[1, 2]. This perception underscores the importance of meticulous and careful consideration prior to its implementation, especially in the context of patient selection.

Achieving favorable clinical outcomes and implant longevity following UKA requires precise bone resection, optimal ligament balancing, accurate implant positioning, and restoration of the pre-arthritic femorotibial geometry to preserve normal knee kinematics[3, 4]. Suboptimal component positioning and lower limb malalignment are major contributing factors to poor clinical outcomes and inferior implant longevity[5]. While mild under correction is considered acceptable, severe under correction with excessive residual varus is associated with increased risk of aseptic loosening and early polyethylene wear[5, 6].

Tibial varus, defined as an extra-articular varus deformity of the proximal tibia, represents a key contributing factor in the development of varus deformities of the knee joint. In our previous work, tibial varus was identified in 33.3% of patients presenting with symptomatic isolated anteromedial OA and a varus knee deformity[7]. Furthermore, the medial proximal tibial angle (MPTA), which reflects the extent of the extra-articular tibial varus deformity, is closely associated with the presence of residual varus following UKA surgery[8]. Prior studies have emphasized the significance of achieving proper tibial component obliquity and restoration of the joint space height, cautioning against the application of UKA in knees with severe tibial varus bone deformities[9]. Ambiguity remains regarding the suitability of patients with excessive proximal tibial varus as ideal candidates for UKA. While prior studies have demonstrated that tibial varus does not yield inferior survivorship and functional outcomes in patients with anteromedial OA undergoing UKA, subjective outcomes remain relatively underexplored within the existing literature[10, 11].

Thus, the primary objective of the present study was to evaluate the impact of preoperative proximal extra-articular tibial varus deformities on subjective outcomes following fixed-bearing medial UKA. It was hypothesized that patients with proximal tibial varus would not exhibit inferior subjective outcomes following medial UKA.

## Material and methods

### *Study design*

This prospective cohort study was conducted at an American academic medical center between January 2021 and April 2022. Institutional Review Board approval (IRB #2021-0583) was secured prior to data collection. Patients were eligible for inclusion if they underwent robotic-arm assisted medial UKA for isolated anteromedial OA and were willing to participate in filling out patient-reported outcome measures (PROMs). Exclusion criteria included inadequate radiographic records, a history of tibial or femoral fractures on the operative limb, or prior arthroplasty procedures involving the ipsilateral ankle or hip. A total of 110 patients were eligible for inclusion, of which two were excluded due to incomplete radiographic records and four due to prior arthroplasty procedures involving the ipsilateral hip, resulting in a final cohort of 104 included patients. The demographic data of the included patients is presented in Table 1.

**Table 1.** Patient demographics of knees with and without excessive preoperative tibial varus deformity.

| Demographics | Total | MPTA <85° | MPTA ≥85° | *p* value[§] |
|---|---|---|---|---|
| No. knees | 104 (100%) | 46 (44.2%) | 58 (55.8%) | |
| Age (y) | 66.3 (45 to 89) | 66.5 (47 to 89) | 66.1 (45 to 85) | .791 |
| Sex (men) | 65 (62.5%) | 36 (78.3%) | 29 (50.0%) | .003* |
| BMI (kg/m$^2$) | 28.9 (19.3 to 42.4) | 28.5 (19.3 to 36.3) | 29.3 (21.1 to 42.4) | .311 |
| Laterality OA (right) | 55 (52.9%) | 23 (50.0%) | 32 (55.2%) | .600 |
| KL grade medial compartment | | | | |
| KL grade II | 3 (2.9%) | 2 (1.7%) | 1 (1.7%) | .688 |
| KL grade III | 34 (32.7%) | 14 (30.4%) | 20 (34.5%) | .688 |
| KL grade IV | 67 (64.4%) | 30 (65.2%) | 37 (63.8%) | .688 |

Patient demographics are given in mean (range) or numbers and frequencies (%) for the entire cohort and stratified by preoperative MPTA. *BMI,* Body Mass Index; *KL,* Kellgren-Lawrence; *OA,* Osteoarthritis.
[§] Comparison of patient demographics by preoperative MPTA.
* Indicates statistical significance.

*Implant design and surgical technique*

The primary surgical indication for medial UKA was the presence of symptomatic, isolated anteromedial compartment OA, with a passively correctable varus deformity and fixed flexion deformity measuring less than 10°. Contraindications included clinical or radiographic evidence of advanced lateral compartment OA, inflammatory arthritis, or ACL deficiency. All procedures were performed by a single senior surgeon (A.D.P) with extensive experience, adhering to a standardized protocol. Each patient underwent cemented medial UKA with a fixed-bearing metal-backed tibial onlay implant (Restoris MCK system, Mako Surgical Corp. (Stryker), Fort Lauderdale, FL, USA), with a robotic-arm assisted system (Mako Surgical Corp. (Stryker). Fort Lauderdale, FL, USA) for precise implant planning and bone preparation. The surgical approach aimed to restore native medial collateral ligament (MCL) tension, guided by a ligament-balancing technique under robotic guidance to restore natural knee kinematics, as previously described[12].

*Radiographic evaluation*

Weightbearing antero-posterior long-leg radiographs were routinely obtained preoperatively and at approximately six weeks postoperatively. Radiographs were independently assessed by two observers blinded to post-operative outcomes (G.V.t.N.d.B. and R.J.M.V.), using a Picture Archiving and Communication System (PACS, Sectra, Imtec AB, version 16, Linköping, Sweden). Radiographic Kellgren-Lawrence grading was performed on preoperative radiographs to describe the presence and severity of OA in the medial and lateral compartment of the operative knee, with 0 representing absence of OA and 4 representing end stage bone on bone OA[13]. The mechanical hip-knee-ankle (mHKA) angle, MPTA, and lateral distal femoral angle (LDFA) were measured both pre- and postoperatively (Figure 1). The mHKA angle is defined as the angle between the mechanical axis of the femur and the mechanical axis of the tibia. The MPTA was measured as the medial angle formed by the mechanical axis of the tibia and the proximal tibial joint line, which is a line extending from the medial to the most lateral area of the tibial plateau, while excluding osteophytes at the tibial plateau surface. The LDFA was measured as the lateral angle formed by the mechanical axis of the femur and the distal femoral joint line. On postoperative radiographs, the MPTA was measured as the medial angle between the tibial mechanical axis and a line parallel to the articulating surface of the tibial component. The LDFA was measured as the lateral angle between the femoral mechanical axis and a line tangent to the distal surface of the femoral component. Overall joint line obliquity (JLO), which describes the orientation of the joint line relative to a neutral horizontal line, was computed by adding the MPTA and LDFA[14, 15]. Intra-class correlation coefficient (ICC) between observers for the mHKA, MPTA, and LDFA were 0.98 (95% confidence interval [CI] 0.97-0.99), 0.91 (95% CI 0.86-0.94), and 0.90 (95% CI 0.86-0.94), respectively, indicating excellent inter-observer reliability for all measurements.

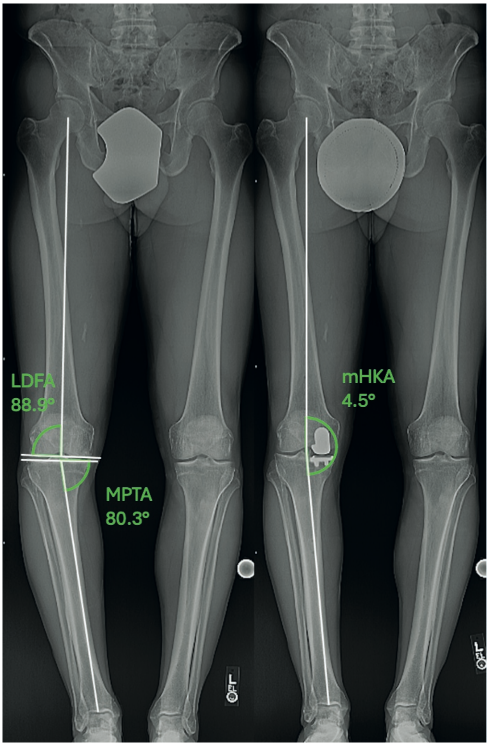


**Figure 1.** Long-leg radiograph of a patient with isolated anteromedial osteoarthritis both preoperatively and following medial UKA. *LDFA,* lateral distal femoral angle; *mHKA*; mechanical hip-knee-ankle angle; *MPTA*; medial proximal tibial angle; *UKA,* Unicompartmental knee arthroplasty.

*Tibial varus*

Patients were stratified into two groups based on the severity of their preoperative tibial varus deformity. In the present study, patients with an MPTA measuring < 85° were considered to have tibial varus bone deformities, whereas those with an MPTA measuring ≥ 85° did not. Malalignment in the knee is a combination of constitutional alignment of the lower extremity and deformation due to degenerative wear[16]. Within the context of OA progression and consequent joint space narrowing, alterations occur in the mechanical axis of the knee, which typically involve deviations of the mHKA away from its pre-arthritic alignment[17]. Measurements of the MPTA and LDFA solely rely on bony landmarks and are independent of the relationship of the femur to the tibia. Therefore, in cases where substantial bone loss is absent, the MPTA and LDFA remain unaffected by joint space narrowing, indicating their consistency throughout the course of OA progression. Traditionally, a neutral MPTA is defined as 90°, serving as a reference for achieving neutral mechanical alignment[18]. However, recent anatomical studies have revealed that the MPTA tends to be approximately 87° in both healthy and osteoarthritic knees, with a reference range of 85-90° and standard deviation of 2°[17, 19-22]. Hence, an MPTA threshold of 85° was established to effectively differentiate between clinically significant tibial varus deformities and those within the normal physiological range.

*Patient-reported outcomes*

Patient-reported outcomes were prospectively collected both preoperatively and at 12- and 24 months postoperatively. Patients completed standardized patient-reported outcome questionnaires in a secure, Health Insurance Portability and Accountability Act (HIPAA)-compliant online portal after being directed to complete the questionnaires via email. Patient-reported outcomes included the University of California at Los Angeles (UCLA) activity score, Oxford Knee Score (OKS), Knee Injury and Osteoarthritis Outcome Score for Joint Replacement (KOOS, JR), Visual Analogue Scale (VAS) for pain score, and satisfaction. The UCLA activity score assesses the level of activity from 1 (wholly inactive, dependent on others, and cannot leave residence) to 10 (regularly participating in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking). The OKS assesses pain and physical function following knee arthroplasty on a scale from 0 (worst possible score) to 48 (best possible score). The KOOS, JR assesses symptoms related to the overall knee health from 0 (total knee disability) to 100 (perfect knee health). The VAS pain score assesses the knee related pain intensity from 0 (worst imaginable pain) to 10 (no pain). Patient satisfaction was assessed by asking patients to report their satisfaction of the operative knee on a 5-point Likert scale ("very satisfied," "satisfied," "neutral," "dissatisfied," or "very dissatisfied").

*Minimum Clinically Important Difference*

To assess differences in clinical improvement following UKA, mean differences between baseline PROMs and their subsequent follow-up evaluations were calculated. Additionally, the proportion of patients meeting the established Minimum Clinically Important Difference (MCIDs) thresholds were assessed, which were defined as 1.0 for the UCLA activity score[23, 24], 5.0 for the OKS[25, 26], 2.0 for the VAS for pain[27, 28], and 14.0 for the KOOS, JR[29, 30].

*Data analyses*

All analyses were performed in IBM SPSS Statistics for Macintosh, version 28.0.1.1 (IBM Corp., Armonk, NY). Patient demographics and PROMs were presented using descriptive statistics across the entire patient cohort, as well as stratified by MPTA. The normality of continuous variables was evaluated employing the Shapiro-Wilk test. Subsequently, to compare means between two independent samples, either the Mann-Whitney U test or independent *t*-test were employed, depending on the distribution of the data. Comparisons of discrete variables and the proportion of patients surpassing the MCID were conducted using the *Chi*-squared test or Fisher's exact test, as deemed appropriate.

## Results

A total of 104 patients were included in the study, of whom 46 (44.2%) presented with preoperative tibial varus (i.e., MPTA <85°), while the remaining 58 (55.8%) did not. No patients required revision surgery within the initial two-year postoperative period subsequent to medial UKA. One patient (0.9%), who did not present with preoperative tibial varus, required re-operation within the first postoperative year in the ipsilateral knee due to scar tissue debridement.

*Radiographic outcomes*

Preoperatively, mean MPTA in knees with and without preoperative tibial varus was 83.3° [range, 79.8 to 84.9] and 87.2° [range, 85.0 to 90.5], respectively (*p* = <.001). Patients presenting with preoperative tibial varus deformities demonstrated significantly greater varus alignment and lower JLO values compared to those without tibial varus (mHKA: 9.9° [range, 4.0 to 17.5] vs. 5.5° [range, -1.7 to 13.4], *p* = <.001 and JLO: 172.0° [range, 165.7 to 177.0] vs. 175.2° [range, 170.5 to 179.6], *p* = <.001). Postoperatively, patients with tibial varus deformities exhibited more pronounced residual varus alignment (3.8° [range, -0.1 to 8.6] vs. 0.7° [range, -4.1 to 6.6], *p* = <.001), as well as lower MPTA and JLO values compared to patients without preoperative tibial varus. Radiographic outcomes of included patients stratified by MPTA are presented in Table 2.

*Patient-reported outcomes*

Preoperatively, as well as at one- and two-year follow-up, no significant differences were observed in the OKS, VAS for pain, and KOOS, JR between groups (Figure 2). Patients with tibial varus exhibited significantly higher UCLA activity scores both at baseline (6.4 [range, 2 to 10] vs. 5.1 [range, 2 to 10], *p* = .006) and one-year follow-up (7.6 [range, 3 to 10] vs. 6.6 [range, 2 to 10], *p* = .018), though UCLA scores became comparable between groups at two-years follow-up. Moreover, at one-year follow-up, a greater proportion of patients with excessive preoperative tibial varus expressed being “satisfied” or “very satisfied” with their surgery compared to patients without tibial varus deformities (93.4% vs. 77.6%, *p* = .026).

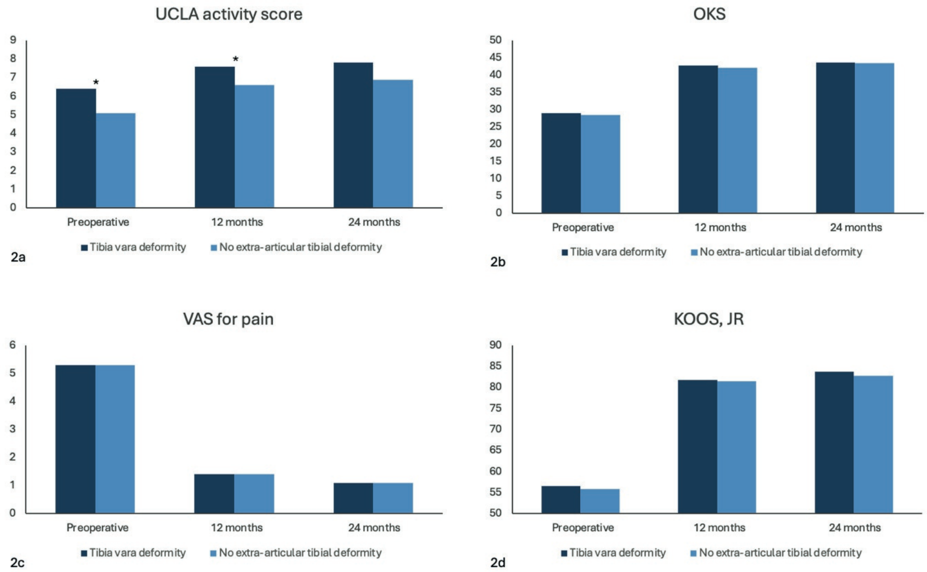


**Figure 2.** Patient-reported outcomes among patients with excessive preoperative tibial varus deformities (MPTA <85°) and patients without extra-articular tibial deformities (MPTA ≥85°). **2a,** UCLA activity score preoperatively and 12- and 24 months following medial UKA. **2b,** OKS preoperatively and 12- and 24 months following medial UKA. **2c,** VAS for pain preoperatively and 12- and 24 months following medial UKA. **2d,** KOOS, JR preoperatively and 12- and 24 months following medial UKA. *KOOS, JR,* Knee Injury and Osteoarthritis Outcome Score for Joint Replacement; *MPTA,* Medial Proximal Tibia Angle; *OKS,* Oxford Knee Score; *UCLA,* University of California Los Angeles; *UKA,* Unicompartmental knee arthroplasty; *VAS*, Visual Analogue Scale. * Indicates statistical significance

*Achievement of clinically relevant thresholds*

No statistically significant differences were identified in the clinical improvement of PROMs between baseline and both one- and two-year follow-up or the proportion of patients attaining the MCID between patients with preoperative tibial varus and those without (Table 3).

**Table 2.** Pre- and postoperative radiographic outcomes in knees with and without excessive preoperative tibial varus deformity.

| | Preoperatively | | | | Postoperative | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Total | MPTA <85° | MPTA ≥85° | *p* value§ | Total | MPTA <85° | MPTA ≥85° | *p* value§ |
| **HKA (°)** | | | | | | | | |
| Mean ± SD | 7.5 ± 3.7 | 9.9 ± 2.7 | 5.5 ± 3.2 | <.001* | 2.1 ± 2.6 | 3.8 ± 2.1 | 0.7 ± 2.1 | <.001* |
| Range | -1.7 to 17.5 | 4.0 to 17.5 | -1.7 to 13.4 | | -4.1 to 8.6 | -0.1 to 8.6 | -4.1 to 6.6 | |
| **LDFA (°)** | | | | | | | | |
| Mean ± SD | 88.3 ± 1.6 | 88.6 ± 1.5 | 88.1 ± 1.7 | .085 | 86.5 ± 1.8 | 86.4 ± 1.9 | 86.5 ± 1.8 | .908 |
| Range | 83.9 to 92.1 | 83.9 to 92.1 | 84.9 to 91.6 | | 82.5 to 94.2 | 82.9 to 94.2 | 82.5 to 91.2 | |
| **MPTA (°)** | | | | | | | | |
| Mean ± SD | 85.5 ± 2.4 | 83.3 ± 1.3 | 87.2 ± 1.5 | <.001* | 87.2 ± 1.9 | 85.8 ± 1.3 | 88.4 ± 1.5 | <.001* |
| Range | 79.8 to 90.5 | 79.8 to 84.9 | 85.0 to 90.5 | | 83.6 to 93.0 | 83.6 to 88.2 | 85.0 to 93.0 | |
| **JLO (°)** | | | | | | | | |
| Mean ± SD | 173.7 ± 2.9 | 172.0 ± 2.1 | 175.2 ± 2.0 | <.001* | 173.7 ± 2.9 | 172.2 ± 2.5 | 174.8 ± 2.7 | <.001* |
| Range | 167.5 to 182.4 | 165.7 to 177.0 | 170.5 to 179.6 | | 167.5 to 182.4 | 167.6 to 182.2 | 167.5 to 182.4 | |

Pre- and postoperative radiographic outcomes are given in mean ± SD and range for the entire cohort and stratified by preoperative MPTA. *HKA,* Hip-knee-ankle angle; *JLO,* Joint line obliquity; *LDFA,* Lateral distal femoral angle; *MPTA,* Medial proximal tibial angle.

§ Comparison of patient demographics by preoperative MPTA.

* Indicates statistical significance.

**Table 3.** Clinical improvement in patient-reported outcomes in knees with and without excessive preoperative tibial varus deformity.

| Outcome variable | Total | MPTA <85° | MPTA ≥85° | *p* value§ |
|---|---|---|---|---|
| **UCLA activity score** | | | | |
| Change from baseline to 12 mos | 1.4 (-5-6) | 1.2 (-3-6) | 1.5 (-5-5) | .492 |
| Change from baseline to 24 mos | 1.7 (-5-6) | 1.2 (-4-6) | 2.1 (-5-6) | .286 |
| Attained MCID at 12 mos | 67 (64.4%) | 26 (56.5%) | 41 (70.7%) | .134 |
| Attained MCID at 24 mos | 28 (66.7%) | 9 (52.9%) | 19 (76.0%) | .120 |
| **Oxford Knee Score** | | | | |
| Change from baseline to 12 mos | 13.7 (-6-35) | 13.9 (-2-35) | 13.6 (-6-30) | .858 |
| Change from baseline to 24 mos | 15.4 (-3-35) | 15.6 (-3-35) | 15.3 (3-30) | .899 |
| Attained MCID at 12 mos | 90 (86.5%) | 40 (87.0%) | 50 (86.2%) | .911 |
| Attained MCID at 24 mos | 35 (89.7%) | 15 (93.8%) | 20 (87.0%) | .492 |
| **VAS for pain** | | | | |
| Change from baseline to 12 mos | -3.9 (-8-2) | -4.0 (-8-1) | -3.9 (-8-2) | .928 |
| Change from baseline to 24 mos | -4.3 (-9-2) | -4.6 (-9-0) | -4.2 (-8-2) | .652 |
| Attained MCID at 12 mos | 85 (81.7%) | 37 (80.4%) | 48 (82.8%) | .761 |
| Attained MCID at 24 mos | 33 (86.8%) | 14 (87.5%) | 19 (86.4%) | .919 |
| **KOOS, JR** | | | | |
| Change from baseline to 12 mos | 25.6 (-18-69) | 25.1 (-3-69) | 26.1 (-18-58) | .790 |
| Change from baseline to 24 mos | 28.5 (-10-69) | 29.7 (4-69) | 27.4 (-10-48) | .733 |
| Attained MCID at 12 mos | 66 (72.5%) | 30 (71.4%) | 36 (73.5%) | .828 |
| Attained MCID at 24 mos | 23 (76.7%) | 12 (85.7%) | 11 (68.8%) | .273 |

Outcomes are given in mean (range) and numbers and frequencies (%) for the entire cohort and stratified by preoperative MPTA. *KOOS JR,* Knee Injury and Osteoarthritis Outcome Score for Joint Replacement; *MCID,* Minimum Clinically Important Difference; *UCLA,* University of California at Los Angeles; *VAS,* Visual Analogue Scale.
§ Comparison of patient demographics by preoperative MPTA.
* Indicates statistical significance.

## Discussion

The most important finding of the present study is that the presence of excessive preoperative tibial varus did not result in inferior subjective outcomes nor differences in clinical improvement following fixed-bearing medial UKA. Patients presenting with proximal tibial varus deformities reported higher satisfaction rates and higher UCLA activity scores both at baseline and at one-year follow-up. These findings challenge prevailing reluctance regarding the suitability of UKA among patients with tibial varus deformities, implying that such concerns may lack substantive basis and affirming the viability of these patients as suitable candidates for medial UKA.

While indications for medial UKA have become less restrictive, specific recommendations and consequences related to the MPTA remain ambiguous. Recent research has underscored the inherent challenges associated with severe bony deformities, raising concerns regarding the appropriateness of UKA for patients presenting with excessive extra-articular deformities[9, 31]. This study observed that 44.2% of patients exhibited extra-articular tibial varus deformities, defined by an MPTA measuring < 85°. Previous studies similarly identified substantial proportions, with approximately 67.0% of patients with anteromedial OA exhibiting proximal tibial varus deformities measuring < 87° and 41.5% presenting proximal tibial varus deformities measuring < 85.5°[7, 31]. Moreover, the predominant knee phenotype observed in cases of anteromedial OA, classified as CPAK I (45.0% of patients), is characterized by an MPTA of 84.3°[32]. Given the significant prevalence of extra-articular tibial varus deformities among patients with isolated anteromedial OA, it is imperative to gain a comprehensive understanding of the implications on surgical outcomes. Erlichman *et a*[11]*l* recently evaluated the influence of extra-articular proximal tibial varus deformities, defined as an MPTA measuring < 80°, on clinical outcomes and survivorship following mobile-bearing UKA, concluding that such deformities did not correlate with higher failure rates nor inferior clinical outcomes. Similarly, Park *et al* found no significant effect of tibial varus on functional outcomes following fixed-bearing medial UKA using an MPTA threshold of 86°. The current study contributes to the body of evidence by demonstrating that tibial varus deformities do not exert a negative influence on subjective outcomes, clinical improvement, and patient satisfaction following robotic-arm assisted medial UKA with a fixed-bearing implant.

Alignment of the lower extremity following medial UKA plays a pivotal role in achieving favorable clinical outcomes and long-term survivorship[9]. Previous research advocates for mild postoperative residual varus alignment following medial UKA, as it has been associated with superior outcomes compared to restoration to a neutral or close-to-neutral mechanical axis[33, 34]. The current study demonstrated that preoperative tibial varus is associated with significantly more pronounced residual varus following UKA compared to patients without severe tibial varus deformities (HKA: 3.8° vs 0.7°). This is consistent with findings from Ji *et al*[8] indicating that a lower MPTA was associated with increased residual varus following medial UKA. Specifically, their study demonstrated that patients who had an MPTA measuring < 85° were found to have a 4.5 times higher likelihood of experiencing postoperative residual varus compared to patients who had an MPTA measuring ≥ 85°.

However, while preoperative tibial varus may predispose patients to a more pronounced residual varus alignment following UKA, thereby reducing the probability of achieving optimal postoperative alignment, this did not translate in inferior outcomes. Nonetheless, it is noteworthy that the observed average postoperative alignment of 3.8° in the present study still falls within the recognized acceptable range of 1-5° established by prior research, which may account for the absence of inferior outcomes[8, 33, 35].

Another significant concern regarding the utilization of UKA in patients with substantial bony deformities pertains to the challenge of achieving proper tibial component obliquity and restoring joint space height to ensure optimal knee kinematics. Chatellard *et al*[9] suggested that the tibial component obliquity should be realigned within 3° of either direction of the physiological obliquity of the joint space and that the joint space height should be restored within 3 mm of either direction of the lateral compartment joint space[9, 36]. However, substantial deformities of the proximal tibia can present significant challenges in meeting these recommendations. As a result, there prevails an advocacy for considering HTO as a preferred alternative in such cases, as it not only addresses OA development but also offers the potential for extra-articular corrections. The present study demonstrated that patients presenting tibial varus deformities exhibited a significantly more pronounced medial downward "varus" slope of the joint line compared to patients devoid of these deformities, both pre- and postoperatively. Similarly, Park *et al*[10] demonstrated that patients who had tibial varus deformities displayed a greater medial downward slope of the JLO and joint surface malalignment (JSM) following medial UKA in comparison to patients without tibial varus deformities. However, it is pertinent to note that these observations did not have a clinically relevant impact on outcomes. Thus, while it may be argued that HTO is preferred over UKA in cases of extreme tibial varus, there is currently no evidence suggesting inferior outcomes of UKA in patients with tibial varus deformities.

This study is not without limitations. First, all surgeries were performed by a single surgeon, which may have introduced selection bias, as the surgeon's expertise and preferences may have influenced patient selection. Second, this study solely focused on short-term patient-reported outcomes and patient satisfaction, neglecting evaluations of long-term survival rates and functional outcomes. Third, this study used an MPTA threshold of 85° to define tibial varus, which was based on established normal values and reference ranges, while other studies have proposed alternative thresholds, such as a threshold of 10° to define extra-articular deformities[11 31]. This discrepancy underscores the necessity for standardization in how tibial varus is defined. Fourth, this study lacks a formal power analysis, which precludes a definitive assessment of whether the sample size was adequate to detect meaningful differences between groups.

## Conclusion

This study supports the safe utilization of fixed-bearing medial UKA as an effective surgical intervention for managing isolated anteromedial OA, even in the presence of preoperative tibial varus deformities. While preoperative tibial varus may predispose patients to a more pronounced residual varus following medial UKA, subjective outcomes appear to remain unaffected. Nonetheless, additional research utilizing long-term data is necessary to thoroughly examine the relationship between preoperative deformities, postoperative alignment, and long-term functional outcomes in UKA patients.

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# RETURN TO SPORT AND PHYSICAL FUNCTION

# Chapter 5

## A greater rate of return to high-impact sports favoring unicompartmental knee arthroplasty compared with total knee arthroplasty

a systematic review and meta-analysis

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**Abstract**

**Purpose:** this systematic review aimed to compare return to sport (RTS) outcomes, as well as RTS rates stratified by sport-impact level, following total knee arthroplasty (TKA), unicompartmental knee arthroplasty (UKA), and patellofemoral arthroplasty (PFA).

**Methods:** a literature search was conducted in PubMed, Embase and Cochrane up to June 2024. Studies reporting on RTS rates following TKA, UKA or PFA were included. RTS rates stratified by sport impact level, along with Tegner-Lysholm and University of California and Los Angeles (UCLA) activity scores were extracted. Outcomes were compared using random-effect models. Thirty-eight studies were included, of which eight were eligible for meta-analysis, comprising a total of 7,634 patients.

**Results:** Patients undergoing UKA demonstrated significantly higher overall RTS rates (80.7%, range 18.4% to 100%) compared to patients undergoing TKA (69.0%, range 4.1% to 100%) and PFA (68,4%, range 63.0% to 73.1%). Meta-analysis demonstrated that patients undergoing TKA had a lower likelihood of returning to sport compared with those undergoing UKA (OR 0.53, 95% CI 0.35 to 0.82, $p$ = 0.004). In high-impact sports, UKA patients were able to RTS at a higher rate than TKA patients (65.4% vs 4.4%). PFA patients returned to sports at a low rate across all impact levels (low-impact 42.4%; moderate-impact 35.0%; high-impact 20.5%).

**Conclusions:** patients undergoing UKA demonstrated a significantly higher overall RTS rate compared to patients undergoing UKA. Over 50% of UKA patients returned to high impact sports, whereas approximately 5% of TKA patients achieved this.

## Introduction

Recent registry data indicate that a considerable proportion of patients who would be suitable candidates for unicompartmental knee arthroplasty (UKA) or patellofemoral knee arthroplasty (PFA) undergo total knee arthroplasty (TKA)[1, 2]. When applied in appropriate selected patients, both UKA and PFA represent compelling alternatives to TKA for the treatment of unicompartmental knee osteoarthritis (OA)[3-6]. The reported higher revision rates of UKA and PFA are often cited as the main reason why some surgeons continue to recommend TKA, even in cases where a UKA or PFA might be more appropriate. Additionally, limited awareness of the indications and insufficient surgical experience with UKA and PFA may further contribute to this preference[7, 8].

The increasingly younger age at which patients are undergoing knee arthroplasties has shifted patient expectations, as a growing number of patients are still of sport-participating age when undergoing knee arthroplasty[9]. As a result, arthroplasties are increasingly expected to provide both excellent functionality and long-term durability. Several studies have demonstrated the importance of managing patient expectations following surgery, as these strongly influence postoperative outcomes[10-12]. Informing patients on the likelihood of return to sport (RTS) following knee arthroplasty is therefore essential.

This systematic review aimed to evaluate overall RTS rates, as well as RTS rates stratified by sport impact level, in patients undergoing primary TKA, UKA, or PFA. It was hypothesized that patients undergoing UKA would demonstrate higher RTS rates compared with those undergoing TKA.

## Methods

*Inclusion Criteria and Study Selection*

The systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines[13]. The study protocol was registered in PROSPERO International prospective register of systematic reviews (CRD-42024559186). The electronic databases MEDLINE via Pubmed, Embase via OvidSP and Cochrane were searched on July 1st, 2024, using the search terms provided in Appendix 1.

Suitable studies were independently selected by two reviewers (R.J.M.V. and G.V.t.N.d.B.) using Rayyan (B.V. Qatar Computing Research Institute)[14]. Any disagreement was resolved by discussion and consensus. Articles were included when these reported on RTS rate following primary TKA, medial UKA or PFA as treatment for symptomatic OA. Additional inclusion criteria were preoperative participation in sports, a minimum one-year follow-up (FU), patient age ≥18 years, articles had to be written in English, German, Dutch or French and had to be published between August 1st 2003 to July 1st 2024. Exclusion criteria were articles reporting on revision arthroplasty and reviews, case reports or cadaveric studies.

*Outcomes of Interest*

The primary outcome was RTS rate. RTS was defined as the patient returning to his or her intended sport[15]. Secondary outcomes were RTS rate per sport impact level according to Vail *et al*[16] and Kuster *et al*[17], the University of California and Los Angeles Activity score (UCLA activity)[18] and the Tegner-Lysholm rating scale (Tegner)[19]. Categorization of sport impact level (low-, moderate- and high-impact sports), is shown in Appendix 2. Categorization was based on the applied force on the knee during sport performance. The outcomes were selected as these were validated in previous literature to illustrate RTS and reflect knee function during sport activities.

*Methodological Quality Assessment*

Risk of bias was assessed using the Methodological Index for Non-Randomized Studies (MINORS) criteria, a validated system for assessing the methodological quality of non-randomized studies looking at the clarity of the research question and data collection methods. Non-comparative studies were rated a maximum score of 16 points and comparative studies were rated a maximum score of 24 points. 0 points when a criterium was not reported, 1 when reported but not adequate, and 2 when reported and adequate. MINORS score was graded as very low quality for 0 to 4 points, low quality for 5 to 8 points, moderate quality for 9 to 12 points, high quality for 13 to 18 points and very high quality for 19 to 24 points[20].

*Data Extraction*

Data was extracted by the first author (R.J.M.V.) and verified by the second author (G.V.t.N.d.B.). A standardized data extraction form was used. Extracted data included: (1) study information including authors, publication year, study design, study sample size and FU duration; (2) patient demographics including sex, age, body mass index (BMI), type of OA; (3) description of outcome measures; (4) preoperative activity level; (5) RTS rate, RTS rates per impact level, UCLA activity and Tegner scores.

*Statistical Analysis*

Patient characteristics, FU and RTS rates were calculated according to Walter *et al*[21]. If the mean was not reported, it was estimated according to a previously described method[22]. A meta-analysis was performed between types of arthroplasties if at least two comparative studies compared outcomes. Review Manager v5.3 (the Nordic Cochrane Center, Copenhagen, Denmark) was used to calculate the odds ratio (OR) with 95% confidence interval (CI). RTS rates in the meta-analysis were compared by use of an $X^2$ test and a random-effects model. Heterogeneity between studies was assessed the $I^2$ statistic. $I^2$ >50% was considered as substantial heterogeneity[23]. Statistical level of significance was set to $p < 0.05$.

## Results

*Literature Search*

The search of the electronic database provided 5,721 relevant articles. After duplicate removal and excluding articles that did not comply with the inclusion criteria, the authors reviewed 43 full-text articles. Consequently, five articles were excluded, providing a total of 38 eligible articles for inclusion (Figure 1).

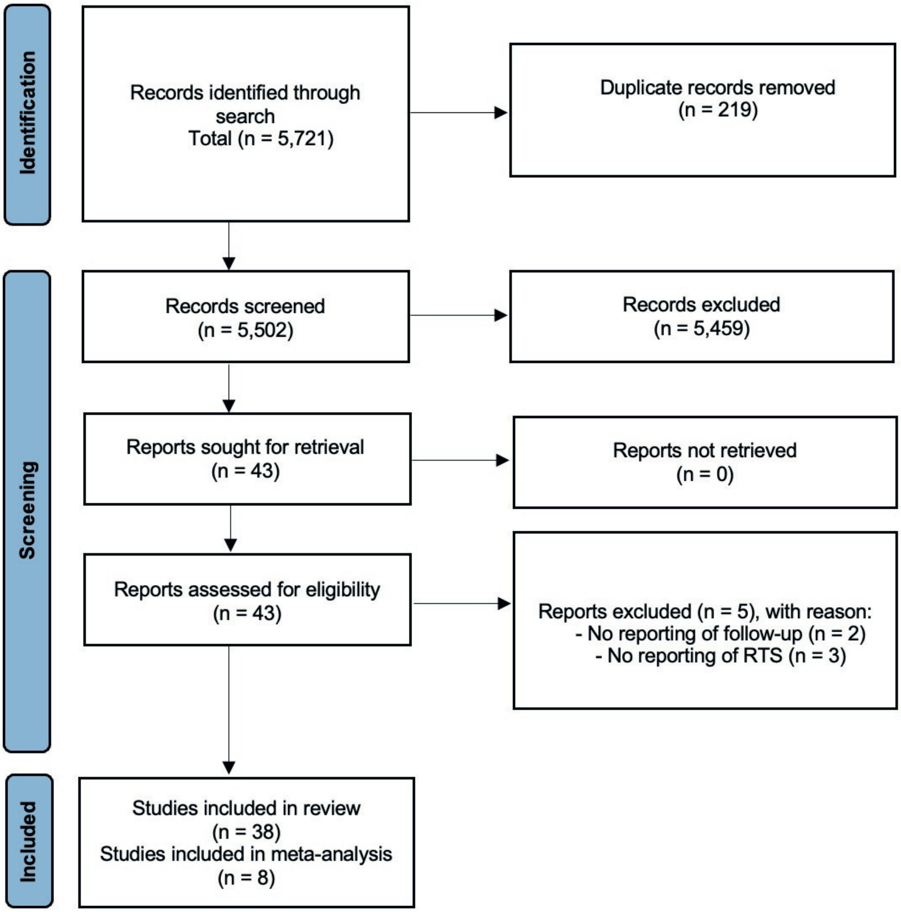


**Figure 1**. PRISMA flowchart of study selection. *RTS*, return to sport.

*Included Studies*

The included studies comprised of eight level III comparative studies, two level IV prospective case series and 28 level IV retrospective case series (Table 1). The total number of patients in the TKA cohort was 5,597 (mean FU 43.1 ± 23.7 months; mean age 64.3 ± 7.0 years), consisting of 22 studies[24-45]. Four articles reported on return to low-impact sports[26, 34, 36, 38], one article reported on return to moderate level[34] and two on return to high-impact sports[34, 45]. The UKA cohort, comprising 22 studies, totaled 1931 patients (mean FU 34.7 ± 15.5 months; mean age 64.3 ± 8.2 years)[26, 27, 29, 33, 37, 39, 45-60]. Four articles reported on low- and moderate-impact level[26, 49, 56, 60], and five articles on high-impact level[26, 45, 49, 56, 60]. The cohort for PFA comprised of 106 patients and three studies (mean FU 39.4 ± 8.9 months; mean age 55.3 ± 9.7 years)[37, 60 61]. Two studies reported on return to low-, moderate- and high-impact level sports[37, 60] (Table 1).

*Methodological Quality Assessment*

Twenty-five studies were assessed as moderate-quality, eight as high-quality and five as very high-quality. Most studies were lacking quality regarding loss to FU, prospective sample size calculation and blinding. A summary of all quality assessments per domain are listed in Table 2.

*Return to Sport*

Preoperative sport participation was similar across all arthroplasty types (TKA 61.9% [range 24.6% to 100%]; UKA 79.6% [range 47.1% to 100%]; PFA 71.7% [range 45.3% to 88.2%]). Postoperative RTS rate for TKA was 69.0% [range 4.1% to 100%] at 3.6 ± 2.0 years of FU, RTS rate for UKA was 80.7% [range 18.4% to 100%] at 2.9 ± 1.3 years of FU and RTS rate for PFA was 68.4% [range 63.0% to 73.1%] at 3.3 ± 0.7 years of FU (Table 1). Meta-analysis, comprising eight comparative studies, demonstrated that patients undergoing TKA were less likely to RTS compared with those undergoing UKA (OR 0.53, 95% CI 0.35 to 0.82, $p = .004$) (Figure 2). As the included studies did not contain comparative analyses of PFA versus either TKA or UKA, a meta-analysis for PFA was not conducted.

RTS to low- and moderate-impact sports was similar between TKA and UKA. However, UKA patients returned to high-impact sports at an approximate thirteen times higher rate than TKA patients (UKA 65.4% [range 18.4% to 100%]; TKA 4.4% [range 4.1% to 12.5%]). Return to low-, moderate and high-impact sports for PFA patients was low (Table 3).

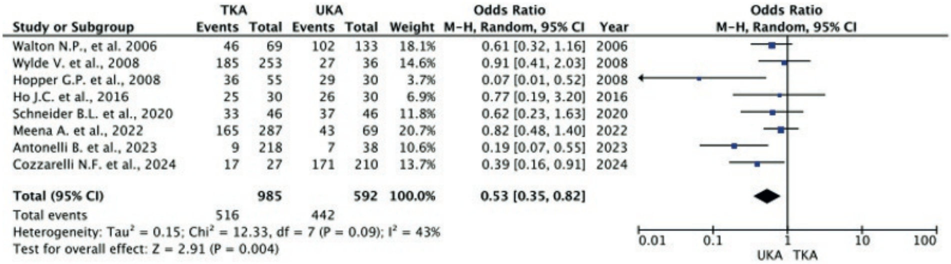


**Figure 2**. Meta-analysis comparing return to sport rates between patients undergoing TKA and patient undergoing UKA.

*Sport Activity parameters*

Ten articles reported on the UCLA activity score. UCLA activity for UKA increased from 5.4 ± 1.8 to 6.8 ± 1.6 and increased for TKA from 2.1 ± 1.9 to 4.6 ± 0.7 (Table 4). Three articles reported on the Tegner scale for TKA and one for UKA. Tegner score for TKA increased from preoperative (3.3 ± 1.4) to postoperative (3.9 ± 1.4). Similarly, Tegner score for UKA increased from preoperative (2.0 ± 1.1) to postoperative (3.8 ± 1.1) (Table 4).

Meta-analyses of UCLA activity score or Tegner scale were unfeasible as the included studies did not contain multiple comparative studies reported on these outcomes.

**Table 1.1** Study characteristics of included studies on TKA.

| Authors | Patients, no | Age, years | FU, months | BMI, kg/m$^2$ | Male, % | Return to sport: Total | Return to sport: Low impact | Return to sport: Moderate impact | Return to sport: High impact |
|---|---|---|---|---|---|---|---|---|---|
| Bock P. et al.[24] | 167 | 55.3 | 74.0 (9.5) | | | 75.4% | | | |
| Huch K. et al.[25] | 389 | 66.3 (6.4) | 60.0 | | 27.3% | 33.7% | | | |
| Hopper G.P. et al.[27] | 76 | 62.1 (8.2) | 21.6 (6.0) | | 45.0% | 65.6% | | | |
| Argenson J.N. et al.[28] | 445 | 71.6 (8.0) | 36.0 (4.0) | 28.3 (4.4) | 54.2% | 82.6% | | | |
| Wylde V. et al.[29] | 866 | 69.6 | 12.0 | | 41.0% | 73.1% | | | |
| Walton N.P. et al.[26] | 120 | 71.5 | 12.0 | | 49.2% | 66.7% | 90.0% | | |
| Chang M.J. et al.[30] | 369 | 68.8 (5.7) | 24.0 (4.2) | 27.4 (3.4) | 8.0% | 76.2% | | | |
| Mayr H.O. et al.[31] | 81 | 71.8 (5.4) | 76.8 (10.8) | 28.4 | | 84.0% | | | |
| Vielgut I. et al.[32] | 236 | | 178.0 (36.0) | | 18.2% | 71.6% | | | |
| Ho J.C. et al.[33] | 40 | 59.3 (4.3) | 50.4 (14.4) | 32.5 (8.3) | 30.0% | 83.3% | | | |
| Hepperger C. et al.[34] | 200 | | 24.0 | | | 100% | 68.2% | 78.4% | 12.5% |
| Valle C. et al.[35] | 130 | 69.2 | 22.0 | | | 67.7% | | | |
| Pioger C et al.[36] | 143 | 65.7 (7.2) | 55.5 (36.9) | | 85.3% | 99.3% | 93.5% | | |
| Schneider B.L. et al.[37] | 46 | | 24.0 | | 13.0% | 99.3% | | | |
| Tramer J.S. et al.[38] | 54 | 66.6 (7.3) | 63.6 (37.2) | 32.3 (6.3) | 81.8% | 81.5% | 81.5% | | |
| Meena A. et al.[39] | 287 | 75.7 | 24.0 (8.1) | | 49.1% | 57.5% | | | |
| D'Ambrosi R. et al.[40] | 345 | 59.8 (4.7) | 63.3 (18.8) | | 31.9% | 98.8% | | | |
| Ventura A. et al.[41] | 97 | 70.1 (3.8) | 50.4 (20.4) | 23.5 (1.6) | | 81.3% | | | |
| Wang D. et al.[42] | 50 | 62.2 (6.1) | 55.6 (10.2) | 26.5 (2.5) | 56.0% | 57.1% | | | |
| Scott D.F. et al.[43] | 63 | 64.0 | 17.8 | 30.5 | 56.0% | 66.7% | | | |
| Arshi A. et al.[44] | 1175 | 64.5 (7.4) | 48.0 (18.9) | 30.3 (5.1) | 47.4% | 71.9% | | | |
| Antonelli B. et al.[45] | 218 | 12.0 | | | | 4.1% | | | 4.1% |
| **Total** | **5597** | **64.3 (7.0)** | **43.1 (23.7)** | **28.8 (4.6)** | **38.7%** | **69.0%** | **87.5%** | **78.4%** | **4.4%** |

Study characteristics of included studies were presented for total knee arthroplasty as mean (standard deviation) or as proportion (%). FU, follow-up; BMI, body mass index.

**Table 1.2** Study characteristics of included studies on UKA.

| Authors | Patients, no | Age, years | FU, months | BMI, kg/m² | Male, % | Return to sport<br>Total | Low impact | Moderate impact | High impact |
|---|---|---|---|---|---|---|---|---|---|
| Jahromi et al.[46] | 150 | 71.5 | 12.0 | | | 71.0% | | | |
| Fisher N. et al.[47] | 66 | 64.0 | 18.0 (8.9) | | 48.5% | 84.8% | | | |
| Naal F.D. et al.[48] | 83 | 65.5 | 18.0 (4.6) | 28.3 (4.4) | 54.2% | 94.8% | | | |
| Hopper G.P. et al.[27] | 34 | 61.3 (6.6) | 22.3 (6.6) | | 59.0% | 96.7% | | | |
| Wylde V. et al.[29] | 100 | 66.0 | 12.0 | | 48.0% | 75.0% | | | |
| Walton N.P. et al.[26] | 150 | 71.5 | 12.0 | | 51.5% | 76.7% | 100% | 73.3% | |
| Pietschmann M.F. et al.[50] | 131 | 65.3 | 50.4 (20.8) | | 43.5% | 80.8% | | | 100% |
| Walker T. et al.[51] | 45 | 60.1 | 35.4 (8.1) | | 42.2% | 100% | | | |
| Walker T. et al.[52] | 93 | 55.0 (5.0) | 52.8 (19.2) | 32.0 (5.6) | 49.5% | 93.0% | | | |
| Ho J.C. et al.[33] | 36 | 60.0 (4.9) | 45.6 (13.2) | 30.0 (4.2) | 33.0% | 86.7% | | | |
| Panzram B. et al.[53] | 27 | 62.5 (6.8) | 60.0 (8.3) | | 55.6% | 100% | | | |
| Canetti R. et al.[54] | 28 | 62.3 (5.1) | 37.4 (13.8) | 25.5 (4.0) | 50.0% | 80.0% | | | |
| Lo Presti M. et al.[49] | 53 | 59.7 (4.6) | 48.0 (6.0) | | 28.3% | 90.0% | 100% | 78.3% | 100% |
| Kim M.S. et al.[55] | 42 | 63.6 (5.5) | 24.0 | 25.3 (2.4) | 16.7% | 94.1% | | | |
| Kleeblad L. et al.[56] | 164 | 62.3 (8.8) | 20.2 (9.5) | 27.6 (4.4) | 68.2% | 100% | 100% | 70.6% | 87.0% |
| Schneider B.L. et al.[37] | 46 | | 24.0 | | 13.0% | 54.3% | | | |
| Zimmerer A. et al.[57] | 19 | 56.7 (10.5) | 55.2 (26.4) | 27.2 (4.7) | 26.0% | 86.7% | | | |
| Panzram B. et al.[58] | 169 | 64.4 (9.7) | 37.1 (9.8) | 30.9 (5.4) | | 92.9% | | | |
| Meena A. et al.[39] | 69 | 74.2 | 24.0 (8.8) | | 60.9% | 62.3% | | | |
| Schmidt A. et al.[59] | 92 | 64.9 (6.4) | 87.6 (20.4) | 27.0 (3.5) | 65.2% | 32.6% | | | |
| Antonelli B. et al.[45] | 38 | 12.0 | | | | 18.4% | | | 18.4% |
| Cozzarelli N.F. et al.[60] | 296 | 60.7 (9.6) | 54.0 (20.4) | | 47.0% | 81.4% | 90.7% | 91.8% | 68.2% |
| **Total** | **1931** | **64.3 (8.2)** | **34.7 (15.5)** | **28.7 (4.5)** | **48.9%** | **80.7%** | **97.7%** | **90.9%** | **65.4%** |

Study characteristics of included studies were presented for unicompartmental knee arthroplasty as mean (standard deviation) or as proportion (%). FU, follow-up; BMI, body mass index.

**Table 1.3** Study characteristics of included studies on PFA.

| Authors | Patients, no | Age, years | FU, months | BMI, kg/m² | Male, % | Return to sport<br>Total | Low impact | Moderate impact | High impact |
|---|---|---|---|---|---|---|---|---|---|
| Shubin Stein B.E. et al.[61] | 39 | 51.6 (10.3) | 26.0 (13.3) | 26.3 (6.3) | 15.4% | 73.1% | | | |
| Schneider B.L. et al.[37] | 23 | | 24.0 | | 13.0% | 69.6% | 43.5% | 34.8% | 17.4% |
| Cozzarelli N.F. et al[60] | 44 | 58.5 (11.3) | 58.8 (9.0) | | 27.3 | 63.0% | 41.2% | 41.2% | 35.3% |
| **Total** | **106** | **55.3 (9.7)** | **39.4 (8.9)** | **26.3 (6.3)** | **19.8%** | **68.4%** | **42.3%** | **35.0%** | **20.5%** |

Study characteristics of included studies were presented for patellofemoral arthroplasty as mean (standard deviation) or as proportion (%). FU, follow-up; BMI, body mass index.

**Table 2.** Methodological quality assessment of included studies utilizing the MINORS criteria.

| | | | | | MINORS Criteria | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Authors** | **Yr** | **Journal, LoE** | | **Study design** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **Total** |
| Bock P. et al.[24] | '03 | Ortho Unf | 4 | R case series | 2 | 2 | 2 | 1 | 1 | 2 | 0 | 0 | | | | | 10 |
| Jahromi et al.[46] | '04 | Int Orthopaedics | 4 | R case series | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | | | | | 13 |
| Huch K. et al.[25] | '05 | Ann Rheum Dis | 4 | P case series | 2 | 2 | 2 | 2 | 1 | 1 | 0 | 2 | | | | | 12 |
| Fisher N. et al.[47] | '06 | The Knee | 4 | R case series | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | | | | | 10 |
| Walton N.P. et al.[26] | '06 | J Knee Surg | 3 | Cross-sectional | 1 | 2 | 2 | 2 | 2 | 1 | 0 | 1 | 2 | 2 | 1 | 1 | 17 |
| Naal F.D. et al.[48] | '07 | American J Sports M | 4 | R case series | 1 | 2 | 2 | 1 | 1 | 2 | 0 | 0 | | | | | 9 |
| Hopper G.P. et al.[27] | '08 | KSSTA | 3 | Cross-sectional | 2 | 2 | 2 | 2 | 0 | 2 | 0 | 0 | 2 | 2 | 1 | 2 | 17 |
| Argenson J.N. et al.[28] | '08 | Clin Orthop Relat Res | 4 | R case series | 2 | 2 | 1 | 2 | 0 | 1 | 0 | 1 | | | | | 9 |
| Wylde V. et al.[29] | '08 | BJJ | 3 | Cross-sectional | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 0 | 1 | 20 |
| Lo Presti M. et al.[49] | '11 | J Knee Surg | 4 | R case series | 2 | 2 | 2 | 1 | 0 | 2 | 0 | 1 | | | | | 10 |
| Pietschmann M.F. et al.[50] | '13 | Int Orthopaedics | 4 | R case series | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | | | | | 12 |
| Walker T. et al.[51] | '14 | KSSTA | 4 | R case series | 1 | 2 | 2 | 2 | 1 | 1 | 2 | 0 | | | | | 11 |
| Chang M.J. et al.[30] | '14 | BMC Musc Dis | 4 | R case series | 2 | 2 | 1 | 2 | 1 | 2 | 0 | 0 | | | | | 10 |
| Mayr H.O. et al.[31] | '15 | JOA | 4 | R case series | 1 | 2 | 2 | 2 | 0 | 2 | 0 | 2 | | | | | 11 |
| Walker T. et al.[52] | '15 | KSSTA | 4 | R case series | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 0 | | | | | 13 |
| Vielgut I. et al.[32] | '16 | Nature Sci reports | 4 | R case series | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 0 | | | | | 11 |
| Ho J.C. et al.[33] | '16 | J Knee Surg | 3 | Cross-sectional | 2 | 2 | 2 | 2 | 1 | 2 | 0 | 2 | 2 | 2 | 2 | 2 | 21 |
| Hepperger C. et al.[34] | '17 | KSSTA | 4 | R case series | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 0 | | | | | 12 |
| Valle C. et al.[35] | '17 | Sportverletz Sportsch | 4 | R case series | 2 | 2 | 1 | 2 | 1 | 1 | 0 | 0 | | | | | 9 |
| Shubin Stein B. et al.[61] | '17 | American J Orth | 4 | R case series | 2 | 2 | 2 | 1 | 0 | 1 | 1 | 0 | | | | | 9 |
| Panzram B. et al.[53] | '18 | BMC Musc DIs | 4 | R case series | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 0 | | | | | 12 |
| Canetti R. et al.[54] | '18 | Orth and Trauma S | 4 | R case series | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 0 | | | | | 9 |
| Kim M.S. et al.[55] | '18 | Int Orthopaedics | 4 | P case series | 2 | 1 | 2 | 2 | 1 | 1 | 0 | 1 | | | | | 10 |
| Kleeblad L. et al.[56] | '20 | The Knee | 4 | R case series | 2 | 2 | 2 | 2 | 2 | 1 | 0 | 2 | | | | | 13 |
| Pioger C et al.[36] | '20 | J of Orthopaedics | 4 | R case series | 2 | 2 | 2 | 2 | 1 | 2 | 0 | 0 | | | | | 11 |
| Schneider B.L. et al.[37] | '20 | Orth J of Sports M | 3 | Cross-sectional | 2 | 1 | 2 | 2 | 0 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 19 |
| Zimmerer A. et al.[57] | '21 | The Knee | 4 | R case series | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 0 | | | | | 11 |
| Tramer J.S. et al.[38] | '21 | AOSSM | 4 | R case series | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 0 | | | | | 13 |
| Pazram B. et al.[58] | '21 | J Knee Surg | 4 | R case series | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 0 | | | | | 9 |
| Meena A. et al.[39] | '22 | KSSTA | 4 | Cross-sectional | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 0 | 2 | 2 | 1 | 1 | 12 |
| D'Ambrosi R. et al.[40] | '22 | KSSTA | 4 | R case series | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | | | | | 15 |
| Ventura A. et al.[41] | '22 | Int. J. of Artificial Org | 4 | R case series | 2 | 2 | 2 | 1 | 1 | 2 | 0 | 0 | | | | | 10 |
| Wang D. et al.[42] | '23 | Frontiers in Surg | 4 | R case series | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 0 | | | | | 10 |
| Scott D.F. et al.[43] | '23 | Bone & Joint Surg | 4 | R case series | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | | | | | 13 |
| Arshi A. et al.[44] | '23 | JOA | 4 | R case series | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 0 | | | | | 9 |
| Schmidt A. et al.[59] | '23 | Orth and Trauma S | 4 | R case series | 1 | 2 | 2 | 2 | 0 | 2 | 2 | 0 | | | | | 11 |
| Antonelli B. et al.[45] | '23 | J of AAOS | 3 | Cross-sectional | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 20 |
| Cozzarelli N.F. et al.[60] | '24 | JOA | 3 | Cross-sectional | 2 | 2 | 2 | 2 | 1 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 19 |

Displaying risk of bias for each of the included studies according to the Methodological Index for Non-Randomized Studies (MINORS) criteria*.
R case series: retrospective case series; P case series: prospective case series; LoE; level of evidence.
*Each MINORS criterium is explained in detail in Appendix 3.

## Discussion

This study demonstrated that the RTS rate for UKA was significantly higher compared to TKA, independent of sport impact level, at similar FU durations, mean age and male to female ratio. Additionally, more than 60% of UKA patient were able to return to high-impact sports, whereas only approximately 5% of TKA patients achieved this outcome. Return to PFA was low, relative to RTS following TKA and UKA, irrespective of sport impact level.

A systematic review by Witjes *et al*[62] reported that TKA patients participated in approximately one sport and UKA patients participate in two sports preoperatively. Additionally, the study stated UKA patients demonstrated higher preoperative activity levels. Results from this study corroborate these findings. The higher preoperative sport participation for UKA patients may be attributed to more compartmentalized OA affecting function and pain. None of the included studies in this systematic review reported on the Kellgren-Lawrence classification, making adjustment for this factor impossible. Additionally, outcomes may be affected by the inconsistency in the reporting of timing of preoperative sport participation assessment. Some studies reported participation at time of surgery[28], others at three years before surgery[29], and others over a patient's lifespan[25]. Overall, literature seems to be unanimous that preoperatively, the majority of patients can compete in sports, but UKA patients seem to be able to perform at a higher activity level.

This study specifically evaluated the likelihood of postoperative RTS in preoperative sport-participating patients[15]. The RTS rate for UKA patients was significantly higher than for TKA patients. Additionally, postoperative UCLA activity score was higher for UKA patients whereas postoperative Tegner scores were similar. Several studies corroborated these outcomes and underlined the variance in RTS rates following TKA and UKA, but did not combine data to derive more meaningful conclusions[19, 62, 63]. Comparative analysis demonstrated that for every TKA patient returning to sport postoperatively, approximately two UKA patients do so. The FU duration was approximately eight months longer for the TKA group, hypothetically providing more time for patients to RTS. Nonetheless, RTS rate remained higher for UKA patients.

The existing literature is largely unanimous that both TKA and UKA patients are able to return to low and moderate-impact sports, if they participated in those sports preoperatively. A difference in return to high-impact sports was observed between TKA (4.4%) and UKA (65.4%). The TKA outcomes for high-impact sports were based on two studies by Hepperger *et al*[34] and Antonelli *et al*[45], in which patients participated in high-level running, considered a highly strenuous sport on the knee joint, possibly resulting in undervalued RTS rates. The superior overall RTS rate and RTS for high-impact sports favoring UKA may be attributed to the superior replication of native knee kinematics, improved range of motion, better knee function and lower pain scores attributed to UKA[64-67].

Data on return to sport impact level for PFA was reported by two studies[37, 60], potentially leading to an inaccurate representation of actual RTS rates. Based on these results, special consideration should be given when selecting PFA for sport-participating patients who aim to resume athletic activities postoperatively, as outcomes appear subpar.

In arthroplasty, as well as various other surgical specialties, the importance of management of patient expectations has been shown, as this is a crucial factor influencing postoperative outcomes[10-12]. Therefore, the ability to inform patients on the likelihood to RTS is essential in improvement of subjective outcomes. Additionally, a consensus statement of the Sport Physical Therapy stated that the reporting on the level of sport participation is essential to define RTS[15]. Previous studies did not report on level of sport participation[19, 62, 63]. This study was the first systematic review to elaborate on RTS for various levels of sports, categorized based on the intensity, following knee arthroplasties. This study will add to existing literature and could be used for patient expectation management and shared decision making.

Current guidelines discourage the postoperative participation of high-impact sports in most cases, primarily based on surgeon experience rather than scientific evidence, as studies on sport-related complications after knee arthroplasties are rarely evaluated[67]. This current study provided evidence that more liberal counseling regarding return to high-impact sports following UKA may be justified.

This systematic review faced several limitations. First, this study was limited by its' inability to distinguish between patients treated for unicompartmental OA with a UKA and generalized OA with a TKA. Potential differences in outcome may have been attributed to the underlying pathology instead of the implant design. Inherent bias was expected from different indications for UKA and TKA, which likely affected differences in patient populations. To address this bias, a future propensity-matched cohort study would be recommended. Second, this study was unable to conduct meta-analyses RTS rate for individual sport impact levels or for the UCLA and Tegner scores, due to a lack of required comparative studies. Lastly, the study could not adjust for individual athletic ability, as this was not provided for each patient. Consequently, former athletes, who may have had a greater propensity to return to their level of sport, were not separately analyzed from casual sport-participants.

**Conclusion**

UKA Patients had a significantly higher overall RTS rate than TKA patients. Over 50% of UKA patient were able to return to high impact sports, whereas only 5% of TKA patients achieved this outcome. The likelihood of RTS appeared lowest among patients who underwent PFA. A more liberal counseling regarding return to high-impact sports following UKA may be justified.

**Table 3.** Return to sport rates per arthroplasty type for low, moderate or high impact sports

| | Pooled RTS, % [range] | | |
|---|---|---|---|
| **Type** | **Return to low impact** | **Return to moderate impact** | **Return to high impact** |
| Total knee arthroplasty | 87.5% [68.2%-93.5%] | 78.4% | 4.4% [4.1%-12.5%] |
| Medial unicompartmental knee arthroplasty | 97.7% [90.7%-100%] | 90.9% [70.6%-91.8%] | 65.4% [18.4%-100%] |
| Patellofemoral arthroplasty | 42.4% [41.2%-43.5%] | 35.0% [34.8%-41.2%] | 20.5% [17.4%-35.3%] |

Proportion (%) with [range] of patients returning to level of impact sport which they participated in preoperatively for individual arthroplasty types. *RTS, return to sport*

**Table 4.** Preoperative sport participation rates, Tegner Score and UCLA score per arthroplasty type

| | **Preoperative sport participation, % [range]** | **Tegner score Mean ± SD** | | **Pooled UCLA-activity Mean ± SD** | |
|---|---|---|---|---|---|
| **Type** | | **Preoperative** | **Postoperative** | **Preoperative** | **Postoperative** |
| Total knee arthroplasty | 61.9% [24.6%-100%] | 3.3 ± 1.4 | 3.9 ± 1.4 | 2.1 ± 1.9 | 4.6 ± 0.7 |
| Medial unicompartmental knee arthroplasty | 79.6% [47.1%-100%] | 2.0 ± 1.1 | 3.8 ± 1.1 | 5.4 ± 1.8 | 6.8 ± 1.6 |
| Patellofemoral arthroplasty | 71.7% [45.3%-88.2%] | - | - | - | - |

Preoperative return to sport (RTS) rates were presented for the three knee arthroplasties and were presented as proportion of total (%) with [range]. Tegner scale and UCLA activity score were presented as mean ± SD (standard deviation). *UCLA, University of California and Los Angeles activity score*

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# Chapter 6

# Successful return to sport following distal femoral osteotomy and lateral unicompartmental knee arthroplasty for isolated lateral knee osteoarthritis

a systematic review and meta-analysis

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Knee Surgery, Sports Traumatology, Arthroscopy

## Abstract

**Purpose:** to evaluate: (I) return to sport (RTS) rates following distal femoral osteotomy (DFO) and lateral unicompartmental knee arthroplasty (UKA), including the likelihood of returning to pre-arthritic or higher levels of performance; (II) participation in low-, intermediate-, and high-impact sports pre- and postoperatively; and (III) the ability of athletes to resume sporting activities at a professional or competitive level.

**Methods:** a systematic literature search was conducted in PubMed, Embase and the Cochrane Library up to 17 June, 2025. Studies were eligible if they focused on symptomatic lateral unicompartmental knee osteoarthritis as the primary indication and provided data on RTS outcomes. Outcomes of interest included RTS and return to performance (RTP) rates, sport participation categorized by impact level, return to play rates, and sports-related patient-reported outcome measures. Random-effects models were utilized to evaluate RTS and RTP outcomes.

**Results:** nine non-comparative studies (256 patients) were included. Five on DFO (127 patients; mean age 40.1 ± 13.3 years; mean follow-up 90.4 ± 72.3 months) and four on lateral UKA (125 patients; mean age 58.0 ± 8.8 years; mean follow-up 39.1 ± 16.2 months). Most studies provided level IV evidence and moderate quality (MINORS score: 8 to 10). Random effect models provided RTS rates of 89.7% (95% CI: 76.9 to 95.8) for DFO and 92.4% (95% CI: 81.5 to 97.1) for lateral UKA. RTP rates were 62.7% (95% CI: 41.1 to 80.2) and 88.5% (95% CI: 75.1 to 95.1), respectively. High-impact sport participation decreased after lateral UKA (11.5% to 3.4%), while remaining relatively stable following DFO (32.8% to 28.0%). Competitive-level athletes achieved a 100% RTS rate following DFO.

**Conclusions:** both DFO and lateral UKA are associated with high rates of RTS. However, lateral UKA often leads to a transition from high-impact to lower-impact activities. Clinicians can leverage these findings to optimize patient counseling and align postoperative RTS expectations with functional outcomes.

## Introduction

With rising patient expectations and an increasing prevalence of younger, physically active individuals undergoing surgical intervention for unicompartmental knee osteoarthritis (OA), the criteria for surgical success have expanded beyond pain relief to include the ability to return to sport (RTS)[1-4]. In the management of unicompartmental knee OA, less invasive surgical interventions, including realignment osteotomy and unicompartmental knee arthroplasty (UKA), are frequently considered as viable alternatives to total knee arthroplasty (TKA)[5-7]. These procedures, being relatively joint- and ligament-sparing, help to preserve the biomechanical integrity of the knee joint, thereby promoting physiological knee kinematics and potentially facilitating a more effective restoration of functional ability[8-10].

This premise is supported by a growing body of evidence demonstrating that both realignment osteotomies and UKA outperform TKA in facilitating RTS[1, 11-13]. However, the literature remains disproportionately focused on medial unicompartmental knee OA, with limited research evaluating RTS outcomes following distal femoral osteotomy (DFO) and lateral UKA in patients with symptomatic lateral unicompartmental knee OA. While previous research has established that both DFO and lateral UKA provide significant symptom relief and favorable long-term outcomes, RTS expectations for these patients remain relatively unclear[14-16].

The objective of the present study was to systematically evaluate the rates of successful RTS following DFO and lateral UKA as reported in the existing literature, including the likelihood of returning to pre-arthritic levels of performance. Moreover, it aimed to assess the extent of participation in low-, intermediate-, and high-impact sports, as well as the ability of athletes to successfully resume their respective sporting activities at a professional or competitive level. Through these objectives, this systematic review seeks to provide orthopedic surgeons with evidence-based insights to guide patient counseling and set realistic RTS expectations following both DFO and lateral UKA.

## Methods

This systematic review adhered to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[17] and followed a pre-established study protocol which was formally registered in the PROSPERO International Prospective Register of Systematic Reviews (registration number CRD-42023414432)[18].

*Literature Search*

A systematic literature search was performed across the electronic databases PubMed (MEDLINE), Embase and the Cochrane Library up to 17 June 2025, for all relevant studies reporting on RTS outcomes following DFO and lateral UKA. Supplementary manual searches were conducted in the PEDro Physiotherapy Evidence Database and SPORTDiscus database. The search strategy consisted of 'Distal femoral osteotomy', 'Lateral unicompartmental knee arthroplasty', and 'Return to sport' (Appendix 1). Following duplicate removal, two independent reviewers (G.V.t.N.d.B. and L.V.R.) screened the remaining studies based on title and abstract, with potentially eligible studies proceeding to full-text review. References of included studies were also reviewed to identify additional relevant literature. Any discrepancies in study eligibility were discussed and resolved between the two reviewers and senior author (H.A.Z.) until consensus was reached.

*Eligibility Criteria*

The inclusion criteria for this review consisted of studies reporting on RTS outcomes in patients who underwent DFO or lateral UKA for symptomatic lateral unicompartmental knee OA. Eligible articles required a minimum follow-up period of one-year and were restricted to those published in English, Dutch, French, or German. Studies involving DFO and lateral UKA performed concurrently with other surgical interventions were permitted. However, to evaluate the independent effect of DFO and lateral UKA on RTS outcomes, a separate analysis was performed, excluding studies involving concomitant procedures. Exclusion criteria included case reports, systematic reviews, narratives, commentaries, editorials, cadaveric or animal studies, abstracts without full-text availability, and studies that did not distinguish between lateral and medial UKA.

*Methodological Quality Assessment*

The methodological quality of included studies was assessed using the Methodological Index for Non-Randomized Studies (MINORS) criteria[19], which utilizes an eight-criterion checklist specifically designed to assess the quality of non-comparative studies. Each item is rated on a three-point scale, yielding a maximum possible score of 16 points. The included studies were rated by two independent reviewers (G.V.t.N.d.B. and L.V.R.). Any differences in scores were discussed and resolved through consensus. The current study adhered to thresholds established in previous studies for interpreting the MINORS score: ≤ 8 for poor quality, 9 to 14 for moderate quality, and ≥ 15 for good quality[20].

*Data Extraction and Outcomes of Interest*

The following data were extracted through a consensus-driven approach by the same two reviewers: (I) study information: author(s), year of publication, study design, and journal; (II) information on study population: sample size, sex, mean age, mean body mass index (BMI), mean follow-up, and concomitant procedures; (III) primary outcomes of interest: preoperative and postoperative sport participation, RTS rates (i.e., the proportion of patients who successfully resumed sporting activities following surgery), time to RTS, return to performance (RTP) rates (i.e., the proportion of patients achieving a functional level of performance equal to or exceeding their pre-arthritic state), proportion of patients participating in low-, intermediate-, and high-impact sports, and return to play rates (i.e., proportion of athletes who successfully resumed their respective sporting activities at a professional or competitive level); (IV) secondary outcomes of interest: sports-related patient-reported outcome measures (PROMs), including the Tegner activity scale[21], Marx activity scale[22], and University of California, Los Angeles (UCLA) activity scale[23]. Authors were contacted if data were missing or only available in graphs. If this information was not provided, available data were extracted directly from the graphs or reported as missing.

The classification of patients into low-, intermediate-, and high-impact sports was conducted using a previously established framework by Vail et al.[24], which is widely utilized in studies investigating RTS outcomes[25, 26]. In cases where studies did not provide explicit classification, sports were manually categorized by their recognized impact level.

*Statistical Analysis*

All statistical analyses were conducted using in SPSS v. 26 (IBM) and R v. 4.2.2. (R Foundation for Statistical Computing). Weighted averages of patient demographics were computed. When data were not reported as means and standard deviations, these values were derived from medians and ranges using a previously described method[27]. RTS and RTP outcomes were calculated using a random-effects model with inverse variance weighting. Log transformation was applied to calculate 95% confidence intervals (CI). Additionally, a sensitivity analysis was conducted excluding studies that involved concomitant procedures. Outcomes regarding participation in sports of varying impact levels were used to classify patients into low-, intermediate-, and high-impact categories, allowing for descriptive comparison.

## Results

A total of nine non-comparative studies met inclusion criteria and were included in this review. Five studies reported on RTS outcomes following DFO, while four reported on RTS outcomes following lateral UKA. The PRISMA flow-chart for study selection is provided in Figure 1.

*Quality of Included Studies*

Seven studies were categorized as level IV studies[28-34], while two studies were classified as level III studies[35, 36]. Quality assessment of included studies revealed that one study was identified as poor quality[34], while the remaining studies were classified as moderate quality[28-33, 35, 36]. The quality assessment of the included studies based on the MINORS criteria is presented in Table 1.

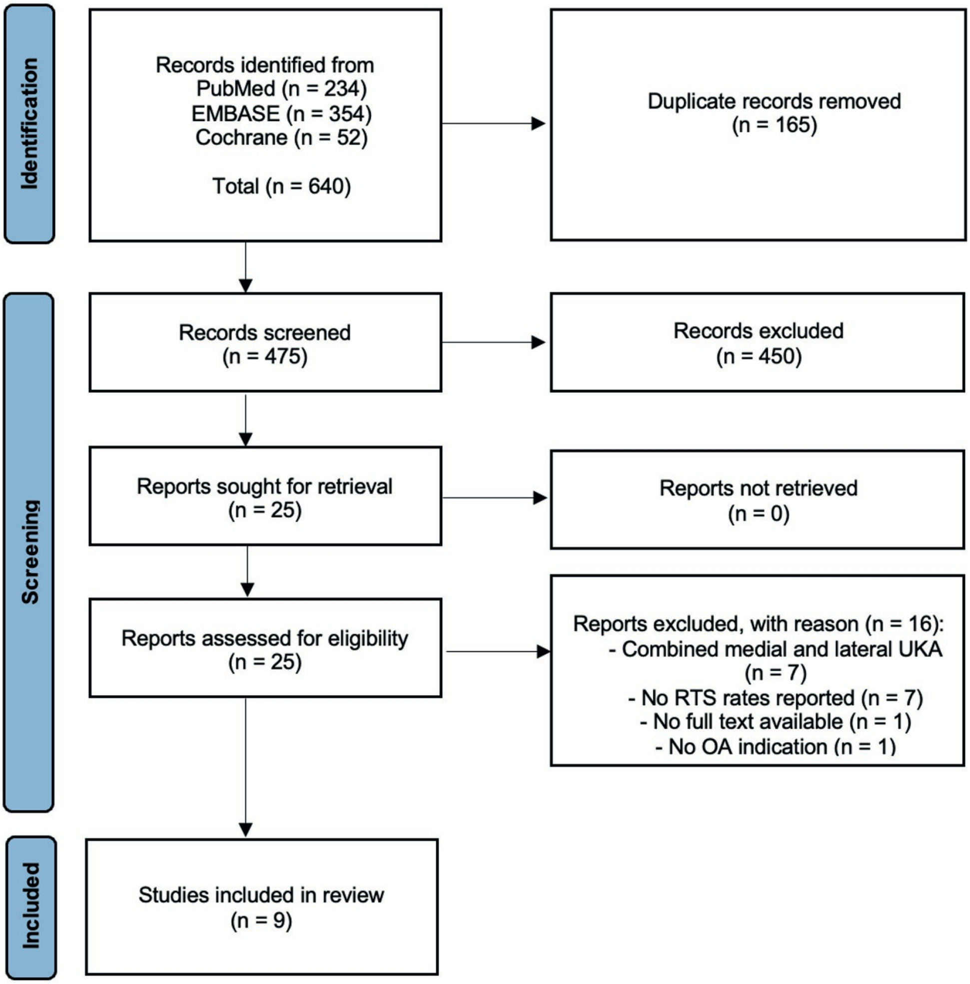


**Figure 1**. PRISMA flowchart of study selection. *OA*, osteoarthritis; *RTS*, return to sport; *UKA*, unicompartmental knee arthroplasty.

**Table 1.** Study characteristics and quality assessment of the included studies utilizing the MINORS criteria.

| | | | | | MINORS criteria* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Authors | Year | Study design | Journal | LoE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Total |
| Voleti et al.[43] | 2017 | Case series | Cartilage | IV | 2 | 1 | 1 | 2 | 0 | 2 | 2 | 0 | 10 |
| De Carvalho et al.[10] | 2012 | Case series | KSSTA | IV | 2 | 1 | 0 | 2 | 0 | 2 | 2 | 0 | 9 |
| Agarwalla et al.[2] | 2020 | Case series | Cartilage | IV | 2 | 2 | 0 | 1 | 0 | 2 | 1 | 0 | 8 |
| Fang et al.[14] | 2023 | Case series | BMC Sports Sci Med Rehab | IV | 2 | 2 | 1 | 2 | 0 | 2 | 1 | 0 | 10 |
| Cance et al.[5] | 2024 | Retr cohort | KSSTA | III | 2 | 2 | 0 | 2 | 0 | 2 | 2 | 0 | 10 |
| Canetti et al.[6] | 2018 | Retr cohort | Arch Orthop Trauma Surg | III | 2 | 1 | 1 | 2 | 0 | 2 | 1 | 0 | 9 |
| Hariri et al.[16] | 2023 | Case series | Journal of Clinical Medicine | IV | 2 | 2 | 1 | 2 | 0 | 2 | 2 | 0 | 11 |
| Walker et al.[44] | 2014 | Case series | KSSTA | IV | 2 | 1 | 1 | 2 | 0 | 2 | 2 | 0 | 10 |
| Zimmerer et al.[48] | 2020 | Case series | The Knee | IV | 2 | 2 | 1 | 2 | 0 | 2 | 1 | 0 | 10 |

Quality assessment of the included studies utilizing the MINORS criteria. Each criterion was assessed on a three-point scale with 0 indicating that it was not reported, 1 indicating that it was reported but inadequately, and 2 indicated that it was reported adequately. In this framework, non-comparative studies were rated a maximum score of 16 points. *LoE,* Level of evidence; *MINORS*, Methodological Index for Non-Randomized Studies.

* Definition of MINORS criteria: (1) A clearly stated aim: the question addressed should be precise and relevant in light of available literature; (2) Inclusion of consecutive patients: all patients potentially fit for inclusion (satisfying the criteria for inclusion) have been included in the study during the study period (no exclusion or details about the reasons for exclusion); (3) Prospective collection of data: data were collected according to a protocol established before the beginning of the study; (4) Endpoints appropriate to the aim of the study: unambiguous explanation of the criteria used to evaluate the main outcome which should be in accordance with the question addressed by the study. Also, the endpoints should be assessed on an intention-to-treat basis; (5) Unbiased assessment of the study endpoint: blind evaluation of objective endpoints and double-blind evaluation of subjective endpoints. Otherwise, the reasons for not blinding should be stated; (6) Follow-up period appropriate to the aim of the study: the follow-up should be sufficiently long to allow the assessment of the main endpoint and possible adverse events; (7) Loss to follow up less than 5%: all patients should be included in the follow up. Otherwise, the proportion lost to follow up should not exceed the proportion experiencing the major endpoint; (8) Prospective calculation of the study size: information of the size of detectable difference of interest with a calculation of 95% confidence interval, according to the expected incidence of the outcome event, and information about the level for statistical significance and estimates of power when comparing the outcomes.

*Study Characteristics*

Five studies, comprising 127 patients (mean age: 40.1 ± 13.3 years), reported on RTS rates following DFO, with a mean follow-up of 90.4 ± 72.3 months[28, 31, 32, 34, 36]. A closing-wedge osteotomy was performed in one study[32], an opening-wedge osteotomy in two studies[34, 36], and both techniques in the remaining study[28]. One study did not specify the type of osteotomy[31]. Four studies, comprising 125 patients (mean age: 58.0 ± 8.8 years), reported on RTS rates following lateral UKA, with a mean follow-up of 39.1 ± 16.2 months[29, 30, 33, 35]. Two studies utilized a fixed-bearing insert[30, 33], one study used a mobile-bearing insert[29], and one study employed an all-polyethylene tibial component[35]. The characteristics of the included studies are presented in Table 2.

**Table 2.** Patient demographics of included studies (*n* = 9).

| Author | Patients | Sex, female | Mean age, years | Mean BMI, kg/m$^2$ | Mean follow-up, months | Concomitant procedures |
|---|---|---|---|---|---|---|
| Voleti et al.[43] | 13 | 5 (39%) | 24.4 ± 6.3 | 27.4 ± NR | 42.9 ± 18.9 | PLM (*n*=2), revision ACL reconstruction (*n*=1), LOA and PT debridement (*n*=1), loose body removal (*n*=1), LM transplant (*n*=1), lateral OC graft (*n*=6) |
| De Carvalho et al.[10] | 26 | 18 (69%) | 48.6 ± 10.6 | NR | 48.0 ± 24.3 | PLM (*n*=6) and lateral chondroplasty (*n*=6) |
| Agarwalla et al.[2] | 17 | 8 (47%) | 32.1 ± 10.1 | 30.5 ± 9.1 | 87.6 ± 52.8 | NR |
| Fang et al.[14] | 33 | 29 (88%) | 35.0 ± NR | 21.3 ± 2.0 | 37.9 ± 6.7 | NR |
| Cance et al.[5] | 38 | 24 (63%) | 47.6 ± 9.4 | 26.3 ± 4.5 | 182.4 ± 52.8 | NR |
| Canetti et al.[6] | 28 | 21 (75%) | 62.3 ± 8.8† | 25.5 ± 4.0† | 37.2 ± 5.3† | NR |
| Hariri et al.[16] | 37 | 22 (60%) | 52.8 ± 3.1 | 30.0 ± 6.8 | 37.2 ± 18 | NR |
| Walker et al.[44] | 45 | 26 (58%) | 60.1 ± 10.5 | NR | 35.4 ± 8.1 | NR |
| Zimmerer et al.[48] | 19 | 14 (74%) | 56.7 ± 10.5 | 27.2 ± 5.7 | 55.2 ± 26.4 | NR |
| Total | **256** | **167 (65%)** | **49.1 ± 13.7** | **N/A** | **64.6 ± 58.2** | **N/A** |

Study characteristics of the included studies. Outcomes are presented as numbers and frequencies (%) or means ± standard deviations. *ACL,* anterior cruciate ligament; *BMI,* body mass index; *DFO*, distal femoral osteotomy; *LM*, lateral meniscus; *LOA*, lysis of adhesions; *NR*, not reported; *OC*, osteochondral; *PLM,* partial lateral meniscectomy; *PT*, patellar tendon; *UKA*, unicompartmental knee arthroplasty.
† Mean and standard deviation were calculated from the subgroup data reported in the original study.

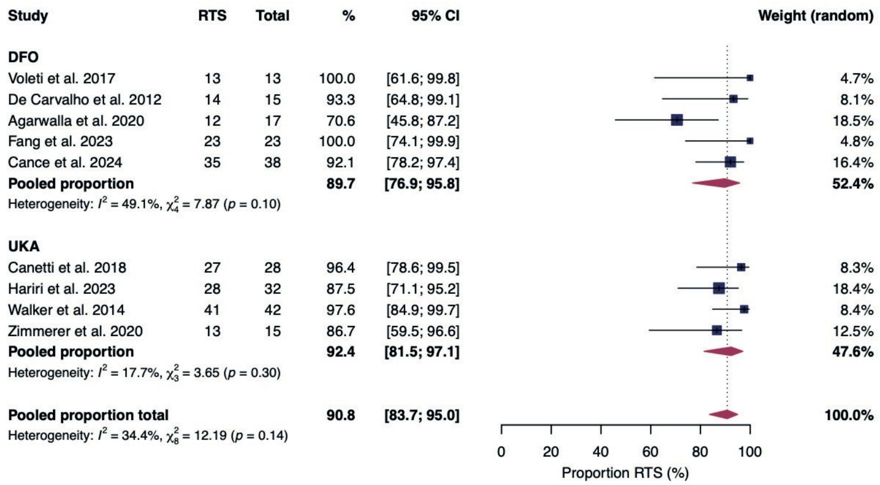


**Figure 2**. Forest plot on return to sport outcomes following distal femoral osteotomy and lateral unicompartmental knee arthroplasty. *CI*, confidence interval; *DFO*, distal femoral osteotomy; *RTS*, return to sport; *UKA*, unicompartmental knee arthroplasty.

*RTS and RTP*

RTS rates were 89.7% (five studies; [95% CI: 76.9 to 95.8]) following DFO and 92.4% (four studies; [95% CI: 81.5 to 97.1]) following lateral UKA (Figure 2). Among patients, 62.7% (four studies; [95% CI: 41.1 to 80.2]) and 88.5% (four studies; [95% CI: 75.1 to 95.1]) were able to RTP following DFO and lateral UKA, respectively (Figure 3). Sensitivity analyses for RTS and RTP following DFO yielded results consistent with the primary findings (Appendices 2 and 3, respectively). During the initial six months following surgery, three studies on lateral UKA reported RTS rates ranging from 69.2% to 85.4%[29, 30, 33], whereas a separate study on DFO reported a RTS rate of 78.3% within the same timeframe[32]. The primary factors contributing to sports discontinuation or performance decline were knee pain (72.7%)[34] for DFO, followed by reduced motivation (18.2%), whereas for lateral UKA, other health issues (50.0%)[33] and precautionary measures to preserve the prosthesis (46.0%)[29] were the leading factors (Figure 4).

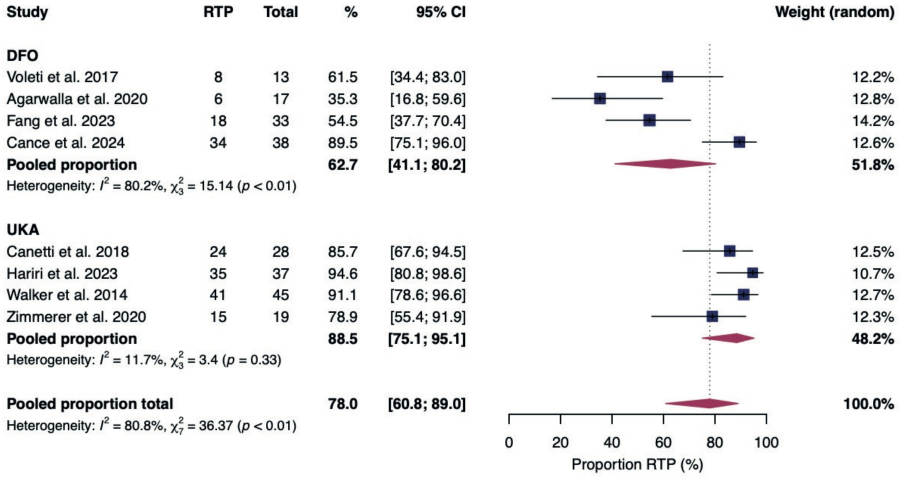


**Figure 3**. Forest plot on return to performance outcomes following distal femoral osteotomy and lateral unicompartmental knee arthroplasty. *CI*, confidence interval; *DFO*, distal femoral osteotomy; *RTP*, return to performance; *UKA*, unicompartmental knee arthroplasty.

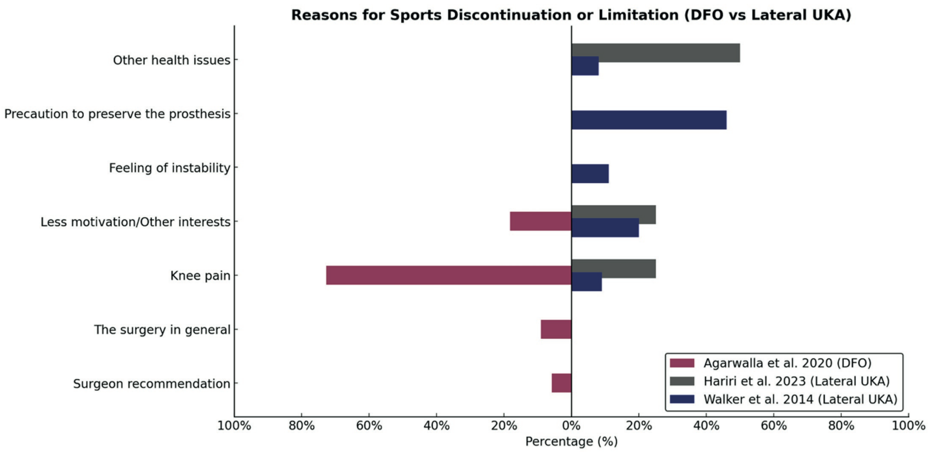


**Figure 4.** Reported reasons for discontinuation or limitation of sport participation following DFO and lateral UKA based on findings from three studies. *DFO*, Distal femoral osteotomy; *UKA*, unicompartmental knee arthroplasty.

*Sport Participation Across Varying Impact Levels*

Seven studies explicitly reported on either the specific type of sport performed, or the number of sporting activities categorized by impact level[28-30, 32-35]. Preoperatively, high-impact sports accounted for 32.8% of activities among patients undergoing DFO, compared 11.5% in those undergoing lateral UKA (Figure 5). Postoperatively, this proportion remained relatively stable at 28.0% in the DFO group, while declining to 3.4% in the lateral UKA group. A comprehensive overview of sport participation across various sports and impact levels is provided in Appendix 4.

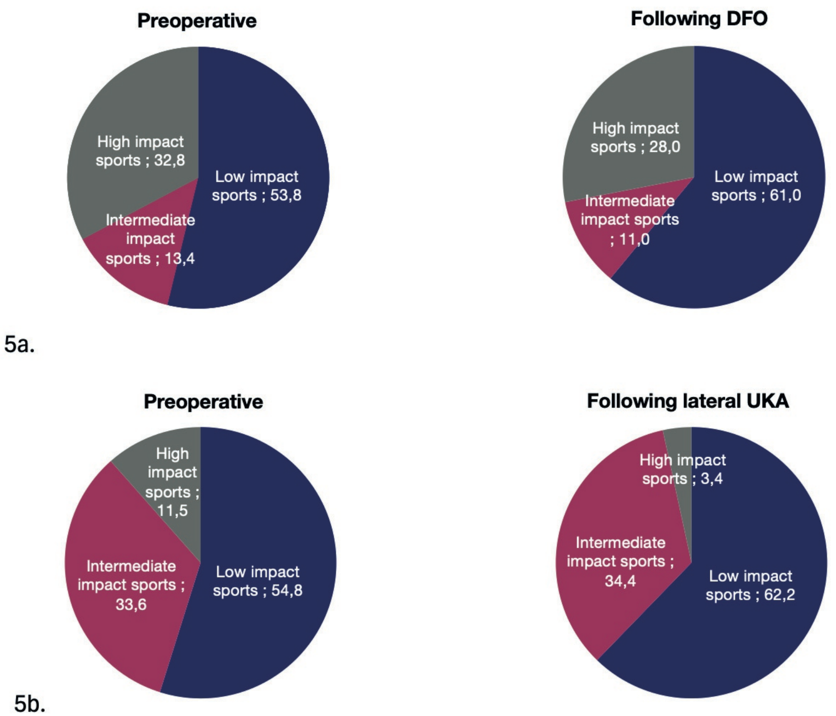


**Figure 5.** The proportion (%) of low-, intermediate-, and high-impact sports both preoperatively and following DFO and lateral UKA. **5a**, Participation levels across various impact levels both preoperatively and following DFO. **5b**, Participation levels across various impact levels both preoperatively and following lateral UKA. *DFO*, Distal femoral osteotomy; *UKA*, unicompartmental knee arthroplasty.

*Return to Play*

A study assessing RTS outcomes following DFO in competitive-level athletes, defined as individuals engaging in sporting activities at least four days per week, reported a 100% return to play rate at a mean of 11 months, with 61.5% of patients (*n* = 8) successfully returning to their pre-arthritic levels of performance[28]. Another study on DFO identified 11.8% (*n* = 2) of patients as competitive-level athletes, all ow whom returned to play[34].

*Patient-Reported Outcome Measures*

Postoperative Tegner activity scores ranged from 3.5 to 4.5 for DFO[31, 32] and 3.3 to 3.5 for lateral UKA[29, 33], reflecting the ability to participate in low- to intermediate-impact sports and light to moderately strenuous labor[21]. The Marx activity scale, assessed exclusively following DFO [28, 34], ranged from 5.0 to 10.8, corresponding to occasional (once a week or less) to frequent (two to three times per week) participation in dynamic movements such as running, cutting, decelerating, and pivoting[22]. The UCLA activity scale, exclusive to lateral UKA studies[29, 30, 33, 35], ranged from 6.0 to 6.7, reflecting engagement in moderate physical activities.

**Discussion**

This systematic review aimed to evaluate RTS outcomes following DFO and lateral UKA in patients with lateral compartment OA. The main finding of the present study indicates that RTS is successfully achieved following both DFO and lateral UKA, with the majority of patients resuming athletic activities in the first six months postoperatively. The rates of successful RTS were 89.7% among patients who underwent DFO and 92.4% among patients who received lateral UKA. Overall, 88.5% of patients who underwent lateral UKA successfully returned to their pre-arthritic or higher levels of performance, whereas 62.7% of those who underwent DFO achieved performance levels equivalent to or exceeding their pre-arthritic level. This discrepancy, wherein lateral UKA is associated with higher RTP rates, is likely attributable to lower baseline performance levels, as indicated by the higher prevalence of preoperative participation in intermediate- to low-impact activities among patients undergoing lateral UKA.

Understanding RTS outcomes is essential for setting realistic patient expectations and informing clinical decision-making, particularly considering the increasing burden of OA[3]. In the present study, the RTS rates observed for DFO aligned with those reported in other systematic reviews on the procedure, which documented RTS rates ranging from 70.0% to 100%[37, 38]. These reviews, however, included heterogeneous patient populations with varying indications beyond OA, thereby limiting the direct applicability of their findings to OA-specific cases. For UKA, RTS ranges have been reported to range from 75.0% to 100%[11, 39]. However, much of the existing literature fails to differentiate between medial and lateral UKA, thereby overlooking the unique pathological and biomechanical characteristics of the lateral compartment and potentially leading to inaccurate assumptions regarding expected RTS rates across distinct osteoarthritic patterns[6, 40].

While these findings are promising for individuals undergoing surgical intervention for symptomatic lateral unicompartmental knee OA, postoperative modifications in activity levels are frequently observed. In the context of lateral UKA, a notable shift toward lower-intensity regimens was observed, with high-impact sports comprising only a modest 3.4% of postoperative activities. Thus, while lateral UKA demonstrates high RTS rates, the nature of this return may favor lower-impact activities that exert less mechanical stress on the prosthetic joint.

The decision to resume athletic activities following knee arthroplasty is largely guided by physician discretions, with recommendations typically favoring non-contact sports and strategies to reduce excessive joint loading. However, the ability and willingness to return to high-impact sports are likely shaped by a multitude of factors. Existing literature has identified various prognostic factors associated with a greater likelihood of returning to higher-impact activities, including prior engagement in the sport, younger age, male sex, low BMI, and adequate bone density[1]. Additionally, the presence of a prosthetic articulation in lateral UKA may introduce concerns regarding aseptic loosening, a leading cause of revision in lateral UKA[41, 42], thereby likely contributing to the more pronounced decline in high-impact sports participation among these patients. This is further supported by the finding that 46.0% of patients who underwent lateral UKA cited precautionary measures to preserve the prosthesis as the primary reason for discontinuation or limiting sport participation, suggesting that the fear of implant failure may play a significant role in patients' decisions to discontinue high-impact activities. However, current evidence does not conclusively support these concerns, as studies have not established a link between greater levels of physical activity and higher rates of failure following UKA[43, 44]. Therefore, a more nuanced approach to patient counseling may be warranted to balance the encouragement of physical activity with appropriate considerations for implant preservation.

With OA increasingly affecting younger patients, there is a growing emphasis on joint-preserving surgical alternatives to avoid the substantial bone resection required in TKA[45-47]. DFO and lateral UKA both serve as viable alternatives in this context. However, while both procedures are unequivocally more effective than TKA in facilitating RTS, they are not universally interchangeable, and the decision regarding their implementation should be carefully guided by both the patient's athletic aspirations as well as the specific characteristics unique to each patient[11, 48, 49]. The present study observed a mean age disparity of approximately 18 years between both procedures, a factor that should be considered when evaluating the generalizability of these findings to distinct patient populations. Thus, while DFO may be particularly beneficial for younger individuals seeking to maintain participation in high-impact sports, for others, UKA may be the preferred surgical intervention when their OA has progressed beyond the point at which joint preservation is feasible[46].

The available data on return to play rates in athletes was limited, with findings solely derived from studies on DFO. Despite this scarcity, the findings were promising, indicating a 100% return to play rate among competitive-level athletes who engaged in high-frequency training (four times per week). However, it is important to acknowledge that the limited sample size (*n* = 13) of this study likely reflects a cohort characterized by a high level of intrinsic motivation and superior baseline physical conditioning. Therefore, further research is necessary to validate these findings.

This systematic review is not without limitations. One of the primary challenges is the substantial heterogeneity among the included studies, encompassing variations in surgical techniques, variability in the use and reporting of concomitant procedures, patient demographics, and disparities in preoperative functional status and OA severity. Moreover, the inconsistent reporting of preoperative PROMs across studies hindered a comprehensive analysis of baseline functional status, which is crucial for contextualizing postoperative outcomes. Definitions of preoperative sport participation also varied, with some studies referencing engagement before the onset of the first restricting symptoms, while others referred to participation within a defined time frame prior to surgery. This variability complicated direct comparisons between treatment groups. In addition, the absence of high-quality comparative studies restricted our ability to draw definitive conclusions regarding the relative effectiveness of the two surgical approaches, underscoring the need for more rigorous research in this area.

**Conclusions**

Both DFO and lateral UKA are associated with high rates of RTS in the literature. However, lateral UKA often leads to a transition from high-impact to lower-impact activities. Clinicians can leverage these findings to optimize patient counseling and align postoperative RTS expectations with functional outcomes.

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## **Appendix 1.** Search strategy.

**PubMed, search strategy:**

(("Osteotomy"[Mesh] AND "Femur"[Mesh]) OR distal femur osteotom*[tiab] OR DFO[tiab] OR femur osteotom*[tiab] OR femoral osteotom*[tiab] OR distal femoral varus osteotom*[tiab] OR DFVO[tiab] OR lateral opening wedge osteotom*[tiab] OR medical closing wedge osteotom*[tiab] OR unicompartmental osteoarthrosis[tiab] OR unicompartmental knee arthroplasty[tiab] OR lateral unicompartmental knee replacement*[tiab] OR lateral unicompartmental knee arthroplast*[tiab] OR lateral unicompartmental unicondylar knee replacement*[tiab] OR lateral unicondylar knee arthroplast*[tiab] OR lateral partial knee replacement*[tiab] OR lateral partial knee arthroplast*[tiab] OR lateral UKA[tiab] OR lateral UKR[tiab])

AND

("Return to Sport"[Mesh] OR "Exercise"[Mesh] OR return to sport*[tiab] OR RTS[tiab] OR return to activ*[tiab] OR activity resumption*[tiab] OR physical activit*[tiab] OR exercise*[tiab])

**Embase classic + Embase, search strategy:**

1. exp osteotomy/ and (exp distal femur/ or femur/)
2. distal femur osteotom* or DFO or femur osteotom* or femoral osteotom* or distal femoral varus osteotom* or DFVO or lateral opening wedge osteotom* or medical closing wedge osteotom* or unicompartmental osteoarthrosis or unicompartmental knee arthroplasty or lateral unicompartmental knee replacement* or lateral unicompartmental knee arthroplast* or lateral unicompartmental unicondylar knee replacement* or lateral unicondylar knee arthroplast* or lateral partial knee replacement* or lateral partial knee arthroplast* or lateral UKA or lateral UKR).ti,ab,kf.
3. 1 or 2
4. return to sport/ or exp exercise/
5. (return* adj3 (sport* or activ* or play*)).ti,ab,kf.
6. (activity resumption* or physical activit* or exercise* or RTS).ti,ab,kf.
7. 4 or 5 or 6
8. 3 and 7

**Cochrane Central Register of Controlled Trials, search strategy:**

#1 (distal femur osteotom* or DFO or femur osteotom* or femoral osteotom* or distal femoral varus osteotom* or DFVO or lateral opening wedge osteotom* or medical closing wedge osteotom* or unicompartmental osteoarthrosis or unicompartmental knee arthroplasty or lateral unicompartmental knee replacement* or lateral unicompartmental knee arthroplast* or lateral unicompartmental unicondylar knee replacement* or lateral unicondylar knee arthroplast* or lateral partial knee replacement* or lateral partial knee arthroplast* or lateral UKA or lateral UKR):ti,ab,kw 787

#2 (return* near/3 (sport* or activ* or play*)):ti,ab,kw 2749

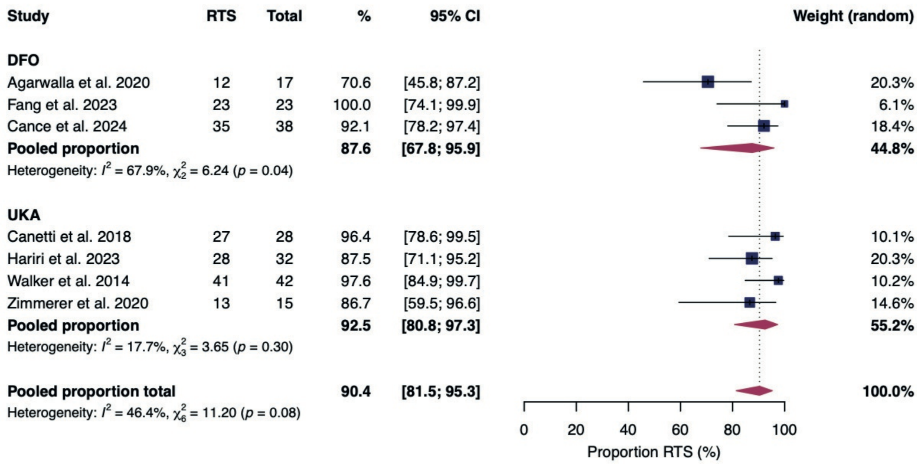
#3 (activity resumption* or physical activit* or exercise* or RTS):ti,ab,kw 191537

#4 MeSH descriptor: [Return to Sport] explode all trees 73

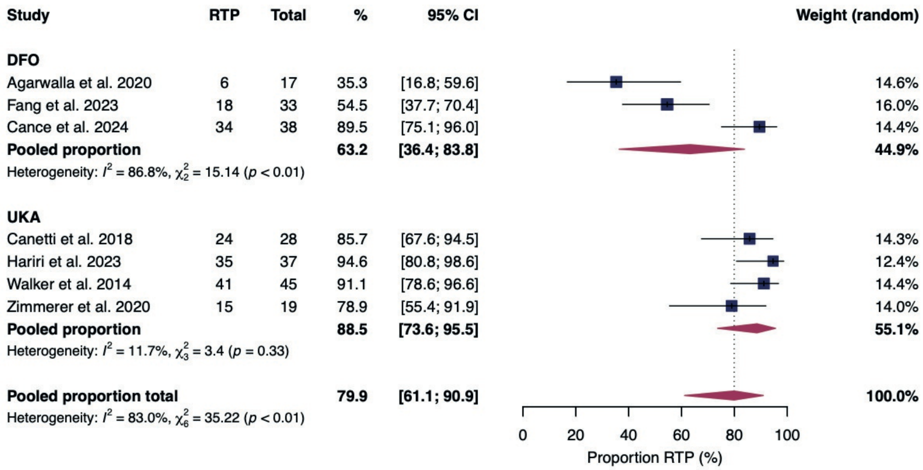
#5 #2 or #3 or #4 193465

#6 #1 and #5 52

**Appendix 2.** Forest plot on return to sport outcomes following distal femoral osteotomy and lateral unicompartmental knee arthroplasty. *CI*, confidence interval; *DFO*, distal femoral osteotomy; *RTS*, return to sport; *UKA*, unicompartmental knee arthroplasty.



**Appendix 3.** Forest plot on return to performance outcomes following distal femoral osteotomy and lateral unicompartmental knee arthroplasty. *CI*, confidence interval; *DFO*, distal femoral osteotomy; *RTP*, return to performance; *UKA*, unicompartmental knee arthroplasty.



**Appendix 4.** Sport participation across various sports and impact levels.

| Level of impact* | Sport | Voleti[43] | | Argarwalla[2] | | Fang[14] | | Canetti[6] | | Hairiri[16] | | Walker[44] | | Zimmerer[48] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| Low | Walking | | | | | | | | | 12 | 11 | 22 | 20 | 13 | 11 |
| Low | Nordic/speed walking | | | | | | | | | 8 | 8 | 11 | 11 | 2 | 3 |
| Low | Cycling/spinning | | | 10 | 7 | 18 | 14 | 13 | 14 | 23 | 21 | 27 | 33 | 11 | 8 |
| Low | Road bicycle racing | | | | | | | | | | | | | | |
| Low | Swimming | | | 1 | 0 | 12 | 12 | 4 | 4 | | | 9 | 15 | | |
| Low | Aqua aerobics | | | | | | | | | 3 | 1 | 4 | 8 | | |
| Low | Cross-country/alpine skiing | | | 1 | 0 | | | | | 1 | 0 | 4 | 1 | 6 | 2 |
| Low | Golf | | | 3 | 1 | | | | | 1 | 1 | | | | |
| Low | Table tennis | | | | | 9 | 6 | | | | | | | | |
| Low | Dancing | | | | | 4 | 4 | | | | | | | | |
| Low | Yoga | | | | | 4 | 4 | 7 | 11 | | | | | | |
| Low | Sailing | | | | | | | | | | | | | | |
| Low | Rowing | 1 | 1 | 1 | 0 | | | | | | | | | | |
| Intermediate | Inline/ice skating | | | | | | | | | | | | | | |
| Intermediate | Hiking | | | | | | | 25 | 23 | 16 | 13 | 22 | 18 | 5 | 5 |
| Intermediate | Mountain climbing | | | | | | | | | | | | | | |
| Intermediate | Mountain biking | | | | | | | | | | | | | | |
| Intermediate | Fitness-/weight-training | | | 9 | 5 | | | | | 8 | 6 | 9 | 17 | 6 | 5 |
| Intermediate | Aerobics | | | | | | | | | | | 4 | 9 | | |
| Intermediate | CrossFit | | | 2 | 1 | | | | | | | | | | |
| Intermediate | Gymnastics | | | | | 3 | 2 | | | | | | | | |
| Intermediate | Downhill skiing | | | 2 | 1 | | | 5 | 5 | | | 8 | 0 | | |
| Intermediate | Snowboarding | | | | | | | | | | | | | | |
| Intermediate | Horse riding | | | | | | | | | | | | | 3 | 0 |
| High | Jogging/running | 2 | 2 | 5 | 2 | 4 | 2 | 1 | 0 | 4 | 1 | 6 | 3 | 2 | 3 |
| High | Ice/field hockey | 1 | 1 | | | | | | | | | | | | |
| High | Tennis (single/double) | | | | | | | | | 2 | 0 | 5 | 0 | | |
| High | Squash | | | | | | | | | | | | | | |
| High | Badminton | | | | | 2 | 1 | | | | | | | | |
| High | Soccer | 5 | 5 | | | 2 | 1 | | | 6 | 1 | 6 | 0 | 2 | 1 |
| High | Martial arts | | | | | | | | | | | | | | |
| High | Water skiing | | | | | | | | | | | | | | |
| High | Basket-, volley-, hand-, baseball | 4 | 4 | 9 | 3 | 5 | 2 | | | 4 | 1 | | | | |

Sport participation before surgery and after distal femoral osteotomy and lateral unicompartmental knee arthroplasty.
* Level of impact according to a modified and updated version of the original framework by Vail et al.[40]

# PHENOTYPIC MANIFESTATIONS OF ISOLATED COMPARTMENT KNEE OSTEOARTHRITIS

# Chapter 7

# Knees with anteromedial osteoarthritis show a substantial phenotypic variation prior and following medial unicompartmental knee arthroplasty

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Hendrik A. Zuiderbaan

Knee Surgery, Sports Traumatology, Arthroscopy

**Abstract**

**Purpose**: the primary aim of this study was to evaluate the phenotypic variation using the Coronal Plane Alignment of the Knee (CPAK) classification among 1000 knees with anteromedial osteoarthritis (OA) both prior to and following medial unicompartmental knee arthroplasty (UKA). The secondary aim of this study was to investigate whether knees maintained their preoperative CPAK phenotype and to evaluate the phenotypic alterations following medial UKA.

**Methods:** the CPAK classification was used to analyze 1000 knees that underwent medial UKA as treatment for anteromedial OA. Knees were categorized into nine distinct CPAK phenotypes based on their arithmetic hip-knee-ankle angle (aHKA), which estimates the pre-arthritic alignment, and joint line obliquity (JLO), both pre- and postoperatively. Phenotypic variation was analyzed by sex and age, and the phenotypic alterations following medial UKA were evaluated by phenotype.

**Results**: preoperatively, CPAK phenotype I had the highest prevalence (45.0%). Among males, the preoperative prevalence of CPAK phenotype I was significantly higher compared to females (53.2% vs. 35.0%, respectively; $p$ = <.001), whereas females exhibited a significantly higher occurrence of CPAK phenotype V compared to males (9.8% vs. 4.4%, respectively; $p$ = <.015). Following medial UKA, CPAK phenotype II had the highest prevalence (53.3%). Overall, 45.1% of knees maintained their preoperative CPAK phenotype following medial UKA, which was most frequently observed among CPAK phenotype II (67.7%) and III (65.8%).

**Conclusion***:* there is a substantial variation in CPAK phenotypes among knees with anteromedial OA, as well as following treatment with medial UKA. This variability challenges the assumption of uniform characteristics among knees with an identical wear pattern associated with anteromedial OA and emphasizes the complexity and variability of this specific form of OA.

## Introduction

Medial unicompartmental knee arthroplasty (UKA) is an effective surgical procedure for patients with symptomatic anteromedial osteoarthritis (OA) of the knee[1, 2]. This specific form of OA manifests when the anterior cruciate ligament (ACL) is intact and the varus deformity is correctable[3]. Component positioning and lower limb alignment are significant factors affecting the survivorship and outcomes of UKA[4-11]. Nevertheless, the optimal component positioning and lower limb alignment continue to be subjects of uncertainty and ongoing debate[10].

Traditionally, alignment strategies have solely focused on classifying knees into a neutral, varus, or valgus alignment and aimed to restore knees to neutral mechanical alignment[12, 13]. However, multiple recent studies have emphasized the substantial variability in coronal plane phenotypes, highlighting the necessity of re-evaluation of traditional alignment strategies for knee arthroplasty[14-22]. Recently, the Coronal Plane Alignment of the Knee (CPAK) classification was introduced[16]. This system utilizes both the pre-arthritic alignment, and knee joint line orientation (JLO) to classify the phenotypic variation in knees.

So far, the CPAK classification has primarily been used to describe healthy and osteoarthritic knees undergoing total knee arthroplasty (TKA), with a specific emphasis on examining the preoperative distribution[15-18, 23-26]. There is a common belief that patients with anteromedial OA consistently present with an identical intra-articular wear pattern. Nevertheless, the extent of phenotypic variation in knees affected by this specific form of OA remains unknow. Furthermore, to understand alignment adjustments that take place during medial UKA, it is essential to evaluate the phenotypic alterations in the coronal plane that occur during medial UKA.

Therefore, the primary aim of this study was to evaluate the phenotypic variation using the CPAK classification among 1000 knees with anteromedial OA both prior to and following medial UKA. The secondary aim of this study was to investigate whether knees maintained their preoperative CPAK phenotype and to evaluate the phenotypic alterations following medial UKA. It was hypothesized that a substantial phenotype variation would be present, challenging the assumption of uniform characteristics among knees affected by anteromedial OA.

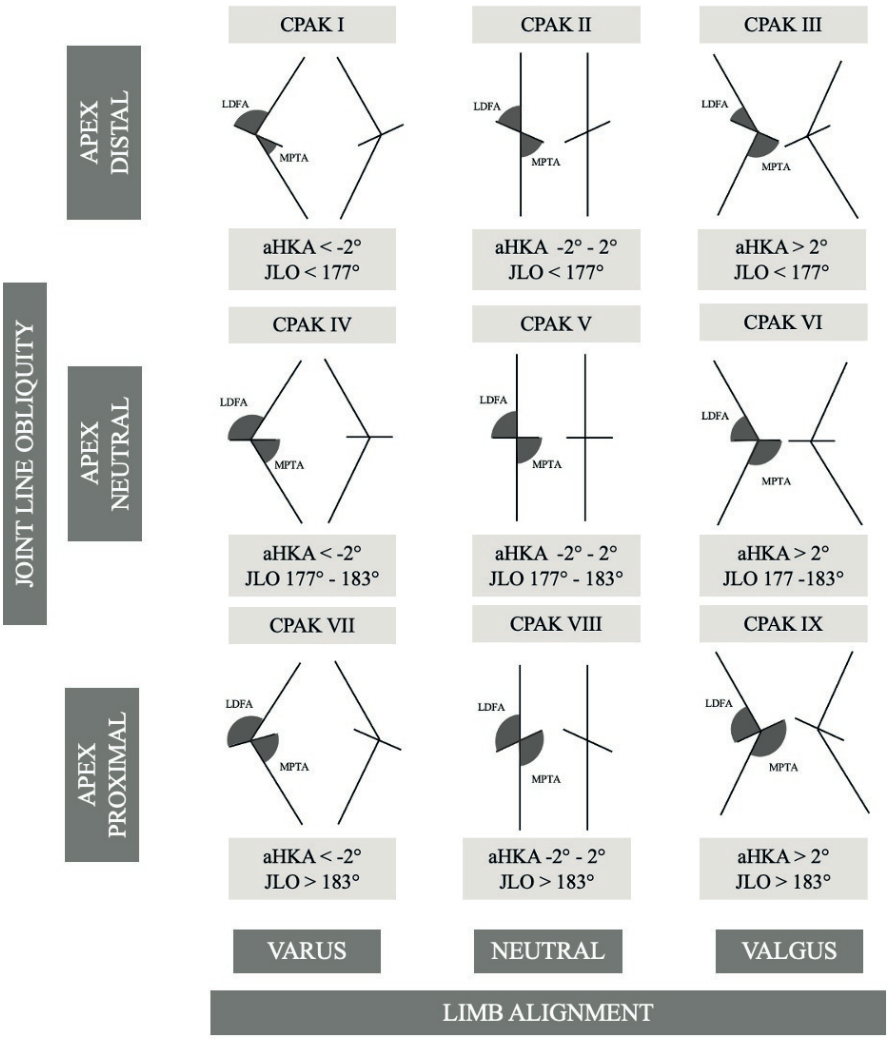


**Figure 1.** Coronal Plane Alignment of the Knee (CPAK) classification with nine identified CPAK knee phenotypes. *aHKA*, arithmetic hip-knee-ankle angle (i.e., MPTA – LDFA); *JLO*, joint line obliquity (i.e., MPTA + LDFA).

## Methods

*Study design*

Following approval from the Institutional Review Board of the Hospital for Special Surgery (New York, NY, United States) (#2022-1401), a retrospective review of a single surgeon's arthroplasty registry was conducted. The first consecutive 1000 knees of 835 patients with anteromedial OA who met the criteria for complete radiographic data collection were selected. All patients underwent robotic-arm assisted medial UKA between January 2012 and July 2022. Patients were included if they had anteromedial OA (Kellgren-Lawrence [KL] grade III-IV[27]) and had complete radiographic records consisting of pre- and postoperative long-leg radiographs. Patients were excluded if they had poor-quality or incomplete radiographic records, a history of ipsilateral tibial or femoral fractures, or prior ipsilateral knee-, ankle-, or hip arthroplasty.

The primary surgical indication for medial UKA was symptomatic, isolated anteromedial compartment OA with a varus deformity correctable to < 10° and fixed flexion deformity of < 10°. Clinical or radiographical signs of advanced lateral compartment OA, signs of inflammatory arthritis, ACL deficiency, or a history of medial collateral ligament (MCL) surgery were considered contraindications for medial UKA.

*Implant and surgical technique*

All patients received a cemented medial UKA with a fixed-bearing tibial onlay implant (Restoris MCK system, Mako Surgical Corp. (Stryker), Fort Lauderdale, FL, USA). The surgeon used a robotic-arm assisted system (Mako Surgical Corp. (Stryker). Fort Lauderdale, FL, USA) for precise implant planning and bone preparation in all cases. The primary surgical objective was to resurface the medial compartment and to restore the knee to its pre-arthritic state, which is associated with improved survivorship and favorable outcomes[9]. This surgical objective was guided by a ligament-guided approach, rather than targeting a specific range of final coronal limb alignment. The specific aim was to restore the native MCL tension throughout the entire range of motion (ROM) in order to recreate the pre-arthritic alignment. The knee was considered well-balanced if a medial gap of 1-2 mm was achieved under valgus stress throughout the ROM and with the polyethylene insert in place. The surgical technique utilized in all cases has been described comprehensively[28, 29].

*Radiographic evaluation*

This study used routine preoperative and 6-week postoperative long-leg radiographs to assess coronal alignment. These radiographs were obtained uniformly, with patients instructed to stand with their feet closely together, knees in full extension, and body weight equally distributed over both limbs, while keeping their patellae aligned with the X-ray beam.

Radiographic measurements were performed by one observer (G.V.t.N.d.B) and independently repeated on a random sample of 100 knees by a second observer (L.V.R). Radiographic measurements included the mechanical hip-knee-ankle angle (mHKA; i.e., the angle subtended by the mechanical axes of the femur and tibia), mechanical lateral distal femoral angle (mLDFA; i.e., the lateral angle subtended by the mechanical femoral axis and distal femoral joint line), and the medial proximal tibia angle (MPTA; i.e., the medial angle subtended by the mechanical tibial axis and proximal tibial joint line). Subsequently, the JLO and arithmetic hip-knee-ankle angle (aHKA), which estimates the pre-arthritic alignment, were derived by adding and subtracting the MPTA and mLDFA, respectively. Inter-observer reliability was assessed using interclass correlation coefficients with a two-way mixed model and absolute agreement. ICC between observers for mHKA, mLDFA, and MPTA, were 0.97 (95% confidence interval [CI,] 0.96-0.98), 0.89 (95% CI, 0.82-0.93), and 0.90 (95% CI, 0.85-0.93), respectively.

*CPAK classification*

Knees were classified according to the CPAK classification[16]. The system combines the aHKA and JLO to categorize knees into nine distinct phenotypes (Fig. 1). The JLO describes the direction of the joint line and classifies knees into three categories (i.e., apex distal, apex neutral, and apex proximal). This clearly specifies the orientation of the knee joint line in relation to a hypothetical neutral horizontal joint line with a range of 3°, which determines whether the joint line of the knee is located below, at the same level as, or above the neutral joint line (i.e., MPTA + mLDFA = 180°). The pre-arthritic alignment of the operative knee is determined by the aHKA and represents the alignment before the onset of OA in the knee in relation to a neutral limb alignment (i.e., MPTA - mLDFA = 0°) with a range of 2°. This categorizes knees into three additional categories (i.e., varus, neutral, and valgus).

*Statistical analysis*

All analyses were performed in R, version 2023.03.1+446 (R Foundation for Statistical Computing, Vienna, Austria), with the significance level set at 0.05. The prevalence of different CPAK phenotypes was assessed, both pre- and postoperatively. Gender-specific differences and age-related variations in the prevalence of different CPAK phenotypes were assessed. Patients were divided into the following three age groups: patients aged under 50 years, those between 50 and 70 years, and those over 70 years. Normal distribution of continuous variables was assessed using the Shapiro-Wilk test. The Pearson's correlation coefficient was used to assess associations for normally distributed variables, while Spearman's rank correlation was utilized for variables without a normal distribution. The Mann-Whitney U test was used to compare the means of two independent samples for variables without a normal distribution. Comparison of discrete variables was performed using the Chi-squared test or Fisher's exact test. Post-hoc power analyses were performed using nQuery version 8.5.1 (Statistical Solutions Ltd, Cork, Ireland). Post-hoc power calculations of evaluated comparisons resulted in a high observed power ranging from 0.87 to 0.99.

**Table 1.** Radiographic outcomes of knees with anteromedial osteoarthritis and following medial unicompartmental knee arthroplasty

| | **Preoperatively** | | | | **Postoperatively** | | | |
|---|---|---|---|---|---|---|---|---|
| | Total *n* = 1000 | Male *n* = 549 | Female *n* = 451 | *p* value § | Total *n* = 1000 | Male *n* = 549 | Female *n* = 451 | *p* value § |
| **HKA (°)** | | | | | | | | |
| Mean ± SD | 7.1 ± 3.4 | 7.4 ± 3.4 | 6.6 ± 3.4 | <.001* | 2.6 ± 2.2 | 2.9 ± 2.3 | 2.3 ± 2.2 | <.001* |
| Range | -3.5 to 17.0 | -3.5 to 17.0 | -2.4 to 16.8 | | -3.6 to 10.1 | -2.5 to 10.1 | -3.6 to 9.8 | |
| **aHKA (°)** | | | | | | | | |
| Mean ± SD | -2.4 ± 2.8 | -2.9 ± 2.8 | -1.7 ± 2.6 | <.001* | -0.3 ± 2.4 | -0.6 ± 2.4 | 0.08 ± 2.3 | <.001* |
| Range | -11.3 to 7.5 | -11.3 to 6.5 | -9.6 to 7.5 | | -13.5 to 7.6 | -13.5 to 6.2 | -8.1 to 7.6 | |
| **LDFA (°)** | | | | | | | | |
| Mean ± SD | 88.3 ± 2.1 | 88.3 ± 2.0 | 88.2 ± 2.1 | n.s. | 87.1 ± 87.0 | 86.9 ± 2.1 | 87.2 ± 2.0 | .04* |
| Range | 81.0 to 98.9 | 81.0 to 98.9 | 81.6 to 95.9 | | 80.5 to 97.3 | 81.3 to 97.3 | 80.5 to 94.4 | |
| **MPTA (°)** | | | | | | | | |
| Mean ± SD | 85.9 ± 2.2 | 85.4 ± 2.1 | 86.5 ± 2.1 | <.001* | 86.8 ± 1.9 | 86.4 ± 1.9 | 87.3 ± 1.8 | <.001* |
| Range | 79.7 to 93.8 | 79.7 to 91.8 | 80.3 to 93.8 | | 78.9 to 92.7 | 78.9 to 92.6 | 81.7 to 92.7 | |
| **JLO (°)** | | | | | | | | |
| Mean ± SD | 174.2 ± 3.2 | 173.8 ± 3.1 | 174.7 ± 3.2 | <.001* | 173.8 ± 3.2 | 173.3 ± 3.2 | 174.5 ± 3.1 | <.001* |
| Range | 164.4 to 188.1 | 164.4 to 188.1 | 164.4 to 187.3 | | 160.5 to 185.1 | 160.5 to 185.1 | 164.9 to 184.3 | |

Preoperative and postoperative radiographic outcomes are given in mean ± standard deviation (SD) and range and stratified by gender. *aHKA,* arithmetic hip-knee-ankle angle; *HKA*, hip-knee-ankle angle; *JLO*, joint line obliquity; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle.

§ Comparison of radiographic outcomes by gender

* Indicates statistical significance

## Results

Among the 1000 patients included in the study, most patients were Caucasian (89.9%) and male (54.9%). The mean age was 63.4 ± 9.2 years. Radiographic outcomes of the included patients are presented in Table 1.

*Preoperative CPAK distribution*

Preoperatively, the majority of knees exhibited CPAK phenotype I (45.0%; Fig. 2). Among males, the prevalence of CPAK phenotype I was significantly higher compared to females (53.2% vs. 35.0%, respectively; *p* = <.001; Table 2). Females exhibited a significantly higher occurrence of CPAK phenotype V compared to males (9.8% vs. 4.4%, respectively; *p* = <.015). A detailed overview of the distribution of phenotypes within distinct age groups is presented in Figure 3.

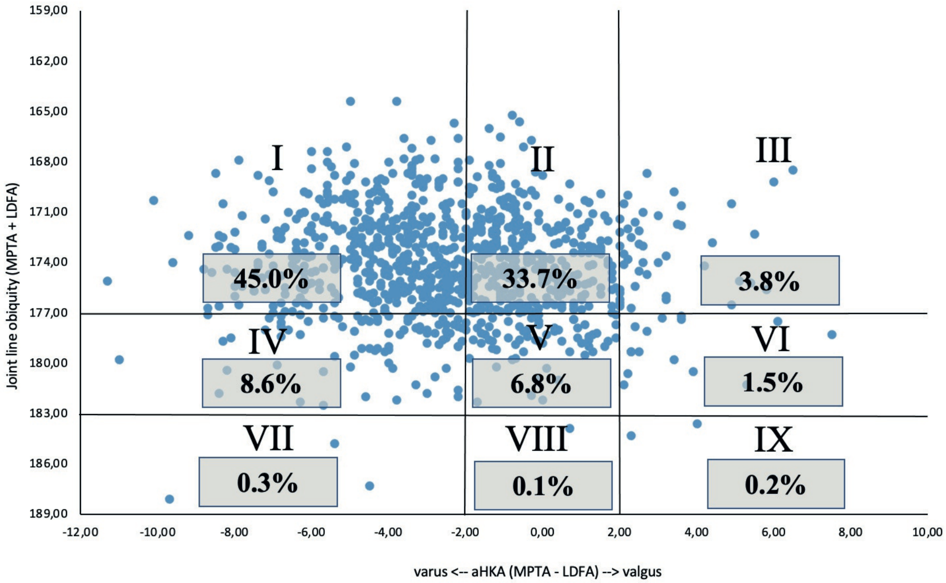


**Figure 2.** Scatterplot of the preoperative phenotype distribution in knees with anteromedial osteoarthritis according to the Coronal Plane Alignment of the Knee (CPAK) classification. Percentages are given for each phenotype. *aHKA*, arithmetic hip-knee-angle angle; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle.

**Table 2.** Preoperative and postoperative CPAK phenotype distribution

| | **Preoperatively** | | | | **Postoperatively** | | | |
|---|---|---|---|---|---|---|---|---|
| CPAK | Total | Male | Female | | Total | Male | Female | |
| phenotype | $n$ = 1000 | $n$ = 549 | $n$ = 451 | $p$ value § | $n$ = 1000 | $n$ = 549 | $n$ = 451 | $p$ value § |
| I | 450 (45.0%) | 292 (53.2%) | 158 (35.0%) | <.001* | 167 (16.7%) | 123 (22.4%) | 44 (9.8%) | <.001* |
| II | 337 (33.7%) | 172 (31.3%) | 165 (36.6%) | n.s. | 533 (53.3%) | 300 (54.6%) | 233 (51.7%) | n.s. |
| III | 38 (3.8%) | 13 (2.4%) | 25 (5.5%) | n.s. | 138 (13.8%) | 64 (11.7%) | 74 (16.4%) | n.s. |
| IV | 86 (8.6%) | 42 (7.7%) | 44 (9.8%) | n.s. | 41 (4.1%) | 17 (3.1%) | 24 (5.3%) | n.s. |
| V | 68 (6.8%) | 24 (4.4%) | 44 (9.8%) | .015* | 92 (9.2%) | 35 (6.4%) | 57 (12.6%) | <.001* |
| VI | 15 (1.5%) | 4 (0.7%) | 11 (2.4%) | n.s. | 26 (2.6%) | 9 (1.6%) | 17 (3.8%) | n.s. |
| VII | 3 (0.3%) | 2 (0.4%) | 1 (0.2%) | *n/a* | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) | *n/a* |
| VIII | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) | *n/a* | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) | *n/a* |
| IX | 2 (0.2%) | 0 (0.0%) | 2 (0.4%) | *n/a* | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | *n/a* |

The preoperative and postoperative incidence of each CPAK phenotype is given in numbers and frequencies (%) and stratified by gender. *CPAK*, Coronal Plane Alignment of the Knee.

§ Comparison of distribution of CPAK phenotypes by gender

* Indicates statistical significance

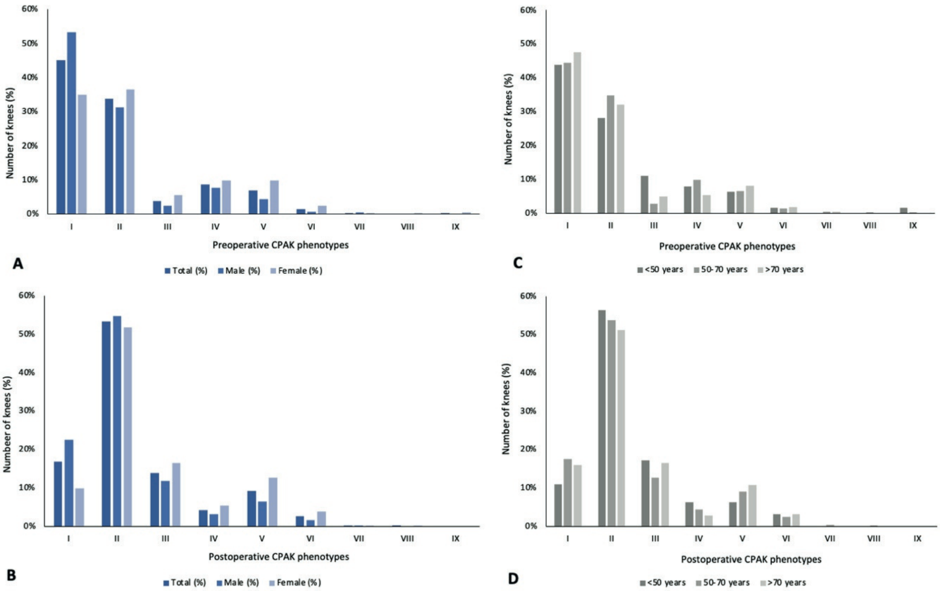


**Figure 3.** Distribution of preoperative and postoperative Coronal Plane Alignment of the Knee (CPAK) phenotypes of knees with anteromedial osteoarthritis and following treatment with medial unicompartmental knee arthroplasty. **3A,** Preoperative CPAK phenotype distribution stratified by sex. **3B,** Postoperative CPAK phenotype distribution stratified by sex. **3C,** Preoperative CPAK phenotype distribution stratified by age. **3D,** Postoperative CPAK phenotype distribution stratified by age.

### *Postoperative CPAK distribution*

Postoperatively, CPAK phenotype II was most frequently observed (53.3%; Fig. 4). Among males, the postoperative prevalence of CPAK phenotype I was significantly higher compared to females (22.4% vs 9.8%, respectively; $p$ = <.001; Table 2), whereas CPAK phenotype V was significantly higher among females (12.6% vs 6.4%, respectively; $p$ = <.001).

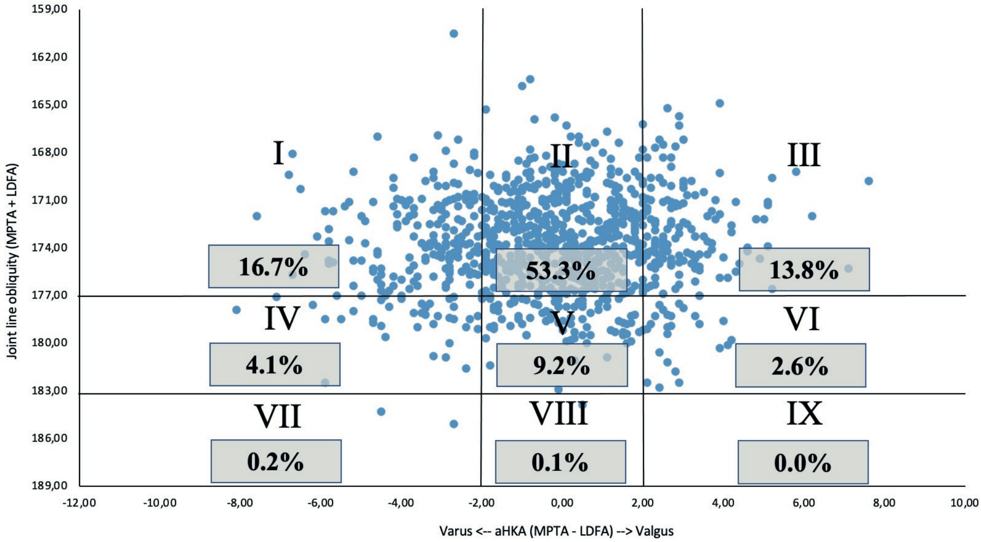


**Figure 4.** Scatterplot of the postoperative phenotype distribution following medial unicompartmental knee arthroplasty according to the Coronal Plane Alignment of the Knee (CPAK) classification. The prevalence is given for each phenotype. *aHKA*, arithmetic hip-knee-angle angle; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle.

*Distribution of limb alignment and JLO*

Preoperatively, 53.9% of knees exhibited pre-arthritic varus alignment (Fig. 5). Males exhibited a significantly higher prevalence of pre-arthritic varus alignment compared to females (61.2% vs. 45.0%, respectively; $p$ = <.001; Table 3). Conversely, the prevalence of pre-arthritic neutral and valgus alignment was significantly greater among females compared to males (neutral alignment: 46.6% vs. 35.7%, respectively; $p$ = <.001 and valgus alignment: 8.4% vs. 3.1%, respectively; $p$ = <.001). Additionally, males exhibited a significantly higher prevalence of apex distal JLO compared to females (86.9% vs 77.2%, respectively; $p$ = <.001), whereas the apex neutral JLO was significantly higher among females (21.9% vs 12.7%; $p$ = .02). A detailed overview of radiographic outcomes by CPAK phenotype is available in Table 4.

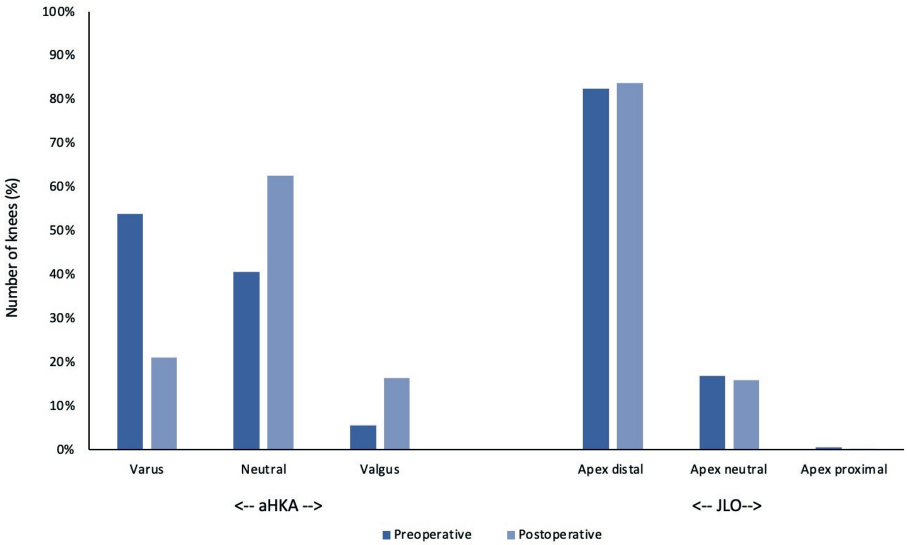


**Figure 5.** Distribution of the preoperative and postoperative pre-arthritic alignment (i.e., aHKA) and joint line orientation. The incidence of the limb alignment and joint line orientation phenotypes are given in frequencies (%). *aHKA*, arithmetic hip-knee-ankle angle; *JLO*, joint line obliquity.

*CPAK phenotype alterations following medial UKA*

Following medial UKA, a total of 45.1% of knees maintained their preoperative CPAK phenotype. Knees with preoperative CPAK phenotype II and III were associated with the highest rate of maintaining their preoperative CPAK phenotype (67.7% and 65.8%, respectively; Table 5). Table 6 provides an overview of the preoperative CPAK phenotype alterations following medial UKA.

**Table 3.** Distribution of limb alignment and joint line orientation

| | **Preoperatively** | | | | **Postoperatively** | | | |
|---|---|---|---|---|---|---|---|---|
| | Total<br>*n* = 1000 | Male<br>*n* = 549 | Female<br>*n* = 451 | *p* value § | Total<br>*n* = 1000 | Male<br>*n* = 549 | Female<br>*n* = 451 | *p* value § |
| **aHKA** | | | | | | | | |
| Varus | 539 (53.9%) | 336 (61.2%) | 203 (45.0%) | <.001* | 210 (21.0%) | 141 (25.7%) | 69 (15.3%) | <.001* |
| Neutral | 406 (40.6%) | 196 (35.7%) | 210 (46.6%) | <.001* | 626 (62.6%) | 335 (61.0%) | 291 (64.5%) | n.s. |
| Valgus | 55 (5.5%) | 17 (3.1%) | 38 (8.4%) | <.001* | 164 (16.4%) | 73 (13.3%) | 91 (20.2%) | n.s. |
| **JLO** | | | | | | | | |
| Apex distal | 825 (82.5%) | 477 (86.9%) | 348 (77.2%) | <.001* | 838 (83.8%) | 487 (88.7%) | 351 (77.8%) | <.001* |
| Apex neutral | 169 (16.9%) | 70 (12.7%) | 99 (21.9%) | .02* | 159 (15.9%) | 61 (11.1%) | 98 (21.8%) | .003* |
| Apex proximal | 6 (0.6%) | 2 (0.4%) | 4 (0.9%) | n.s. | 3 (0.3%) | 1 (0.2%) | 2 (0.4%) | n.s. |

Preoperative and postoperative incidence of neutral-, varus-, or valgus alignment and apex-neutral-, distal-, or proximal joint line orientation are given in numbers and frequencies (%) and stratified by gender. *aHKA,* arithmetic hip-knee-ankle angle; *JLO*, joint line obliquity.

§ Comparison of limb alignment and joint line obliquity by gender

* Indicates statistical significance

**Table 4.** Preoperative radiographic outcomes by CPAK phenotype in knees with anteromedial osteoarthritis

| | CPAK I<br>*n* = 450 | CPAK II<br>*n* = 337 | CPAK III<br>*n* = 38 | CPAK IV<br>*n* = 86 | CPAK V<br>*n* = 68 | CPAK VI<br>*n* = 15 | CPAK VII<br>*n* = 3 | CPAK VIII<br>*n* = 1 | CPAK IX<br>*n* = 2 |
|---|---|---|---|---|---|---|---|---|---|
| **HKA (°)** | | | | | | | | | |
| Mean ± SD | 9.1 ± 2.6 | 5.1 ± 2.2 | 1.7 ± 2.3 | 8.9 ± 2.7 | 4.7 ± 2.7 | 2.4 ± 2.9 | 11.2 ± 2.5 | 2.3 ± *n/a* | 3.4 ± 6.9 |
| Range | 2.2 to 17.0 | -2.0 to 11.8 | -3.5 to 7.5 | 2.8 to 16.4 | -2.0 to 11.6 | -2.4 to 6.2 | 8.4 to 13.3 | *n/a* | -1.5 to 8.2 |
| **aHKA (°)** | | | | | | | | | |
| Mean ± SD | -4.5 ± 1.7 | -0.4 ± 1.1 | 3.4 ± 1.3 | -4.4 ± 1.9 | -0.2 ± 1.1 | 3.5 ± 1.6 | -6.5 ± 2.8 | 0.7 ± *n/a* | 3.2 ± 1.2 |
| Range | -11.3 to -2.1 | -2 to 2 | 2.1 to 6.5 | -11.0 to -2.1 | -2.0 to 1.9 | 2.1 to 7.5 | -9.7 to -4.5 | *n/a* | 2.3 to 4.0 |
| **LDFA (°)** | | | | | | | | | |
| Mean ± SD | 88.7 ± 1.5 | 86.9 ±1.2 | 84.8 ± 1.3 | 91.5 ± 1.2 | 89.4 ± 0.8 | 87.7 ±1.2 | 96.6 ± 2.0 | 91.6 ± *n/a* | 90.4 ± 0.8 |
| Range | 84 to 93.2 | 83 to 89.4 | 81.0 to 87.2 | 89.7 to 95.4 | 87.6 to 92.0 | 85.4 to 89.6 | 95.1 to 98.9 | *n/a* | 89.8 to 91.0 |
| **MPTA (°)** | | | | | | | | | |
| Mean ± SD | 84.3 ± 1.5 | 86.5 ± 1.4 | 88.1 ± 1.2 | 87.1 ± 1.2 | 89.2 ± 0.8 | 91.3 ±1.0 | 90.1 ± 1.2 | 92.3 ± *n/a* | 93.6 ± 0.4 |
| Range | 79.7 to 87.1 | 82.2 to 89.3 | 85.7 to 90.7 | 84.2 to 89.9 | 87.6 to 91.1 | 90.1 to 93.3 | 89.2 to 91.4 | *n/a* | 93.3 to 93.8 |
| **JLO (°)** | | | | | | | | | |
| Mean ± SD | 173.0 ± 2.5 | 173.5 ± 2.4 | 172.9 ± 2.2 | 178.6 ± 1.5 | 178.6 ± 1.2 | 179.0 ± 1.5 | 186.7 ± 1.7 | 183.9 ± *n/a* | 183.9 ± 0.5 |
| Range | 164.4 to 176.9 | 165.2 to 176.9 | 168.5 to 176.7 | 177.0 to 182.5 | 177.0 to 182.3 | 177.2 to 181.3 | 184.8 to 188.1 | *n/a* | 183.6 to 184.3 |

Preoperative radiographic outcomes are given in mean ± standard deviation (SD) and range. *aHKA,* arithmetic hip-knee-ankle angle; *CPAK,* Coronal Plane Alignment of the Knee classification; *HKA*, hip-knee-ankle angle; *JLO*, joint line obliquity; *LDFA*, lateral distal femoral angle; *MPTA*, medial proximal tibial angle.

**Table 5.** Distribution of CPAK phenotype restoration

| | | **Postoperative** | |
|---|---|---|---|
| Preoperative CPAK phenotype | Number of knees | Maintained their preoperative CPAK phenotype | Not maintained their preoperative CPAK phenotype |
| I | 450 (45.0%) | 143 (31.8%) | 307 (68.2) |
| II | 337 (33.7%) | 228 (67.7%) | 109 (32.3%) |
| III | 38 (3.8%) | 25 (65.8%) | 13 (34.2%) |
| IV | 86 (8.6%) | 21 (24.4%) | 65 (75.6%) |
| V | 68 (6.8%) | 27 (39.7%) | 41 (60.3%) |
| VI | 15 (1.5%) | 5 (33.3%) | 10 (66.7%) |
| VII | 3 (0.3%) | 2 (66.7%) | 1 (33.3%) |
| VIII | 1 (0.1%) | 0 (0.0%) | 1 (100.0%) |
| IX | 2 (0.2%) | 0 (0.0% | 2 (100.0%) |
| **Total** | **1000 (100.0%)** | **451 (45.1%)** | **549 (54.9%)** |

The preoperative and postoperative incidence is given in numbers and frequencies (%). *CPAK,* Coronal Plane Alignment of the Knee classification.

## Discussion

The most important findings were that knees with anteromedial OA express a substantial variability in CPAK phenotypes, both prior to and following medial UKA. Preoperatively, CPAK phenotype I and II exhibited the highest prevalence (45.0% and 33.7%, respectively). Postoperatively, there was a noticeable shift towards a more neutral alignment, with CPAK phenotype II exhibiting the highest prevalence (53.3%). Overall, 45.1% of knees maintained their preoperative CPAK phenotype following medial UKA. The term “anteromedial OA” refers to a unique clinicopathological pattern of osteoarthritis affecting the anteromedial compartment of the knee. This specific type of OA, including an intact ACL and a correctable varus deformity, is considered to be the primary suitable indication for medial UKA[3, 30]. However, the findings of the present study reveal that despite the well-defined identical intra-articular anteromedial wear pattern, knees with this type of OA exhibit a significant variability in their phenotypic expression. These findings challenge the assumption that all anteromedial osteoarthritic knees share uniform features and highlight the complexity and heterogeneity of this specific form of OA.

The present findings are in accordance with previous studies demonstrating that either CPAK phenotypes I or II were the most commonly observed knee phenotypes in both healthy knees[15-17] and arthritic patients undergoing TKA[16-18, 23, 24, 31]. A recent study evaluating the CPAK phenotype distribution among 8739 osteoarthritic knees, identified CPAK phenotype I and II as the predominant phenotypes, with incidences of 28.1% and 27.3% respectively[31]. Nonetheless, the aforementioned studies primarily focused on healthy individuals and arthritic patients undergoing TKA. Therefore, it is noteworthy that the prevalence of CPAK phenotype I, characterized by varus alignment and an apex distal JLO, was higher in the present study as compared to the previously mentioned studies[15, 16, 18, 24, 25, 31, 32]. This may potentially be attributed to the association between pre-arthritic varus alignment, increased loading of the medial compartment of the knee, and consequently the higher risk of OA progression primarily affecting the anteromedial compartment of the knee[33-35].

Previous reports have demonstrated a higher prevalence of varus alignment among males compared to females[36-38]. Moreover, a prior study, specifically evaluating the gender-specific distribution of CPAK knee phenotypes in osteoarthritic knees, reported that CPAK phenotypes characterized by a varus alignment were more common in males, whereas phenotypes characterized by a neutral or valgus alignment were more frequently observed in females[31]. These findings are supported by the current study evaluating patients with identical anteromedial OA, demonstrating a statistically significant predominance of pre-arthritic varus alignment among males, both prior to and following medial UKA. Additionally, a higher prevalence of pre-arthritic valgus alignment was observed among females prior to medial UKA.

Traditionally, the surgical objective in medial UKA has been to achieve a neutral mechanical alignment[39]. However, contrary to previously held beliefs, the majority of knees are not mechanically aligned, with only 15.4% and 14.6% of healthy and arthritic patients undergoing TKA exhibiting a neutral alignment, respectively[16]. Findings of the present study demonstrate an even lower prevalence, with only 6.8% of patients with anteromedial OA exhibited a neutral mechanical alignment. The present study demonstrated that 53.9% of patients with isolated medial compartment OA had a pre-arthritic alignment of 2° of varus or more. Consequently, restoring their knee to neutral mechanical alignment would be considered abnormal, and thus, may require a certain degree of medial soft tissue release, which should be avoided during UKA[40, 41]. More interestingly, 5.5% of patients with isolated medial OA had a pre-arthritic alignment in valgus (CPAK III, VI, and IX). Since the development of progressive lateral compartment OA is one of the most common causes of failure following medial UKA, caution should be exercised to avoid excessive overcorrection into valgus alignment when aiming to restore pre-arthritic alignment in these knees[42].

Utilizing individualized alignment strategies by restoring a knee to its pre-arthritic alignment during knee arthroplasty has been associated with improved survivorship and favorable functional outcomes[9, 11, 38, 43-45]. Moreover, recent TKA studies have demonstrated that altering limb and femoral phenotypes is associated with lower clinical outcome scores, whereas restoring a distal JLO is associated with less postoperative pain[18, 46]. This study demonstrated that 45.1% of knees maintained their preoperative CPAK phenotype following medial UKA. These findings suggest that relying solely on MCL re-tensioning might not be sufficient to restore both the pre-arthritic alignment and knee phenotype. Considering the preoperative CPAK phenotype during preoperative surgical planning may offer several advantages, as it enables surgeons to aim for the restoration of the knee to its pre-arthritic alignment and phenotype using a relatively straightforward and pragmatic classification system.

This study has several limitations. First, all procedures were performed by a single surgeon, which may affect the generalizability of the results. Second, the study cohort predominantly consisted of Caucasian patients. A recent systematic review demonstrated significant variation in the distribution of CPAK phenotypes across intercontinental populations, thereby limiting the generalizability of the current findings to individuals from other ethnic groups[26]. Third, the CPAK classification system neglects knee morphology in the sagittal plane, which may lead to an incomplete assessment of the entirety of the knee joint. Additionally, while the CPAK classification simplifies classification by relying on just two variables, Hirschmann et al.[47] introduced an alternative and more comprehensive system that integrates three variables (i.e., the mHKA, femoral mechanical angle, and tibial mechanical angle) enabling separate classification of the femur and tibia[21, 22, 47, 48]. Future studies should consider incorporating this classification system and explore its relation to clinical outcomes. Fourth, the present study lacks an analysis of functional outcomes. Therefore, it remains uncertain which pre- to postoperative alterations in CPAK phenotypes yield the most favorable functional outcomes following medial UKA. Future studies should investigate the specific advantages of maintaining the preoperative CPAK phenotype and identify the acceptable limits for pre- to postoperative alterations in CPAK phenotypes during medial UKA in relation to functional outcomes.

## Conclusion

There is a substantial variation in CPAK phenotypes among knees with anteromedial OA, as well as following treatment with medial UKA. This variability challenges the assumption of uniform characteristics among knees with an identical wear pattern associated with anteromedial OA and emphasizes the complexity and variability of this specific form of OA.

**Table 6**. Preoperative CPAK phenotype alterations following medial unicompartmental knee arthroplasty

| Preoperative CPAK phenotype | Number of knees | Postoperative CPAK phenotype | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | V | VI | VII | VIII | IX |
| I | 450 (45.0%) | 143 (31.8%) | 249 (55.3%) | 18 (4.0%) | 16 (3.6%) | 22 (4.9%) | 2 (0.4%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| II | 337 (33.7%) | 11 (3.3%) | 228 (67.6%) | 82 (24.3%) | 0 (0.0%) | 12 (3.6%) | 4 (1.2%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| III | 38 (3.8%) | 0 (0.0%) | 12 (31.6%) | 25 (65.8%) | 1 (2.6%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| IV | 86 (8.6%) | 10 (11.6%) | 24 (27.9%) | 1 (1.2%) | 21 (24.4%) | 26 (30.2%) | 4 (4.7%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| V | 68 (6.8%) | 2 (2.9%) | 18 (26.5%) | 8 (11.8%) | 2 (2.9%) | 27 (39.7%) | 10 (14.7%) | 0 (0.0%) | 1 (1.5%) | 0 (0.0%) |
| VI | 15 (1.5%) | 1 (6.7%) | 2 (13.3%) | 4 (26.7%) | 0 (0.0%) | 3 (20.0%) | 5 (33.3%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| VII | 3 (0.3%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 1 (33.3%) | 0 (0.0%) | 0 (0.0%) | 2 (66.7%) | 0 (0.0%) | 0 (0.0%) |
| VIII | 1 (0.1%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 1 (100.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| IX | 2 (0.2%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 1 (50.0%) | 1 (50.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) |
| **Total** | **1000 (100.0%)** | **167 (16.7%)** | **533 (53.3%)** | **138 (13.8%)** | **41 (4.1%)** | **92 (9.2%)** | **26 (2.6%)** | **2 (0.2%)** | **1 (0.1%)** | **0 (0.0%)** |

The preoperative and postoperative incidence of CPAK phenotypes is given in numbers and frequencies (%). *CPAK*, Coronal Plane Alignment of the Knee classification.

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# Chapter 8

# The phenotypic diversity of anteromedial osteoarthritis before and after treatment with medial unicompartmental knee arthroplasty

## a radiographic analysis of 1000 knees

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Knee Surgery, Sports Traumatology, Arthroscopy

## Abstract

**Purpose**: This study aimed to assess phenotypic variation in the coronal plane of knees with anteromedial osteoarthritis using the functional knee phenotype classification, before and after treatment with medial unicompartmental knee arthroplasty (UKA).

**Methods:** The study comprised 1000 knees of 835 patients who underwent medial UKA for anteromedial osteoarthritis. Pre- and postoperative alignment was evaluated through the hip-knee-ankle angle (HKA), femoral mechanical angle (FMA), and tibial mechanical angle (TMA). Knees were classified according to the functional knee phenotype system which combines limb phenotype (HKA), and femoral and tibial knee phenotypes (FMA and TMA, respectively). Restoration of pre-arthritic coronal alignment following medial UKA was evaluated by phenotype.

**Results:** Preoperatively, 76 distinct and 25 relevant (prevalence ≥ 1%) functional knee phenotypes were identified, of which $VAR_{HKA}6°VAR_{FMA}3°NEU_{TMA}0°$ was the most common (9.4% of knees). The most prevalent limb phenotype, $VAR_{HKA}6°$, comprised 15 distinct knee phenotypes (FMA and TMA combinations). Postoperatively, 58 distinct and 17 relevant functional knee phenotypes were observed, of which $VAR_{HKA}3°NEU_{FMA}0°NEU_{TMA}0°$ had the highest prevalence at 18.3%. Knees with combined tibial and femoral deformities were associated with a lower probability of restoration of pre-arthritic coronal alignment following medial UKA, compared to knees without extra-articular deformities, or knees with an isolated tibial or femoral deformity.

**Conclusion:** Phenotype analysis demonstrated a wide diversity of coronal alignment phenotypes among knees with anteromedial osteoarthritis in a predominantly Caucasian population. Following medial UKA, a reduction from 25 preoperative to 17 postoperative relevant phenotypes was observed. Consideration of phenotypic variation can be of importance when aiming to restore pre-arthritic coronal alignment during medial UKA.

## Introduction

Medial unicompartmental knee arthroplasty (UKA) is an effective surgical treatment for isolated anteromedial osteoarthritis (OA) of the knee[1]. However, the optimal alignment targets for UKA remain undefined and there continues to be uncertainty about patient selection criteria[2-4]. In order to optimize alignment strategies and improve patient selection, a better understanding of the phenotypic variability of medial OA-affected knees would be of interest.

Recent studies have observed a broad variation in coronal alignment and joint line orientation in healthy and osteoarthritic knees[5-8]. These findings have underlined the shortcomings of the traditional classification of neutral, varus or valgus alignment, which disregards the phenotypes of femoral and tibial alignment that can exist within these three categories. Several novel classification systems, including the functional knee phenotype classification[6], have been put forth to comprehensively describe the relation between the mechanical axis (i.e., limb phenotype) and femoral and tibial joint line orientation (i.e., knee phenotype) of the individual knee[6, 9, 10]. However, most of these studies included both lateral and medial compartment OA-affected knees, or healthy knees, and focused on guidelines and implications for total knee arthroplasty[6, 9-12].

Although knees affected by medial compartment OA typically exhibit an anteromedial wear pattern and a varus mechanical axis, the specific coronal plane phenotypes within this group and their change during medial UKA remain largely undefined. Furthermore, it is currently unknown whether the type of phenotype affects the ability to restore pre-arthritic coronal alignment during medial UKA, which has been shown to have clinical implications[13, 14].

The objective of this study was to describe the variability in coronal plane phenotypes of knees with isolated anteromedial OA, before and after treatment with medial UKA, using the functional knee phenotype classification[6]. Based on current literature[6, 8, 12], and the concept of an individualized alignment strategy for medial UKA[15], we hypothesized a large pre- and postoperative diversity of coronal plane phenotypes.

## Methods

*Study design*

A single surgeon's arthroplasty registry was retrospectively reviewed. A total of 1000 consecutive knees of 835 patients, who underwent robotic-arm assisted medial UKA between January 2012 and July 2022 for anteromedial OA, were randomly selected.

Patients were eligible for study inclusion if they had advanced anteromedial OA (Kellgren-Lawrence [KL] grade 3-4 on anteroposterior [AP] weight-bearing views)[16], an unaffected and asymptomatic lateral compartment (KL grade ≤ 2), underwent robotic-arm assisted primary medial UKA, and had complete radiographic records (pre- and postoperative long-leg radiographs). Patients with a history of prior joint arthroplasty, or femoral or tibial fractures on the operative side were excluded from the study. Characteristics of included patients are presented in Table 1.

**Table 1**. Demographics (*n* =1000).

| Variable | Mean ± SD, or *n* (%) |
|---|---|
| Age (years) | 63.4 ± 9.2 |
| Sex (female) | 451 (45.1) |
| Race | |
| Caucasian | 899 (89.9) |
| Black or African American | 27 (2.7) |
| Asian | 16 (1.6) |
| Other | 26 (2.6) |
| Unknown | 32 (3.2) |
| Laterality OA (left) | 508 (50.8) |
| Bilateral knee OA | 330 (33.0) |
| KL grade medial compartment | |
| KL grade 3 | 388 (38.8) |
| KL grade 4 | 612 (61.2) |

Demographics are presented as mean ± standard deviation (SD), or in numbers with the frequency in parentheses. *KL,* Kellgren-Lawrence grade; *OA,* osteoarthritis.

The surgical indication for medial UKA was symptomatic isolated anteromedial OA, with a varus deformity correctable to < 10°, and fixed flexion deformity of < 10°. Patients with significant clinical or radiographic signs of lateral compartment OA, degeneration of the lateral patellar facet, anterior cruciate ligament deficiency with clinical instability, previous medial collateral ligament (MCL) surgery, or signs of inflammatory arthritis were not deemed candidates for medial UKA.

*Surgical technique*

A cemented fixed-bearing medial only implant (Restoris MCK System, Mako Surgical Corp. [Stryker]) was used in all cases. A robotic-arm assisted system (Mako Surgical Corp. [Stryker]) was used for implant planning and osseous resection. The detailed surgical technique has previously been described[17]. The alignment goal was to recreate pre-arthritic coronal alignment (i.e., mechanical axis) by restoration of MCL tension throughout the range of motion, aiming for a 1-2 mm medial gap under valgus stress, with the implants and polyethylene insert in place. This individualized alignment technique was restricted by neutral alignment, meaning that a neutral mechanical axis was pursued in knees with estimated native valgus alignment, based on MCL tension. Given the retrospective design of this study, phenotypes were not considered during the surgery.

*Radiographic evaluation*

Routine weight-bearing long-leg AP radiographs were used for assessment of coronal alignment. Radiographs were obtained preoperatively and 6 weeks postoperatively. According to a standardized protocol, patients were instructed to stand with their feet together as close as possible while having their knees in full extension, their patellae aligned with the X-ray beam, and their bodyweight evenly distributed over both limbs.

The hip-knee-ankle angle (HKA) was defined as the angle between the mechanical axes of the femur and tibia (Fig. 1). The lateral femoral angle (LDFA) was measured as the lateral angle between the mechanical femoral axis and joint line of the distal femur. The femoral mechanical angle (FMA; Fig. 1) was derived from the LDFA (FMA

=180°-mLDFA). The tibial mechanical angle (TMA) was defined as the medial angle of the mechanical tibial axis and proximal tibial joint line (Fig. 1). Measurements were taken by one observer (G.V.t.N.d.B) and independently repeated by a second observer (L.V.R) on a random sample (*n* =100). Angles were measured to the tenth of a degree. Inter-observer reliability was analyzed through interclass correlation coefficients (ICC), using a two-way mixed-model with absolute agreement. ICC among observers was 0.97 (95% confidence interval [CI] 0.96-0.98) for HKA, 0.89 (95% CI, 0.82-0.93) for FMA, and 0.90 (95% CI, 0.85-0.93) for TMA.

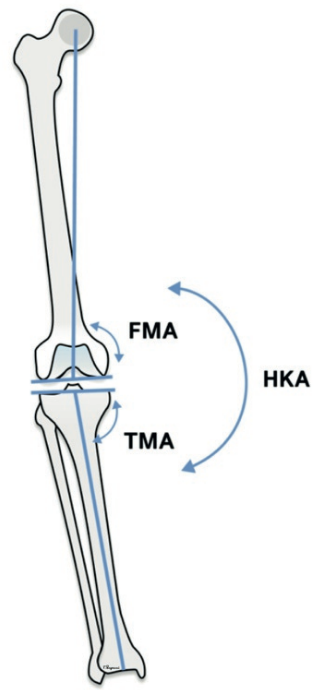


**Figure 1.** Schematic representation of measurement of the hip-knee-ankle angle (HKA), femoral mechanical angle (FMA), and tibial mechanical angle (TMA).

*Functional knee phenotype classification*

Knees were classified according to the functional knee phenotype system, introduced by Hirschmann *et al*[6]. The system integrates three coronal alignment parameters, including limb phenotype (HKA) and femoral and tibial knee phenotype

(FMA and TMA, respectively) into a "functional knee phenotype". Each phenotype covers a range of ± 1.5° from the baseline value for that specific parameter, derived from previously reported means of healthy individuals (HKA: 0°; FMA: 93°; TMA: 87°)[6]. The classification first describes the direction of alignment (i.e., neutral, varus, or valgus), with the respective parameter subsequently indicated in subscript (i.e., HKA, FMA, TMA). The mean deviation from the phenotype-specific baseline value is indicated in increments of 3° (e.g., $VAR_{HKA}3°$, $VAR_{HKA}6°$ etc.). For example, the functional knee phenotype of a patient with a neutral HKA, neutral FMA, and neutral TMA would be $NEU_{HKA}0°NEU_{FMA}0°NEU_{TMA}0°$. Table 2 displays the definition and range of each phenotype.

**Table 2**. Functional knee phenotype classification.

| Parameter | Direction | Type | Range |
|---|---|---|---|
| **HKA** Limb phenotype | $VAR_{HKA}$ | $VAR_{HKA}18°$ | 16.5 to 19.5° |
| | | $VAR_{HKA}15°$ | 13.5 to 16.5° |
| | | $VAR_{HKA}12°$ | 10.5 to 13.5° |
| | | $VAR_{HKA}9°$ | 7.5 to 10.5° |
| | | $VAR_{HKA}6°$ | 4.5 to 7.5° |
| | | $VAR_{HKA}3°$ | 1.5 to 4.5° |
| | $NEU_{HKA}$ | $NEU_{HKA}0°$ | -1.5 to 1.5° |
| | $VAL_{HKA}$ | $VAL_{HKA}3°$ | -1.5 to -4.5° |
| **FMA** Femoral phenotype | $VAR_{FMA}$ | $VAR_{FMA}12°$ | 79.5 to 82.5° |
| | | $VAR_{FMA}9°$ | 82.5 to 85.5° |
| | | $VAR_{FMA}6°$ | 85.5 to 88.5° |
| | | $VAR_{FMA}3°$ | 88.5 to 91.5° |
| | $NEU_{FMA}$ | $NEU_{FMA}0°$ | 91.5 to 94.5° |
| | $VAL_{FMA}$ | $VAL_{FMA}3°$ | 94.5 to 97.5° |
| | | $VAL_{FMA}6°$ | 97.5 to 100.5° |
| **TMA** Tibial phenotype | $VAR_{TMA}$ | $VAR_{TMA}9°$ | 76.5 to 79.5° |
| | | $VAR_{TMA}6°$ | 79.5 to 82.5° |
| | | $VAR_{TMA}3°$ | 82.5 to 85.5° |
| | $NEU_{TMA}$ | $NEU_{TMA}0°$ | 85.5 to 88.5° |
| | $VAL_{TMA}$ | $VAL_{TMA}3°$ | 88.5 to 91.5° |
| | $VAL_{TMA}$ | $VAL_{TMA}6°$ | 91.5 to 94.5° |

The functional knee phenotype classification [6] consists of a combination of three parameters, including the hip-knee-ankle angle (HKA), the femoral mechanical angle (FMA), and the tibial mechanical angle (TMA). The definition and corresponding range in degrees is given for each parameter. *NEU,* neutral; *VAL*, valgus; *VAR*, varus.

*Restoration of pre-arthritic coronal alignment*

Pre-arthritic (i.e., native) coronal alignment was estimated using the arithmetic hip-knee-ankle angle (aHKA)[15, 18]. Restoration of pre-arthritic coronal alignment following medial UKA was classified according to a previously reported system[14] as pre-arthritically aligned (Group 1, Fig 2A), overcorrection from the pre-arthritic coronal alignment (Group 2, Fig. 2B), or under correction from the pre-arthritic coronal alignment (Group 3, Fig. 2C). One-hundred fifty-nine knees (15.9%) with an estimated pre-arthritic coronal alignment in valgus (aHKA ≤ -1º) were excluded from this specific analysis, as those knees were typically neutralized during medial UKA and no attempt was made to restore pre-arthritic coronal alignment.

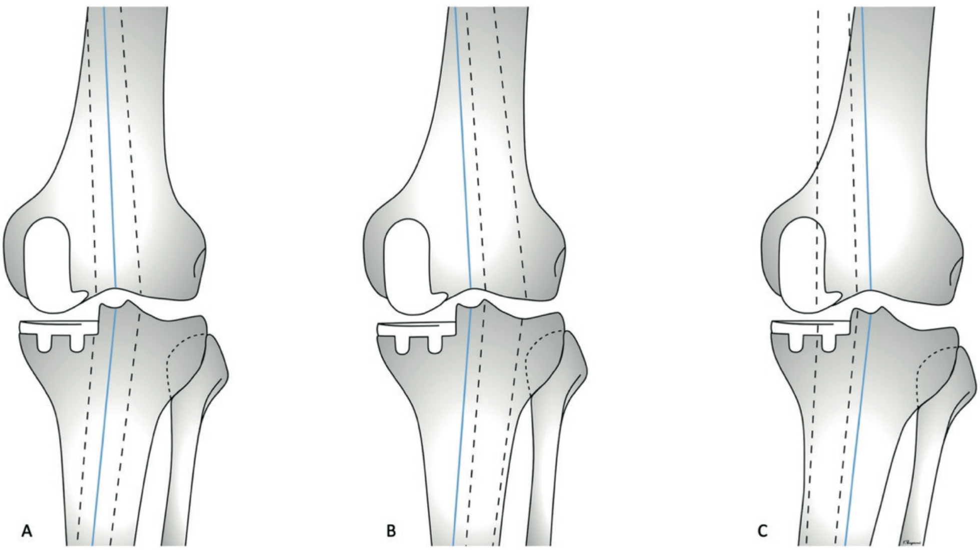


**Figure 2.** Classification of pre-arthritic alignment restoration following medial unicompartmental knee arthroplasty[14]. The continuous blue line indicates the postoperative mechanical axis (i.e., hip-knee-ankle angle [HKA]). The margins of ±2.0º of estimated pre-arthritic alignment (i.e., arithmetic hip-knee-ankle angle [aHKA]) are indicated by the dashed lines. **A**, Pre-arthritically aligned knee (Group 1), defined by a postoperative HKA within ±2.0º of its aHKA. **B**, Non-pre-arthritically aligned knee with overcorrection from its pre-arthritic alignment (Group 2), defined by a postoperative HKA of >2.0º smaller than its aHKA. **C**, Non-pre-arthritically aligned knee with under correction of its pre-arthritic alignment (Group 3), defined by a postoperative HKA of >2.0º larger than its aHKA (Group 3). Image reproduced from original work with permission of Bayoumi *et al*[14].

*Statistical analysis*

Prevalence of pre- and postoperative phenotypes were calculated and presented in numbers and frequencies for the total sample and by sex. The Shapiro-Wilk test was used to test continuous variables for a normal distribution. Independent *t*-tests or Mann-Whitney U tests were conducted to compare parametric and non-parametric continuous data between sexes, respectively. Correlations were analyzed using Pearson's correlation coefficient for parametric data and Spearman's rank correlation coefficient for non-parametric data. Discrete variables were compared using Chi-square test or Fisher's exact test when appropriate. Post hoc power analysis were performed using G*Power 3.1[19], yielding high power (0.99) for the observed differences in prevalence of deformity location between males and females, and proportions of knees with restored pre-arthritic coronal alignment between subgroups with extra-articular deformities. The level of significance was set at 0.05 for all tests. All analyses were performed in R version 4.1.2. (R Foundation for Statistical Computing).

*Ethical Aspects*

Institutional Review Board approval from the Institutional Review Board of the Hospital for Special Surgery (#2022-1401) was obtained prior to the start of the study. Given the retrospective nature of this study, patient consent was not applicable.

## Results

*Functional knee phenotypes*

Preoperatively, 76 functional knee phenotypes were identified. Fifty-one phenotypes had a prevalence of < 1% (Appendix Table 1). Hence, the 25 phenotypes with a prevalence of ≥ 1% were considered relevant. The most common preoperative functional phenotype was $VAR_{HKA}6^{o}VAR_{FMA}3^{o}NEU_{TMA}0^{o}$ (9.4%; Table 3). Independent of HKA, the most prevalent preoperative combination of femoral and tibial phenotype (i.e., knee phenotype) was $NEU_{FMA}0^{o}NEU_{TMA}0^{o}$ (Table 4). Following medial UKA, a total of 58 functional knee phenotypes were identified. Forty-one postoperative phenotypes had a prevalence of < 1%. Hence, 17 postoperative phenotypes were considered relevant. The most prevalent postoperative functional knee phenotype was $VAR_{HKA}3°NEU_{FMA}0°NEU_{TMA}0°$ (18.3%).

The five most frequently observed pre- and postoperative functional knee phenotypes are presented in Table 3. An overview of all observed functional knee phenotypes is available in Table 1. Sex-based analysis demonstrated differences in mean values of pre- and postoperative coronal alignment parameters between males and females (Appendix Table 2), however, there was no sex-related variation in distribution of the five most common functional knee phenotypes (Table 3).

**Table 3.** The five most common pre- and postoperative functional knee phenotypes.

| Rank | Functional knee phenotype | Total *n* =1000 | Male *n* =549 | Female *n* =451 |
|---|---|---|---|---|
| | **Preoperatively** | n (%) | | |
| 1 | $VAR_{HKA}6°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 94 (9.4) | 51 (9.3) | 43 (9.5) |
| 2 | $VAR_{HKA}6°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 93 (9.3) | 54 (9.8) | 39 (8.6) |
| 3 | $VAR_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 91 (9.1) | 49 (8.9) | 42 (9.3) |
| 4 | $VAR_{HKA}9°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 74 (7.4) | 49 (8.9) | 25 (5.5) |
| 5 | $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 64 (6.4) | 42 (7.7) | 22 (4.9) |
| | *p* value § | | | .324 |
| **Total** | | 416 (41.6) | 245 (44.6) | 171 (37.9) |
| | **Following medial UKA** | | | |
| 1 | $VAR_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 183 (18.3) | 97 (17.7) | 86 (19.1) |
| 2 | $NEU_{HKA}0°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 98 (9.8) | 60 (10.9) | 38 (8.4) |
| 3 | $NEU_{HKA}0°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 69 (6.9) | 37 (6.7) | 32 (7.1) |
| 4 | $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 68 (6.8) | 42 (7.7) | 26 (5.8) |
| 5 | $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 58 (5.8) | 24 (4.4) | 34 (7.5) |
| | *p* value § | | | .114 |
| **Total** | | 705 (47.6) | 260 (47.4) | 216 (47.9) |

Top five most common functional phenotypes of knees with advanced isolated anteromedial osteoarthritis, prior to and following medial unicompartmental knee arthroplasty (UKA) are presented in numbers with the frequency in parentheses. The prevalence of each functional knee phenotype is given for the total cohort and by sex. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU,* neutral; *VAL*, valgus; *VAR*, varus.
§ Comparison of prevalence of functional knee phenotypes by sex.

**Table 4**. Distribution of preoperative femoral and tibial phenotypes

| | **FMA** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $VAR_{FMA}$12° | $VAR_{FMA}$9° | $VAR_{FMA}$6° | $VAR_{FMA}$3° | $NEU_{FMA}$0° | $VAL_{FMA}$3° | $VAL_{FMA}$6° | **Total** |
| **TMA** | | | | | | | | |
| $VAR_{TMA}$6° | - | - | 2 (0.2) | 15 (1.5) | 32 (3.2) | 10 (1.0) | - | 59 (5.9) |
| $VAR_{TMA}$3° | - | 1 (0.1) | 23 (2.3) | 135 (13.5) | 167 (16.7) | 30 (3.0) | - | 356 (35.6) |
| $NEU_{TMA}$0° | - | 1 (0.1) | 21 (2.1) | 187 (18.7) | 220 (22.0) | 35 (3.5) | 2 (0.2) | 466 (46.6) |
| $VAL_{TMA}$3° | 1 (0.1) | 2 (0.2) | 8 (0.8) | 46 (4.6) | 46 (4.6) | 7 (0.7) | - | 110 (11.0) |
| $VAL_{TMA}$6° | - | - | 1 (0.1) | 3 (3.0) | 4 (0.6) | 1 (0.1) | - | 9 (0.9) |
| **Total** | 1 (0.1) | 4 (0.4) | 55 (5.5) | 386 (38.6) | 469 (46.9) | 83 (8.3) | 2 (0.2) | 1000 (100) |

The distribution of combinations of femoral and tibial phenotypes (i.e., knee phenotype) of knees with advanced anteromedial osteoarthritis is presented in numbers with the frequencies in parentheses. The heatmap represents the prevalence of each combination (green indicates the highest and red the lowest prevalence). *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU,* neutral; *VAL*, valgus; *VAR*, varus.

*Distribution of limb phenotypes*

Preoperatively, limb phenotypes $VAR_{HKA}6°$ (33.8%) and $VAR_{HKA}9°$ (27.5%) were most frequently observed and included 15 distinct knee phenotypes each (Fig. 3A). Postoperatively, limb phenotypes $VAR_{HKA}3°$ (47.1%), and $NEU_{HKA}0$ ° (31.4%), were most common and these included 14 and 17 knee phenotypes, respectively (Fig. 3B). Figure 3 demonstrates a similar distribution between sexes of pre- and postoperative knee phenotypes, in relation to the observed limb phenotypes.

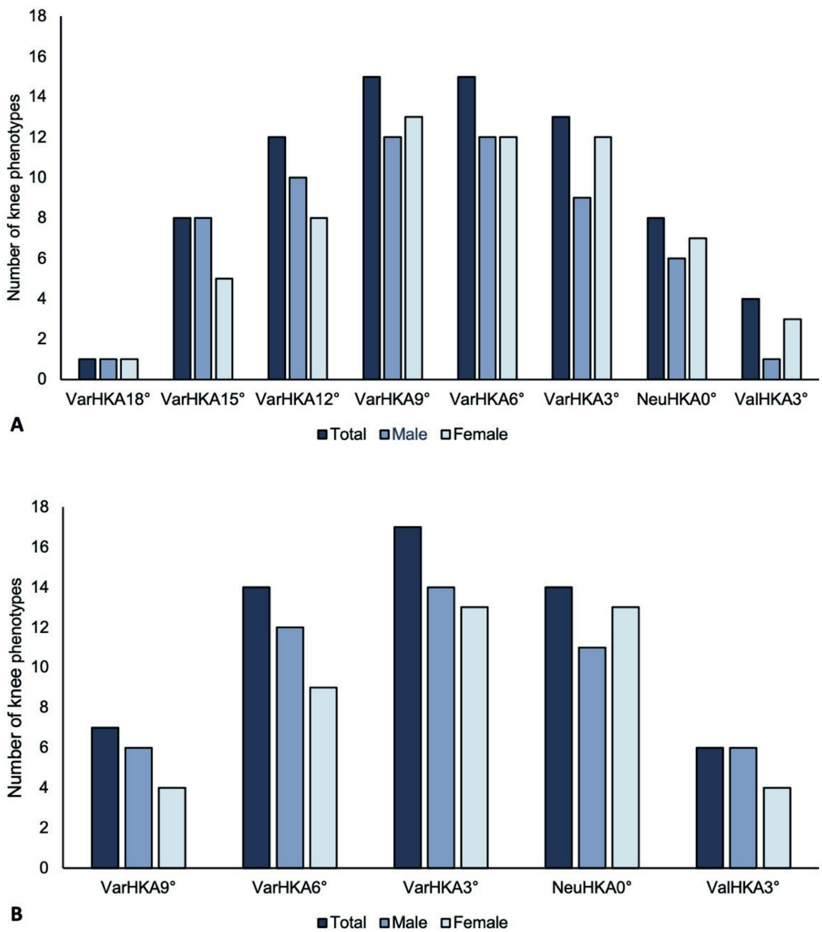


**Figure 3.** Distribution of knee phenotypes (i.e., combination of femoral and tibial phenotype) in relation to the observed limb phenotypes of knees with advanced isolated medial compartment osteoarthritis. **A**, preoperative distribution. **B**, distribution following medial unicompartmental knee arthroplasty.

*Location of the extra-articular deformity*

Among knees with limb phenotype $VAR_{HKA}3^{o}$, nearly half (48.4%) had no extra-articular deformity (Table 5). Limb phenotypes $VAR_{HKA}6^{o}$ and $VAR_{HKA}9^{o}$ were observed more frequently in combination with isolated tibial or femoral deformities, while more severe varus limb phenotypes more often exhibited a combined tibial and femoral deformity. Similar patterns were observed when analyzed by age, without overall differences between age groups ($p$ =.970; Appendix Table 3). Females more frequently had an isolated femoral deformity ($p$ =0.3; Table 6).

*Restoration of pre-arthritic coronal alignment*

Rates of pre-arthritically aligned knees following medial UKA were comparable among the five most common preoperative functional knee phenotypes (Appendix Table 4). Significant variations were observed in rates of pre-arthritically aligned knees when analyzed by location of the preoperative deformity (Table 7). Post hoc pairwise comparison demonstrated a smaller overall proportion of pre-arthritically aligned knees among knees with a combined deformity compared to knees without extra-articular deformity ($p$ =.002), isolated tibial deformity ($p$ <.001), or isolated femoral deformity ($p$ =.01). The magnitude of restoration of pre-arthritic coronal alignment was weakly correlated with preoperative TMA (correlation coefficient, 0.30, $p$ <.001; Fig. 4), and FMA (correlation coefficient, 0.26, $p$ <.001; Fig. 5).

## Discussion

The most important findings of this study were that phenotype analysis of 1000 knees with isolated anteromedial OA demonstrated a high diversity of functional knee phenotypes in a predominantly Caucasian study population. Preoperatively, 25 relevant functional knee phenotypes were identified. Following treatment with medial UKA, a reduction in diversity was observed, including 17 relevant postoperative functional knee phenotypes. Knees with combined tibial and femoral deformities were overall less frequently restored to their pre-arthritic coronal alignment following medial UKA.

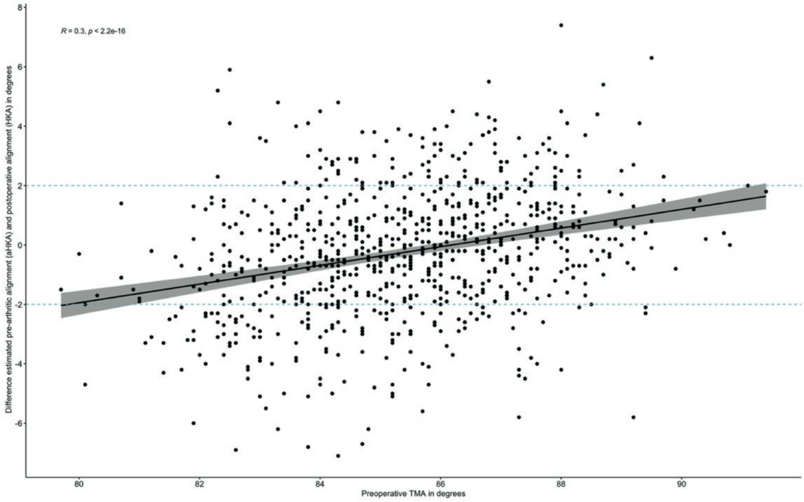


**Figure 4.** Relation between preoperative tibial mechanical angle (TMA) and the magnitude of restoration of pre-arthritic alignment (i.e., difference between arithmetic hip-knee-ankle angle [aHKA] and postoperative mechanical alignment [HKA]) following medial unicompartmental knee arthroplasty (correlation coefficient 0.30, $R^2$ 0.09; $p$ <.001). The dashed blue lines represent the boundaries of restoration of postoperative HKA within ±2.0° of pre-arthritic alignment.

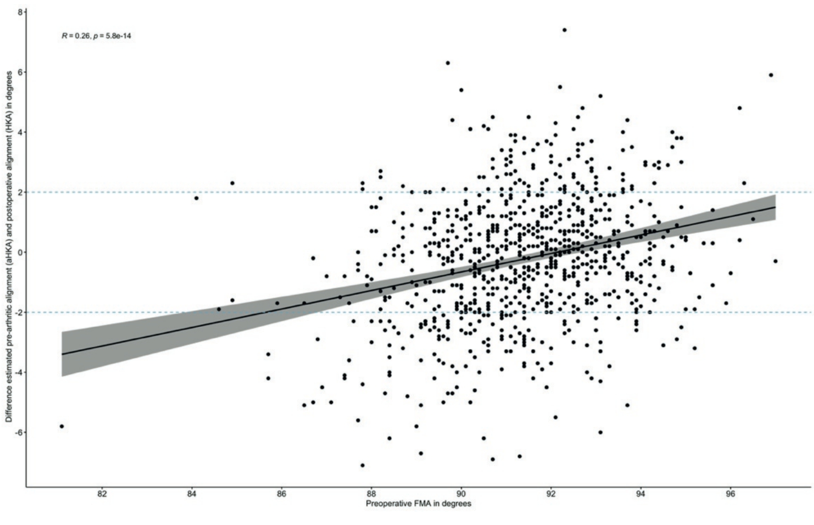


**Figure 5.** Relation between preoperative femoral mechanical angle (FMA) and the magnitude of restoration of pre-arthritic alignment (i.e., difference between arithmetic hip-knee-ankle angle [aHKA] and postoperative mechanical alignment [HKA]) following medial unicompartmental knee arthroplasty (correlation coefficient 0.26, $R^2$ 0.07; $p$ <.001). The dashed blue lines represent the boundaries of restoration of postoperative HKA within ±2.0° of estimated pre-arthritic alignment.

**Table 5.** Distribution of location of the deformity in varus limb phenotypes.

| Location of deformity | Definition | **Total** (*n* =952) n (%) | **$VAR_{HKA}3^{o}$** (*n* = 188) | **$VAR_{HKA}6^{o}$** (*n* =338) | **$VAR_{HKA}9^{o}$** (*n* =275) | **$VAR_{HKA}12^{o}$** (*n* =125) | **$VAR_{HKA}15^{o}$** (*n* =26) |
|---|---|---|---|---|---|---|---|
| No extra-art. deformity | $NEU_{FMA}$ - $NEU_{TMA}$ | **213 (22.3)** | **91 (48.4)** | **93 (27.5)** | **29 (10.5)** | **-** | **-** |
| Tibial deformity | $NEU_{FMA}$ -$VAR_{TMA}$ | 199 (20.9) | 16 (8.5) | 65 (19.2) | 88 (32.0) | 26 (20.8) | 4 (15.4) |
| | $NEU_{FMA}$ -$VAL_{TMA}$ | 30 (3.1) | 19 (10.1) | 11 (3.3) | - | - | - |
| | **Total** | **229 (24.0)** | **35 (18.6)** | **76 (22.5)** | **88 (32.0)** | **26 (20.8)** | **4 (15.4)** |
| Femoral deformity | $VAR_{FMA}$ - $NEU_{TMA}$ | 206 (21.6) | 11 (5.9) | 99 (29.3) | 72 (26.2) | 22 (17.6) | 2 (7.7) |
| | $VAL_{FMA}$ - $NEU_{TMA}$ | 27 (2.8) | 17 (9.0) | 9 (2.7) | 1 (0.4) | - | - |
| | **Total** | **233 (24.4)** | **28 (14.9)** | **108 (32.0)** | **73 (26.5)** | **22 (17.6)** | **2 (7.7)** |
| Combined deformity | $VAR_{FMA}$ -$VAR_{TMA}$ | 174 (8.2) | - | 19 (5.6) | 64 (23.3) | 71 (56.8) | 20 (76.9) |
| | $VAR_{FMA}$ - $VAL_{TMA}$ | 58 (6.1) | 19 (10.1) | 23 (6.8) | 12 (4.4) | 4 (3.2) | - |
| | $VAL_{FMA}$ - $VAL_{TMA}$ | 5 (0.5) | 5 (2.7) | - | - | - | - |
| | $VAL_{FMA}$ - $VAR_{TMA}$ | 40 (4.2) | 10 (5.3) | 19 (5.6) | 9 (3.3) | 2 (1.6) | - |
| | **Total** | **277 (29.0)** | **34 (18.1)** | **61 (18.0)** | **85 (30.9)** | **77 (61.6)** | **20 (76.9)** |

Distribution of location of the deformity in varus limb phenotypes is presented in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU,* neutral; *VAL*, valgus; *VAR*, varus.

**Table 6.1** Distribution of the location of the deformity in varus limb phenotypes by sex.

| Location of deformity | Definition | **Total** Male | **Total** Female | *p* value | **$VAR_{HKA}3°$** Male | **$VAR_{HKA}3°$** Female | *p* value | **$VAR_{HKA}6°$** Male | **$VAR_{HKA}6°$** Female | *p* value |
|---|---|---|---|---|---|---|---|---|---|---|
| No extra-art. deformity | $NEU_{FMA}$ - $NEU_{TMA}$ | **112 (21.2)** | **101 (23.9)** | .319 | **49 (58.3)** | **42 (40.0)** | .01* | **54 (29.3)** | **39 (25.3)** | .409 |
| Tibial deformity | $NEU_{FMA}$ -$VAR_{TMA}$ | 130 (24.6) | 69 (16.3) | | 7 (8.3) | 9 (8.7) | | 43 (23.4) | 22 (14.3) | |
| | $NEU_{FMA}$ -$VAL_{TMA}$ | 9 (1.7) | 21 (5.0) | | 6 (7.1) | 13 (12.5) | | 3 (1.6) | 8 (5.2) | |
| | **Total** | **139 (26.3)** | **90 (21.3)** | .073 | **13 (15.5)** | **22 (21.2)** | .320 | **46 (25.0)** | **30 (19.5)** | .226 |
| Femoral deformity | $VAR_{FMA}$ - $NEU_{TMA}$ | 108 (20.4) | 98 (23.2) | | 3 (3.6) | 8 (7.7) | | 53 (28.8) | 46 (29.9) | |
| | $VAL_{FMA}$ - $NEU_{TMA}$ | 7 (1.3) | 20 (4.7) | | 3 (3.6) | 14 (13.5) | | 4 (2.2) | 5 (3.2) | |
| | **Total** | **115 (21.7)** | **118 (27.9)** | .03* | **6 (7.1)** | **22 (21.2)** | .01* | **57 (31.0)** | **51 (33.1)** | .674 |
| Combined deformity | $VAR_{FMA}$ -$VAR_{TMA}$ | 113 (21.4) | 61 (14.4) | | - | - | | 9 (4.9) | 10 (6.5) | |
| | $VAR_{FMA}$ - $VAL_{TMA}$ | 24 (4.5) | 34 (8.0) | | 9 (10.7) | 10 (9.6) | | 7 (3.8) | 16 (10.4) | |
| | $VAL_{FMA}$ - $VAL_{TMA}$ | 2 (0.4) | 3 (0.7) | | 2 (2.4) | 3 (2.9) | | - | - | |
| | $VAL_{FMA}$ - $VAR_{TMA}$ | 24 (4.5) | 16 (3.8) | | 5 (6.0) | 5 (4.8) | | 11 (6.0) | 8 (5.2) | |
| | **Total** | **163 (30.8)** | **114 (27.0)** | .192 | **16 (19.0)** | **18 (17.3)** | .758 | **27 (14.7)** | **34 (22.1)** | .070 |

Distribution of the location of the deformity in varus limb phenotypes by sex is presented in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU,* neutral; *VAL*, valgus; *VAR*, varus. *n/a,* not applicable. *Indicates statistical significance.

**Table 6.2** Distribution of the location of the deformity in varus limb phenotypes by sex.

| | | **$VAR_{HKA}9º$** | | | **$VAR_{HKA}12º$** | | | **$VAR_{HKA}15º$** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location deformity | Definition | Male | Female | *p* value | Male | Female | *p* value | Male | Female | *p* value |
| No extra-art. deformity | $NEU_{FMA}$ - $NEU_{TMA}$ | **9 (5.6)** | **20 (17.7)** | .001* | **-** | **-** | *n/a* | **-** | **-** | *n/a* |
| Tibial deformity | $NEU_{FMA}$ -$VAR_{TMA}$ | 61 (37.7) | 27 (23.9) | | 16 (19.3) | 10 (23.8) | | 3 (18.8) | 1 (10.0) | |
| | $NEU_{FMA}$ -$VAL_{TMA}$ | - | - | | - | - | | - | - | |
| | **Total** | **61 (37.7)** | **27 (23.9)** | .02* | **16 (19.3)** | **10 (23.8)** | .555 | **3 (18.8)** | **1 (10.0)** | .667 |
| Femoral deformity | $VAR_{FMA}$ - $NEU_{TMA}$ | 38 (23.5) | 32 (30.1) | | 12 (14.5) | 10 (23.8) | | 2 (12.5) | - | |
| | $VAL_{FMA}$ - $NEU_{TMA}$ | - | 1 (0.9) | | - | - | | - | - | |
| | **Total** | **38 (23.5)** | **33 (31.0)** | .164 | **12 (14.5)** | **10 (23.8)** | .194 | **2 (12.5)** | **-** | *n/a* |
| Combined deformity | $VAR_{FMA}$ -$VAR_{TMA}$ | 42 (25.9) | 22 (19.5) | | 51 (61.4) | 20 (47.6) | | 11 (68.8) | 9 (90.0) | |
| | $VAR_{FMA}$ - $VAL_{TMA}$ | 6 (3.7) | 6 (5.3) | | 2 (2.4) | 2 (4.8) | | - | - | |
| | $VAL_{FMA}$ - $VAL_{TMA}$ | - | - | | - | - | | - | - | |
| | $VAL_{FMA}$ - $VAR_{TMA}$ | 6 (3.7) | 3 (2.7) | | 2 (2.4) | - | | - | - | |
| | **Total** | **54 (33.3)** | **31 (27.4)** | .297 | **55 (63.3)** | **22 (52.4)** | .131 | **11 (68.8)** | **9 (90.0)** | .211 |

Distribution of the location of the deformity in varus limb phenotypes by sex is presented in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU,* neutral; *VAL*, valgus; *VAR*, varus. *n/a,* not applicable.
*Indicates statistical significance.

**Table 7.** Probability of restoring pre-arthritic coronal alignment following medial unicompartmental knee arthroplasty based on location of the deformity.

| Location of Deformity | Definition | No. knees† | **Pre-arthritically aligned** | **Non-pre-arthritically aligned** | |
|---|---|---|---|---|---|
| | | | **Group 1** Within 2.0° of pre-arthritic coronal alignment n (%) | **Group 2** >2.0° overcorrected from the pre-arthritic coronal alignment n (%) | **Group 3** >2.0° under corrected from the pre-arthritic coronal alignment n (%) |
| No extra-art. deformity | $NEU_{FMA}$ - $NEU_{TMA}$ | **172** | **128 (74.4)** | **5 (2.9)** | **39 (22.7)** |
| Tibial deformity | $NEU_{FMA}$ -$VAR_{TMA}$ | 199 | 149 (74.9) | 27 (13.6) | 23 (11.6) |
| | $NEU_{FMA}$ -$VAL_{TMA}$ | 0 | - | - | - |
| | **Total** | **199** | **149 (74.9)** | **27 (13.6)** | **23 (11.6)** |
| Femoral deformity | $VAR_{FMA}$ - $NEU_{TMA}$ | 209 | 148 (70.8) | 34 (16.3) | 27 (12.9) |
| | $VAL_{FMA}$ - $NEU_{TMA}$ | 0 | - | - | - |
| | **Total** | **209** | **148 (70.8)** | **34 (16.3)** | **27 (12.9)** |
| Combined deformity | $VAR_{FMA}$ -$VAR_{TMA}$ | 176 | 94 (53.4) | 75 (42.6) | 7 (4.0) |
| | $VAR_{FMA}$ - $VAL_{TMA}$ | 46 | 36 (78.2) | 3 (6.5) | 7 (15.2) |
| | $VAL_{FMA}$ - $VAL_{TMA}$ | 0 | - | - | - |
| | $VAL_{FMA}$ - $VAR_{TMA}$ | 39 | 26 (66.7) | 4 (10.3) | 9 (23.1) |
| | **Total** | **261** | **156 (59.8)** | **82 (31.4)** | **23 (8.8)** |
| | *p* value § | | .001* | | |

The probability of restoring pre-arthritic coronal alignment is given for the five most prevalent preoperative functional knee phenotypes. The distribution is presented in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU,* neutral; *VAL*, valgus; *VAR*, varus.

† A total of 159 knees with an estimated pre-arthritic coronal alignment were excluded from this analysis.

§ Comparison of overall proportions of knees restored to their pre-arthritic coronal alignment (within ±2.0°) by location of the deformity (total numbers in bold).

* Indicates statistical significance.

Up until recently, there was a lack of literature evaluating the diversity of coronal phenotypes in knees with anteromedial OA[8]. The current study demonstrated a wide variation of functional knee phenotypes among knees with this type of OA, identifying 76 distinct phenotypes in total, as opposed to 43 different phenotypes previously observed in a non-OA population[6]. The most common phenotype represented only 9.4% of all knees, and the five most prevalent phenotypes comprised 41.6% of all included knees. The range of functional knee phenotypes, as well as the variety of knee phenotypes within each limb phenotype group (Fig. 3A), further underline the level of phenotypic heterogeneity that can exists among knees with anteromedial OA, even among those with a similar mechanical axis.

While the clinical relevance of this multitude of phenotypes remains to be further explored, one can argue that certain phenotypes may be less suitable for UKA treatment, or, may require a different alignment strategy in order to achieve favorable outcomes. It has recently been demonstrated that restoration of pre-arthritic alignment during medial UKA may lead to improved outcomes[13, 14]. The current study showed similar rates of knees restored to their pre-arthritic coronal alignment among the most prevalent functional knee phenotypes. However, knees with combined femoral and tibial deformities were overall less frequently restored to their pre-arthritic coronal alignment, compared to knees without deformity, or isolated femoral or tibial deformity. This finding is consistent with the weak correlation between pre-arthritic alignment restoration and the magnitude of preoperative TMA and FMA, suggesting that TMA or FMA outliers alone do not necessarily influence restoration of pre-arthritic coronal alignment. Hence, a better understanding of phenotypic variability of anteromedial OA may aid to optimize candidate selection and alignment strategies, but further research into the correlation between phenotypes and postoperative performance is warranted to elucidate which alignment technique is best suited for which phenotype.

Consistent with the current observations, previous literature has reported a wide variability of phenotypes among healthy and OA-affected knees[6, 8, 11, 12]. To our knowledge, one other study[8] has described functional knee phenotypes of medial OA. Huan *et al*[8] identified a large variation of functional knee phenotypes in a Japanese population, which appeared to be greater compared to the present study.

Their five most common functional knee phenotypes represented 21.8% of all 879 knees, as opposed to 41.6% in the current study. Phenotypic differences seemed mainly characterized by more severe varus limb phenotypes (range, $NEU_{HKA}0°$ to $VAR_{HKA}24°$), and larger proportions of knees with a varus femur (56.8% vs. 44.6% in the present study), and varus tibia (76.0% vs. 41.5% in the present study), implicating a higher prevalence of extra-articular deformities in the Japanese population with anteromedial OA[8]. Additionally, the unequal sex distribution in their cohort[8], (80% females) may have further contributed to differences compared to the current study. In line with these observations, a recent systematic review reported a wide geographic variation in coronal knee phenotypes of healthy and arthritic knees[20]. These findings further emphasize the importance of considering ethnic differences in understanding knee phenotypic variation at the population level.

To that end, this study also examined phenotypic variation by sex. Despite differences in mean values of radiographic parameters, the distribution of functional knee phenotypes was similar between sexes. Nevertheless, the five most prevalent phenotypes covered a lower proportion of the female population (37.9% of knees) compared to the male population (44.6% of knees), suggesting a higher degree of phenotypic variation among female knees. Furthermore, there was a higher prevalence of isolated femoral deformities among females compared males. Although the present study did not assess the clinical impact of sex-related phenotype differences, it has previously been suggested that anatomical variations may contribute to divergent outcomes between males and females following medial UKA, and these may therefore be important to consider[21-26].

This study recognizes several limitations. First, the study and phenotype system did not address sagittal plane alignment, which may be a major variable in the overall alignment of the individual knee. Second, radiographic evaluation was performed using weight-bearing AP radiographs, and any pre- or postoperative flexion deficits may have influenced our observations. However, weight-bearing radiographs may more accurately reflect the patient's functional position compared to evaluation in supine position. Third, the study population consisted primarily of Caucasian patients and results may therefore not be generalizable to other ethnic groups. Fourth, estimation of pre-arthritic coronal alignment was based on a methodology with limitations of its own[18] and may deviate from the actual pre-disease alignment. Fifth, associations between functional knee phenotypes and clinical outcomes were not assessed, leaving the clinical relevance of functional knee phenotypes and implications for UKA candidacy yet to be further established. Nonetheless, data of this study, which delineates the phenotypic variation among knees with a specific form of OA using a combination of coronal alignment parameters, may provide a first step towards a more personalized approach in knee arthroplasty.

**Conclusion**

Phenotype analysis using the functional knee phenotype system demonstrated a wide diversity of coronal alignment phenotypes among knees with anteromedial OA in a predominantly Caucasian population. Following treatment with medial UKA, a reduction from 25 preoperative to 17 relevant postoperative phenotypes was observed. Consideration of phenotypic variation can be of importance when aiming to restore pre-arthritic coronal alignment during medial UKA.

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**Appendix 1.1** Functional knee phenotypes of 1000 knees with medial compartment osteoarthritis, preoperatively and following medial unicompartmental knee arthroplasty.

**Preoperatively**

| Functional knee phenotype | Total $n$ = 1000 | Male $n$ = 549 | Female $n$ = 451 |
|---|---|---|---|
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 94 (9.4%) | 51 (9.3%) | 43 (9.5%) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 93 (9.3%) | 54 (9.8%) | 39 (8.6%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 91 (9.1%) | 49 (8.9%) | 42 (9.3%) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 74 (7.4%) | 49 (8.9%) | 25 (5.5%) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 64 (6.4%) | 42 (7.7%) | 22 (4.9%) |
| $VAR_{HKA}9°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 63 (6.3%) | 34 (6.2%) | 29 (6.4%) |
| $VAR_{HKA}9°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 58 (5.8%) | 39 (7.1%) | 19 (4.2%) |
| $VAR_{HKA}12°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 46 (4.6%) | 31 (5.6%) | 15 (3.3%) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 29 (2.9%) | 9 (1.6%) | 20 (4.4%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 19 (1.9%) | 6 (1.1%) | 13 (2.9%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 19 (1.9%) | 6 (1.1%) | 13 (2.9%) |
| $VAR_{HKA}3°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 17 (1.7%) | 8 (1.5%) | 9 (2.0%) |
| $VAR_{HKA}3°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 17 (1.7%) | 3 (0.5%) | 14 (3.1%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 17 (1.7%) | 9 (1.6%) | 8 (1.8%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 16 (1.6%) | 8 (1.5%) | 8 (1.8%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 15 (1.5%) | 7 (1.3%) | 8 (1.8%) |
| $VAR_{HKA}12°$ $VAR_{FMA}6°$ $VAR_{TMA}3°$ | 15 (1.5%) | 10 (1.8%) | 5 (1.1%) |
| $VAR_{HKA}12°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 15 (1.5%) | 8 (1.5%) | 7 (1.6%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 14 (1.4%) | 6 (1.1%) | 8 (1.8%) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $VAR_{TMA}6°$ | 14 (1.4%) | 12 (2.2%) | 2 (0.4%) |
| $VAR_{HKA}12°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 14 (1.4%) | 8 (1.5%) | 6 (1.3%) |
| $VAR_{HKA}12°$ $NEU_{FMA}0°$ $VAR_{TMA}6°$ | 12 (1.2%) | 8 (1.5%) | 4 (0.9%) |
| $VAR_{HKA}15°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 12 (1.2%) | 6 (1.1%) | 6 (1.3%) |
| $VAR_{HKA}3°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 11 (1.1%) | 3 (0.5%) | 8 (1.8%) |
| $VAR_{HKA}12°$ $VAR_{FMA}3°$ $VAR_{TMA}6°$ | 10 (1.0%) | 10 (1.8%) | 0 (0.0%) |
| $VAR_{HKA}3°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 9 (0.9%) | 5 (0.9%) | 4 (0.9%) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 9 (0.9%) | 3 (0.5%) | 6 (1.3%) |
| $VAR_{HKA}6°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 9 (0.9%) | 4 (0.7%) | 5 (1.1%) |
| $VAR_{HKA}9°$ $VAR_{FMA}6°$ $NEU_{TMA}0°$ | 9 (0.9%) | 4 (0.7%) | 5 (1.1%) |
| $NEU_{HKA}0°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 8 (0.8%) | 4 (0.7%) | 4 (0.9%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 7 (0.7%) | 3 (0.5%) | 4 (0.9%) |
| $VAR_{HKA}9°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 6 (0.6%) | 2 (0.4%) | 4 (0.9%) |

| **Preoperatively** | | | |
|---|---|---|---|
| Functional knee phenotype | Total | Male | Female |
| $VAR_{HKA}$12° $VAR_{FMA}$6° $NEU_{TMA}$0° | 6 (0.6%) | 4 (0.7%) | 2 (0.4%) |
| $VAR_{HKA}$6° $VAR_{FMA}$6° $NEU_{TMA}$0° | 5 (0.5%) | 2 (0.4%) | 3 (0.7%) |
| $VAR_{HKA}$9° $VAL_{FMA}$3° $VAR_{TMA}$3° | 5 (0.5%) | 3 (0.5%) | 2 (0.4%) |
| $VAR_{HKA}$3° $VAL_{FMA}$3° $VAL_{TMA}$3° | 4 (0.4%) | 2 (0.4%) | 2 (0.4%) |
| $VAR_{HKA}$9° $VAR_{FMA}$6° $VAR_{TMA}$3° | 4 (0.4%) | 1 (0.2%) | 3 (0.7%) |
| $VAR_{HKA}$9° $VAR_{FMA}$6° $VAL_{TMA}$3° | 4 (0.4%) | 4 (0.7%) | 0 (0.0%) |
| $VAR_{HKA}$9° $VAL_{FMA}$3° $VAR_{TMA}$6° | 4 (0.4%) | 3 (0.5%) | 1 (0.2%) |
| $VAR_{HKA}$15° $NEU_{FMA}$0° $VAR_{TMA}$6° | 4 (0.4%) | 3 (0.5%) | 1 (0.2%) |
| $VAL_{HKA}$3° $NEU_{FMA}$0° $VAL_{TMA}$3° | 4 (0.4%) | 0 (0.0%) | 4 (0.9%) |
| $NEU_{HKA}$0° $VAR_{FMA}$3° $NEU_{TMA}$0° | 3 (0.3%) | 2 (0.4%) | 1 (0.2%) |
| $NEU_{HKA}$0° $VAL_{FMA}$3° $VAL_{TMA}$3° | 3 (0.3%) | 2 (0.4%) | 1 (0.2%) |
| $VAR_{HKA}$6° $VAR_{FMA}$6° $VAL_{TMA}$3° | 3 (0.3%) | 0 (0.0%) | 3 (0.7%) |
| $VAR_{HKA}$6° $VAL_{FMA}$3° $VAR_{TMA}$6° | 3 (0.3%) | 3 (0.5%) | 0 (0.0%) |
| $VAR_{HKA}$15° $VAR_{FMA}$3° $VAR_{TMA}$6° | 3 (0.3%) | 2 (0.4%) | 1 (0.2%) |
| $NEU_{HKA}$0° $VAR_{FMA}$3° $VAL_{TMA}$3° | 2 (0.2%) | 0 (0.0%) | 2 (0.4%) |
| $VAR_{HKA}$6° $VAR_{FMA}$6° $VAR_{TMA}$3° | 2 (0.2%) | 0 (0.0%) | 2 (0.4%) |
| $VAR_{HKA}$6° $NEU_{FMA}$0° $VAL_{TMA}$6° | 2 (0.2%) | 0 (0.0%) | 2 (0.4%) |
| $VAR_{HKA}$9° $VAR_{FMA}$3° $VAR_{TMA}$6° | 2 (0.2%) | 2 (0.4%) | 0 (0.0%) |
| $VAR_{HKA}$12° $VAR_{FMA}$3° $VAL_{TMA}$3° | 2 (0.2%) | 0 (0.0%) | 2 (0.4%) |
| $VAR_{HKA}$12° $VAL_{FMA}$3° $VAR_{TMA}$6° | 2 (0.2%) | 2 (0.4%) | 0 (0.0%) |
| $VAR_{HKA}$15° $VAR_{FMA}$6° $VAR_{TMA}$6° | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) |
| $VAR_{HKA}$15° $VAR_{FMA}$6° $VAR_{TMA}$3° | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) |
| $VAR_{HKA}$18° $VAR_{FMA}$3° $VAR_{TMA}$3° | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) |
| $NEU_{HKA}$0° $NEU_{FMA}$0° $VAL_{TMA}$6° | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $NEU_{HKA}$0° $VAL_{FMA}$6° $NEU_{TMA}$0° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$3° $VAR_{FMA}$6° $VAL_{TMA}$3° | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}$3° $VAR_{FMA}$6° $VAL_{TMA}$6° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$3° $NEU_{FMA}$0° $VAR_{TMA}$6° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$3° $VAL_{FMA}$3° $VAR_{TMA}$6° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$3° $VAL_{FMA}$3° $VAL_{TMA}$6° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$6° $VAR_{FMA}$3° $VAL_{TMA}$6° | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}$6° $NEU_{FMA}$0° $VAR_{TMA}$6° | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}$9° $VAR_{FMA}$9° $VAL_{TMA}$3° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$9° $VAR_{FMA}$3° $VAL_{TMA}$6° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$9° $Val_{FMA}$3° $NEU_{TMA}$0° | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}$12° $Var_{FMA}$12° $VAL_{TMA}$3° | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |

| **Preoperatively** | | | |
|---|---|---|---|
| Functional knee phenotype | Total | Male | Female |
| $VAR_{HKA}12^{o}$ $Var_{FMA}9^{o}$ $NEU_{TMA}0^{o}$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}12^{o}$ $Var_{FMA}9^{o}$ $VAL_{TMA}3^{o}$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}15^{o}$ $Var_{FMA}9^{o}$ $VAR_{TMA}3^{o}$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}15^{o}$ $Var_{FMA}6^{o}$ $NEU_{TMA}0^{o}$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}15^{o}$ $Var_{FMA}3^{o}$ $NEU_{TMA}0^{o}$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAL_{HKA}3^{o}$ $Var_{FMA}3^{o}$ $VAL_{TMA}6^{o}$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAL_{HKA}3^{o}$ $Neu_{FMA}0^{o}$ $VAL_{TMA}6^{o}$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAL_{HKA}3^{o}$ $Val_{FMA}6^{o}$ $NEU_{TMA}0^{o}$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |

Functional phenotypes of knees with medial compartment osteoarthritis, prior to, and following medial unicompartmental knee arthroplasty. The incidence of each functional knee phenotype is given in numbers and frequencies, for the whole cohort and by gender.

**Appendix 1.2** Functional knee phenotypes of 1000 knees with medial compartment osteoarthritis, preoperatively and following medial unicompartmental knee arthroplasty.

**Following medial UKA**

| Functional knee phenotype | Total *n* = 100 | Male *n* = 549 | Female *n* = 451 |
|---|---|---|---|
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 183 (18.3%) | 97 (17.7%) | 86 (19.1%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 98 (9.8%) | 60 (10.9%) | 38 (8.4%) |
| $NEU_{HKA}0°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 69 (6.9%) | 387(6.7%) | 32 (7.1%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 68 (6.8%) | 42 (7.7%) | 26 (5.8%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 58 (5.8%) | 24 (4.4%) | 34 (7.5%) |
| $VAR_{HKA}3°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 58 (5.8%) | 32 (5.8%) | 26 (5.8%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 46 (4.6%) | 26 (4.7%) | 20 (4.4%) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 46 (4.6%) | 32 (5.8%) | 14 (3.1%) |
| $VAR_{HKA}3°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 44 (4.4%) | 34 (6.2%) | 10 (2.2%) |
| $VAR_{HKA}3°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 36 (3.6%) | 15 (2.7%) | 21 (4.7%) |
| $VAR_{HKA}3°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 34 (3.4%) | 15 (2.7%) | 19 (4.2%) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 31 (3.1%) | 16 (2.9%) | 15 (3.3%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 28 (2.8%) | 12 (2.2%) | 16 (3.5%) |
| $NEU_{HKA}0°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 27 (2.7%) | 7 (1.3%) | 20 (4.4%) |
| $NEU_{HKA}0°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 23 (2.3%) | 17 (3.1%) | 6 (1.3%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 14 (1.4%) | 12 (2.2%) | 2 (0.4%) |
| $VAL_{HKA}3°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 11 (1.1%) | 3 (0.5%) | 8 (1.8%) |
| $NEU_{HKA}0°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 9 (0.9%) | 4 (0.7%) | 5 (1.1%) |
| $VAR_{HKA}6°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 9 (0.9%) | 6 (1.1%) | 3 (0.7%) |
| $VAL_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 9 (0.9%) | 4 (0.7%) | 5 (1.1%) |
| $NEU_{HKA}0°$ $VAL_{FMA}6°$ $VAR_{TMA}3°$ | 8 (0.8%) | 5 (0.9%) | 3 (0.7%) |
| $VAR_{HKA}9°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 7 (0.7%) | 7 (1.3%) | 0 (0.0%) |
| $NEU_{HKA}0°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 6 (0.6%) | 1 (0.2%) | 5 (1.1%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 6 (0.6%) | 2 (0.4%) | 4 (0.9%) |
| $NEU_{HKA}0°$ $VAR_{FMA}3°$ $VAL_{TMA}6°$ | 5 (0.5%) | 1 (0.2%) | 4 (0.9%) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 5 (0.5%) | 4 (0.7%) | 1 (0.2%) |
| $VAL_{HKA}3°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 5 (0.5%) | 1 (0.2%) | 4 (0.9%) |
| $VAR_{HKA}3°$ $VAR_{FMA}6°$ $VAL_{TMA}3°$ | 4 (0.4%) | 3 (0.5%) | 1 (0.2%) |
| $VAR_{HKA}3°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 4 (0.4%) | 2 (0.4%) | 2 (0.4%) |
| $VAR_{HKA}6°$ $VAR_{FMA}6°$ $NEU_{TMA}0°$ | 4 (0.4%) | 0 (0.0%) | 4 (0.9%) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 4 (0.4%) | 3 (0.5%) | 1 (0.2%) |
| $VAR_{HKA}3°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 3 (0.3%) | 0 (0.0%) | 3 (0.7%) |

| **Following medial UKA** | | | |
|---|---|---|---|
| Functional knee phenotype | Total | Male | Female |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAR_{TMA}6°$ | 3 (0.3%) | 3 (0.5%) | 0 (0.0%) |
| $VAR_{HKA}9°$ $VAR_{FMA}6°$ $NEU_{TMA}0°$ | 3 (0.3%) | 2 (0.4%) | 1 (0.2%) |
| $VAL_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 3 (0.3%) | 2 (0.4%) | 1 (0.2%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 2 (0.2%) | 0 (0.0%) | 2 (0.4%) |
| $VAR_{HKA}3°$ $VAL_{FMA}3°$ $VAR_{TMA}6°$ | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) |
| $VAR_{HKA}3°$ $VAL_{FMA}6°$ $VAR_{TMA}6°$ | 2 (0.2%) | 2 (0.4%) | 0 (0.0%) |
| $VAR_{HKA}6°$ $VAR_{FMA}6°$ $VAL_{TMA}3°$ | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) |
| $VAR_{HKA}9°$ $VAR_{FMA}6°$ $VAR_{TMA}3°$ | 2 (0.2%) | 1 (0.2%) | 1 (0.2%) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $VAR_{TMA}6°$ | 2 (0.2%) | 2 (0.4%) | 0 (0.0%) |
| $NEU_{HKA}0°$ $VAR_{FMA}6°$ $NEU_{TMA}0°$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $NEU_{HKA}0°$ $VAR_{FMA}6°$ $VAL_{TMA}6°$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $NEU_{HKA}0°$ $VAL_{FMA}6°$ $NEU_{TMA}0°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}3°$ $VAR_{FMA}6°$ $NEU_{TMA}0°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAR_{TMA}6°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}3°$ $VAL_{FMA}6°$ $VAR_{TMA}3°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}3°$ $VAL_{FMA}6°$ $VAL_{TMA}3°$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}6°$ $VAR_{FMA}9°$ $VAR_{TMA}3°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAR_{TMA}6°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAR_{HKA}6°$ $VAL_{FMA}3°$ $VAR_{TMA}6°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}6°$ $VAL_{FMA}6°$ $VAR_{TMA}6°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}9°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 1 (0.1%) | 0 (0.0%) | 1 (0.2%) |
| $VAL_{HKA}3°$ $VAR_{FMA}3°$ $VAL_{TMA}6°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |
| $VAL_{HKA}3°$ $VAL_{FMA}6°$ $NEU_{TMA}0°$ | 1 (0.1%) | 1 (0.2%) | 0 (0.0%) |

Functional phenotypes of knees with medial compartment osteoarthritis, prior to, and following medial unicompartmental knee arthroplasty. The incidence of each functional knee phenotype is given in numbers and frequencies, for the whole cohort and by gender.

**Appendix 2.1** Distribution of deformity location of varus limb phenotypes by age.

| Location deformity | Definition | **Total** n (%) | **$VAR_{HKA}3^{o}$** | **$VAR_{HKA}6^{o}$** | **$VAR_{HKA}9^{o}$** | **$VAR_{HKA}12^{o}$** | **$VAR_{HKA}15^{o}$** |
|---|---|---|---|---|---|---|---|
| **Age < 50 years** | | (*n* =56) | (*n* =14) | (*n* =17) | (*n* =16) | (*n* =8) | (*n* =1) |
| No extra-art. deformity | Neutral FMA - Neutral TMA | **11 (19.6)** | **5 (35.7)** | **4 (23.5)** | **2 (12.5)** | **-** | **-** |
| Tibial deformity | Neutral FMA -Varus TMA | 11 (19.6) | 2 (14.3) | 5 (29.4) | 2 (12.5) | 2 (12.5) | - |
| | Neutral FMA -Valgus TMA | 2 (3.6) | 2 (14.3) | - | - | - | - |
| | **Total** | **13 (23.2)** | **4 (28.6)** | **5 (29.4)** | **2 (12.5)** | **2 (12.5)** | **-** |
| Femoral deformity | Varus FMA - Neutral TMA | 11 (19.6) | 2 (14.3) | 4 (23.5) | 4 (25.0) | 1 (12.5) | - |
| | Valgus FMA - Neutral TMA | 3 (5.4) | 2 (14.3) | 1 (5.9) | - | - | - |
| | **Total** | **14 (25.0)** | **4 (28.6)** | **5 (29.4)** | **4 (25.0)** | **1 (12.5)** | **-** |
| Combined deformity | Varus FMA -Varus TMA | 13 (23.2) | - | 1 (5.9) | 6 (37.5) | 5 (62.5) | 1 (100.0) |
| | Varus FMA - Valgus TMA | 4 (7.1) | 1 (7.1) | 1 (5.9) | 2 (12.5) | - | - |
| | Valgus FMA - Valgus TMA | - | - | - | - | - | - |
| | Valgus FMA - Varus TMA | 1 (1.8) | - | 1 (5.9) | - | - | - |
| | **Total** | **18 (32.1)** | **1 (7.1)** | **3 (17.6)** | **8 (50.0)** | **5 (62.5)** | **1 (100.0)** |

Distribution of location of the deformity for varus limb phenotypes is presented by age in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *VAR*, varus.

**Appendix 2.2** Distribution of deformity location of varus limb phenotypes by age

| Location deformity | Definition | **Total** n (%) | **$VAR_{HKA}3^o$** | **$VAR_{HKA}6^o$** | **$VAR_{HKA}9^o$** | **$VAR_{HKA}12^o$** | **$VAR_{HKA}15^o$** |
|---|---|---|---|---|---|---|---|
| **Age 50 – 70 years** | | (*n* =684) | (*n* =131) | (*n* =243) | (*n* =202) | (*n* =90) | (*n* =18) |
| No extra-art. deformity | Neutral FMA - Neutral TMA | **159 (23.2)** | **67 (51.1)** | **72 (29.6)** | **20 (9.9)** | **-** | **-** |
| Tibial deformity | Neutral FMA -Varus TMA | 142 (20.8) | 12 (9.2) | 44 (18.1) | 66 (32.7) | 17 (18.9) | 3 (16.7) |
| | Neutral FMA -Valgus TMA | 20 (2.9) | 11 (8.4) | 9 (3.7) | - | - | - |
| | **Total** | **162 (23.7)** | **23 (17.6)** | **53 (21.8)** | **66 (32.7)** | **17 (18.9)** | **3 (16.7)** |
| Femoral deformity | Varus FMA - Neutral TMA | 152 (22.2) | 8 (6.1) | 73 (30.0) | 52 (25.7) | 18 (20.0) | 1 (5.6) |
| | Valgus FMA - Neutral TMA | 15 (2.2) | 10 (7.6) | 4 (1.6) | 1 (0.5) | - | - |
| | **Total** | **167 (24.4)** | **18 (13.7)** | **77 (31.6)** | **53 (26.2)** | **18 (20.0)** | **1 (5.6)** |
| Combined deformity | Varus FMA -Varus TMA | 127 (18.6) | - | 11 (4.5) | 48 (23.8) | 53 (58.9) | 14 (77.8) |
| | Varus FMA - Valgus TMA | 41 (6.0) | 13 (9.9) | 18 (7.4) | 8 (4.0) | 2 (2.2) | - |
| | Valgus FMA - Valgus TMA | 4 (0.6) | 4 (3.1) | - | - | - | - |
| | Valgus FMA - Varus TMA | 25 (3.7) | 6 (4.6) | 12 (4.9) | 7 (3.5) | - | - |
| | **Total** | **196 (28.7)** | **23 (17.6)** | **41 (16.9)** | **63 (31.2)** | **55 (61.1)** | **14 (77.8)** |

Distribution of location of the deformity for varus limb phenotypes is presented by age in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *VAR*, varus.

**Appendix 2.3** Distribution of deformity location of varus limb phenotypes by age

| Location deformity | Definition | **Total** n (%) | **VAR$_{HKA}$3º** | **VAR$_{HKA}$6º** | **VAR$_{HKA}$9º** | **VAR$_{HKA}$12º** | **VAR$_{HKA}$15º** |
|---|---|---|---|---|---|---|---|
| **Age >70 years** | | (*n* =212) | (*n* =43) | (*n* =78) | (*n* =57) | (*n* =27) | (*n* =7) |
| No extra-art. deformity | Neutral FMA - Neutral TMA | **43 (20.3)** | **19 (44.2)** | **17 (21.8)** | **7 (12.3)** | **-** | **-** |
| Tibial deformity | Neutral FMA -Varus TMA | 47 (22.2) | 3 (7.0) | 16 (20.5) | 20 (35.1) | 7 (25.9) | 1 (14.3) |
| | Neutral FMA -Valgus TMA | 7 (3.3) | 5 (11.6) | 2 (2.6) | - | - | - |
| | **Total** | **54 (25.5)** | **8 (18.6)** | **18 (23.1)** | **20 (35.1)** | **7 (25.9)** | **1 (14.3)** |
| Femoral deformity | Varus FMA - Neutral TMA | 43 (20.3) | 1 (2.3) | 22 (28.2) | 16 (28.1) | 3 (11.1) | 1 (14.3) |
| | Valgus FMA - Neutral TMA | 9 (4.2) | 5 (11.6) | 4 (5.1) | - | - | - |
| | **Total** | **52 (24.5)** | **6 (14.0)** | **26 (33.3)** | **16 (28.1)** | **3 (11.1)** | **1 (14.3)** |
| Combined deformity | Varus FMA -Varus TMA | 36 (17.0) | - | 7 (9.0) | 10 (17.5) | 13 (48.1) | 5 (71.4) |
| | Varus FMA - Valgus TMA | 13 (6.1) | 5 (11.6) | 4 (5.1) | 2 (3.5) | 2 (7.4) | - |
| | Valgus FMA - Valgus TMA | 1 (0.5) | 1 (2.3) | - | - | - | - |
| | Valgus FMA - Varus TMA | 14 (6.6) | 4 (9.3) | 6 (7.7) | 2 (3.5) | 2 (7.4) | - |
| | **Total** | **63 (29.7)** | **10 (23.3)** | **17 (24.6)** | **14 (24.6)** | **17 (63.0)** | **5 (71.4)** |

Distribution of location of the deformity for varus limb phenotypes is presented by age in numbers with the frequencies in parentheses. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *VAR*, varus.

**Appendix 3.** Probability of restoring pre-arthritic alignment following medial unicompartmental knee arthroplasty based on preoperative functional knee phenotypes

| | | Pre-arthritically aligned | Non-pre-arthritically aligned | |
|---|---|---|---|---|
| Preoperative functional knee phenotype | No. knees† | **Group 1** Within 2.0° of pre-arthritic alignment n (%) | **Group 2** >2.0° overcorrected from the pre-arthritic alignment n (%) | **Group 3** >2.0° under corrected from the pre-arthritic alignment n (%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 94 | 67 (71.3) | 15 (16.0) | 12 (12.8) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 81 | 59 (72.8) | 2 (2.5) | 20 (24.7) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 63 | 53 (84.1) | 2 (3.2) | 8 (12.7) |
| $VAR_{HKA}9°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 74 | 53 (71.6) | 9 (12.2) | 12 (16.2) |
| $VAR_{HKA}6°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 64 | 51 (79.7) | 7 (10.9) | 6 (9.4) |
| *p* value § | | .296 | | |

The probability of restoring pre-arthritic alignment is given for the five most prevalent preoperative functional knee phenotypes. *HKA*, hip-knee-ankle angle; *FMA*, femoral mechanical angle; *TMA*, tibial mechanical angle; *NEU*, neutral; *VAR*, varus.

† A total of 40 knees with an estimated pre-arthritic alignment in valgus were excluded from this analysis.

§ Comparison of proportions of knees restored to their pre-arthritic alignment (within ±2.0°) by preoperative functional knee phenotype.

# Chapter 9

# Knees with isolated lateral compartment osteoarthritis show a substantial variability in functional knee phenotypes with demographic-specific variations

phenotypic analysis of 305 knees

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The Knee

**Abstract**

**Purpose:** the primary aim of this study was to assess and describe the phenotypic variation in the coronal plane of knees affected by isolated lateral compartment osteoarthritis (OA). The secondary aim of this study was to investigate the potential gender-specific and age-related differences in functional knee phenotypes among knees with isolated lateral compartment OA.

**Methods:** a comprehensive classification system was used to categorize 305 knees with isolated lateral compartment OA based on their mechanical hip-knee-ankle angle (HKA), femoral mechanical angle (FMA), and tibial mechanical angle (TMA). The phenotypic variation of functional knee phenotypes was assessed for the entire cohort and stratified by gender and age.

**Results:** among knees with isolated lateral compartment OA, a total of 60 distinct functional knee phenotypes were identified, with phenotype $VAL_{HKA}6°NEU_{FMA}0°VAL_{TMA}3°$ being the most prevalent (10.8%). Gender-specific differences were evident, with females exhibiting significantly greater valgus alignment in both mean HKA and TMA values compared to males (HKA: -6.4 vs. -5.4, respectively; *p* = 0.02 and TMA 94.4 vs 89.0, respectively; *p* = .005). Age-related variations included younger patients predominantly displaying femoral deformities, while older patients primarily exhibited isolated tibial- or combined femoral and tibial deformities.

**Conclusion:** there is a broad variation of functional knee phenotypes among knees affected by isolated lateral compartment OA, with gender-specific and age-related differences. Recognizing this inherent phenotypic diversity during preoperative planning may facilitate the implementation of tailored approaches that account for the unique characteristics and bony deformities of the individual knee.

## Introduction

Over the last decade, there has been noteworthy academic interest in lower limb alignment and the distribution of knee phenotypes. Traditionally, lower limb alignment was assessed independently from the orientation of the knee joint line, which oversimplifies the anatomic variation in the coronal plane of the individual knee[1]. Consequently, recent studies have highlighted the significance of accounting for the femoral and tibial joint lines when classifying knees, reflecting a growing interest toward the implementation of more personalized alignment strategies[2-12]. This evolutionary shift has led to the introduction of a more comprehensive classification system based on functional knee phenotypes[9].

The current literature has highlighted substantial variations in alignment phenotypes within both the general and arthritic population, emphasizing that these distinctive phenotypes contribute to diverse patterns of articular degeneration and cartilage loss[2-5, 8, 9, 12-17]. However, there is a lack of studies specifically investigating the phenotypic expression in knees affected by isolated lateral compartment osteoarthritis (OA). Isolated lateral compartment OA is a relatively rare manifestation, affecting approximately 5-10% of individuals with knee OA, for which surgical treatment options include corrective osteotomies or knee arthroplasty[18, 19]. Despite its relative rarity, it remains crucial to acknowledge the substantial anatomical and biomechanical distinctions between the lateral and medial compartment of the knee, highlighting the necessity to conduct a separate evaluation of both compartments[20-22]. Enhancing our clinical understanding of the phenotypic expression among knees with isolated lateral compartment OA is essential for the effective personalization of alignment strategies and the accurate selection of appropriate surgical interventions.

Therefore, the aim of this study was to evaluate the distribution of distinct functional knee phenotypes among patients affected by isolated lateral compartment OA. Additionally, this study aimed to investigate potential gender-specific and age-related differences in functional knee phenotypes among patients with isolated lateral compartment OA. Building upon prior research, it was hypothesized that a significant diversity in functional knee phenotypes would be evident in knees with isolated lateral compartment OA, with both gender and age likely serving as influential factors.

## Methods

*Study design*

Following Institutional Review Board (IRB #2022-1401) approval, the senior author's (A.D.P) registry was retrospectively reviewed to identify patients with isolated lateral compartment OA who underwent lateral unicompartmental knee arthroplasty between January 2012 and July 2022. Patients were eligible for inclusion if they had complete preoperative long-leg radiographs and advanced isolated lateral compartment OA (i.e., Kellgren-Lawrence [KL] grade III-IV on anteroposterior- or Rosenberg view radiographs[23, 24], alongside localized pain confined solely to the lateral compartment). Patients were not eligible for inclusion if they had incomplete or poor-quality radiographic records, signs of OA in the medial compartment of the knee, a history of ipsilateral tibial- or femoral fractures, or prior ipsilateral knee-, hip, or ankle arthroplasty.

*Radiographic evaluation*

Prior to surgery, all patients underwent standard weight-bearing long-leg radiographs as part of routine preoperative evaluation. When obtaining these radiographs, patients were instructed to stand upright with their feet and patellae facing forward, knees fully extended and bearing weight on both legs to minimize for variation among radiographs[25]. Radiographic measurements were performed independently by two observers (G.V.t.N.d.B. and L.V.R.) blinded to postoperative outcomes, using a Picture Archiving and Communication System (PACS, Sectra, Imtec, AB, version 16, Linköping, Sweden); interclass correlation coefficients (ICC) ranged from 0.78 to 0.87 for all measurements.

The coronal alignment of the knee was assessed by measuring the mechanical hip-knee-ankle angle (HKA), lateral distal femoral angle (LDFA), and the medial proximal tibial angle (MPTA) (Fig. 1). The MPTA is equivalent to the tibial mechanical angle (TMA), and the LDFA was converted into the femoral mechanical angle (FMA) by subtracting it from 180 degrees (FMA = 180° - LDFA).

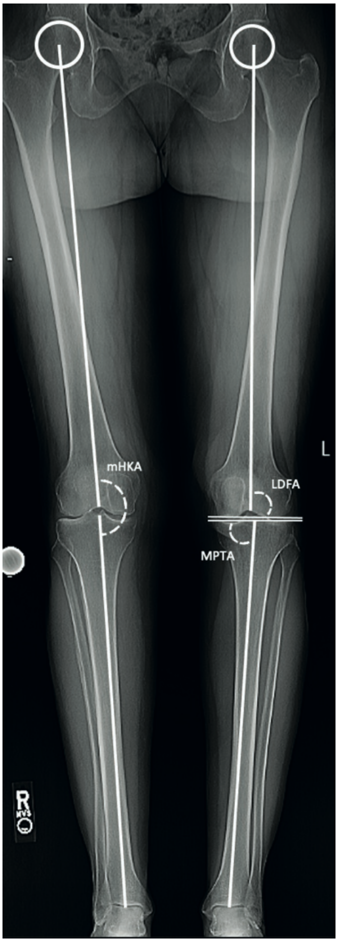


**Figure 1.** Long-leg standing anteroposterior (OA) radiograph. Measurement of the mechanical hip-knee-ankle angle (mHKA, the angle subtended by the mechanical axis of the femur and the mechanical axis of the tibia), medial proximal tibial angle (MPTA, the angle subtended by the mechanical axis of the tibia and the proximal tibial joint line) and the lateral distal femoral angle (LDFA, the lateral angle subtended by the mechanical axis of the femur and the distal femoral joint line).

*Functional knee phenotype classification*

Knees with isolated lateral compartment OA were categorized based on the functional knee phenotype system previously reported by Hirschmann *et al*[8, 9]. This system combines three parameters to classify knees into distinct functional knee phenotypes, including the limb phenotype (HKA) and femoral and tibial knee phenotypes (FMA and TMA, respectively). Each parameter has a range of 1.5° from its baseline, which is based on the average values of knees without OA (i.e., HKA: 0°; FMA: 93°; TMA: 87°)[9]. To classify a knee, the system first describes the alignment of the parameter (i.e., neutral, varus or valgus) and then adds the respective parameter in subscript (e.g., $NEU_{HKA}$). Finally, the mean deviation from the average for that parameter is given in increments of 3°, to establish the phenotype of each parameter (e.g., $NEU_{HKA}0°$, $VAL_{HKA}3°$, $VAL_{HKA}6°$). By combining the three different parameter phenotypes, knees can be categorized into various functional knee phenotypes (e.g., $NEU_{HKA}0°NEU_{FMA}0°NEU_{TMA}0°$). The functional knee phenotype classification system is presented in Table 1.

*Gender-specific and age-related differences*

The distribution of functional knee phenotypes was assessed for the entire cohort and stratified by gender and age. Gender is defined as the chromosomal or genetic sex assigned at birth. In order to assess age-related variances in functional knee phenotypes, knees were classified into three distinct age groups: patients < 50 years, patients between 50 to 70 years, and patients > 70 years.

*Statistical analyses*

All analyses were performed in R, version 2023.03.1+446 (R Foundation for Statistical Computing, Vienna, Austria), with a predefined significance level of 0.05. The prevalence of various functional knee phenotypes was assessed for the entire cohort and stratified by gender and age. Normality of continuous variables was evaluated using the Shapiro-Wilk test. To compare the means of continuous variables the *t*-test was employed. For comparison of the prevalence of distinct functional knee phenotypes, either the Chi-squared test or Fisher's exact test was performed. Post-hoc power calculations were conducted using nQuery version

8.5.1. (Statistical Solutions Ltd, Cork, Ireland). Considering the intrinsic relationship between observed power and the observed *p* values [26, 27], post-hoc power assessments were performed for all significant comparisons, resulting in an average observed power of 81%.

**Table 1.** Functional knee phenotype classification system

| Variable | Alignment | Phenotype | Range | Average value |
|---|---|---|---|---|
| **Limb phenotype** | Varus | $VAR_{HKA}6°$ | 4.5 to 7.5° | 6° |
| HKA | | $VAR_{HKA}3°$ | 1.5(6) to 4.5° | 3° |
| | Neutral | $NEU_{HKA}0°$ | -1.5 to 1.5 | 0° |
| | Valgus | $VAL_{HKA}3°$ | -1.5 to -4.5° | -3° |
| | | $VAL_{HKA}6°$ | -4.5 to -7.5° | -6° |
| | | $VAL_{HKA}9°$ | -7.5 to -10.5° | -9° |
| | | $VAL_{HKA}12°$ | -10.5 to -13.5° | -12° |
| | | $VAL_{HKA}15°$ | -13.5 to -16.5° | -15° |
| **Femoral phenotype** | Varus | $VAR_{FMA}6°$ | 85.5 to 88.5° | 87° |
| FMA | | $VAR_{FMA}3°$ | 88.5 to 91.5° | 90° |
| | Neutral | $NEU_{FMA}0°$ | 91.5 to 94.5° | 93° |
| | Valgus | $VAL_{FMA}3°$ | 94.5 to 97.5° | 96° |
| | | $VAL_{FMA}6°$ | 97.5 to 100.5° | 99° |
| **Tibial phenotype** | Varus | $VAR_{TMA}6°$ | 79.5 to 82.5° | 81° |
| TMA | | $VAR_{TMA}3°$ | 82.5 to 85.5° | 84° |
| | Neutral | $NEU_{TMA}0°$ | 85.5 to 88.5° | 87° |
| | Valgus | $VAL_{TMA}3°$ | 88.5 to 91.5° | 90° |
| | | $VAL_{TMA}6°$ | 91.5 to 94.5° | 93° |
| | | $VAL_{TMA}9°$ | 94.5 to 97.5° | 96° |
| | | $VAL_{TMA}12°$ | 97.5 to 100.5° | 99° |

The functional knee phenotype classification utilizes three variables –the limb phenotype (HKA), femoral phenotype (FMA), and the tibial phenotype (TMA) – each defined with their corresponding range. For each variable the data is presented in degrees. *FMA*, femoral mechanical angle; *HKA*, mechanical hip-knee-ankle angle; *TMA*, tibial mechanical angle.

## Results

A total of 305 knees with isolated lateral compartment OA of 276 patients were included in this study (Fig.2). The mean age was 64.0 ± 10.0 years and mean body mass index (BMI) was 26.6 ± 4.6. The vast majority of patients were Caucasian (88.9%), and 128 patients (42.0%) were male.

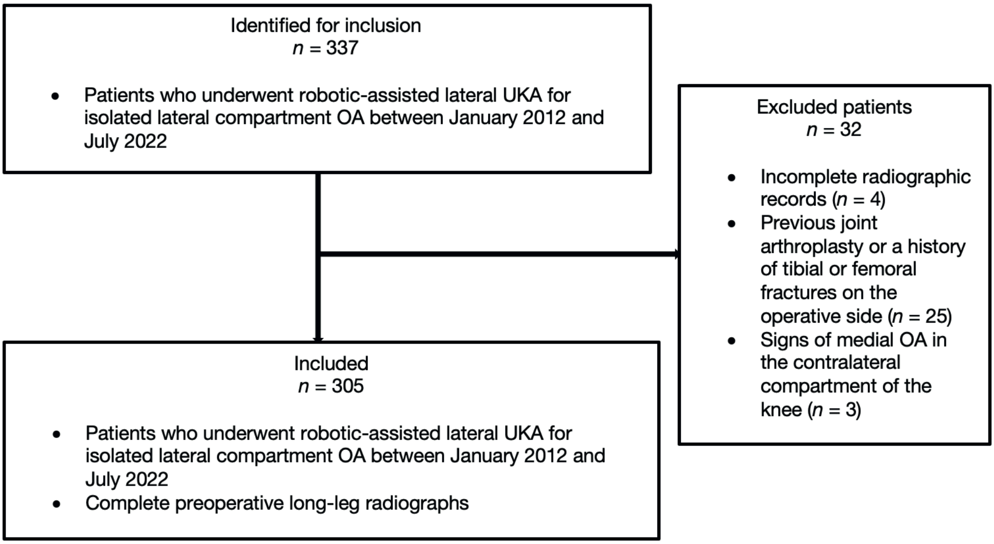


**Figure 2.** Flowchart of patient inclusion. *OA,* Osteoarthritis; *UKA,* Unicompartmental Knee Arthroplasty.

*Functional knee phenotypes*

A total of 60 functional knee phenotypes were identified in patients with isolated lateral compartment OA, 24 of which occurred only once. The 10 most prevalent functional knee phenotypes collectively accounted for 63.9% of the cases, as detailed in Table 2. The most frequently occurring functional knee phenotype was $\text{VAL}_{HKA}6^{\circ}\text{NEU}_{FMA}0^{\circ}\text{VAL}_{TMA}3^{\circ}$, with an incidence of 10.8%. An overview of all identified functional knee phenotypes is displayed in Appendix 1.

*Distribution of limb-, femoral-, and tibial phenotypes*

The overall mean values of the HKA, FMA and TMA for the entire cohort are shown in Table 3. When evaluated as individual parameters, the most frequently observed limb phenotype, femoral phenotype, and tibial phenotype in knees with isolated lateral compartment OA were $\text{VAL}_{HKA}6^{\circ}$, $\text{NEU}_{FMA}0^{\circ}$, and $\text{VAL}_{TMA}3^{\circ}$, with incidences of 34.1%, 51.8%, and 52.5%, respectively (Fig. 3).

**Table 2.** The ten most common functional knee phenotypes of knees with isolated lateral compartment osteoarthritis

| Rank | Functional knee phenotype | Total<br>*n* = 231 | Male<br>*n* = 89 | Female<br>*n* = 106 |
|---|---|---|---|---|
| 1 | $VAL_{HKA}6°NEU_{FMA}0°VAL_{TMA}3°$ | 33 (10.8%) | 16 (12.5%) | 17 (9.6%) |
| 2 | $VAL_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 29 (9.5%) | 15 (11.7%) | 14 (7.9%) |
| 3 | $VAL_{HKA}6°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 24 (7.9%) | 7 (5.5%) | 17 (9.6%) |
| 4 | $VAL_{HKA}6°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 22 (7.2%) | 11 (8.6%) | 11 (6.2%) |
| 5 | $VAL_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 19 (6.2%) | 10 (7.8%) | 9 (5.1%) |
| 6 | $VAL_{HKA}9°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 18 (5.9%) | 8 (6.3%) | 10 (5.6%) |
| 7 | $VAL_{HKA}9°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 17 (5.6%) | 6 (4.7%) | 11 (6.2%) |
| 8 | $NEU_{HKA}0°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 12 (3.9%) | 6 (4.7%) | 6 (3.4%) |
| 9 | $VAL_{HKA}6°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 11 (3.6%) | 3 (2.3%) | 8 (4.5%) |
| 10 | $VAL_{HKA}3°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 10 (3.3%) | 7 (5.5%) | 3 (1.7%) |
| **Total** | | **195 (63.9%)** | **89 (69.5%)** | **106 (59.9%)** |

Top 10 functional phenotypes of knees with lateral compartment osteoarthritis. The incidence of each functional knee phenotype is given in numbers and frequencies (%), for the entire cohort and stratified by gender. *FMA,* femoral mechanical angle; *HKA,* mechanical hip-knee-ankle angle; *NEU,* neutral; *TMA*, tibial mechanical angle; *VAL*, valgus; *VAR*, varus.

**Table 3.** Radiographic outcomes

| **Variable** | Total<br>*n* = 305 | Male<br>*n* = 128 | Female<br>*n* = 177 | *p*-value |
|---|---|---|---|---|
| **HKA (°)** | | | | |
| Mean ± SD | -6.0 ± 3.78 | -5.4 ± 3.87 | -6.4 ± 3.66 | .02* |
| Range | -16.2 to 5.6 | -16.2 to 5.6 | -15.3 to 2.6 | |
| **FMA (°)** | | | | |
| Mean ± SD | 94.3 ± 2.06 | 94.1 ± 1.89 | 89.7 ± 2.06 | n.s. |
| Range | 87.1 to 99.4 | 90 to 99.3 | 87.1 to 99.4 | |
| **TMA (°)** | | | | |
| Mean ± SD | 89.4 ± 2.21 | 89.0 ± 2.35 | 94.4 ± 2.17 | .005* |
| Range | 82.2 to 98.0 | 82.2 to 98.0 | 84.4 to 94.8 | |

Radiographic outcomes are given in means ± standard deviation (SD) for the entire cohort and stratified by gender. *FMA*, femoral mechanical angle; *HKA*, mechanical hip-knee-ankle angle; *TMA*, tibial mechanical angle.

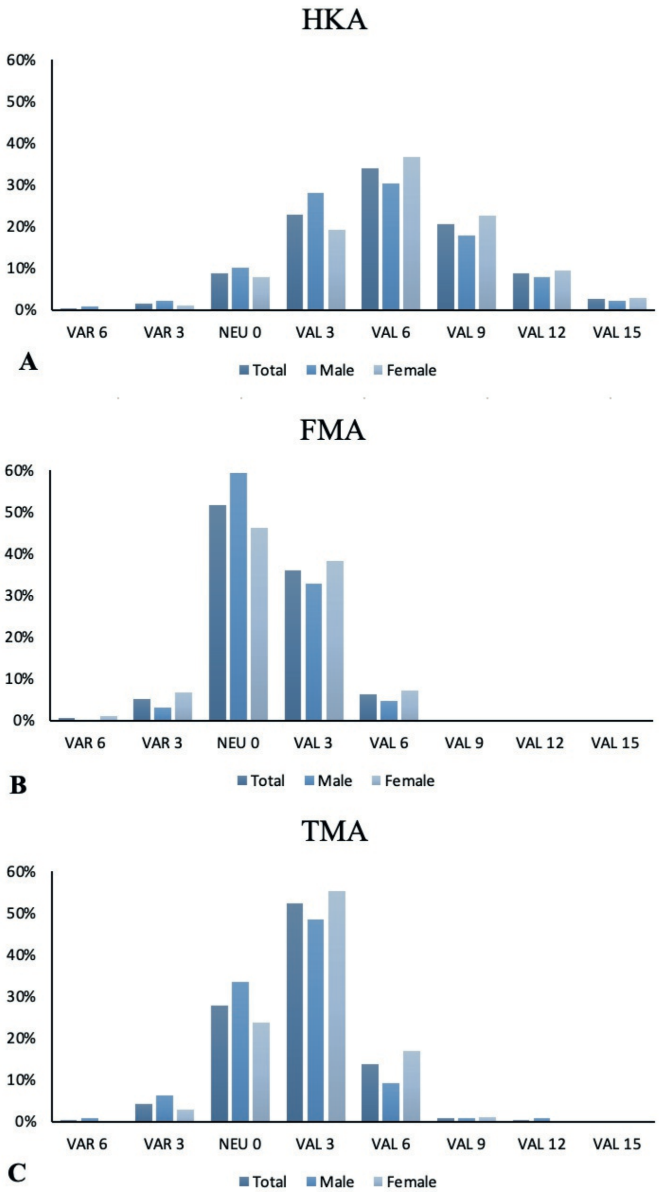


**Figure 3.** Distribution of limb-, femoral-, and tibial phenotypes of knees with isolated lateral compartment osteoarthritis. **2A,** Distribution of limb phenotype (HKA, mechanical hip-knee-ankle angle). **2B,** Distribution of femoral phenotype (FMA, femoral mechanical angle). **2C,** Distribution of tibial phenotype (TMA, tibial mechanical angle). The incidence of each functional knee phenotype is given in frequencies (%) for the entire cohort and stratified by gender.

*Distribution of knee phenotypes and location of the coronal deformity*

The most frequently observed coronal knee phenotype (i.e., the combination of the tibial phenotype and femoral phenotype) in knees with isolated lateral compartment OA was $NEU_{FMA}0°VAL_{TMA}3°$, with an incidence of 28.9% (Table 4). In the majority of patients, the coronal deformity predominantly presented as an isolated tibial valgus deformity, with 37.4% of patients exhibiting this specific deformity. In contrast, among patients with isolated lateral compartment OA, only 15.1% of patients presented with an isolated valgus deformity of the femur. Patients with limb phenotype $NEU_{HKA}0°$ predominantly exhibited an absence of extra-articular deformities, whereas limb phenotypes $VAL_{HKA}3°$ and $VAL_{HKA}6°$ were predominantly associated with isolated tibial deformities. Those with greater valgus limb (i.e., $VAL_{HKA}9°$, $VAL_{HKA}12°$, $VAL_{HKA}15°$) phenotypes exhibited either isolated tibial deformities or concurrent deformities in both the femur and tibia (Table 5). The distribution of all coronal deformity combinations in knees with isolated lateral compartment OA is presented in Figure 4.

**Table 4.** Distribution of knee phenotypes of knees with isolated lateral compartment osteoarthritis

| | **FMA** | | | | | |
|---|---|---|---|---|---|---|
| | $VAR_{FMA}6°$ | $VAR_{FMA}3°$ | $NEU_{FMA}0°$ | $VAL_{FMA}3°$ | $VAL_{FMA}6°$ | Total |
| **TMA** | | | | | | |
| $VAR_{TMA}6°$ | 0 (0.0%) | 0 (0.0%) | 1 (0.3%) | 0 (0.0%) | 0 (0.0%) | **1 (0.3%)** |
| $VAR_{TMA}3°$ | 0 (0.0%) | 1 (0.3%) | 7 (2.3%) | 4 (1.3%) | 1 (0.3%) | **13 (4.3%)** |
| $NEU_{TMA}0°$ | 0 (0.0%) | 3 (1.0%) | 36 (11.8%) | 40 (13.1%) | 6 (2.0%) | **85 (27.9%)** |
| $VAL_{TMA}3°$ | 0 (0.0%) | 9 (3.0%) | 88 (28.9%) | 53 (17.4%) | 10 (3.3%) | **160 (52.5%)** |
| $VAL_{TMA}6°$ | 1 (0.3%) | 3 (1.0%) | 24 (7.9%) | 12 (3.9%) | 2 (0.7%) | **42 (13.8%)** |
| $VAL_{TMA}9°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.3%) | 1 (0.3%) | 0 (0.0%) | **3 (1.0%)** |
| $VAL_{TMA}12°$ | 0 (0.0%) | 0 (0.0%) | 1 (0.3%) | 0 (0.0%) | 0 (0.0%) | **1 (0.3%)** |
| **Total** | **2 (0.7%)** | **16 (5.2%)** | **158 (51.8%)** | **110 (36.1%)** | **19 (6.2%)** | **305 (100%)** |

The distribution of knee phenotypes (i.e., the combination of the femoral and tibial phenotype) of knees with isolated lateral compartment osteoarthritis is given in numbers and frequencies (%) for the entire cohort. *FMA,* femoral mechanical angle; *NEU,* neutral; *TMA*, tibial mechanical angle; *VAL*, valgus; *VAR*, varus.

**Table 5.** Coronal deformity location in knees with isolated lateral compartment osteoarthritis by limb phenotype

| | | **Limb phenotype** | | | | | |
|---|---|---|---|---|---|---|---|
| | | $NEU_{HKA}0°$ (*n* = 27) | $VAL_{HKA}3°$ (*n* = 70) | $VAL_{HKA}6°$ (*n* = 104) | $VAL_{HKA}9°$ (*n* = 63) | $VAL_{HKA}12°$ (*n* = 27) | $VAL_{HKA}15°$ (*n* = 8) |
| **Location of deformity** | **Knee phenotype** | | | | | | |
| No extra-articular deformity | $NEU_{FMA} – NEU_{TMA}$ | **12 (44.4%)** | **19 (27.1%)** | **2 (1.9%)** | **-** | **1 (3.7%)** | **-** |
| Femoral deformity | $VAL_{FMA} – NEU_{TMA}$ | 2 (7.4%) | 10 (14.3%) | 24 (23.1%) | 6 (9.5%) | 4 (14.8%) | - |
| | $VAR_{FMA} – NEU_{TMA}$ | 1 (3.7%) | 1 (1.4%) | 1 (1.0%) | - | - | - |
| | **Total** | **3 (11.1%)** | **11 (15.7%)** | **25 (24.0%)** | **6 (9.5%)** | **4 (14.8%)** | - |
| Tibial deformity | $NEU_{FMA} – VAL_{TMA}$ | 3 (11.1%) | 30 (42.9%) | 44 (42.3%) | 25 (39.7%) | 10 (37.0%) | 2 (25.0%) |
| | $NEU_{FMA} – VAR_{TMA}$ | 5 (18.5%) | - | - | - | - | - |
| | **Total** | **8 (29.6%)** | **30 (42.9%)** | **44 (42.3%)** | **25 (39.7%)** | **10 (37.0%)** | **2 (25.0%)** |
| Combined deformity | $VAL_{FMA} – VAL_{TMA}$ | - | 5 (7.1%) | 29 (27.9%) | 28 (44.4%) | 10 (37.0%) | 6 (75.0%) |
| | $VAL_{FMA} – VAR_{TMA}$ | - | 2 (2.9%) | 1 (1.0%) | 2 (3.2%) | 0 (0.0%) | - |
| | $VAR_{FMA} – VAL_{TMA}$ | 4 (14.8%) | 3 (4.3%) | 3 (2.9%) | 2 (3.2%) | 2 (7.4%) | - |
| | $VAR_{FMA} – VAR_{TMA}$ | - | - | - | - | - | - |
| | **Total** | **4 (14.8%)** | **10 (14.3%)** | **33 (31.7%)** | **32 (50.8%)** | **12 (44.4%)** | **6 (75.0%)** |

Distribution of the coronal deformity location is given for neutral and valgus limb phenotypes in numbers and frequencies (%). *FMA,* femoral mechanical angle; *HKA,* mechanical hip-knee-ankle angle; *NEU,* neutral; *TMA*, tibial mechanical angle; *VAL*, valgus; *VAR*, varus.

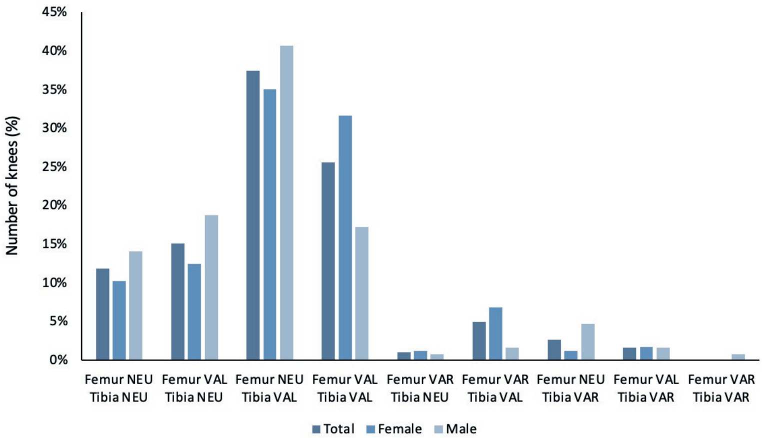


**Figure 4.** Location of the coronal deformity in knees with isolated lateral compartment OA. This figure does not account for the severity of the deformity present. The incidence of the deformity is given in frequencies (%) and stratified by gender.

*Gender-specific differences*

Of the 60 functional knee phenotypes identified, 27 (45.0%) phenotypes were common to both males and females. Among females, both HKA and TMA values exhibited a significantly greater mean valgus alignment compared to males (HKA: -6.4 vs. -5.4, respectively; $p$ = 0.02 and TMA 94.4 vs. 89.0, respectively; $p$ = .005; Table 3). Additionally, males exhibited a significantly higher prevalence of the neutral femoral phenotype compared to females ($NEU_{FMA}0°$: 59.4% vs. 46.3%, respectively; $p$ = 0.02; Table 4). The distribution of coronal knee phenotypes and the location of the coronal deformities in knees with isolated lateral compartment OA stratified by gender are displayed in Table 6 and Figure 4, respectively.

*Age-related differences*

Patients under the age of 50 years predominantly presented with isolated femoral deformities, which were observed in 31.0% of cases. Patients aged 50 and above primarily exhibited isolated tibial- or combined femoral and tibial deformities (Table 7). The distribution of the different limb-, femoral- and tibial knee phenotypes and the distribution of the coronal deformity location across different age groups are displayed in Figures 5 and 6, respectively.

**Table 6.** Distribution of knee phenotypes of knees with isolated lateral compartment osteoarthritis by gender

| **Male** | **FMA** | | | | | |
|---|---|---|---|---|---|---|
| | $VAR_{FMA}6°$ | $VAR_{FMA}3°$ | $NEU_{FMA}0°$ | $VAL_{FMA}3°$ | $VAL_{FMA}6°$ | **Total** |
| **TMA** | | | | | | |
| $VAR_{TMA}6°$ | 0 (0.0%) | 0 (0.0%) | 1 (0.8%) | 0 (0.0%) | 0 (0.0%) | **1 (0.8%)** |
| $VAR_{TMA}3°$ | 0 (0.0%) | 1 (0.8%) | 5 (3.9%) | 1 (0.8%) | 1 (0.8%) | **8 (6.3%)** |
| $NEU_{TMA}0°$ | 0 (0.0%) | 1 (0.8%) | 18 (14.1%) | 21 (16.4%) | 3 (2.3%) | **43 (33.6%)** |
| $VAL_{TMA}3°$ | 0 (0.0%) | 1 (0.8%) | 43 (33.6%) | 16 (12.5%) | 2 (1.6%) | **62 (48.4%)** |
| $VAL_{TMA}6°$ | 0 (0.0%) | 1 (0.8%) | 7 (5.5%) | 4 (3.1%) | 0 (0.0%) | **12 (9.4%)** |
| $VAL_{TMA}9°$ | 0 (0.0%) | 0 (0.0%) | 1 (0.8%) | 0 (0.0%) | 0 (0.0%) | **1 (0.8%)** |
| $VAL_{TMA}12°$ | 0 (0.0%) | 0 (0.0%) | 1 (0.8%) | 0 (0.0%) | 0 (0.0%) | **1 (0.8%)** |
| **Total** | **0 (0.0%)** | **4 (3.1%)** | **76 (59.4%)** | **42 (32.8%)** | **6 (4.7%)** | **128 (100%)** |
| **Female** | **FMA** | | | | | |
| | $VAR_{FMA}6°$ | $VAR_{FMA}3°$ | $NEU_{FMA}0°$ | $VAL_{FMA}3°$ | $VAL_{FMA}6°$ | |
| **TMA** | | | | | | |
| $VAR_{TMA}6°$ | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | **0 (0.0%)** |
| $VAR_{TMA}3°$ | 0 (0.0%) | 0 (0.0%) | 2 (1.1%) | 3 (1.7%) | 0 (0.0%) | **5 (2.8%)** |
| $NEU_{TMA}0°$ | 0 (0.0%) | 2 (1.1%) | 18 (10.2%) | 19 (10.7%) | 3 (1.7%) | **42 (23.7%)** |
| $VAL_{TMA}3°$ | 0 (0.0%) | 8 (4.5%) | 45 (25.4%) | 37 (20.9%) | 8 (4.5%) | **98 (55.4%)** |
| $VAL_{TMA}6°$ | 1 (0.6%) | 2 (1.1%) | 17 (9.6%) | 8 (4.5%) | 2 (1.1%) | **30 (16.9%)** |
| $VAL_{TMA}9°$ | 1 (0.6%) | 0 (0.0%) | 0 (0.0%) | 1 (0.6%) | 0 (0.0%) | **2 (1.1%)** |
| $VAL_{TMA}12°$ | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | **0 (0.0%)** |
| **Total** | **2 (1.1%)** | **12 (6.8%)** | **82 (46.3%)** | **68 (38.4%)** | **13 (7.3%)** | **177 (100%)** |

Distribution of knee phenotypes (i.e., the combination of the femoral and tibial phenotype) of knees with isolated lateral compartment osteoarthritis is given in numbers and frequencies (%) and stratified by gender. *FMA,* femoral mechanical angle; *NEU,* neutral; *TMA*, tibial mechanical angle; *VAL*, valgus; *VAR*, varus.

**Table 7.** Coronal deformity location in knees with isolated lateral compartment osteoarthritis by age category

| | | Age category<br>< 50 years<br>(*n* = 29) | 50 to 70 years<br>(*n* = 185) | > 70 years<br>(*n* = 91) | Total<br>(*n* = 305) |
|---|---|---|---|---|---|
| **Location of deformity** | **Knee phenotype** | | | | |
| No extra-articular deformity | $NEU_{FMA} – NEU_{TMA}$ | **6 (20.7%)** | **23 (12.4%)** | **7 (7.7%)** | **36 (11.8%)** |
| Femoral deformity | $VAL_{FMA} – NEU_{TMA}$ | 9 (31.0%) | 29 (15.7%) | 11 (12.1%) | 46 (15.1%) |
| | $VAR_{FMA} – NEU_{TMA}$ | - | 2 (1.1%) | 1 (1.1%) | 3 (1.0%) |
| | **Total** | **9 (31.0%)** | **31 (16.8%)** | **12 (13.2%)** | **49 (16.1%)** |
| Tibial deformity | $NEU_{FMA} – VAL_{TMA}$ | 6 (20.7%) | 68 (36.8%) | 37 (40.7%) | 114 (37.4%) |
| | $NEU_{FMA} – VAR_{TMA}$ | 2 (6.9%) | 5 (2.7%) | 1 (1.1%) | 8 (2.6%) |
| | **Total** | **8 (27.6%)** | **73 (39.5%)** | **38 (41.8%)** | **122 (40.0%)** |
| Combined deformity | $VAL_{FMA} – VAL_{TMA}$ | 5 (17.2%) | 46 (24.9%) | 27 (29.7%) | 78 (25.6%) |
| | $VAL_{FMA} – VAR_{TMA}$ | - | 4 (2.2%) | 1 (1.1%) | 5 (1.6%) |
| | $VAR_{FMA} – VAL_{TMA}$ | 1 (3.4%) | 8 (4.3%) | 5 (5.5%) | 14 (4.6%) |
| | $VAR_{FMA} – VAR_{TMA}$ | - | - | 1 (1.1%) | 1 (0.3%) |
| | **Total** | **6 (20.7%)** | **58 (31.4%)** | **34 (37.4%)** | **98 (32.1%)** |

Distribution of the coronal deformity location is given for different age categories in numbers and frequencies (%). *FMA,* femoral mechanical angle; *NEU,* neutral; *TMA*, tibial mechanical angle; *VAL*, valgus; *VAR*, varus.

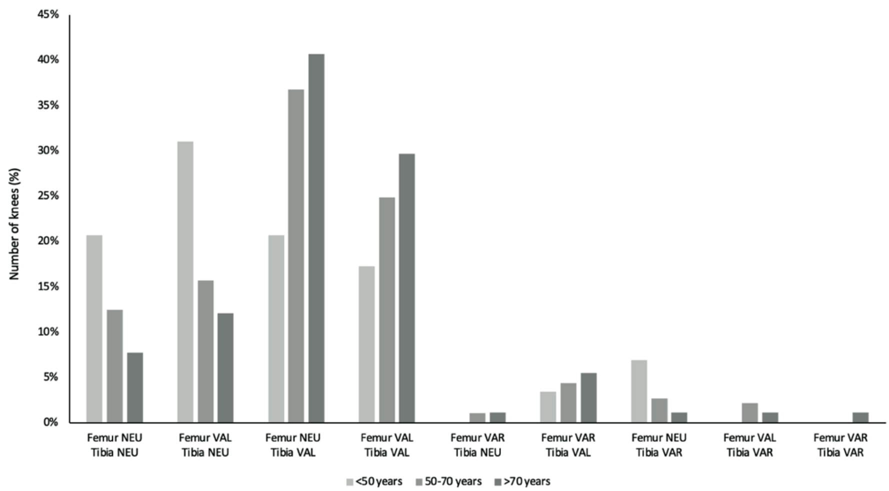


**Figure 5.** Location of the coronal deformity in knees with isolated lateral compartment OA. This figure does not account for the severity of the deformity present. The incidence of the deformity is given in frequencies (%) and stratified by age.

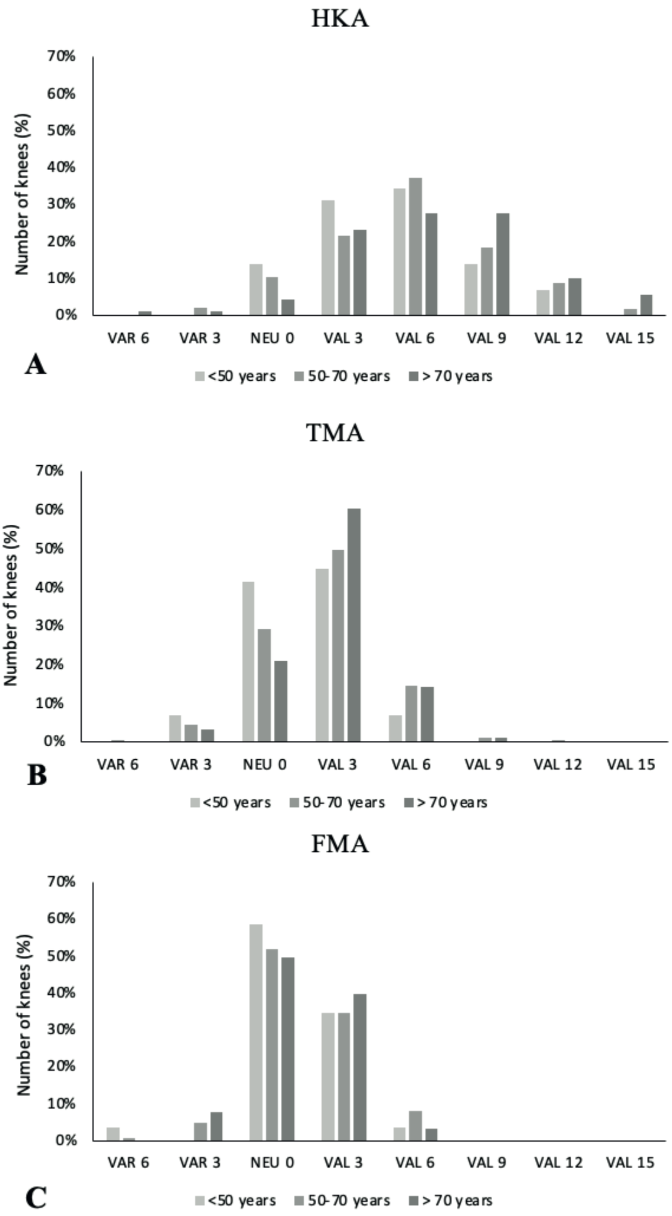


**Figure 6.** Distribution of limb-, femoral-, and tibial phenotypes of knees with isolated lateral compartment osteoarthritis stratified by age. **4A,** Distribution of limb phenotype (HKA, mechanical hip-knee-ankle angle). **4B,** Distribution of femoral phenotype (FMA, femoral mechanical angle). **4C,** Distribution of tibial phenotype (TMA, tibial mechanical angle). The incidence of each functional knee phenotype is given in frequencies (%).

**Discussion**

The most important findings of the present study were that there was a substantial variation of functional knee phenotypes in patients with isolated lateral compartment OA, with gender-specific and age-related differences. $VAL_{HKA}6°NEU_{FMA}0°VAL_{TMA}3°$ was the most prevalent phenotype among the 60 identified functional knee phenotypes, accounting for 10.8% of all knees. The coronal deformity predominantly manifested as an isolated tibial deformity. However, it is noteworthy that greater valgus limb phenotypes (i.e., $VAL_{HKA}9°$, $VAL_{HKA}12°$, $VAL_{HKA}15°$) were more often associated with concurrent tibial and femoral deformities. Secondly, females exhibited more pronounced valgus HKA and TMA values and were nearly twice as likely to present with combined tibial and femoral valgus deformities compared to males. Finally, when assessing functional knee phenotypes in distinct age groups, it was observed that in younger patients the deformity mainly manifested in the femur, whereas in older patients the deformity primarily manifested as isolated tibial- or combined femoral and tibial deformities. Enhancing our understanding of the phenotypic expression in knees affected by isolated lateral compartment OA contributes to the existing body of literature advocating for more personalized strategies, thereby accounting for the unique characteristics and bony deformities of the individual knee.

Recent studies have highlighted substantial variations in alignment phenotypes within both the non-arthritic and arthritic population. Among the non-arthritic population, the majority of knees displayed neutral femoral and tibial phenotypes (57.5% and 44.2%, respectively), with the most common functional knee phenotype in both males and females being $NEU_{HKA}0°NEU_{FMA}0°NEU_{TMA}0°$ (19.0% and 17.7%, respectively) [8, 9]. Conversely, among osteoarthritic knees more pronounced varus alignment phenotype characteristics have been observed[12, 15, 28]. The current study further contributes to the existing literature by highlighting the phenotypic diversity in knees with isolated lateral compartment OA. Excessive varus and valgus malalignment are associated with abnormal load distribution within the knee joint, which is an important risk factor for progressive degeneration and the onset of OA within the overloaded compartment of the knee[19, 29-31]. These findings are supported by a recent study emphasizing the intricate relationship between knee alignment and the progression of cartilage degeneration in specific anatomical regions, wherein distinct patterns were observed among various alignment phenotypes. Specifically, among those phenotypes, a valgus tibial phenotype and a valgus femoral phenotype were identified as strongly correlated with cartilage loss in the central lateral tibial subregion and the central weightbearing region of the lateral femorotibial compartment, respectively[17]. This may account for the more pronounced valgus phenotype expressions observed in cases of isolated lateral compartment OA.

In order to effectively personalize alignment strategies, it is of importance to analyze the unique phenotypic expressions and the specific locations of coronal deformities in the individual knee. Surgical interventions for lateral compartment OA include corrective osteotomy, unicompartmental knee arthroplasty, and total knee arthroplasty[19, 32]. Corrective osteotomies, especially suitable for young and active patients aspiring to return to high-impact sports, typically require femoral osteotomies in cases of valgus OA[19, 33-35]. This study highlights a crucial distinction in younger patients with isolated lateral compartment OA, where the primary deformity predominantly resides within the femur, making these patients highly suitable candidates for femoral varus osteotomies to manage lateral compartment OA. In these cases, osteotomies hold the potential to yield favorable outcomes by realigning the lower limb, correcting the underlying deformity, and unloading the lateral compartment, all while potentially delaying or even avoiding the need for knee replacement arthroplasty[19]. Nevertheless, while femoral varus osteotomies are a highly promising approach for this specific patient category, it is essential to exercise caution and avoid assuming their universal applicability for all cases of lateral compartment OA. In the present study, tibial involvement was evident in 67.7% of cases, with 37.4% of patients presenting with isolated extra-articular tibial valgus deformities. In cases of tibial-based valgus deformities or combined extra-articular deformities, which were more commonly observed among older patients and patients with more severe valgus limb phenotypes, alternative and more pragmatic approaches might involve double level osteotomies or knee arthroplasty[36, 37]. These findings emphasize that careful consideration of the distinct functional knee phenotypes and coronal deformity manifestations becomes pertinent when planning surgical interventions.

The predominant functional knee phenotype in both males and females was $VAL_{HKA}6^{o}NEU_{FMA}0^{o}VAL_{TMA}3^{o}$. However, gender-related differences in coronal alignment parameters were evident, with females manifesting more pronounced valgus values in both HKA and TMA parameters. This may offer an explanation for the higher observed prevalence of combined extra-articular valgus deformities among females. Nevertheless, the literature lacks consistency in its assessment of TMA values, as some studies report higher TMA values among females[2, 3, 8, 9, 28, 38-42], while others report comparable TMA values between males and females[15, 40, 43, 44]. This inconsistency may be attributed to the variations in the presence or absence of OA, as well as the inclusion of diverse ethnic groups in the aforementioned studies[5, 40].

This study is not without any limitations. First, the retrospective nature of our study may have introduced bias related to data collection and patient selection. Specifically, this study exclusively focused on patients with isolated lateral compartment OA who underwent lateral UKA. Consequently, there is a possibility that patients with isolated lateral OA who did not meet the specific inclusion criteria for lateral UKA or opted for TKA instead were not included, potentially introducing selection bias. Second, the predominant inclusion of patients of Caucasian ethnicity may limit the generalizability of our findings to populations with different ethnic backgrounds, considering recent studies suggesting potential ethnic variations in coronal alignment parameters[5, 40]. Third, this study lacks a phenotype assessment in the sagittal plane, which may restrict the comprehensive evaluation of the complete phenotypic expression within the knee. Fourth, the present study lacks an analysis of the association between functional knee phenotypes and clinical outcomes scores, which could have provided valuable insights into the practical implications of our findings. Therefore, future studies evaluating functional knee phenotypes should include the assessment of clinical outcome scores.

## Conclusion

There is a broad variation of functional knee phenotypes present in knees affected by isolated lateral compartment OA, with gender-specific and age-related differences. Acknowledging the inherent phenotypic diversity in isolated lateral compartment osteoarthritic knees during preoperative planning may facilitate the implementation of tailored approaches that account for the unique characteristics and bony deformities of the individual knee.

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**Appendix 1.** Functional knee phenotypes of knees with isolated lateral compartment osteoarthritis

| Functional knee phenotype<br>*n* = 60 | Total<br>*n* = 305 | Male<br>*n* = 128 | Female<br>*n* = 177 |
|---|---|---|---|
| $VAL_{HKA}6°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 33 (10.8%) | 16 (12.5%) | 17 (9.6%) |
| $VAL_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 29 (9.5%) | 15 (11.7%) | 14 (7.9%) |
| $VAL_{HKA}6°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 24 (7.9%) | 7 (5.5%) | 17 (9.6%) |
| $VAL_{HKA}6°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 22 (7.2%) | 11 (8.6%) | 11 (6.2%) |
| $VAL_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 19 (6.2%) | 10 (7.8%) | 9 (5.1%) |
| $VAL_{HKA}9°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 18 (5.9%) | 8 (6.3%) | 10 (5.6%) |
| $VAL_{HKA}9°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 17 (5.6%) | 6 (4.7%) | 11 (6.2%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 12 (3.9%) | 6 (4.7%) | 6 (3.4%) |
| $VAL_{HKA}6°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 11 (3.6%) | 3 (2.3%) | 8 (4.5%) |
| $VAL_{HKA}3°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 10 (3.3%) | 7 (5.5%) | 3 (1.7%) |
| $VAL_{HKA}9°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 7 (2.3%) | 3 (2.3%) | 4 (2.3%) |
| $VAL_{HKA}9°$ $VAL_{FMA}6°$ $VAL_{TMA}3°$ | 6 (2.0%) | 1 (0.8%) | 5 (2.8%) |
| $VAL_{HKA}12°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 5 (1.6%) | 1 (0.8%) | 4 (2.3%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 5 (1.6%) | 3 (2.3%) | 2 (1.1%) |
| $VAL_{HKA}3°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 5 (1.6%) | 1 (0.8%) | 4 (2.3%) |
| $VAL_{HKA}9°$ $VAL_{FMA}3°$ $VAL_{TMA}6°$ | 5 (1.6%) | 2 (1.6%) | 3 (1.7%) |
| $VAL_{HKA}12°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 4 (1.3%) | 2 (1.6%) | 2 (1.1%) |
| $VAL_{HKA}9°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 4 (1.3%) | 1 (0.8%) | 3 (1.7%) |
| $VAL_{HKA}12°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 4 (1.3%) | 2 (1.6%) | 2 (1.1%) |
| $NEU_{HKA}0°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 3 (1.0%) | 2 (1.6%) | 1 (0.6%) |
| $VAL_{HKA}12°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 3 (1.0%) | 1 (0.8%) | 2 (1.1%) |
| $VAL_{HKA}15°$ $VAL_{FMA}3°$ $VAL_{TMA}3°$ | 3 (1.0%) | 0 (0.0%) | 3 (1.7%) |
| $VAL_{HKA}12°$ $VAL_{FMA}3°$ $VAL_{TMA}6°$ | 3 (1.0%) | 1 (0.8%) | 2 (1.1%) |
| $VAL_{HKA}6°$ $VAL_{FMA}3°$ $VAL_{TMA}6°$ | 3 (1.0%) | 0 (0.0%) | 3 (1.7%) |
| $NEU_{HKA}0°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 3 (1.0%) | 0 (0.0%) | 3 (1.7%) |
| $VAL_{HKA}3°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 3 (1.0%) | 1 (0.8%) | 2 (1.1%) |
| $VAL_{HKA}6°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 2 (0.7%) | 1 (0.8%) | 1 (0.6%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 2 (0.7%) | 0 (0.0%) | 2 (1.1%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAR_{TMA}3°$ | 2 (0.7%) | 2 (1.6%) | 0 (0.0%) |
| $VAL_{HKA}3°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 2 (0.7%) | 1 (0.8%) | 1 (0.6%) |
| $VAL_{HKA}6°$ $VAL_{FMA}6°$ $NEU_{TMA}0°$ | 2 (0.7%) | 0 (0.0%) | 2 (1.1%) |
| $VAL_{HKA}9°$ $VAL_{FMA}6°$ $NEU_{TMA}0°$ | 2 (0.7%) | 1 (0.8%) | 1 (0.6%) |
| $VAL_{HKA}6°$ $VAL_{FMA}6°$ $VAL_{TMA}3°$ | 2 (0.7%) | 0 (0.0%) | 2 (1.1%) |
| $VAL_{HKA}12°$ $VAL_{FMA}6°$ $VAL_{TMA}6°$ | 2 (0.7%) | 0 (0.0%) | 2 (1.1%) |

| Functional knee phenotype<br>*n* = 60 | Total<br>*n* = 305 | Male<br>*n* = 128 | Female<br>*n* = 177 |
|---|---|---|---|
| $VAL_{HKA}9°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 2 (0.7%) | 0 (0.0%) | 2 (1.1%) |
| $VAL_{HKA}6°$ $VAR_{FMA}3°$ $VAL_{TMA}6°$ | 2 (0.7%) | 1 (0.8%) | 1 (0.6%) |
| $VAL_{HKA}12°$ $NEU_{FMA}0°$ $NEU_{TMA}0°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}15°$ $NEU_{FMA}0°$ $VAL_{TMA}12°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}15°$ $NEU_{FMA}0°$ $VAL_{TMA}3°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}3°$ $NEU_{FMA}0°$ $VAL_{TMA}6°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}12°$ $NEU_{FMA}0°$ $VAL_{TMA}9°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAR_{HKA}3°$ $NEU_{FMA}0°$ $VAR_{TMA}6°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $NEU_{HKA}0°$ $VAL_{FMA}3°$ $NEU_{TMA}0°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}15°$ $VAL_{FMA}3°$ $VAL_{TMA}6°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}15°$ $VAL_{FMA}3°$ $VAL_{TMA}9°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}6°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}9°$ $VAL_{FMA}3°$ $VAR_{TMA}3°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $NEU_{HKA}0°$ $VAL_{FMA}6°$ $NEU_{TMA}0°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}12°$ $VAL_{FMA}6°$ $NEU_{TMA}0°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}12°$ $VAL_{FMA}6°$ $VAL_{TMA}3°$ | 1 (0.3%) | 0 (0.0%) | 0 (0.6%) |
| $VAL_{HKA}15°$ $VAL_{FMA}6°$ $VAL_{TMA}3°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}9°$ $VAL_{FMA}6°$ $VAR_{TMA}3°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $NEU_{HKA}0°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}3°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}6°$ $VAR_{FMA}3°$ $NEU_{TMA}0°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}6°$ $VAR_{FMA}3°$ $VAL_{TMA}3°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $NEU_{HKA}0°$ $VAR_{FMA}3°$ $VAL_{TMA}6°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAR_{HKA}6°$ $VAR_{FMA}3°$ $VAR_{TMA}3°$ | 1 (0.3%) | 1 (0.8%) | 0 (0.0%) |
| $VAL_{HKA}12°$ $VAR_{FMA}6°$ $VAL_{TMA}6°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |
| $VAL_{HKA}12°$ $VAR_{FMA}6°$ $VAL_{TMA}9°$ | 1 (0.3%) | 0 (0.0%) | 1 (0.6%) |

The classification of functional knee phenotypes of knees with isolated lateral compartment osteoarthritis. The incidence of each functional knee phenotype is given in numbers and frequencies (%), for the entire cohort and stratified by gender. The data is presented in a descending order of prevalence for each functional knee phenotype. *FMA,* femoral mechanical angle; *HKA,* mechanical hip-knee-ankle angle; *NEU,* neutral; *TMA*, tibial mechanical angle; *VAL*, valgus; *VAR*, varus.

# Chapter 10

# Large variance in a lateral osteoarthritic population prior to and following lateral unicompartmental knee arthroplasty

## an analysis of knees phenotypes

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The Knee

**Abstract**

**Purpose:** disagreement exists on the optimal coronal alignment target for lateral unicompartmental knee arthroplasty (UKA). An improved understanding of the distribution of coronal alignment and joint line orientation in lateral osteoarthritis (OA) might prove beneficial. The aim of this study was to evaluate the pre- and postoperative Coronal Plane Alignment of the Knee (CPAK) distribution following lateral UKA and to evaluate the association between phenotypic variation and patient-reported outcome measures (PROMs).

**Methods:** a single surgeon's registry was retrospectively reviewed between 2012 and 2022 to identify patients who received primary lateral UKA for advanced, lateral compartment OA. Radiographic measurements were performed and CPAK phenotypes were determined. The Knee Injury and Osteoarthritis Outcome Score (KOOS), the Kujala score, and patient satisfaction were analyzed at one and two-year follow-up.

**Results:** a total of 305 knees were included. Preoperatively, seven phenotypes were observed and CPAK 3 (54.1%) was most commonly observed. Postoperatively, all nine phenotypes were observed and CPAK 6 (32.8%) was predominant. Preoperatively, 23.6% of knees did not have a pre-arthritic valgus alignment. No significant differences in PROMs were found between individual phenotypes nor between preserved and altered phenotypes.

**Conclusion:** coronal alignment and joint line orientation were highly variable within a lateral compartment OA cohort. However, no association was demonstrated between superior postoperative PROMs and phenotype variation or phenotype preservation, which might suggest that there is not one universal optimal alignment target. Interestingly, 23.6% of knees with lateral compartment OA did not have a pre-arthritic valgus alignment, which may have been affected by joint line orientation.

## Introduction

Unicompartmental knee arthroplasty (UKA) is an effective surgical treatment for lateral compartment knee osteoarthritis (OA) when non-operative treatments have failed[1-4]. Traditionally, the surgical aim of lateral UKA is to resurface the lateral compartment and avoid overcorrection into varus in order to prevent medial compartment degeneration[5]. However, disagreement exists about the optimal coronal alignment target. An improved understanding of the distribution of coronal alignment and joint line orientation in knees with lateral compartment OA can aid in determining superior patient-individualized alignment.

Although the conventional coronal alignment nomenclature was solely focused on neutral, varus and valgus alignment, several studies have shown a variation in coronal alignment and broad phenotype distribution in healthy knees and knees with generalized OA[6-8]. MacDessi *et al*[8] introduced the Coronal Plane Alignment of the Knee (CPAK) classification which differentiates knees into nine CPAK phenotypes, based on their coronal alignment and joint line obliquity. The study included symptomatic osteoarthritic patients, not differentiating between the various forms of OA such as isolated medial-, lateral- and patellofemoral OA.

Lateral compartment OA is an uncommon form of OA with a prevalence of approximately 10% and likely contributed minimally to Macdessi's outcomes[8, 9]. Additionally, the biomechanical characteristics of the lateral compartment of the knee differ considerably to the medial compartment[2, 10]. Hence, it is interesting to evaluate the phenotypic distribution specifically for lateral compartment OA. Furthermore, the association between phenotype variability and patient-reported outcome measures (PROMs) remains unknown.

The present study aimed to evaluate the pre- and postoperative CPAK distribution for patients who underwent primary lateral UKA for lateral compartment OA and to compare PROMs between CPAK phenotypes.

## Methods

*Study design*

Following IRB approval (#2021-0627), the registry of the senior author (A.D.P) was reviewed for patients who received a primary, fixed-bearing, cemented lateral UKA using a robotic-arm assisted system (Restoris MCK System; MAKO System, Stryker, Fort Lauderdale, Florida, USA) for lateral compartment OA between March 2012 and March 2022. Patients were included if they had pre- and postoperative anteroposterior (AP) long-leg weightbearing radiographs. Patients with a history of prior lower limb arthroplasty or femoral- or tibial fractures on either side were excluded. Additionally, available postoperative PROMs were collected for all included patients at one-year and two-year follow-up.

*Surgical technique*

All surgeries were performed by the senior author (A.D.P), who had extensive experience in both medial- and lateral UKA. Lateral UKA was indicated in patients with symptomatic lateral compartment OA (Kellgren-Lawrence [KL] grade[11] ≥ 3). Radiographic patellofemoral OA without clinical symptoms was not a contraindication[12]. Medial compartment OA (KL ≥ 3), clinical symptoms of anterior-cruciate ligament deficiency (knee instability), signs of inflammatory arthritis and clinical symptoms of patellofemoral pain syndrome were contraindications. A three-dimensional model, based on a preoperative computer tomography (CT) scan, and robotic navigation were used for preoperative virtual implant planning and real-time intraoperative alterations. The surgical goal was to resurface the lateral compartment and target the coronal alignment to neutral or minimal valgus to restore pre-arthritic alignment and avoid the progression of OA in the medial compartment. This is achieved by ministering to internally rotating the tibia, avoiding tibial overhang anteriorly and avoiding overtightening of the lateral flexion space. Furthermore, special care was taken into registering if the femur and tibia line up through the whole range of motion. The surgical technique has been explained in detail[13].

*Radiographic evaluation*

Radiographic imaging was performed preoperatively and at six weeks postoperatively, according to a standardized protocol. Measurements including the mechanical hip-knee-ankle angle (mHKA), mechanical lateral distal femoral angle (mLDFA) and medial proximal tibial angle (MPTA) were measured on AP long-leg weightbearing radiographs and independently performed by two observers (G.V.t.N.d.B and L.V.R) (refer to Figure 1 in Chapter 8 of this thesis). Inter-rater reliability, assessed using the Interclass Correlation Coefficient (ICC), demonstrated good reliability (ICC range 0.82 to 0.87).

*CPAK classification*

The CPAK classification was used to determine knee phenotypes. The classification system is based on two independent factors and combines the arithmetic hip-knee-ankle angle (aHKA) and joint line obliquity (JLO) (refer to Figure 1 in Chapter 6 of this thesis). The aHKA is calculated by subtracting the mLDFA from the MPTA and can be categorized in three subgroups: neutral (aHKA 0° ± 2°), varus (aHKA ≤ -2°), and valgus (aHKA ≥ 2°). The JLO is determined by the sum of mLDFA and MPTA and consists of three subgroups: apex neutral (JLO 180° ± 3°), apex distal (JLO ≤ 177°), and apex proximal (JLO ≥ 183°). The apex terminology describes the orientation of the joint line relative to a horizontal plane[8].

*Postoperative patient-reported outcome measures*

The validated KOOS, JR[14] and Kujala[15] scores were collected at one- and two-year follow-up. PROMs were routinely collected through a digital, standardized questionnaire. Additionally, patient satisfaction was addressed using two anchor questions; 'What is the level of satisfaction with the overall function of the operative knee?' (very satisfied, satisfied, neutral, dissatisfied, very dissatisfied) and 'would you have undergone the surgery knowing that the current state of your knee would be the outcome of the surgery?' (yes, no). To determine satisfactory PROMs, patient acceptable symptom state (PASS) thresholds were defined using an anchor-based method[16]. As dichotomous outcomes were necessary to determine PASS thresholds and satisfaction was determined on the 5-point patient satisfaction

Likert scale, patients who were 'very satisfied' and 'satisfied' were defined as 'satisfied'. To discriminate between satisfied- and non-satisfied patients, Receiver Operating Characteristic (ROC) curve analyses were performed. Optimal threshold for each score was determined at the point where sensitivity and specificity were maximal (Youden Index)[17].

*Statistical analysis*

Analyses were performed using SPSS version 29.0 software (SPSS, Inc., Chicago, IL, USA). Continuous variables were presented as means with standard deviations (SD) and discrete variables as frequencies with percentages (%). Data was tested for a normal distribution using the Shapiro-Wilks test and compared using independent two-sample *t*-tests, one-way ANOVA, or Kruskal-Wallis test depending on the number of independent variables and distribution. Categorical data was compared using Chi-squared test or Fisher's exact test, and ordinal data was compared using the Wilcoxon's signed-rank test. Multivariable linear- and logistic regression analyses were performed to determine differences in PROMs between groups, while adjusting for the potential confounding effects of sex, age, body-mass index (BMI) and follow-up. Statistical level of significance was set to $p < 0.05$.

## Results

A total of 305 knees were included for evaluation of pre- and postoperative CPAK phenotyping. Mean age was 64.0 ± 10.0 years, mean BMI was 26.6 ± 4.6, and 58.0% of patients were female (Table 1).

*Preoperative radiographic evaluation*

Seven phenotypes were observed preoperatively. CPAK 3 was the most common observed phenotype (54.1%), followed by CPAK 6 (21.0%) and CPAK 2 (16.1%). Valgus aligned CPAK phenotypes were predominant (76.4%) and most joint lines were apex distally positioned (71.8%) (Figure 1). CPAK 2, characterized by a neutral

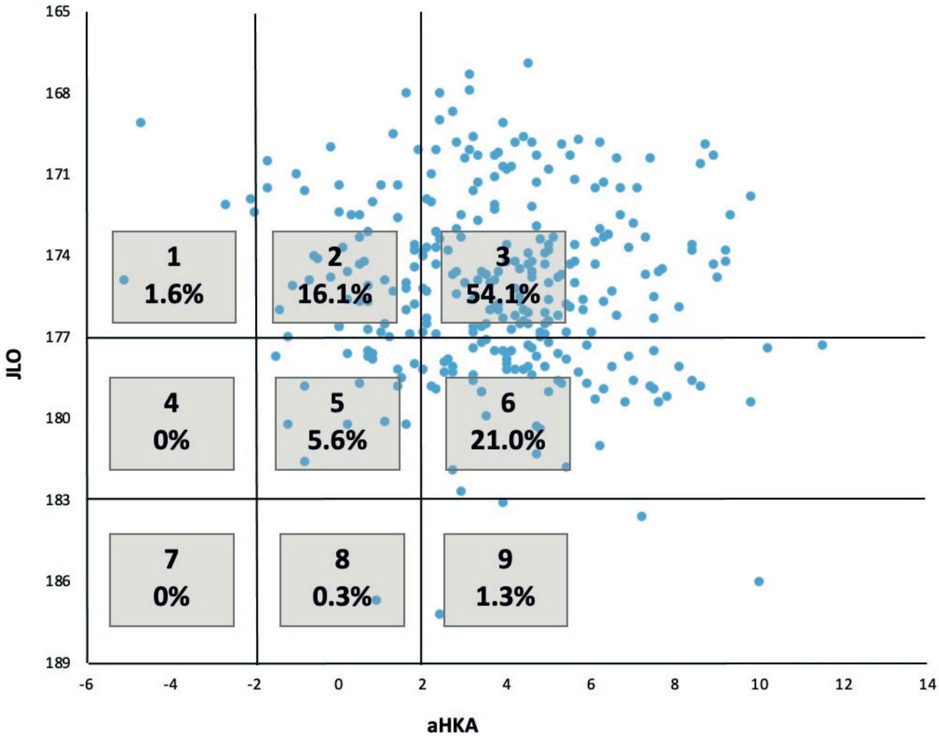


**Figure 1.** Scatterplot of the preoperative phenotype distribution in knees with lateral compartment osteoarthritis according to the Coronal Plane Alignment of the Knee (CPAK) classification. Percentages are given for each phenotype. *aHKA*, arithmetic hip-knee-angle angle; *JLO*, Joint line obliquity.

Pre-arthritic coronal alignment and apex distally oriented joint line was significantly more prevalent in male patients (male: 59.1%; female: 40.9%, $p$ = .008). Additionally, CPAK 2 was significantly more prevalent in patients aged between 50 and 70 years than in the other age groups (50 to 70 years: 55.1%; < 50 years: 20.4%; > 70 years: 24.5%, $p$ = .022). Similarly, CPAK 6, characterized by a valgus pre-arthritic coronal alignment and neutrally oriented joint line, was significantly more common in patients between 50 and 70 years old (50 to 70 years: 64.1%; < 50 years: 1.6%; > 70 years: 34.4%, $p$ = .048) (Table 2).

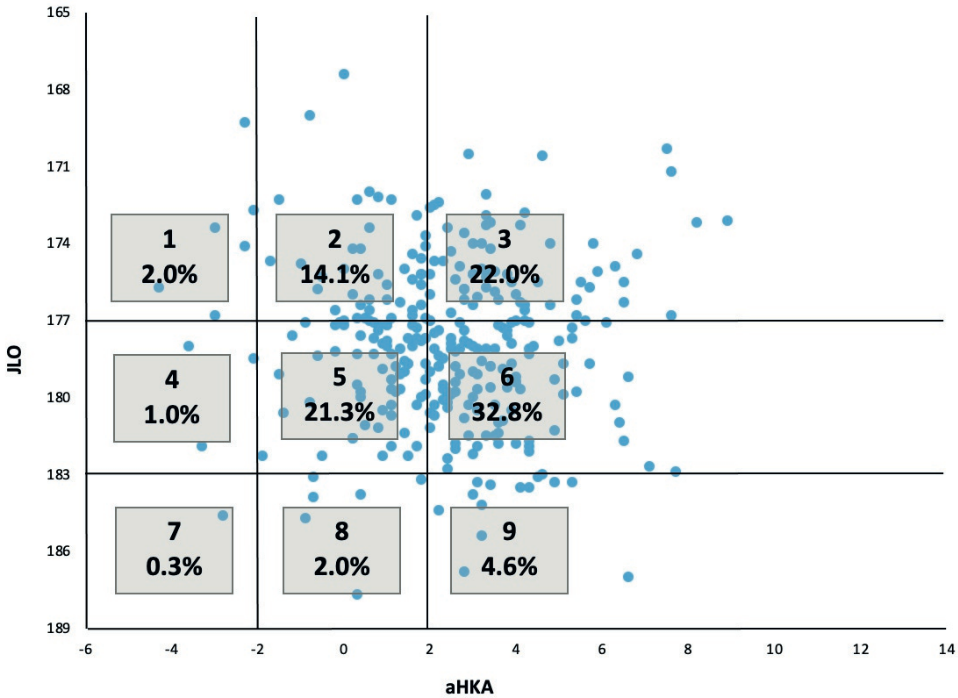


**Figure 2.** Scatterplot of the postoperative phenotype distribution in knees with lateral compartment osteoarthritis according to the Coronal Plane Alignment of the Knee (CPAK) classification. Percentages are given for each phenotype. *aHKA*, arithmetic hip-knee-angle angle; *JLO*, Joint line obliquity.

*Postoperative radiographic evaluation*

All nine phenotypes were observed postoperatively. CPAK 6 was the most common phenotype (32.8%), followed by CPAK 3 (22.0%) and CPAK 5 (21.3%). Valgus aligned phenotypes (59.4%), and neutrally oriented joint lines (55.1%) were most common (Figure 2). CPAK 2 was significantly more prevalent in male patients (male: 67.4%; female: 32.6%, $p < .001$), whereas CPAK 6 was significantly more prevalent in female patients (male: 27.0%; female: 73.0%, $p < .001$). CPAK 2 remained the most common phenotype following surgery in the age group between 50 and 70 years (50 to 70 years: 76.7%; < 50 years: 9.3%; > 70 years: 14.0%, $p = .041$).

*Postoperative patient-reported outcome measures*

PROMs were collected for 188 patients at one-year follow-up and for 145 patients at two-year follow-up. At two-years of follow-up, the mean KOOS, JR for the total cohort was 86.2 ± 13.7 and mean Kujala score was 84.8 ± 15.0. Of all patients, 93.1% were either 'very satisfied' or 'satisfied' with their surgery and 93.8% of patients reported that they would have undergone the surgery again. When comparing PROMs between individual postoperative CPAK phenotypes, PROMs did not differ significantly (Table 3). Additionally, no significant association was observed between preservation of CPAK phenotypes and superior PROMs (Table 4). Initially, patients with preservation of CPAK 5 had a significantly higher Kujala score than patients who had an altered postoperative phenotype (preservation: 97.6 ± 2.6; alteration: 79.0 ± 15.6, $p$ = 0.015). However, after adjusting for the potential confounders, this difference did not remain significant (β: -0.809 [-1.433 to -0.416], $p$ = 0.066), as age had a significant effect (β: -0.385 [-0.985 to -0.118], $p$ = 0.027). Additionally, postoperative PROMs did not significantly change from one-year to two-years postoperative (Figure 3).

**Table 1.** Demographics and radiographic measurements of 305 knees

| **Demographic** | | **Radiographic measurements** | |
|---|---|---|---|
| Age (years) | 64.0 ± 10.0 | Preoperative mHKA | 174° ± 3.8° |
| Follow-up (years) | 2.0 ± 0.0 | Postoperative mHKA | 176.8° ± 2.2° |
| BMI (kg/m$^2$) | 26.6 ± 4.6 | Preoperative aHKA | 183.7° ± 2.7° |
| Laterality of UKA | | Postoperative aHKA | 182.4° ± 2.1° |
| Right knee | 170 (55.7%) | Preoperative JLO | 175.1° ± 3.3° |
| Left knee | 117 (38.4%) | Postoperative JLO | 177.9° ± 3.3° |
| Bilateral | 18 (5.9%) | | |
| Sex (female) | 177 (58.0%) | | |
| KL-grade | | | |
| 3 | 28 (9.2%) | | |
| 4 | 277 (90.8%) | | |

Demographics and radiographic measurements were presented as mean ± standard deviations, or in numbers and frequencies (%) for the total cohort of 305 knees. Postoperative radiographic measurements were determined on six-weeks postoperative radiographs. *aHKA,* arithmetic hip-knee-ankle angle; *BMI,* body mass index; *JLO*, joint line obliquity; *KL,* Kellgren-Lawrence; *mHKA,* mechanical hip-knee-ankle angle; *UKA*, unicompartmental knee arthroplasty.

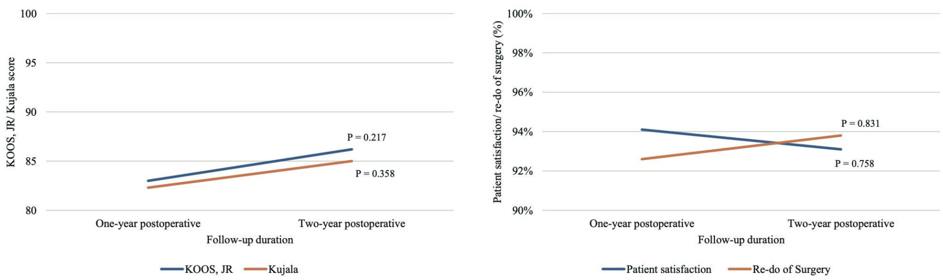


**Figure 3.** Change in PROMs from one-year to two-years postoperatively. Data on PROMs was available for 188 patients at one year and 145 patients at two years PROMs. The percentages for patient satisfaction reflect the proportion of patients who were either 'very satisfied' or 'satisfied' with their surgical outcome, while the percentages for redo of surgery represents the proportion of patients who would undergo the surgery again. The *p* value indicates the statistical significance of the changes in mean PROMs between the one-year and two-year postoperative intervals. *KOOS, JR;* Knee Injury and Osteoarthritis Outcome Score for Joint Replacement.

## Discussion

The main finding of this study was that coronal alignment and joint line orientation of lateral compartment osteoarthritic knees demonstrated a large pre- and postoperative variability. Interestingly, 23.6% of knees with isolated lateral compartment OA did not have a pre-arthritic valgus alignment. No significant differences in postoperative PROMs were found between individual postoperative CPAK phenotypes or between preservation- or alteration of CPAK phenotypes.

Recent studies have provided evidence to support a patient-specific, phenotype-dependent surgical approach of UKA[6-8]. These studies observed that approximately 15% of the healthy and generalized OA population have a neutral coronal alignment with a neutral joint line, suggesting that coronal alignment and joint line orientation is highly variable. Isolated lateral compartment OA is a relatively rare form of OA with a reported prevalence of 10%[9, 18]. To the authors' knowledge, no previous study analyzed the phenotype distribution specifically in a population with isolated lateral compartment OA prior to- and following lateral UKA. Moreover, no study has analyzed the association between phenotype distribution and postoperative PROMs in a lateral OA cohort.

This study demonstrated a highly variable preoperative CPAK phenotype distribution. This emphasizes the high level of coronal alignment, as well as joint line orientation diversity within a specific cohort of patients with isolated lateral compartment OA. The observed diversity might suggest that there is not one universal optimal alignment target and that a patient-, and knee phenotype specific approach might be superior. Additionally, it was observed that 76.4% of the preoperative cohort had a valgus alignment (CPAK 3, 6 and 9). The high prevalence of valgus aligned phenotypes observed in the present study is in line with existing literature[19]. Valgus aligned knees have increased load on the lateral compartment, based on the morphology of the joint surfaces and the mechanical axis of the lower limb. Due to increased load, the lateral compartment is more prone to the progression of OA[9, 10, 20]. However, since lateral compartment OA is believed to be a valgus-related disease, it is intriguing to note that 23.6% of patients within this lateral compartment OA cohort did not demonstrate a pre-arthritic valgus alignment. A pre-arthritic neutral alignment was observed in 22.0% of patients (CPAK 2, 5 and 8) and a pre-arthritic varus alignment was observed in 1.6% of patients (CPAK 1, 4 and 7). Within both sub-cohorts, the CPAK phenotypes with the apex distally positioned joint line (CPAK 1 and 2) were predominant (varus subgroup: CPAK 1 1.6%; CPAK 4 0%; CPAK 7 0%) (neutral subgroup: CPAK 2 16.1%; CPAK 5 5.6%; CPAK 8 0.3%). MacDessi *et al*[8] and Hirschmann *et al*[6] investigated phenotype distribution in both non-arthritic and generalized OA cohorts. MacDessi *et al*[8] reported a similar prevalence of knees with an apex distally positioned joint line in a generalized OA cohort (67.0%), which might suggest that progression of OA does not affect the morphology of the joint line[8].

Postoperatively, variability in phenotype distribution increased. This outcome contrasts with the initial hypothesis, which proposed that postoperative variability would decrease, given that all patients underwent the same surgical approach, with a uniform objective of achieving coronal realignment to 0° to 4° of valgus. The increase in phenotype variability might be caused by an unaccounted-for factor. Mochizuki *et al*[21] reported that, in addition to component position, several intrinsic factors including preoperative rotational alignment, knee range of motion and tibial torsion affected postoperative rotational lower limb alignment, which might have influenced the increase in variability of distribution in this study.

Short-term postoperative PROMs observed in the present study were satisfactory. Our data suggests that the association between CPAK phenotype preservation and patient outcomes is minimal. Initially, this study noted that patients with preservation of CPAK 5 had a significantly higher Kujala score than patients who had an altered postoperative phenotype. However, after adjusting for potential confounders, this difference did not remain significant, as age had a significant confounding effect. This contrasts with findings from Howell *et al*[22] and Kaneko *et al*[23], who analyzed the Hirschmann phenotype distribution of medial, lateral and generalized osteoarthritic knees, demonstrating a significant difference in PROMs between phenotypes[6]. Thus, additional studies are necessary to determine a final conclusion of this association.

This study has several limitations, including the retrospective study design which might have caused selection bias. Second, some phenotypes were absent. This scarcity made inter-phenotype analyses of PROMs underpowered and thus were unable to be conducted. Nonetheless, this study represented the largest cohort to date with 305 patients that described the distribution of CPAK phenotypes and their association with PROMs in knees with lateral compartment OA. Third, the JLO angle describes the combined femoral- and tibial joint line as a single value, and the femoral- and tibial joint line orientations can differ considerably[6]. As CPAK utilizes the JLO, this difference is not accounted for in the present study. Furthermore, the CPAK classification does not take the sagittal alignment into account. Some literature has suggested that modification of the tibial posterior slope is essential in achieving native knee kinematics[24, 25]. Knee phenotyping remains a relatively novel issue in knee arthroplasty and will require additions regarding the previously mentioned shortcomings of CPAK. However, up until now, CPAK phenotyping has already shown some clinical relevance in phenotype-specific alignment strategies[26].

**Conclusion**

Coronal alignment and joint line orientation were highly variable within a lateral compartment OA cohort. However, no association was demonstrated between superior postoperative PROMs and phenotype variation or phenotype preservation, which might suggest that there is not one universal optimal alignment target. Interestingly, 23.6% of knees with lateral compartment OA did not have a pre-arthritic valgus alignment which may have been affected by joint line orientation.

**Table 2.** Preoperative and postoperative CPAK distribution by sex, obesity and age groups.

| | *N* (%) | | | *N* (%) | | | *N* (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| CPAK | Male | Female | *p* value | Obese | Non-obese | *p* value | <50 years | 50-70 years | >70 years | *p* value[x] |
| **Preoperative distribution** | | | | | | | | | | |
| 1 | 5 (100%) | 0 (0.0%) | 0.122 | 0 (0.0%) | 5 (100.0%) | 1.000 | 0 (0.0%) | 3 (60.0%) | 2 (40.0%) | 0.724 |
| 2 | 29 (59.1%) | 20 (40.9%) | 0.008* | 6 (15.8%) | 32 (84.2%) | 0.311 | 10 (20.4%) | 27 (55.1%) | 12 (24.5%) | 0.022* |
| 3 | 61 (37.0%) | 104 (63.0%) | 0.551 | 27 (22.3%) | 94 (77.7%) | 0.912 | 16 (9.7%) | 100 (60.6%) | 49 (29.7%) | 0.992 |
| 4 | 0 (0.0%) | 0 (0.0%) | - | 0 (0.0%) | 0 (0.0%) | - | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | - |
| 5 | 5 (29.4%) | 12 (70.6%) | 0.294 | 2 (15.4%) | 11 (84.6%) | 0.554 | 1 (5.9%) | 11 (64.7%) | 5 (29.5%) | 0.861 |
| 6 | 26 (40.6%) | 38 (59.4%) | 0.813 | 14 (30.4%) | 32 (69.6%) | 0.123 | 1 (1.6%) | 41 (64.1%) | 22 (34.5%) | 0.048* |
| 7 | 0 (0.0%) | 0 (0.0%) | - | 0 (0.0%) | 0 (0.0%) | - | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | - |
| 8 | 0 (0.0%) | 1 (100.0%) | 1.000 | 1 (100.0%) | 0 (0.0%) | 1.000 | 1 (100.0%) | 0 (0.0%) | 0 (0.0%) | 1.000 |
| 9 | 2 (50.0%) | 2 (50.0%) | 1.000 | 0 (0.0%) | 2 (100.0%) | 1.000 | 0 (0.0%) | 3 (75.0%) | 1 (25.0%) | 0.853 |
| **Postoperative distribution** | | | | | | | | | | |
| 1 | 5 (83.3%) | 1 (16.7%) | 0.094 | 0 (0.0%) | 5 (100.0%) | 1.000 | 0 (0.0%) | 4 (66.7%) | 2 (33.3%) | 0.732 |
| 2 | 29 (67.4%) | 14 (32.6%) | <0.001* | 10 (30.3%) | 23 (69.7%) | 0.223 | 4 (9.3%) | 33 (76.7%) | 6 (14.0%) | 0.041* |
| 3 | 25 (37.3%) | 42 (62.7%) | 0.382 | 11 (22.0%) | 39 (78.0%) | 0.992 | 7 (10.4%) | 38 (56.7%) | 22 (32.8%) | 0.763 |
| 4 | 3 (100%) | 0 (0.0%) | 1.000 | 0 (0.0%) | 3 (100.0%) | 1.000 | 1 (33.3%) | 2 (66.7%) | 0 (0.0%) | 0.261 |
| 5 | 34 (52.3%) | 31 (47.7%) | 0.064 | 9 (19.1%) | 38 (80.9%) | 0.592 | 9 (13.8%) | 34 (52.3%) | 22 (33.8%) | 0.222 |
| 6 | 27 (27.0%) | 73 (73.0%) | <0.001* | 18 (24.3%) | 56 (75.7%) | 0.561 | 8 (8.0%) | 57 (57.0%) | 35 (35.0%) | 0.364 |
| 7 | 0 (0.0%) | 1 (100.0%) | 1.000 | 0 (0.0%) | 1 (100.0%) | 1.000 | 0 (0.0%) | 1 (100.0%) | 0 (0.0%) | 1.000 |
| 8 | 1 (16.7%) | 5 (83.3%) | 0.412 | 0 (0.0%) | 6 (100.0%) | 1.000 | 0 (0.0%) | 5 (83.3%) | 1 (16.7%) | 0.482 |
| 9 | 3 (21.4%) | 11 (78.6%) | 0.111 | 2 (20.0%) | 8 (80.0%) | 0.874 | 0 (0.0%) | 11 (78.6%) | 3 (21.4%) | 0.282 |

Preoperative and postoperative CPAK phenotype distribution is presented in numbers and frequencies (%) and stratified by sex, obesity and age. Obesity was classified as having a body mass index of 30 kg/$m^2$ or above. *CPAK,* coronal plane alignment of the knee.

[x] Kruskal-Wallis test

* Indicates significant value

**Table 3.** Preoperative and postoperative CPAK distribution by sex, obesity and age groups.

| | | Postoperative CPAK phenotypes | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Variables | Total | CPAK1 | CPAK2 | CPAK3 | CPAK5 | CPAK6 | CPAK9 | *p* value |
| **One-year postoperative PROMs** | | | | | | | | |
| Number of knees | 188 | 5 | 34 | 88 | 11 | 47 | 3 | |
| **KOOS, JR** | | | | | | | | |
| Mean ± SD | 83.0 ± 12.6 | 88.1 ± 13.3 | 79.2 ± 11.3 | 82.6 ± 13.9 | 82.3 ± 14.5 | 83.5 ± 11.0 | 100.0 ± 0.0 | 0.359 |
| *N* (%) achieved PASS (≥ 70.0) | 165 (87.7%) | 4 (80.0%) | 30 (88.2%) | 76 (86.4%) | 10 (90.9%) | 42 (89.4%) | 3 (100.0%) | 0.811 |
| *N* (%) achieved maximum (100) | 56 (29.8%) | 2 (40.0%) | 6 (17.6%) | 31 (35.2%) | 4 (36.4%) | 10 (21.3%) | 3 (100.0%) | 0.193 |
| **Kujala** | | | | | | | | |
| Mean ± SD | 82.3 ± 12.3 | 84.2 ± 12.0 | 81.3 ± 14.8 | 84.7 ± 13.1 | 90.9 ± 8.4 | 80.4 ± 12.6 | 86.1 ± 9.3 | 0.852 |
| *N* (%) achieved PASS (≥ 70.0) | 140 (74.4%) | 5 (100.0%) | 21 (82.4%) | 69 (89.8%) | 10 (90.9%) | 34 (89.4%) | 3 (100.0%) | 0.714 |
| *N* (%) achieved maximum (100) | 66 (35.1%) | 3 (60.0%) | 15 (47.0%) | 30 (34.1%) | 2 (18.2%) | 15 (31.9%) | 0 (0.0%) | 0.498 |
| **Patient satisfaction** | | | | | | | | |
| *N* (%) answered 'very satisfied' or 'satisfied | 177 (94.1%) | 4 (80.0%) | 31 (91.2%) | 85 (96.6%) | 10 (90.9%) | 44 (93.6%) | 3 (100.0%) | 0.928 |
| **Re-do surgery** | | | | | | | | |
| *N* (%) answered 'yes' | 174 (92.6%) | 4 (80.0%) | 31 (91.2%) | 84 (95.4%) | 8 (72.7%) | 44 (93.6%) | 3 (100.0%) | 0.956 |
| **Two-year postoperative PROMs** | | | | | | | | |
| Number of knees | 145 | 2 | 23 | 75 | 8 | 35 | 2 | |
| **KOOS, JR** | | | | | | | | |
| Mean ± SD | 86.2 ± 13.7 | 100.0 ± 0.0 | 83.4 ± 12.1 | 86.0 ± 14.9 | 86.8 ± 15.6 | 86.8 ± 12.0 | 100.0 ± 0.0 | 0.421 |
| *N* (%) achieved PASS (≥ 70.0) | 130 (89.7%) | 2 (100.0%) | 21 (91.3%) | 65 (86.7%) | 7 (87.5%) | 33 (94.3%) | 2 (100.0%) | 0.835 |
| *N* (%) achieved maximum (100) | 56 (38.6%) | 2 (100.0%) | 6 (26.1%) | 28 (37.3%) | 4 (50.0%) | 14 (40.0%) | 2 (100.0%) | 0.074 |
| **Kujala** | | | | | | | | |
| Mean ± SD | 85.0 ± 15.0 | 89.0 ± 0.0 | 88.0 ± 17.0 | 92.0 ± 17.0 | 92.0 ± 11.0 | 85.0 ± 14.0 | 88.0 ± 4.0 | 0.563 |
| *N* (%) achieved PASS (≥ 70.0) | 123 (84.8%) | 2 (100.0%) | 21 (91.3%) | 61 (81.3%) | 7 (87.5%) | 30 (85.7%) | 2 (100.0%) | 0.815 |
| *N* (%) achieved maximum (100) | 54 (37.2%) | 1 (50.0%) | 12 (52.2%) | 21 (41.3%) | 3 (37.5%) | 17 (48.6%) | 0 (0.0%) | 0.674 |
| **Patient satisfaction** | | | | | | | | |
| *N* (%) answered 'very satisfied' or 'satisfied | 135 (93.1%) | 2 (100.0%) | 22 (95.7%) | 70 (93.3%) | 7 (87.5%) | 32 (91.4%) | 2 (100.0%) | 0.954 |
| **Re-do surgery** | | | | | | | | |
| *N* (%) answered 'yes' | 136 (93.8%) | 2 (100.0%) | 22 (95.7%) | 68 (91.1%) | 8 (100.0%) | 34 (97.1%) | 2 (100.0%) | 0.832 |

One-year and two-year postoperative patient-reported outcomes measures (PROMs) were presented for the total cohort of patients with PROMs data available and for each postoperative CPAK phenotype individually. Continuous variables were presented as mean ± standard deviation (SD) and dichotomous variables in numbers and frequencies (%). *aHKA,* arithmetic hip-knee-ankle angle; *CPAK,* coronal plane alignment of the knee; *KOOS, JR,* Knee injury and Osteoarthritis Outcomes Score for Joint Replacement.

**Table 4.** Two-year postoperative PROMs according to preservation of CPAK phenotype.

| Variables | *N* (%) of knees | KOOS, JR | Kujala | Patient satisfaction | Re-do surgery |
|---|---|---|---|---|---|
| **Preservation of CPAK phenotype, total cohort** | | | | | |
| Preserved | 61 (42.1%) | 86.4 ± 13.6 | 83.6 ± 15.0 | 91.9% | 95.1% |
| Altered | 84 (57.9%) | 86.1 ± 13.9 | 85.5 ± 15.1` | 94.0% | 94.0% |
| *p* value | | 0.428 | 0.267 | 0.418 | 0.539 |
| **Preservation of CPAK phenotype 1** | | | | | |
| Preserved | 1 (50.0%) | 100 ± 0.0 | - | 100.0% | 100.0% |
| Altered | 1 (50.0%) | 100 ± 0.0 | 89.0 ± 0.0 | 100.0% | 100.0% |
| *p* value | | 0.399 | 0.111 | 0.5222 | 0.522 |
| **Preservation of CPAK phenotype 2** | | | | | |
| Preserved | 9 (29.1%) | 84.1 ± 10.3 | 82.8 ± 16.4 | 100.0% | 100.0% |
| Altered | 14 (70.9%) | 82.7 ± 14.0 | 91.1 ± 8.1 | 91.7% | 91.7% |
| *p* value | | 0.399 | 0.111 | 0.522 | 0.522 |
| **Preservation of CPAK phenotype 3** | | | | | |
| Preserved | 22 (29.3%) | 85.2 ± 16.3 | 80.0 ± 17.1 | 91.3% | 91.3% |
| Altered | 53 (70.7%) | 86.3 ±14.4 | 83.5 ± 16.6 | 94.2% | 92.2% |
| *p* value | | 0.384 | 0.237 | 0.639 | 0.901 |
| **Preservation of CPAK phenotype 5** | | | | | |
| Preserved | 5 (62.5%) | 93.7 ± 10.3 | 97.6 ± 2.6 | 100.0% | 100.0% |
| Altered | 3 (37.5%) | 69.6 ± 14.5 | 79.0 ± 15.6 | 66.7% | 100.0% |
| *p* value | | 0.107 | 0.015* | 0.375 | - |
| **Preservation of CPAK phenotype 6** | | | | | |
| Preserved | 18 (51.4%) | 84.9 ± 12.5 | 82.7 ± 13.6 | 84.2% | 94.7% |
| Altered | 17 (48.6%) | 88.9 ± 11.4 | 89.1 ± 14.3 | 100.0% | 100.0% |
| *p* value | | 0.175 | 0.142 | 0.234 | 0.543 |
| **Preservation of CPAK phenotype 9** | | | | | |
| Preserved | 2 (100.0%) | 100.0 ± 0.0 | 88.0 ± 4.0 | 100.0% | 100.0% |
| Altered | 0 (0.0%) | - | - | - | - |
| *p* value | | - | - | - | - |

Two-year postoperative patient-reported outcome measures (PROMs) were presented for preserved and altered CPAK phenotypes, described as mean ± SD standard deviation (SD). The percentages for patient satisfaction reflect the proportion of patients who were either 'very satisfied' or 'satisfied' with their surgical outcome, while the percentages for redo of surgery represents the proportion of patients who would undergo the surgery again, both described in numbers and frequencies (%). *CPAK,* coronal plane alignment of the knee; *KOOS, JR;* Knee Injury and Osteoarthritis Outcome Score for Joint Replacement.

* indicates statistical significance

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# GENERAL DISCUSSION AND SUMMARY

# Chapter 11

## General discussion and future perspectives

*"It is a wonderful alternative to more invasive treatments for knee arthritis"*

*Dr. Andrew D. Pearle*

By addressing the guiding questions outlined in this thesis, structured into three main sections, this thesis endeavors to refine and expand the prevailing perspectives on UKA as treatment for isolated compartment knee OA, with the overarching objective of promoting its broader adoption and acceptance within clinical practice.

*Patient suitability and implant selection*

Patient selection is key: proper patient selection and the appropriate choice of fixation are fundamental aspects of surgical planning in UKA, as they are intrinsically linked to implant longevity and overall surgical outcomes[1]. The current debate concerning the comparative superiority of different fixation methods for individual patients remains inconclusive. This lack of resolution may be attributed to a narrow research paradigm that centers predominantly on comparing cemented and cementless UKA, while frequently neglecting other critical variables and patient characteristics that can substantially influence the efficacy and outcomes of distinct fixation methods[2]. Considering the significant liberalization of the stringent 1989 Kozinn and Scott criteria[3], which originally restricted patient selection to individuals aged over 60 years (**Chapter 1**), along with the observable trend toward of a progressively younger demographic seeking knee arthroplasty, it is imperative to reassess outcomes of both cemented and cementless UKA, while accounting for age as a variable. The extensive ($n$ = 25,762) national joint registry study conducted in **Chapter 2** of this thesis confirmed our initial hypothesis, demonstrating that the implant survival of cemented and cementless Oxford mobile-bearing medial UKA, which is recognized as one of the most commonly utilized UKA implants in the Western world[4-6], is significantly associated with age. Our findings demonstrated that cemented fixation is associated with inferior short-term survival compared to cementless fixation in younger patients undergoing UKA. Specifically, cementless UKA was associated with a 27% lower risk of revision in patients aged between 50 and 60 years and a 54% lower risk in those under 50 years. Conversely, cementless fixation demonstrated a non-significant trend toward a 22% higher risk of revision compared to cemented fixation in older patients (> 70 years). The most significant observation, moreover, was the pronounced shift in failure patterns identified in cementless UKA within the older patient demographic. In contrast to the relatively low revision rates for periprosthetic fractures in patients younger than 60 years for both cemented and cementless UKA, periprosthetic fractures emerged as the predominant cause for revision in patients over 60 years undergoing specifically cementless UKA. This demographic demonstrated a significantly higher incidence of periprosthetic fractures compared to those receiving cemented UKA, which, in turn, was associated with increased revision rates due to tibial loosening across all age demographics. The inferior short-term survival rates of cemented fixation in younger patients, along with the distinctive failure modes observed across age demographics, may be attributed to the following premises: (1) bone quality, which tends to decline with age, serves as a crucial contributing determinant: denser bone is associated with significantly reduced cement infiltration at the bone-cement interface[7, 8], while poor bone quality likely constitutes the primary risk factor for periprosthetic fractures in cementless procedures[9, 10]; (2) unnecessary early revisions for tibial loosening may arise from the misinterpretation of radiolucent lines that lack clinical significance, a phenomenon more prevalent following cemented UKA[11-13]; and (3) the inability of cement to remodel (unlike cementless components that rely on osseointegration and press-fit fixation) combined with the higher activity levels among younger patients, expose the cement mantle to repetitive stress and loading, likely contributing to the elevated failure rates of cemented implants in this specific demographic[14]. Therefore, it is crucial to emphasize, that age alone should not serve as the sole determinant in opting for or against a specific mode of fixation. Instead, we advocate for a more nuanced approach, considering factors such as bone quality and the clinical significance of radiolucent lines, alongside age, when assessing the feasibility of performing cementless or cemented UKA, an approach endorsed by previous authors[9, 10]. In addition to the aforementioned recommendations, and irrespective of age, it is imperative to utilize both fixation methods with a requisite level of proficiency[1]. Successful cementation necessitates adequate bone preparation, the application of a thin and even layer of cement, sufficient penetration of the cement into the bone surface, and the removal of any debris. In the context of cementless UKA, it is crucial to avoid excessive resection, and to ensure careful impaction on the tibial plateau during the hammering phase of the procedure, especially in older patients with osteopenic bone. Consequently, a comprehensive approach that integrates both these recommendations with a thorough preoperative assessment is essential for optimizing the appropriate selection of fixation methods, thereby ensuring that interventions are appropriately tailored to the distinct characteristics of each patient.

While revision rates have significantly improved over the years, approximately 10% of unicompartmental knee arthroplasties in the Netherlands still necessitate revision surgery within the first 10 years postoperatively[15]. The clinical implications of revision arthroplasties are profound, given their inherent technical complexities and success rates, which are often markedly inferior to those of primary arthroplasties[16, 17]. While considerable attention has been directed to physical factors influencing the surgical success of UKA, non-physical, psychological factors are often inadequately addressed. As revision surgeries are frequently performed for unspecified reasons or unexplained pain[18, 19] (**Chapter 2**), it is imperative to identify additional predictors of dissatisfaction and unfavorable outcomes that may lead to revision surgery for symptoms devoid of identifiable pathology or technical complications. Though this phenomenon cannot be solely attributed to the following factors, it is recognized that a lack of both psychological and mental resilience, along with unrealistic patient expectations, may contribute to unmet outcomes and suboptimal rehabilitation following elective orthopedic surgeries[20]. We therefore assessed the relatively underexplored impact of several psychological factors, including pain catastrophizing, anxiety, and depression, on subjective outcomes in patients undergoing UKA (**Chapter 3**). Our prospective cohort study revealed that patients with these specific pre-existing psychological factors not only presented with suboptimal preoperative conditions but also experienced inferior postoperative subjective outcomes compared to patients without these psychological impairments. Additionally, patients with anxiety and depression experienced hospitalizations lasting over twice as long as those without these pre-existing psychological vulnerabilities. Interestingly, while anxiety and depression were associated with experiencing more severe postoperative pain, our findings revealed that patients with pain catastrophizing tendencies reported postoperative pain levels comparable to those without such tendencies, which contrasts with the existing literature on TKA[21, 22]. Furthermore, it is important to emphasize that, despite the relatively inferior outcomes associated with these psychological risk factors, patients with depression, anxiety, and pain catastrophizing tendencies demonstrated comparable improvements in subjective outcomes compared to those without these pre-existing conditions. These findings imply that the inferior postoperative outcomes primarily stem from the suboptimal preoperative condition, rather than an inherent inability to benefit from UKA. Consequently, the precise nature of the relationship between psychological frailty and adverse postoperative outcomes remains ambiguous. Do patients experience inferior outcomes as a direct consequence of their pre-existing psychological vulnerabilities, or does postoperative pain serve to exacerbate these conditions, ultimately culminating in worse overall outcomes? Regardless, the significance of mental health and predisposing psychological risk factors within the context of UKA should not be underestimated: “the mind matters” (**Chapter 3**). Nonetheless, we do not contend that patients with mental health problems should be unequivocally excluded from candidacy for UKA (or any joint replacement surgery). On the contrary, these patients may, in fact, experience substantial benefits from effective pain relief following UKA. Recognizing and identifying high-risk patients, however, is important to facilitate early screening and intervention, which may help to establish realistic patient expectations. While existing literature supports this assertion, it simultaneously identifies persistent barriers that hinder effective intervention, including the stigma surrounding mental health issues and the constraints of time and discomfort that surgeons often encounter when addressing these matters[23]. Thus, substantial potential persists for enhancing awareness and implementing strategies that effectively integrate psychological assessments into clinical practice.

The evaluation of patients for UKA is predominantly contingent upon comprehensive physical and radiographic assessments, which are essential for determining surgical candidacy. Pain localized to the medial compartment, along with radiographic isolated medial bone-on-bone OA, serve as the principal indication for medial UKA. When considering anatomical criteria, surgeons often demonstrate considerable hesitance regarding the suitability of patients presenting with severe extra-articular deformities as ideal candidates for UKA, often opting for corrective osteotomies or TKA instead. While definitive thresholds for the severity of extra-articular deformities deemed acceptable remain elusive, this inherent ambiguity may inadvertently result in the exclusion of a significant proportion of patients from consideration for UKA. In the context of anteromedial OA, extensive phenotypic characterization has demonstrated that approximately 33% of patients present with proximal tibial varus deformities, either in isolation or concomitantly with femoral deformities (**Chapter 7**). This underscores the considerable prevalence of such deformities within a population that would otherwise likely be perceived as highly appropriate candidates for UKA. Our study demonstrated that patients with preoperative tibial varus deformities undergoing medial UKA did not show significant differences in PROMs nor differences in clinical improvement when compared to those devoid of such deformities (**Chapter 4**). This phenomenon may be explained by the observation that the MPTA demonstrates a weak correlation with pre-arthritic alignment restoration (**Chapter 7**), a nuance that will be discussed in greater depth later in this thesis. By aligning our findings with existing literature demonstrating no adverse effects of tibial varus deformities on survivorship and functional outcomes in patients with isolated medial OA undergoing UKA[24, 25], we endorse for the safe utilization of medial UKA as an effective surgical intervention for managing isolated anteromedial OA, even in the presence of preoperative extra-articular tibial varus deformities. Implying that concerns regarding the implications of these deformities may lack a substantive basis and affirming the viability of these patients as suitable candidates for medial UKA.

*Return to sport and physical function*

*"My only goal was to be pain free, so it's pretty wild to look back and see the work and steps that led me back to ski racing" – Lindsey Vonn, renowned U.S. Olympic and World Cup alpine skiing champion, after returning to the World Cup podium as runner-up less than a year after undergoing lateral UKA at the age of 39*

Vonn's remarkable return to elite competition after lateral UKA exemplifies the gradual relaxation of the stringent criteria initially imposed on UKA, which once restricted the procedure to patients who did not engage in heavy labor or moderate to high-impact physical activities (**Chapter 1**). In contemporary clinical practice, the growing prevalence of physically active patients considering knee replacement reflects a fundamental shift, wherein surgical intervention is increasingly regarded not merely as a means of pain alleviation but as a deliberate approach to reclaim high levels of physical performance. Beyond the relaxation of surgical indications, this phenomenon is driven by a demographic transition, characterized by the growing number of younger patients undergoing knee arthroplasty. **Chapter 5** and **6** of this thesis not only systematically evaluate return to sport outcomes following both medial and lateral UKA. They also offer a comparative analysis against alternative interventions for isolated compartment OA and differentiate outcomes according to varying levels of impact. Consistent with earlier studies, our findings confirm that UKA is associated with significantly higher rates of return to sport compared to TKA, with patients undergoing TKA demonstrating a 47% lower likelihood of resuming sporting activities postoperatively (**Chapter 5**). Of even greater significance are the markedly higher rates of patients returning to high-impact sports following UKA compared to those undergoing TKA or patellofemoral arthroplasty. This demonstrates that UKA not only achieves superior RTS rates, but it also facilitates patients' resumption of high-impact physical activities to a greater extent than TKA.

While the anticipated RTS outcomes for patients with medial compartment OA undergoing UKA are becoming increasingly well defined, as evidenced by the predominance of studies focusing on medial UKA in the preceding chapter, those for patients receiving treatment for lateral compartment OA remain largely undefined. Through a comprehensive and systematic review of the literature on RTS outcomes among patients with lateral compartment OA undergoing lateral UKA or DFO, it became evident that both procedures enable the vast majority of patients to resume athletic activity, with many also reclaiming their preoperative level of performance (**Chapter 6**). When stratifying RTS outcomes by impact level, it was demonstrated that lateral UKA, despite achieving high overall RTS rates (92%), is associated with a shift toward less demanding, lower-intensity regimes. This phenomenon likely reflects the older age at which patients typically undergo lateral UKA compared with DFO (mean 58 vs 40 years), as well as the concerns regarding implant failure, which patients commonly cite as reason for reducing or discontinuing sports (**Chapter 6**). While both DFO and lateral UKA serve as effective and relatively joint-preserving interventions for lateral compartment OA, and markedly outperform TKA in facilitating RTS, their indications are not universally interchangeable. Accordingly, the decision regarding their implementation should be guided by a nuanced, patient-specific assessment that carefully considers the presence and severity of anatomical deformities, athletic aspirations, and the extent of joint degeneration, thereby ensuring a thorough evaluation of patient suitability and optimizing the potential for high levels of physical performance. Collectively, these chapters emphasize the importance of systematically incorporating return to sport outcomes into preoperative counseling, enabling clinicians to establish realistic and informed patient expectations, minimize the likelihood of postoperative dissatisfaction, and tailor surgical approaches to individual functional aspirations.

*Phenotypic manifestations of isolated compartment knee osteoarthritis*

Amidst the considerable progress made in the exploration of unique phenotypic manifestations and personalized alignment methodologies in TKA, the findings presented in this thesis represent a novel contribution as the first effort to extend these principles to the context of UKA. At present, two novel systems for the classification of phenotypes have been established, both of which are utilized in this thesis. In contrast to the CPAK classification, which condenses characterization to nine predefined phenotypes based on two variables[26], the functional knee phenotype classification allows for a more comprehensive categorization[27]. While some may argue that the functional knee phenotype system offers a more nuanced assessment by allowing the separate evaluation of the femur and tibia, the emergence of a plethora of phenotypes, only a few of which are deemed relevant, raises questions about its practical utility and potential for disarray. By employing both classification systems, however, this thesis sought to maintain a broad perspective, while intentionally avoiding the discourse regarding the superiority of one classification system over the other. Instead, it posits that the effectiveness and relevance of each system are fundamentally determined by the specific objectives and contextual factors guiding their application.

The relatively large ($n$ = 1,000) studies performed in **Chapter 7** and **8**, which specifically focus on anteromedial OA, demonstrate that there is considerable inter-patient variability in the expression of coronal knee phenotypes in knees affected by this specific form of OA. These findings challenge the historically accepted notion that the well-defined clinicopathological pattern of anteromedial OA, recognized as the primary indication for medial UKA, exhibits uniform features. Suggesting instead that its manifestation may vary substantially among individual patients. The majority of knees exhibited CPAK phenotype I (45%), which is consistent with a pre-arthritic varus alignment and distal-oriented joint line obliquity (**Chapter 7**), the prevalence of which was significantly higher than that observed in both non-arthritic knees and those affected by generalized OA[26, 28-31]. Moreover, approximately 6% of patients exhibited a pre-arthritic valgus alignment, thereby contradicting the prevailing biomechanical assumption that medial OA occurs exclusively in varus-aligned knees. Following an even more nuanced examination of distinct phenotypes, a total of 76 functional knee phenotypes were identified, 25 of which were considered relevant (i.e., prevalence ≥ 1%), thereby putting an even greater emphasis on the extensive variability inherent in this specific form of OA (**Chapter 8**). Sex-related anatomical variations were evident among patients with isolated anteromedial OA, with males displaying more pronounced pre-arthritic varus alignment and a higher prevalence of CPAK I, whereas females demonstrated a greater predisposition to neutral and valgus alignment phenotypes. Awareness of these sex-specific anatomical differences is essential for surgeons, as it informs preoperative assessment and supports surgical decision-making.

The gold standard for implantation of knee components has historically adhered to a standardized approach, designed to ensure uniformity across all patients. In the context of medial UKA, the optimal alignment target has been established within a varus alignment range of 1° and 4°[32]. This methodology was initially conceived to simplify implantation, thereby enhancing both the reliability and predictability of the procedure in the hands of the surgeon. However, given the increasing recognition of the inherent complexities associated with knee anatomy, it is essential to explore patient specific approaches that prioritize tailored solutions over dogmatic, one-size-fits-all strategies. Modern discourse asserts that achieving optimal knee stability, kinematics and clinical functionality requires meticulous restoration of each patient's unique joint anatomy and soft tissue balance, highlighting the adverse clinical ramifications of applying uniform principles without considering individual anatomical variations[33]. Recent evidence has demonstrated that the implementation of these so-called personalized alignment approaches, which involve restoring the knee to its pre-arthritic alignment, is associated with improved survivorship and favorable functional outcomes, a practice also commonly referred to as the kinematic alignment technique[33-36]. It was observed that only 45% of patients preserved their preoperative CPAK phenotype (**Chapter 7**). The CPAK classification serves as a surrogate indicator of the pre-arthritic state by integrating both the pre-arthritic alignment and the joint line obliquity, parameters that remain unaffected by degenerative loss of medial joint space, provided that significant bone loss is absent. These findings suggest that, while a ligament-guided approach is effective in restoring soft tissue balance, it does not necessarily achieve restoration of a patient's native phenotype. **Chapter 8** provided further elucidation on this topic, demonstrating that knees exhibiting combined tibial and femoral deformities were associated with a lower probability of restoring pre-arthritic alignment compared to knees without extra-articular deformities or those with isolated femoral or tibial deformities. This implies that an exclusive reliance on medial collateral ligament re-tensioning, considered the surgical objective for restoring pre-arthritic alignment, might not be sufficient to restore both the pre-arthritic alignment and the corresponding knee phenotype. Consequently, this suggests that the implementation of additional strategies may be necessary to achieve a comprehensive restoration of both the native anatomical integrity and knee phenotype. While our study did not examine clinical outcomes, thereby leaving the implications of these findings in this context ambiguous, existing literature indicates that patients who preserve their native CPAK phenotype following medial UKA demonstrate favorable clinical outcomes[37, 38]. Thus, it may be inferred that phenotypes demonstrating minimal restoration of pre-arthritic alignment may be less suitable for medial UKA.

Although the lateral compartment of the knee considerably differs from the medial compartment in terms of anatomy, kinematics, and loading during movement, factors that likely contribute to its relative protection and lower prevalence of OA (**Chapter 1**), many studies continue to neglect its consideration as a separate entity. In **Chapter 9** and **10**, a comprehensive examination is dedicated specifically to this unique manifestation of isolated compartment OA. A total of 60 functional knee phenotypes were identified, among which 26 were considered relevant. Preoperatively, more than half of the patients were classified as exhibiting CPAK phenotype III, characterized by a pre-arthritic valgus alignment and distal-oriented joint line obliquity. Following lateral UKA, the majority of knees were restored to a phenotype defined by valgus alignment and a neutral-oriented joint line obliquity (**Chapter 10**). While the coronal deformity predominantly manifested as isolated tibial deformity, greater valgus limb phenotypes were more often associated with concurrent tibial and femoral deformities. A notable distinction was identified in younger patients, wherein the predominant deformity was primarily localized to the femur. These findings imply that careful consideration of distinct functional knee phenotypes and coronal deformity manifestations could prove beneficial when planning surgical intervention. Corrective osteotomies, especially suitable for young, active patients aspiring to return to high-impact sports, typically require femoral osteotomies in cases of valgus OA (**Chapter 6**). In cases of isolated femoral deformities, osteotomies may hold the potential to yield favorable outcomes by realigning the lower limb, correcting the underlying deformity, and unloading the lateral compartment, all while potentially delaying or even avoiding the need for knee arthroplasty. However, while femoral varus osteotomies may be considered as highly promising option for this specific patient demographic, it is advised to refrain from assuming their universal applicability for all cases of lateral compartment OA, especially considering that a significant proportion of patients exhibit tibial involvement (**Chapter 9**). It is important to highlight, however, that optimal care begins with accurate and informed patient selection, wherein the selection of the most appropriate and minimally invasive intervention is guided by a thorough understanding of the patient's unique clinical, anatomical, and functional characteristics.

The final chapter of this thesis represents a preliminary investigation into the potential association between phenotypic restoration and improved clinical outcomes following lateral UKA. Previous studies, including a subsequent investigation conducted by our research group, though not included in this thesis, have demonstrated that preservation of the preoperative phenotype and pre-arthritic alignment is associated with superior postoperative outcomes following both medial UKA and TKA[37, 39-41]. In contrast, in the present chapter no significant differences in PROMS were observed among the various phenotypes, nor was any association identified between the preservation of preoperative CPAK phenotypes and superior PROMs. This discrepancy may be attributable to the fact that the majority of knees fall within the so-called "safe zone", wherein ligament-guided approaches are generally sufficient to achieve favorable outcomes. Accordingly, it is plausible that the most profound avenues for advancement reside within the anatomical outliers, knees in which the alignment and biomechanical characteristics deviate substantially from the normative framework. These cases are likely to benefit most from nuanced, patient-specific approaches, as conventional strategies may fail to adequately address their unique anatomical complexities. Collectively, these observations highlight the still relatively unknown implications of knee phenotypes and their significance in clinical practice. Nevertheless, we contend that a fundamental transition toward innovative, personalized approaches, incorporating individual anatomical variations and patient-specific characteristics into surgical decision-making, will be instrumental in defining the future of modern knee arthroplasty.

## Future perspectives

*Dr. Charles Rivière: "With talent, expertise and technological support, there is no doubt that a personalized & à la carte philosophy for replacing joints will play a significant role in our future"*

This thesis was motivated by the continuous pursuit of promoting the wider adoption and acceptance of UKA, while simultaneously contributing to the development of more refined, innovative strategies tailored to the individual variations among patients. The transition towards personalized, patient-specific, approaches is expected to confront numerous challenges in the future, including economic constraints and the inherent technical complexities associated with delivering personalized care. These challenges necessitate a higher level of expertise, potentially confining the implementation of these methodologies to subspecialized, high-volume expert surgeons. Moreover, advancements in surgical precision, now possible through innovative techniques using computer-assisted navigation and robotics, herald an exciting era for knee replacement surgery. These innovations hold profound promise to play a significant role in the evolution of orthopedic practice, offering substantial opportunities for improving clinical outcomes and enhancing patient satisfaction in the field of UKA. It is through the adoption of tailored strategies and innovative techniques that we can move beyond the constraints of the uniform mold, appreciating the inherent complexity of individual knees and fostering more nuanced, patient-centered approaches in UKA.

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# Chapter 12

Summary

**Chapter 1** presents a general introduction to isolated compartment OA and meticulously discusses the merits and drawbacks of UKA as minimally invasive alternative to TKA for managing this specific form of knee OA. It addresses various misconceptions surrounding UKA and introduces the guiding question outlined in this thesis.

*Patient suitability and implant selection*

The first part of this thesis primarily focused on identifying patient-related factors that influence patient suitability for UKA, as well as discerning the most appropriate fixation strategy for its implementation.

**Chapter 2** of this thesis compared the short-term implant survival and modes of failure between cemented and cementless fixation for the mobile-bearing Oxford medial UKA across various age groups. In this Dutch registry study, which included 25,762 patients of whom 8,023 (31.1%) underwent cemented fixation and 17,747 (68.9%) cementless fixation, it was demonstrated that implant survival for both cemented and cementless UKA was significantly associated with age. Notably, cementless fixation outperformed cemented fixation in short-term survival among younger patients (< 60 years) undergoing medial UKA, while among older patients (> 70 years), a noticeable yet statistically non-significant trend towards a higher revision rate for cementless UKA was observed compared to cemented UKA. Distinct failure patterns between fixation techniques emerged across various age groups, with revision for tibial loosening being associated with cemented UKA, while elevated rates of periprosthetic fractures were specifically identified among elderly patients (> 60 years) undergoing cementless UKA.

**Chapter 3** prospectively investigated how psychological factors (pain catastrophizing, anxiety and depression) affect preoperative and postoperative subjective outcomes in 150 patients undergoing medial or lateral UKA. It was observed that preoperative pain catastrophizing, anxiety and depression were associated with inferior outcomes both prior to and following UKA. Depression seemed to exert the most substantial adverse impact on outcomes resulting in significantly inferior outcomes in subjective function, quality of life, forgotten joint score, and pain compared to patient without these psychological factors during all follow-up assessments. Notably, patients with anxiety and depression experienced a length of hospital stay exceeding twice that of their counterparts without such psychological impairments. Nonetheless, it was demonstrated that patients with pre-existing psychological factors demonstrated comparable improvements in subjective outcomes compared with patients without these psychological factors.

In **Chapter 4** a retrospective study was performed among 104 patients undergoing robotic-arm assisted fixed-bearing medial UKA, aimed to evaluate the impact of preoperative extra-articular proximal tibial varus deformities on preoperative and postoperative subjective outcomes. Patients were categorized based on their preoperative medial proximal tibial angle into patients with (44%) and without (56%) excessive tibial varus deformities. The most important finding of this study was that the presence of such deformities did not result in inferior subjective outcomes, patient satisfaction nor differences in clinical improvement following UKA. Thus, while preoperative tibial varus may predispose patients to a more pronounced residual varus alignment following UKA, this does not translate into inferior outcomes.

*Return to sport and physical function*

The second part of this thesis aimed to elucidate on the expected return to sport rates and level of physical function following both medial and lateral UKA.

In **Chapter 5**, a systematic review of 38 studies (7,634 patients) was performed to evaluate the outcomes of return to sport following TKA (22 studies; 5,597 patients), UKA (22 studies; 1,931 patients), and patellofemoral arthroplasty (3 studies; 106 patients). Return to sport rates were higher for UKA (80.7%) compared to TKA (69.0%) and patellofemoral arthroplasty (68.4%). A meta-analysis of eight comparative studies examining return to sport rates following UKA vs TKA demonstrated that patients undergoing TKA were significantly less likely to resume sporting activities (OR 0.53). Additionally, patients undergoing UKA were more likely to resume high-impact activities compared to patients undergoing TKA.

**Chapter 6** comprises a systematic literature review of nine studies (256 patients) examining return to sport outcomes following lateral UKA (four studies; 125 patients) and DFO (five studies; 127 patients). Both procedures demonstrated high return to sport rates of 89.7% for DFO and 92.4% for lateral UKA, with return to performance rates of 62.7% and 88.5%, respectively. High impact sport participation decreased following lateral UKA (11.5% to 3.4%), while remaining relatively stable following DFO (32.8% to 28.0%). Competitive-level athletes (10 patients) achieved a 100% RTS rate following DFO.

*Phenotypic manifestations of isolated compartment knee osteoarthritis*

The final section of this thesis provides novel insights into the phenotypic expressions of both isolated medial and lateral OA of the knee.

**Chapter 7** utilized the CPAK classification to evaluate the phenotypic variation among 1,000 knees with isolated anteromedial knee OA, both prior to and following medial UKA. A substantial diversity in CPAK phenotypes was observed, with 45% of knees maintaining their preoperative CPAK phenotype following medial UKA. CPAK phenotype I, characterized by a pre-arthritic varus alignment and an apex distal oriented JLO, had the highest prevalence. Furthermore, pre-arthritic varus alignment was significantly more prevalent among males, whereas pre-arthritic neutral and valgus alignments were significantly more common among females presenting with medial OA.

**Chapter 8** served as a continuation of the previous chapter, providing further elucidation on the anatomical location of deformities and examining the extent to which phenotypic variation influences the likelihood of pre-arthritic alignment correction in knees undergoing medial UKA for isolated anteromedial OA.

Preoperatively, 76 distinct functional knee phenotypes were identified, of which 25 were deemed relevant (i.e., prevalence ≥ 1%). Postoperatively, the number of relevant functional knee phenotypes was reduced to 17 functional knee phenotypes. Knees with limb phenotypes associated with a more close-to neutral alignment predominantly displayed no extra-articular deformities, whereas more pronounced preoperative varus alignments were most frequently associated with isolated tibial or femoral deformities. The coexistence of both tibial and femoral deformities was associated with an even greater pre-arthritic varus alignment. Knees with combined tibial and femoral deformities were associated with a lower probability of restoring pre-arthritic coronal alignment following medial UKA.

**Chapter 9** conducted a retrospective assessment of preoperative phenotypic variations in the coronal plane of knees affected by the less commonly observed form of isolated lateral compartment OA. A total of 60 functional knee phenotypes were identified, of which 26 were classified as relevant, with the coronal deformity primarily manifesting as isolated tibial deformity. However, instances of severe valgus limb phenotypes were more frequently associated with concurrent tibial and femoral deformities. Notable gender-specific and age-related differences emerged, with females exhibiting significantly greater valgus values in both the mHKA and TMA. Additionally, younger patients (< 50 years) predominantly presented with isolated femoral deformities, while older patients primarily manifested isolated tibial or combined femoral and tibial deformities.

**Chapter 10** served as a continuation of the preceding chapter, incorporating an assessment of postoperative knee phenotypes while also making a preliminary attempt to integrate clinical outcomes in its assessment. A highly variable distribution of phenotypes was observed both preoperatively and following lateral UKA. CPAK phenotype III, characterized by a pre-arthritic valgus alignment and an apex distal oriented JLO, exhibited the highest prevalence. Following lateral UKA, the majority of knees were restored to CPAK phenotype VI. No significant differences in PROMs were observed among the various phenotypes, nor was any association identified between the preservation of preoperative CPAK phenotypes and superior PROMs.

Finally, a general discussion including conclusions and future perspectives, followed by a succinct summary that provides answers to the guiding questions of this thesis, is presented in **Chapter 11 & 12**.

## Summarized answers to the guiding questions outlined in this thesis

*"How do survival rates and failure patterns compare between cemented and cementless medial UKA across different age demographics, and should age be a determinative factor in selecting the most suitable fixation technique for individual patients?"*

- Cementless fixation outperforms cemented fixation in short-term survival among younger patients (< 60 years) undergoing medial UKA.
- Distinct failure patterns between fixation techniques emerged across various age groups, with revision for tibial loosening being associated with cemented UKA, while elevated rates of periprosthetic fractures were specifically identified among elderly patients (> 60 years) undergoing cementless UKA.
- Age alone should not serve as the sole determinant in opting for or against a specific fixation method. Instead, a more nuanced approach is advocated, which considers additional factors such as bone quality and the clinical significance of radiolucent lines, alongside age, when assessing the feasibility of performing cementless or cemented UKA.

*"How do psychological factors influence subjective outcomes following UKA, and should preoperative psychological status be a critical factor in the decision to proceed with UKA?"*

- Psychological factors, including pain catastrophizing, anxiety and depression are associated with inferior subjective outcomes both prior to and following UKA.
- Anxiety and depression were associated with extended duration of hospitalization lasting over twice as long as patients without these psychological factors.
- Depression seemed to exert the most substantial adverse impact on outcomes following UKA.
- Patients with pre-existing psychological factors demonstrated comparable improvements in subjective outcomes compared with patients without these psychological factors. Hence, it is plausible that the inferior outcomes primarily stem from the suboptimal preoperative condition rather than an inherent inability to benefit from UKA.
- Even in the context of influential psychological risk factors, UKA represents as a promising surgical intervention for addressing isolated compartment knee OA. However, the identification of high-risk patients is crucial for facilitating early screening and intervention.
- Failing to identify those elevated at risk may represent a missed opportunity to improve their functional recovery.

*"Does the presence of an extra-articular tibial varus deformity adversely affect outcomes following fixed-bearing medial UKA, and should caution be exercised when considering UKA in patients with excessive preoperative deformities?"*

- Extra-articular tibial varus deformities were evident in 44% of patients with anteromedial OA undergoing UKA.
- The presence of excessive preoperative extra-articular tibial deformities does not result in inferior subjective outcomes, patient satisfaction nor differences in clinical improvement following medial UKA.
- Preoperative tibial varus may predispose patients to a more pronounced residual varus alignment following medial UKA.
- The safe utilization of medial UKA as an effective surgical intervention for managing isolated medial OA was supported, even in the presence of preoperative tibial varus deformities.

*"What are the anticipated outcomes regarding return to sport and physical function following TKA, UKA and patellofemoral arthroplasty, and does one procedure demonstrate superior efficacy in achieving postoperative physical function over the other?"*

- Return to sport rates following TKA, UKA and patellofemoral arthroplasty were 69.0%, 80.7% and 68.4%, respectively.
- Patients undergoing TKA had 47% lower odds of returning to sport compared to those undergoing UKA.
- Patients undergoing UKA demonstrated a higher rate of return to high-impact sports compared to those undergoing TKA (65.4% vs 4.4%).
- UKA consistently outperforms both TKA and PFA in enabling patients to RTS. Its superiority is evident not only in overall return to activity rates but also in the successful resumption of high-impact sports.

*"What outcomes can be expected in terms of physical performance and return to sport following lateral UKA and distal femoral osteotomy?"*

- Return to sport rates following DFO and lateral UKA were 89.7% and 92.4%, while return to performance rates were 62.7% and 88.5%, respectively.
- Lateral UKA often leads to a transition from high-impact to lower-impact activities, while high-impact sport participation remained relatively stable following DFO.
- Nearly half of patients (46.0%) who underwent lateral UKA reported that precautionary measures to protect the prosthesis were their main reason for reducing or discontinuing sports.
- These findings suggest that both lateral UKA and DFO yield excellent RTS outcomes, with DFO being associated with greater durability of participation in high-impact sports.

*"To what extent do knees affected by anteromedial OA display uniform characteristics, and how are phenotypic expressions differentiated by gender and age?"*

- Despite the well-defined identical intra-articular wear-pattern in knees with anteromedial OA, there exist a significant variability in the phenotypic expressions in knees affected by this specific pattern of OA both preoperatively and postoperatively.
- CPAK phenotype I and II exhibited the highest prevalence (45% and 34%, respectively) and postoperatively there was a shift towards a more neutral alignment (CPAK II; 53%).
- Notably, approximately 6% of patients exhibited a pre-arthritic alignment in valgus.
- Gender-specific differences were evident with males exhibiting a significantly higher prevalence of pre-arthritic varus alignment compared to females, whereas the prevalence of pre-arthritic neutral and valgus alignment was significantly greater among females.
- Phenotypes exhibited no substantial variation among distinct age groups.
- Overall, 45% of knees maintained their preoperative CPAK phenotype following medial UKA, suggesting that relying solely on MCL re-tensioning might not be sufficient to restore both the pre-arthritic alignment and knee phenotype.

*"Which functional knee phenotypes are observed in knees with anteromedial OA, and is consideration of phenotypic variation of importance when aiming to restore pre-arthritic alignment?"*

- Preoperatively, 76 distinct and 25 relevant (prevalence ≥ 1%) functional knee phenotypes were identified, of which $VAR_{HKA}6°VAR_{FMA}3°NEU_{TMA}0°$ was the most common (9.4% of knees).
- Following medial UKA, a reduction from 25 to 17 postoperative relevant phenotypes was observed.
- Knees with combined deformities of the femur and tibia were associated with a lower probability of restoration of pre-arthritic coronal alignment compared to knees without extra-articular deformities, or knees with isolated deformities of the tibia or femur.

*"What is the extent of phenotypic diversity among patients with isolated lateral compartment OA, and how are the specific anatomical locations of extra-articular deformities distributed within these knees?"*

- Preoperatively, 80 distinct and 26 relevant (prevalence ≥ 1%) functional knee phenotypes were identified, of which $VAL_{HKA}6°NEU_{FMA}0°VAL_{TMA}3°$ was the most common (10.8% of knees).
- Females exhibited more pronounced valgus HKA and TMA values and were almost twice as likely to present with combined tibial and femoral valgus deformities compared with males.

- In younger patients (< 50 years), the deformity mainly manifested as isolated deformity in the femur, whereas in older patients (> 50 years) the deformity primarily manifested as isolated tibial- or combined femoral and tibial deformities.

*"In the context of isolated lateral compartment OA, is there a particular preoperative knee phenotype associated with superior outcomes, and does phenotypic restoration following lateral UKA yield superior postoperative outcomes?"*

- CPAK phenotype III was identified as the most prevalent preoperative phenotype (54%), whereas postoperatively, the majority of knees were restored to CPAK phenotype VI (33%).
- No significant differences were observed in PROMs among the various individual phenotypes.
- The restoration of phenotypes following lateral UKA was not associated with superior postoperative outcomes.

# Chapter 13

## Summary (in Dutch)

In **Hoofdstuk 1** wordt een uitgebreide inleiding gegeven waarin de unicondylaire knieprothese (UKP) wordt beschreven als minimaal invasief alternatief voor de totale knieprothese (TKP) bij de behandeling van geïsoleerde mediale en laterale gonartrose. Daarbij komen zowel de klinische voor- en nadelen van de UKP aan bod als veelvoorkomende misvattingen over deze ingreep. Tot slot worden de centrale onderzoeksvragen van dit proefschrift geïntroduceerd.

*Selectiecriteria en keuze van implantaatfixatie*

Het eerste deel van dit proefschrift richt zich primair op het identificeren van patiëntgerelateerde determinanten die de geschiktheid voor UKP beïnvloeden, evenals op het vaststellen van de optimale fixatiemethode voor de implantatie van deze prothese.

In **Hoofdstuk 2** werden de kortetermijnoverleving en de bijbehorende aanleidingen voor revisie van gecementeerde en ongecementeerde Oxford mediale UKP's geëvalueerd binnen verschillende leeftijdsgroepen. Deze omvangrijke Nederlandse registerstudie omvatte 25.762 patiënten. Er werd geconcludeerd dat ongecementeerde fixatie resulteerde in een betere kortetermijnoverleving bij jongere patiënten (< 60 jaar), terwijl bij oudere patiënten (> 70 jaar) een duidelijke, zij het statistisch niet-significante, trend werd waargenomen richting hogere revisiepercentages bij ongecementeerde fixatie. Daarnaast werden er leeftijdsgebonden verschillen gevonden in de redenen voor revisie. Aseptische loslating trad relatief vaker op in de gecementeerde groep, terwijl periprothetische fracturen voornamelijk voorkwamen bij oudere patiënten (> 60 jaar) in de ongecementeerde groep. Deze resultaten benadrukken het belang van een patiënt- en leeftijdsspecifieke afweging bij de keuze van implantaatfixatie voor mediale UKP.

**Hoofdstuk 3** onderzocht de invloed van psychologische factoren, waaronder pijncatastroferen, angst en depressie, op pre- en postoperatieve subjectieve uitkomsten bij 150 patiënten die een UKP ondergingen. De pre-existente aanwezigheid van deze psychologische risicofactoren werd geassocieerd met slechtere subjectieve uitkomsten, zowel voor als na de ingreep. Met name depressieve klachten bleken het sterkst gerelateerd aan een ongunstig beloop. De aanwezigheid van depressieve symptomen voorafgaand een UKP werd geassocieerd met slechtere functionele uitkomsten, lagere gezondheid gerelateerde kwaliteit van leven, lagere forgotten joint scores en hogere pijnscores. Daarnaast was de gemiddelde opnameduur bij patiënten met verhoogde angst- en depressieve klachten meer dan twee keer zo lang als bij patiënten zonder deze klachten. Opmerkelijk is dat patiënten met psychologische risicofactoren, ondanks hun ongunstige uitgangspositie, een vergelijkbare mate van verbetering in subjectieve uitkomstmaten realiseerden. Deze bevinding suggereert dat psychologische risicofactoren weliswaar een negatieve invloed hebben op het functionele eindresultaat en de ervaren ziektelast, maar dat de mate van postoperatieve verbetering niet wezenlijk wordt beperkt.

In **Hoofdstuk 4** werd retrospectief onderzocht hoe preoperatieve extra-articulaire proximale tibiale varusdeformiteiten de postoperatieve uitkomsten beïnvloeden onder 104 patiënten die een fixed-bearing mediale UKP ondergingen. Op basis van de mediale proximale tibia hoek werden patiënten ingedeeld in een groep mét (44%) en zonder (56%) significante extra-articulaire afwijking. De belangrijkste bevinding was dat de aanwezigheid van dergelijke extra-articulaire afwijkingen geen negatieve invloed had op subjectieve functionele uitkomsten, patiënttevredenheid of klinische verbetering na een UKP. Hoewel patiënten met een tibiale varusdeformiteit postoperatief vaker een residuele varus vertoonden, vertaalde dit zich niet in slechtere uitkomsten, wat erop wijst dat dergelijke afwijkingen geen absolute contra-indicatie hoeven te vormen voor mediale UKP.

*Sporthervatting en fysieke functie*

Het tweede deel van dit proefschrift richt zich op sporthervatting (RTS) en fysieke functionele uitkomsten na mediale en laterale UKP.

**Hoofdstuk 5** van dit proefschrift betrof een systematisch literatuuroverzicht van 38 studies (*n* = 7.634), waarin de RTS-uitkomsten werden geëvalueerd na TKP (22 studies, *n* = 5.597), UKP (22 studies, *n* = 1.931) en patellofemorale prothese (PFP; 3 studies, *n* = 106). De hoogste RTS-percentages werden waargenomen bij patiënten die een UKP ondergingen (80.7%), vergeleken met TKP (69.0%) en PFP (68.4%). Onze meta-analyse van acht vergelijkende studies bevestigde dat patiënten met een TKP significant minder vaak hun sportactiviteiten hervatten dan patiënten met een UKP (OR 0.53). Bovendien bleken patiënten na een UKP vaker in staat om terug te keren naar high-impact sporten. Deze bevindingen benadrukken dat UKP, in vergelijking met TKP en PFP, superieure functionele uitkomsten ondersteunt en een grotere kans biedt op behoud van een hoog functioneel en fysiek prestatieniveau.

**Hoofdstuk 6** omvatte een literatuurstudie van negen studies (*n* = 256), waarin de RTS-uitkomsten werden geëvalueerd na laterale UKP (4 studies, *n* = 125) en distale femurosteotomie (DFO; 5 studies, *n* = 127). RTS-percentages waren hoog voor zowel DFO (89.7%) als laterale UKP (92.4%), waarbij respectievelijk 62.7% en 88.5% het oorspronkelijke prestatieniveau bereikte. Na laterale UKP nam deelname aan high-impact sporten af (van 11.5% naar 3.4%), terwijl dit na DFO nagenoeg stabiel bleef. Opvallend was dat alle topsporters (*n* = 10) hun sport hervatten na DFO. Deze resultaten suggereren dat zowel laterale UKP als DFO uitstekende RTS-uitkomsten opleveren, waarbij DFO geassocieerd lijkt met gunstigere uitkomsten ten aanzien van terugkeer naar high-impact sporten.

*Fenotypische manifestaties van geïsoleerde*
*mediale en laterale gonartrose*

Het afsluitende deel van dit proefschrift biedt nieuwe inzichten in de fenotypische expressies van zowel geïsoleerde mediale als laterale gonartrose.

**Hoofdstuk 7** maakte gebruik van de CPAK-classificatie om de fenotypische diversiteit van 1,000 knieën met geïsoleerde mediale gonartrose te karakteriseren, zowel voorafgaand aan als na mediale UKP. Er werd een aanzienlijke variatie aan CPAK-fenotypes waargenomen. CPAK-fenotype I, gekarakteriseerd door een varusuitlijning en een distaal georiënteerde joint line, had de hoogste prevalentie. Bij mannen werden fenotypische varuskenmerken vaker waargenomen, terwijl fenotypische valguskenmerken overwegend bij vrouwen aanwezig waren. Na de ingreep behielden 45% van de patiënten hun oorspronkelijke pre-artrotische fenotype.

**Hoofdstuk 8** bouwde voort op deze bevindingen door de anatomische locaties van deformiteiten nader te analyseren en te onderzoeken in welke mate fenotypische variatie de kans op herstel van het oorspronkelijke alignement beïnvloedt. Preoperatief werden er 76 functionele fenotypen geïdentificeerd, waarvan 25 klinisch relevant werden geacht (prevalentie > 1%). Postoperatief reduceerde dit tot 17 relevante fenotypen. Knieën met een nagenoeg neutrale uitlijning vertoonden minimale extra-articulaire afwijkingen, terwijl uitgesproken varusuitlijning vaak samenhing met tibiale of femorale afwijkingen. Combinaties van tibiale en femorale afwijkingen waren geassocieerd met een verminderde kans op herstel van het oorspronkelijke alignement.

**Hoofdstuk 9** concentreerde zich op de preoperatieve fenotypische variatie in knieën met geïsoleerde laterale gonartrose. In totaal werden 60 functionele fenotypes vastgesteld, waarvan 26 als relevant werden beschouwd. De deformiteit manifesteerde zich voornamelijk als een geïsoleerde tibiale afwijking, terwijl meer uitgesproken valgusfenotypes vaker samengingen met gecombineerde tibiale en femorale afwijkingen. Significante geslachts- en leeftijdgebonden verschillen werden waargenomen. De fenotypische presentatie bij vrouwen onderscheidde zich door prominentere valguskenmerken ten opzichte van mannen. Jongere patiënten (< 50 jaar) hadden vooral femorale afwijkingen, terwijl oudere patiënten vaker tibiale of gecombineerde femorotibiale afwijkingen vertoonden.

In **Hoofdstuk 10** werd de relatie tussen postoperatieve fenotypes en klinische uitkomsten onderzocht. Een aanzienlijke fenotypische heterogeniteit werd waargenomen, zowel voor als na laterale UKP. Preoperatief vertoonde CPAK-fenotype III, gekarakteriseerd door een pre-existente valgusuitlijning en een distaal georiënteerde joint line, de hoogste prevalentie, terwijl postoperatief de meerderheid van de knieën werd hersteld naar een CPAK-fenotype VI. Er werd geen significant verband gevonden tussen het behoud van het oorspronkelijke fenotype en betere klinische uitkomsten, wat suggereert dat het behoud van het oorspronkelijke fenotype geen voorspellende waarde is voor beter functioneel herstel.

In **Hoofdstuk 11** en **12** volgt een algemene discussie, waarin de belangrijkste bevindingen worden samengevat, de centrale onderzoeksvragen worden beantwoord en een reflectie wordt geboden op toekomstige ontwikkelingen binnen het veld.

# APPENDICES

## Acknowledgements

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## Curriculum Vitae

Gaby Victoria ten Noever de Brauw was born on April 15, 1998, and grew up in Driebergen-Zeist, the Netherlands. After graduating from the Katholieke Scholengemeenschap in Zeist, she began her medical studies at the University of Amsterdam. In the period preceding the start of her clinical clerkship, she worked as an operating room assistant at Medische Kliniek Velsen in Velsen-Noord, the Netherlands. There, she assisted in a wide range of surgical procedures, particularly those involving the hip and knee. This hands-on experience provided her with her first meaningful exposure to orthopedic surgery and sparked a lasting interest in the field.

Prior to the start of her clinical clerkships, she had the opportunity to complete a research internship at the Hospital for Special Surgery in New York, United States, under the supervision of dr. A.D. Pearle. Upon returning to the Netherlands, she began her clinical clerkships while simultaneously initiating her PhD research, under the mentorship of dr. H.A. Zuiderbaan and prof. G.M.M.J. Kerkhoffs. Following the completion of her medical degree in 2026, she started working as a resident (not in training) at the Department of Orthopedic Surgery at Amphia Hospital in Breda, the Netherlands, where she continues to further develop her clinical and academic career in orthopedics.

# List of publications and presentations

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6. Vossen, R. J. M., Ten Noever de Brauw, G. V., Willems, J. H., Eshuis, R., Sierevelt, I. N., Spekenbrink-Spooren, A., & Zuiderbaan, H. A. (2025). The direct anterior approach in total hip arthroplasty may be associated with lower short-term mortality compared to various other approaches: a Dutch arthroplasty register study comprising 379,108 procedures. *Hip Int*. Published online August 18, 2025.

7. Rinne, J. S., Vossen, R. J. M., Ten Noever de Brauw, G. V., van der List, J. P., Custers, R. J. H., Pearle, A. D., & Zuiderbaan, H. A. (2025). Tobacco's toll: Comparable anterior cruciate ligament graft failure rates and inferior functional outcomes in smokers compared to non-smokers: A systematic review and meta-analysis. *Knee surgery, sports traumatology, arthroscopy.* Advance online publication.

8. Burger, J. A., Vossen, R. J. M., Bayoumi, T., Sierevelt, I. N., Ten Noever de Brauw, G. V., Spekenbrink-Spooren, A., & Zuiderbaan, H. A. (2025). National Trends in Unicompartmental Knee Arthroplasty During a Period of Significant Survivorship Improvements: Insights from the Dutch Arthroplasty Register. *The Journal of arthroplasty*. Advance online publication.

## Peer reviewed articles featured at scientific conferences

1. Bayoumi, T., ten Noever de Brauw, G.V., Ruderman, L.V., Zuiderbaan, H.A., & Pearle, A.D.: Magnitude of change in leg length and clinical impact following medial unicompartmental knee arthroplasty. Orthopaedic Research Society (ORS) annual meeting, 2023 February, Dallas, Texas, United States of America.

2. Bayoumi, T., ten Noever de Brauw, G.V., Ruderman, L.V., Zuiderbaan, H.A., & Pearle, A.D.: Magnitude of change in leg length and clinical impact following medial unicompartmental knee arthroplasty. American Academy of Orthopaedic Surgeons (AAOS) annual meeting, 2023 March, Las Vegas, Nevada, United States of America.

3. Ten Noever de Brauw, G.V., Aalders, M.B., Kerkhoffs, G.M.M.J., Zuiderbaan, H.A., Keijser, L.C.M., & Benner, J.L.: The mind matters: psychological factors influence subjective outcomes following unicompartmental knee arthroplasty: a prospective study. 4$^{th}$ World Arthroplasty Congress (WAC), 2024 April, Madrid, Spain.

4. Ten Noever de Brauw, G.V., Bayoumi, T., Ruderman, L.V., Kerkhoffs, G.M.M.J., Pearle, A.D., & Zuiderbaan, H.A.: Knees with anteromedial osteoarthritis show a substantial phenotypic variation prior and following medial unicompartmental knee arthroplasty. 21st European Society of Sports Traumatology, Knee Surgery & Arthroscopy (ESSKA) congress, 2024 May, Milan, Italy.

5. Vossen, R.J.M., Burger, J.A., ten Noever de Brauw, G.V., Bayoumi, T., Fiore, J.A., Ruderman, L.V., Zuiderbaan, H.A., & Pearle, A.D.: Preservation of pre-arthritic coronal knee phenotype and pre-arthritic coronal alignment yielded improved Kujala scores following ligament-guided medial unicompartmental knee arthroplasty. 21st European Society of Sports Traumatology, Knee Surgery & Arthroscopy (ESSKA) congress, 2024 May, Milan, Italy.

6. Bayoumi, T., ten Noever de Brauw, G.V., Ruderman, L.V., van der List, J.P., Kerkhoffs, G.M.M.J., Pearle, A.D., & Zuiderbaan, H.A.: Phenotype analysis of medial compartment osteoarthritis and treatment with medial unicompartmental knee arthroplasty: a radiographic review of 1000 knees. 21st European Society of Sports Traumatology, Knee Surgery & Arthroscopy (ESSKA) congress, 2024 May, Milan, Italy.

7. Vossen, R.J.M., Benner, J.L., ten Noever de Brauw, G.V., Kerkhoffs, G.M.M.J., Pearle, A.D., Zuiderbaan, H.A., & Keijser, L.C.M.: A different course of recovery for extension and flexion strengths following total and medial unicompartmental knee arthroplasty: a prospective cohort study of 369 cases. Personalized Arthroplasty Society Meeting, 2024 October, Chicago, United States of America.

8. Ten Noever de Brauw, G.V., Vossen, R.J.M., Bayoumi, T., Sierevelt, I.N., Pearle, A.D., Kerkhoffs, G.M.M.J., Spekenbrink-Spooren, A., & Zuiderbaan, H.A.: Distinct age-related modes of failure in cemented and cementless oxford medial unicompartmental knee arthroplasty: results from the Dutch arthroplasty register comprising 25,762 patients. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

9. Ten Noever de Brauw, G.V., Bayoumi, T., Ruderman, L.V., Kerkhoffs, G.M.M.J., Pearle, A.D., & Zuiderbaan, H.A.: Knees with anteromedial osteoarthritis show a substantial phenotypic variation prior and following medial unicompartmental knee arthroplasty. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

10. Ten Noever de Brauw, G.V., Aalders, M.B., Kerkhoffs, G.M.M.J., Zuiderbaan, H.A., Keijser, L.C.M., & Benner, J.L.: The mind matters: psychological factors influence subjective outcomes following unicompartmental knee arthroplasty: a prospective study. International Society of

Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

11. Ten Noever de Brauw, G.V., Bayoumi, T., Ruderman, L.V., Kerkhoffs, G.M.M.J., Zuiderbaan, H.A., & Pearle, A.D.: Knees with lateral compartment osteoarthritis show a substantial variability in functional knee phenotypes with gender-specific and age-related differences: phenotypic analysis of 305 knees. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

12. Vossen, R.J.M., Benner, J.L., ten Noever de Brauw, G.V., Kerkhoffs, G.M.M.J., Pearle, A.D., Zuiderbaan, H.A., & Keijser, L.C.M.: A different course of recovery for extension and flexion strengths following total and medial unicompartmental knee arthroplasty: a prospective cohort study of 369 cases. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

13. Vossen, R.J.M., ten Noever de Brauw, G.V., Willems, J.H., Eshuis, R., Sierevelt, I.N., Spekenbrink-Spooren, A., Pearle, A.D., & Zuiderbaan, H.A.: The association between mortality rate and various surgical approaches in primary total hip arthroplasty: a Dutch national joint registry study comprising 379,108 patients. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

14. Vossen, R.J.M., Burger, J.A., ten Noever de Brauw, G.V., Bayoumi, T., Fiore, J.A., Ruderman, L.V., Zuiderbaan, H.A., & Pearle, A.D.: Preservation of pre-arthritic coronal knee phenotype and pre-arthritic coronal alignment yielded improved Kujala scores following ligament-guided medial unicompartmental knee arthroplasty. International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) conference, June 2025, Munich, Germany.

15. Ten Noever de Brauw, G. V., Ruderman, L. V., Vossen, R. J. M., Sierevelt, I. N., van der List, J. P., Kerkhoffs, G. M. M. J., & Zuiderbaan, H. A.: Successful return to sport following distal femoral osteotomy and lateral unicompartmental knee arthroplasty for isolated lateral knee osteoarthritis: A systematic review and meta-analysis. Nederlandse Vereniging voor Arthroscopie (NVA) conference, September 2025, Noordwijk, The Netherlands.

## PhD portfolio

### Relevant workshops/masterclasses/meetings/courses

| | |
|---|---|
| 2023 | Smith & Nephew Academy Meeting: Physiological alignment of the knee and patient assessment (CPAK) meeting Utrecht, The Netherlands |
| 2024 | European Knee Society Meeting: "*Personalized alignment in TKA"* |
| 2024 | ESSKA-EKA Meeting: "*Personalized TKA. Where are we?"* |

### Peer review activities

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|---|---|
| 2025 to present | Reviewer for the *Journal of Experimental Orthopaedics, BMC Musculoskeletal Disorders, Acta Orthopaedica, The Knee, Journal of Orthopaedic Surgery and Research* |
| 2026 | Member of the national final review panel for the ESSKA formal consensus project entitled *"Indications in medial unicompartmental knee arthroplasty (UKA). The formal ESSKA-EKA consensus"* (presented at the ESSKA Annual Congress in Prague, May 2026). |

### Parameters of Esteem: Grands/Awards/Scholarships

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|---|---|
| 2022 | Awarded the U.V.S.V./N.V.V.S.U. Academy Grant to support a research internship at the Hospital for Special Surgery |

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| 2024 | ISAKOS Young Professional Task Force Scholarship |
| 2025 | Recipient of the NVA Best Poster Award for the study titled *'Successful return to sport following distal femoral osteotomy and lateral unicompartmental knee arthroplasty for isolated lateral knee osteoarthritis: a systematic review and meta-analysis'* |

**Research fellowships**

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|---|---|
| Sep 2022 to May 2023 | Research intern Hospital for Special Surgery, Weil Cornell University<br>New York, United States of America |
| March 2024 to May 2024 | Research fellow Hospital for Special Surgery, Weil Cornell University<br>New York, United States of America |
| 2024 | Research fellow Noordwest Ziekenhuisgroep, Centre for Orthopaedic Research Alkmaar (CORAL)<br>Alkmaar, The Netherlands |

## List of abbreviations and symbols

| | |
|---|---|
| aHKA | Arithmetic hip-knee-ankle angle |
| ACL | Anterior cruciate ligament |
| ASA | American Society of Anesthesiologists |
| BMI | Body mass index |
| CPAK | Coronal plane alignment of the knee |
| CI | Confidence interval |
| EQ5D | EuroQol quality of life outcome measure - five dimensions |
| FJS | Forgotten Joint Score |
| HKA | Hip-knee-ankle angle |
| HR | Hazard ratio |
| ICC | Intraclass correlation coefficient |
| JLO | Joint line obliquity |
| KA | Kinematic alignment |
| KOOS | Knee Osteoarthritis Outcome Score |
| KSS | Knee Society Score |
| LDFA | Lateral distal femoral angle |
| mHKA | Mechanical hip-knee-ankle angle |
| MA | Mechanical alignment |
| MCL | Medial collateral ligament |
| MPTA | Medial proximal tibial angle |
| n | Number |
| OA | Osteoarthritis |
| OKS | Oxford Knee Score |
| PROM(s) | Patient-reported outcome measure(s) |
| SD | Standard deviation |
| THA | Total hip arthroplasty |
| TKA | Total knee arthroplasty |
| UKA | Unicompartmental knee arthroplasty |
| VAS | Visual analogue scale |
| Δ | Change |
| ° | Degree |
| * | Statistically significant |

Amsterdam Movement Sciences

VU VRIJE UNIVERSITEIT AMSTERDAM

Amsterdam UMC

Amsterdam Movement Sciences conducts scientific research to optimize physical performance in health and disease based on a fundamental understanding of human movement in order to contribute to the fulfillment of a meaningful life.