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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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ABSTRACT

Background: 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 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 category.

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 with males (HKA: −6.4° vs. −5.4°, respectively; $P = 0.02$ and TMA 94.4° vs. 89.0°, respectively; $P = 0.005$). Age-related variations included younger patients predominantly displaying femoral deformities, while older patients primarily exhibited isolated tibial- or combined femoral and tibial deformities.

Conclusions: 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.

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1. 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 in 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 on 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.

2. Materials & methods

2.1. Study design

Following Institutional Review Board (IRB #2022-1401) approval, the senior author's (A.D. Pearle) 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.

2.2. 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 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 (ICCs) 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) (Figure 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° (FMA = 180° − LDFA).

2.3. 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., $NEU_{HKA}0°$, $VAL_{HKA}3°$, $VAL_{HKA}6°$).

Figure 1. Long-leg standing anteroposterior 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).

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.

2.4. 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 and 70 years, and patients >70 years.

2.5. 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 group. 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 HKA	Varus	$VAR_{HKA}6°$	4.5 to 7.5°	6°
		$VAR_{HKA}3°$	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 FMA	Varus	$VAR_{FMA}6°$	85.5 to 88.5°	87°
		$VAR_{FMA}3°$	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 TMA	Varus	$VAR_{TMA}6°$	79.5 to 82.5°	81°
		$VAR_{TMA}3°$	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.

3. Results

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

3.1. 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

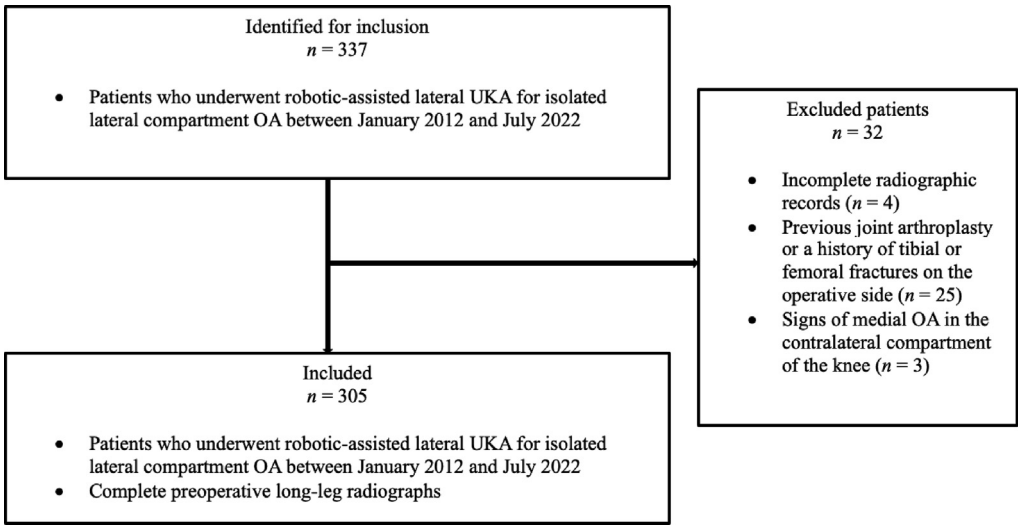

Figure 2. Flowchart of patient inclusion. OA, osteoarthritis; UKA, unicompartmental knee arthroplasty.

detailed in Table 2. The most frequently occurring functional knee phenotype was $VAL_{HKA}6°NEU_{FMA}0°VAL_{TMA}3°$, with an incidence of 10.8%. An overview of all identified functional knee phenotypes is displayed in Supplementary Table S1.

3.2. 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 $VAL_{HKA}6°$, $NEU_{FMA}0°$, and $VAL_{TMA}3°$, with incidences of 34.1%, 51.8%, and 52.5%, respectively (Figure 3).

3.3. 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 2
The 10 most common functional knee phenotypes of knees with isolated lateral compartment osteoarthritis.

Rank	Functional knee phenotype	Total n = 231	Male n = 89	Female 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 n = 305	Male n = 128	Female n = 177	*p*-value
HKA (°)				
Mean ± SD	−6.0 ± 3.78	−5.4 ± 3.87	−6.4 ± 3.66	0.02*
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	0.005*
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.

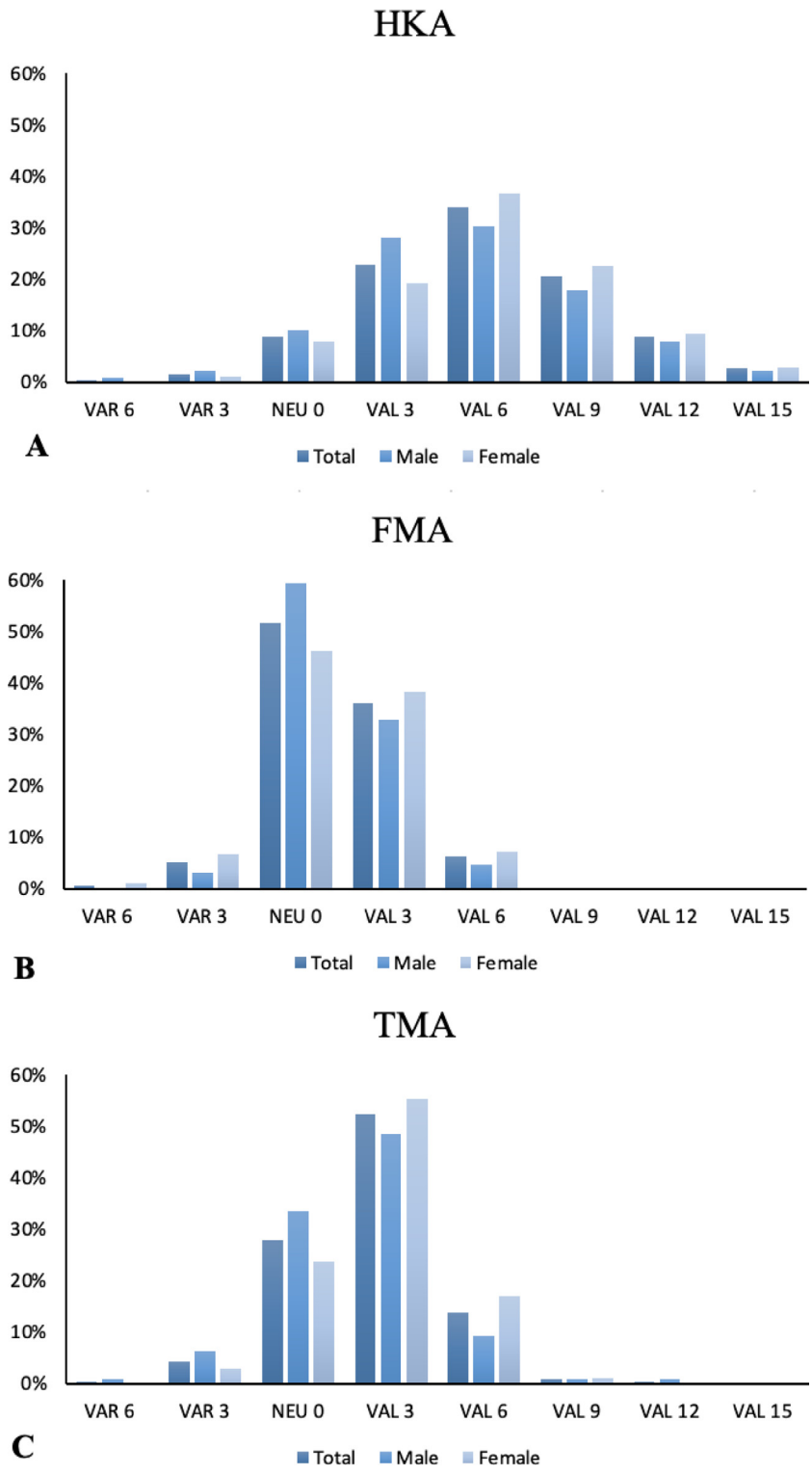

Figure 3. Distribution of limb-, femoral-, and tibial phenotypes of knees with isolated lateral compartment osteoarthritis. (a) Distribution of limb phenotype (HKA, mechanical hip-knee-ankle angle). (b) Distribution of femoral phenotype (FMA, femoral mechanical angle). (c) Distribution of tibial phenotype (TMA, tibial mechanical angle). The incidence of each functional knee phenotype is given in frequencies (%) for the entire cohort and stratified by gender. NEU, neutral; VAL, valgus; VAR, varus.

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.

3.4. 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; $P = 0.005$; Table 3). Additionally, males exhibited a

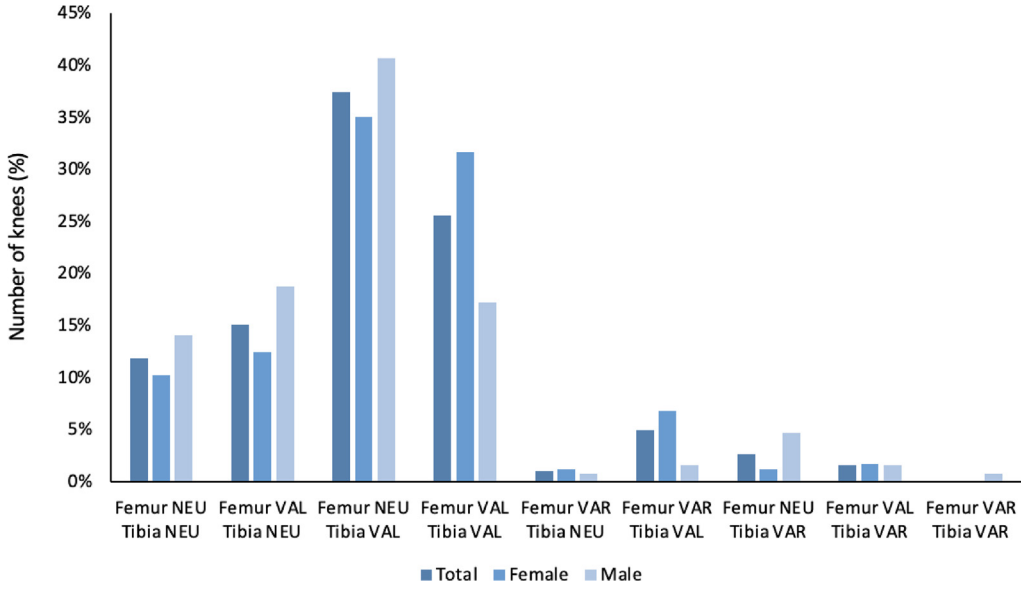

Figure 4. Location of the coronal deformity in knees with isolated lateral compartment osteoarthritis. This figure does not account for the severity of the deformity present. The incidence of the deformity is given in frequencies (%) and stratified by gender. NEU, neutral; VAL, valgus; VAR, varus.

significantly higher prevalence of the neutral femoral phenotype compared with 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.

3.5. 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 years 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.

4. 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 almost twice as likely to present with combined tibial and femoral valgus deformities compared with 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].

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.

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 accounts 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 arthroplasty [19]. Nev-

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

		Age category			
		< 50 years (n = 29)	50 to 70 years (n = 185)	> 70 years (n = 91)	Total (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.

ertheless, 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 $VAL_{HKA}6°NEU_{FMA}0°VAL_{TMA}3°$. 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 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 unicompartmental knee arthroplasty. Consequently, there is a possibility that patients with isolated lateral OA who did not meet the specific inclusion criteria for lateral unicompartmental knee arthroplasty or opted for total knee arthroplasty 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.

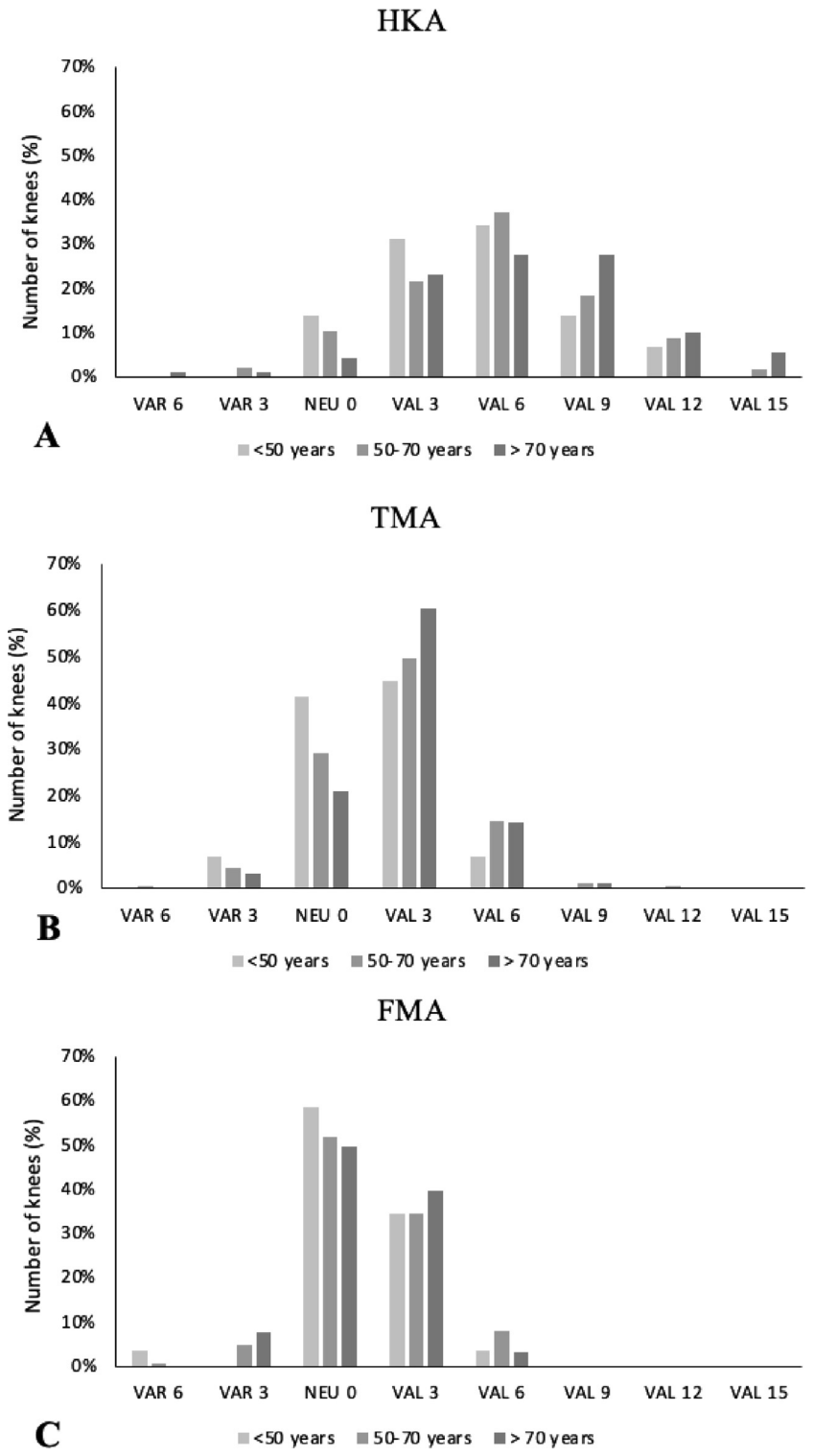

Figure 5. Distribution of limb-, femoral-, and tibial phenotypes of knees with isolated lateral compartment osteoarthritis stratified by age. (a) Distribution of limb phenotype (HKA, mechanical hip–knee–ankle angle). (b) Distribution of femoral phenotype (FMA, femoral mechanical angle). (c) Distribution of tibial phenotype (TMA, tibial mechanical angle). The incidence of each functional knee phenotype is given in frequencies (%). VAL, valgus; VAR, varus.

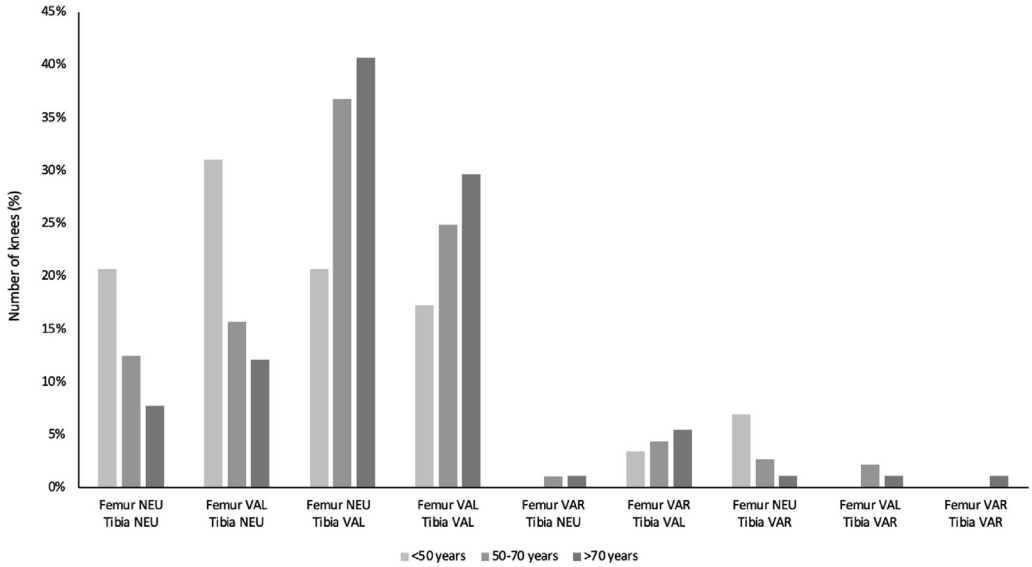

Figure 6. Location of the coronal deformity in knees with isolated lateral compartment osteoarthritis. This figure does not account for the severity of the deformity present. The incidence of the deformity is given in frequencies (%) and stratified by age. NEU, neutral; VAL, valgus; VAR, varus.

5. Conclusions

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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CRediT authorship contribution statement

G.V. ten Noever de Brauw: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **T. Bayoumi:** Conceptualization, Writing – review & editing. **L.V. Ruderman:** Conceptualization, Writing – review & editing. **G.M.M.J. Kerkhoffs:** Conceptualization, Supervision, Writing – review & editing. **H.A. Zuiderbaan:** Conceptualization, Supervision, Writing – review & editing. **A.D. Pearle:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [A.D. Pearle reports a relationship with Smith and Nephew Inc that includes: consulting or advisory. A.D. Pearle reports a relationship with DePuy Synthes that includes: consulting or advisory. H.A. Zuiderbaan reports a relationship with Smith and Nephew Inc that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.].

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2024.05.001.

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