acta orthopaedica belgica, 2026, 92, online-only

doi.org/10.52628/92.2.15398

Association between Kinematic Patterns and Patient-Reported Outcome Measures in Revision Total Knee Arthroplasty

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ABSTRACT

Introduction: While knee kinematics are well-documented in primary TKA, less is understood regarding revision TKA (rTKA), where altered soft tissue conditions may influence kinematics. This study aimed to investigate the relationship between kinematic parameters, specifically anteroposterior (AP) translation and post-cam engagement, and patient-reported outcome measures (PROMs) in rTKA patients.

Materials and Methods: Thirty patients who underwent rTKA between 2022 and 2024 were assessed at a minimum six-month follow-up. Tibiofemoral kinematics, measured as femoral AP translation relative to the tibia, were evaluated during open-chain flexion-extension (FE) and closed-chain exercises (sit-to-stand (STS) and a lunge) using fluoroscopy. Two clusters, categorized by higher and lower PROMs, were compared for AP translation and post-cam engagement.

Results: In the medial compartment, the low-PROMs group exhibited a more anterior femoral position compared to the high-PROMs group, with statistical significance observed during mid-flexion of the STS (50.87% (SD, 4.04) vs. 47.57% (SD, 2.75); $p = 0.043$) and FE exercise (51.97% (SD, 3.83) vs. 48.55% (SD, 3.62); $p = 0.037$). No significant differences were found in the lateral compartment. Post-cam engagement did not differ between the groups in either open- or closed-chain exercises.

Conclusions: Poorer PROM scores were associated with a more anterior femoral position in the medial compartment during mid-flexion of STS and FE exercises. Further research is needed to explore the relationship between kinematic variations and PROMs in rTKA patients.

Keywords: Revision Knee Arthroplasty, Kinematics, PROMs, Knee Arthroplasty.

INTRODUCTION

By 2050, the incidence of primary Total Knee Arthroplasty (pTKA) is projected to increase by 143%[1]. This trend is driven by favorable clinical outcomes, the unrelenting challenge of obesity, an aging population, and TKA among younger and active patients[2-5]. Moreover, the incidence of revision Total Knee Arthroplasty (rTKA) is growing at a faster rate compared to pTKA, with projections indicating a 149% increase by 2040 and a 520% rise by 2060 in the United States[3]. In contrast to pTKA, rTKA poses greater technical challenges and is associated with inferior clinical outcomes, imposing a substantial burden on patients, surgeons, and healthcare systems[2,6–9].

While the outcomes following pTKA are well-documented, the factors affecting outcomes following rTKA are less robustly supported by the literature[10,11]. As knee kinematics are one of the main drivers of patient satisfaction in pTKA, understanding their impact on outcomes in rTKA patients is mandatory for optimizing rTKA outcomes[4,12–15].

Kinematic patterns following TKA can differ considerably from those of the native knee. These altered kinematics have been suggested as potential contributors for affecting outcomes following pTKA. In response, new TKA designs have sought to restore more "physiological" knee motion in an effort to improve clinical outcomes[13,16]. Additionally, evidence suggests that favorable outcomes are closely linked to specific kinematic parameters, including the avoidance of anterior tibial subluxation during full weight-bearing extension, as well as the promotion of posterior femoral translation (predominantly on the lateral side) and femoral external rotation from early to mid-flexion[13,17]. Recent studies have further explored the relationship between kinematics and Patient-Reported Outcome Measures (PROMs), highlighting the role of anteroposterior (AP) femoral translation relative to the tibia during both closed-chain and open-chain exercises[12,14,18]. However, all available evidence is based on pTKA patients. Revision TKA differs considerably due to distinct technical challenges, including surgical exposure, pre-existing stiffness, adhesions, ligamentous insufficiency, and compromised bone stock[10]. These factors can disrupt the surgical balancing of ligaments and soft tissues, affecting weight-bearing kinematics and rendering direct extrapolation from pTKA data to rTKA patients unfeasible[19].

To the best of the authors' knowledge, no study has yet examined the kinematic patterns in revision TKA patients, particularly regarding their association with PROMs. This information may guide both clinicians and patients in informed decision-making and setting realistic postoperative expectations. Accordingly, the primary aim of this study was to explore the relationship between kinematic patterns in revision TKA patients, as measured by AP translation during both open-chain and closed-chain exercises, and a custom aggregate of PROMs targeting symptoms, pain, activities of daily living (ADL), quality of life (QoL), patient satisfaction, and general health. Since the revision prostheses in these cohorts were either posterior-stabilized (PS) or condylar constrained knee (CCK), the secondary aim was to evaluate whether the flexion angle at which post-cam engagement occurred was influenced by the aggregate of PROMs.

METHODOLOGY

Study design and setting

A prospective single-center study was conducted at Ghent University Hospital, following institutional review board approval (BC-11194-AM01). Informed consent was obtained from all participants.

Participants

A total of 30 patients who received rTKA between January 2022 and January 2024 were included in this study. Revision arthroplasty was defined as the removal and replacement of the femoral and/or tibial components. The indications for revision were defined based on the criteria outlined in a recent publication [5]. Patients who required revision due to periprosthetic joint infections (PJI) or periprosthetic fractures were excluded to reduce clinical heterogeneity, as these indications are associated with distinct rehabilitation trajectories and may substantially influence postoperative kinematics and PROMs. Additionally, only patients who received a PS or CCK implant from the Legion Knee System (Smith & Nephew, Memphis, TN, USA) were included. An overview of patient inclusion is provided in Figure 1.

Eligibility for participation required patients to be at least six months postoperative without re-revision (mean 9.4 months; range, 6 to 25 months), have a minimum knee flexion of 90°, and maintain the ability to walk. No patients were excluded postoperatively based on insufficient range of motion or inability to walk. The cohort included 14 women and 16 men, with a mean age of 64 years (range, 49 to 82) and a mean body mass index (BMI) of 29.8 kg/m² (range, 22 to 38). Among the patients, 25 underwent a primary revision, and 5 had a re-revision. Detailed patient characteristics are provided in Table I.

Procedure

All the revision surgeries were carried out by two experienced orthopedic surgeons (NA, JV). Each patient received the Legion Revision implant, which is compatible with both the PS and CCK versions of the Genesis II polyethylene insert. The decision for selecting the CCK insert was based on inadequate stability observed after trialing the less constrained PS insert. Postoperatively, all patients followed the same rehabilitation protocol for outpatient care. Routine follow-up evaluations were conducted at six weeks, three months, six months and 12 months postoperatively. Kinematic analysis was performed once per patient, at a minimum of six months postoperatively.

Kinematic analysis

Fluoroscopic images were captured in the sagittal plane using a flat-panel fluoroscopy system (Siemens Axiom Luminos dRF, Erlangen, Germany) at 15 frames per second. The patients participated in three activities, which included one open-chain and two closed-chain exercises. In the first closed-chain exercise, the patient performed a lunge movement with the operated leg, descending to maximal knee

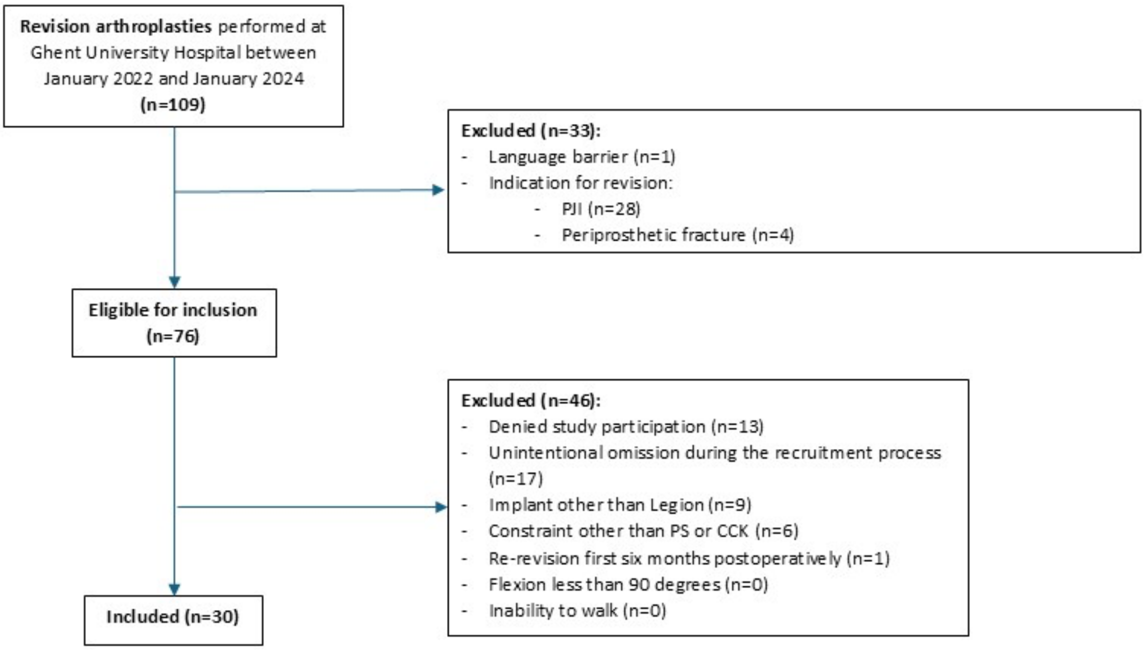


Fig. 1 — Flowchart for patient inclusion. PJI, periprosthetic joint infection. PS, posterior-stabilized. CCK, condylar constrained knee.

flexion, while positioning the non-operated leg on a lower step of a staircase (Figure 2). The second closed-chain exercise was the sit-to-stand (STS) test, where the patient began seated with the knee flexed at 90° and stood up, ensuring that the non-operated knee remained positioned away from the operated knee. Handrail support was available during both closed-chain exercises if needed. The open-chain exercise consisted of a flexion-extension (FE) movement performed from a seated position, with the operated leg moving from maximum flexion to full extension and back. As the knee passed the same flexion angle twice, the average of the two measurements was calculated. Each exercise was performed three times, and the attempt with the greatest consistency was chosen, defined by the clearest representation of both the initiation and completion of the movement, as captured by the fluoroscope. Kinematics were assessed across the full range of motion (fROM) and following three flexion ranges: early flexion (0° to 30°), mid-flexion (30° to 60°), and deep flexion (60° to 90°).

The relevant frames of interest were selected and processed using the open-source software package JointTrack Auto (University of Florida, Gainesville, FL, USA), employing a 2-D to 3-D image registration technique[20]. In this technique, computer-aided design models, determined by the size of the implant components, were overlaid onto the fluoroscopic images according to their silhouettes. This enabled the creation of transformation matrices for the components in the image space. This method was recently validated, showing errors for in-plane rotations from 0.37° to 1.2°, with an average of 0.73°, and for translations from 0.72 mm to 0.92 mm, with an average of 0.81 mm[20].

A joint coordinate system was established for the femur and tibia, following the framework of Grood and Suntay[21,22]. It was assumed that the polyethylene component was rigidly attached to the tibia, as it is nearly invisible in fluoroscopic images.

Anteroposterior translation

The centers of the spheres fitting the bearing surfaces of the femoral condyles were used as landmarks to define the femoral origins for translation. These two points were subsequently plotted in relation to a tibial reference frame, where 0% and 100% corresponded to the most posterior and anterior points of the tibia, respectively (Figure 3). This normalization ensured that the values were unaffected by tibial size.

Post-cam engagement

The moment of post-cam engagement was defined as the flexion angle at which the distance between post and cam became less than one millimeter.

PROMs analysis

Patients were evaluated by the validated Dutch translations of the following PROMs: Knee Injury and Osteoarthritis Outcome Score (KOOS)[23], Knee

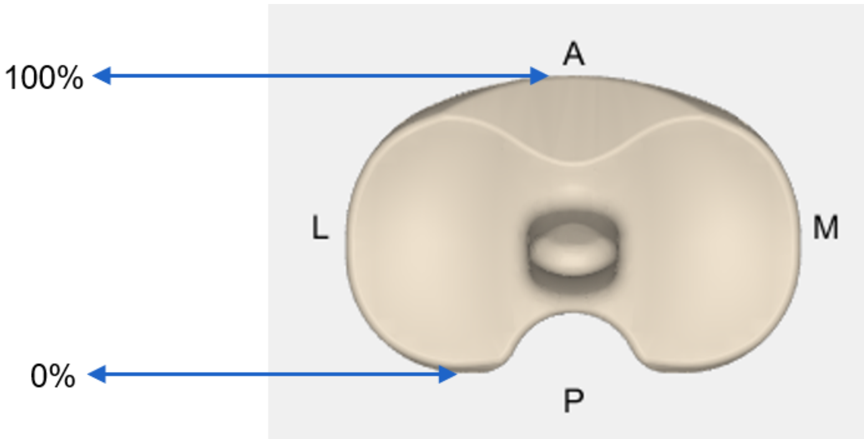
Table I. — Patient characteristics.

Variable	Patients (n=30)
Sex	
Men	16 (53.3)
Women	14 (46.7)
Age (years)	
Primary arthroplasty	57.4 ± 6.9
Revision arthroplasty	63.6 ± 6.9
Re-revision: first revision	58.2 ± 8.3
BMI (kg/m²)	29.8 ± 3.9
ASA classification	
1	6 (20)
2	22 (73.3)
3	2 (6.7)
4	0 (0)
Type of primary procedure	
TKA	24 (80)
UKA	5 (16.7)
UKA + PF	1 (3.3)
Type of revision procedure	
Primary revision	25 (83.3)
Re-revision	5 (16.7)
Δ Time primary – revision arthroplasty (months)	
Primary revision patients (n=25)	41 [20-95.5]
Re-revision patients (n=5)	
Primary – first revision	14 [8.5-74]
First – current revision	83.4 ± 62.8
Indication revision arthroplasty*	
Aseptic loosening	10 (33.3)
Malalignment	12 (40)
Instability	6 (20)
Progressive disease	1 (3.3)
Polyethylene wear	1 (3.3)
Side	
Left	12 (40)
Right	18 (60)

Data are presented as mean ± SD or median [IQR], based on normality assumptions, for continuous variables. Categorical variables are presented as absolute number (percentage). BMI, body mass index. kg, kilogram. m, meter. ASA, classification of the American Society of Anesthesiologists. TKA, Total Knee Arthroplasty. UKA, Unicompartmental Knee Arthroplasty. PF, Patellofemoral prosthesis. * based on definitions from a previously published study (Stroobant L, Ackerman T, Vermue H, et al. Revision Knee Arthroplasty in a Tertiary Center: Infection Remains the Leading Cause for Primary Revisions, While Aseptic Loosening Led Causes for Rerevisions. J Arthroplasty. Published online February 19, 2025. doi:10.1016/j.arth.2025.02.045).

Society satisfaction score (KSSs)[22], and EuroQol five-dimension five-level questionnaire (EQ-5D-5L)[24]. The KOOS comprises 42 knee-related items, each rated on a scale from 0 to 4, and organized into five subscales: symptoms, pain, activities of daily living (ADL), sports, and quality of life (QoL). The scores for each subscale were standardized to a 0 to 100 scale, where zero represents the most severe knee-related impairment[25]. The KSSs contains five items, each scored from 0 to 8. The total score,

Fig. 2 — Patient performing a lunge exercise while under fluoroscopic surveillance.



Size Tibia	AP length
1	40,5 mm
2	44 mm
3	47 mm
4	48,5 mm
5	51 mm
6	53 mm
7	55 mm
8	58,5 mm

Fig. 3 — The AP dimension of the tibial insert is shown, with 0% and 100% corresponding to the most posterior and anterior points of the tibia, respectively. On the right, an overview of the different tibial sizes and their corresponding AP lengths is provided. AP, anteroposterior.

ranging up to 40, reflects greater satisfaction with higher values[26]. The EQ-5D-5L is a widely used standardized assessment tool with five items that measures self-reported general health and generates a single utility value, calculated based on country-specific coefficients[24].

To establish a single differentiator, patients were categorized into two clusters based on their PROM scores (based on a cluster analysis with a silhouette coefficient of 0.7, see details below). Previous research on the same study population found no significant differences in kinematics between the PS and CCK inserts, allowing them to be grouped together for the cluster analysis[27]. Cluster 1 (CL1) consisted of eight patients and Cluster 2 (CL2) of 22 patients. No significant differences in age, gender, or BMI were observed between the two clusters (Table II). All PROM scores were significantly higher in CL1 than CL2 (Table II), classifying CL1 as the "high-PROMs group" and CL2 as the "low-PROMs group".

Data Analyses

The sample size was determined based on a comparable study by Van Onsem et al. in a primary TKA population, which included 30 patients[12].

Statistical analyses were performed using SPSS (SPSS version 29, Chicago, IL, United States). Descriptive data are presented as means and standard deviations (SD) or medians and interquartile ranges

Table II. — Demographics and PROMs per cluster.

Variables	Cluster 1 (n=8)	Cluster 2 (n=22)	P-value
Demographics			
Age revision (years)	62.4 ± 6.6	64.1 ± 7	0.564‡
Sex			0.689*
Male	5 (62.5)	11 (50)	
Female	3 (37.5)	11 (50)	
BMI (kg/m²)	30.2 [28.6-34.9]	30.5 [26.9-31.9]	0.565†
Follow-up moment (months)	9.5 [8-14.8]	8.5 [6-10]	0.320†
PROMs			
KOOS Pain	92 ± 9	57.1 ± 16.4	<0.001‡
KOOS Symptoms	84.8 ± 11.9	60.1 ± 16	<0.001‡
KOOS ADL	97.8 [92.7-99.6]	61.8 [47.4-67.7]	<0.001†
KOOS QoL	100 [73.4-100]	31.3 [23.4-45.3]	<0.001†
KSS Satisfaction	40 [36.5-40]	22 [16-28.5]	<0.001†
EQ-5D-5L	1 [0.9-1]	0.7 [0.6-0.8]	<0.001†

Data are presented as mean ± SD or median [IQR], based on normality assumptions, for continuous variables. Categorical variables are presented as absolute number (percentage). BMI, body mass index. kg, kilogram. m, meter. PROMs, patient-reported outcome measures. KOOS, Knee Injury and Osteoarthritis Outcome Score. ADL, activities of daily living. QoL, quality of life. KSSs, Knee Society Score satisfaction. EQ-5D-5L, EuroQol five-dimension five-level questionnaire. ‡, Independent Student T-Test. †, Mann-Whitney U-Test. *, Fisher's Exact Test.

(IQR) for continuous variables, depending on normality tests (Shapiro-Wilk), and as counts (percentages) for categorical variables. All fluoroscopic data are reported as mean and SD for consistency.

A uniform cluster method was applied, utilizing an agglomerative two-step cluster analysis of the KOOS scores (with the sports subscale excluded), KSSs, and EQ-5D-5L. The sports subscale was omitted due to the limited sports activity typically observed in revision TKA patients, resulting in reduced relevance and variability of this subscale within this population. Although the variables differed in scale and were not normalized, clustering quality was strong, as indicated by a silhouette coefficient of 0.7[28]. Group differences were analyzed using t-test or Mann-Whitney U tests for continuous variables, and Chi-square or Fisher's exact tests for categorical variables. The level of significance was set at 0.05.

Study power

The effect size for the primary significant outcome (FE movement in the medial compartment during mid-flexion) was quantified using Cohen's d, yielding a value of 0.93. A post hoc power analysis was performed using G*Power 3.1.9.7 (Heinrich Heine Universität, Düsseldorf, Germany), specifying a two-tailed t-test, an effect size of 0.93, an alpha level of 0.05, and group sizes of 8 and 22. Based on these parameters, the estimated statistical power was 58.5%, indicating a moderate likelihood of detecting the observed effect given the sample size. Nevertheless, the result was statistically significant.

RESULTS

Anteroposterior translation

The anteroposterior translation for the medial and lateral compartment is shown in Table III and Figure 4.

Medial compartment

During the open-chain FE, the low-PROMs group demonstrated a more anterior positioning of the femoral component relative to the tibial reference frame across the entire ROM. This difference reached statistical significance at mid-flexion, where the low-PROMs group exhibited a femoral position of 52% (SD, 3.8), compared to 48.6% (SD, 3.6) in the high-PROMs group (p = 0.037). However, when considering the entire ROM, the AP translation was comparable between the two groups (high-PROMs: 14.5% (SD, 7.9); low-PROMs: 14.9% (SD, 8.8); p = 0.912).

In the mid-flexion range of the lunge, there was no significant difference in the anterior position between the low-PROMs group (50.1% (SD, 5)) and the high-PROMs group (48% (SD, 4.2)) (p = 0.387). Femoral positioning during early flexion and deep flexion was comparable between both groups.

Table III. — Comparison of AP translation (expressed as percentage based on the tibial reference frame) between revision TKA patients with high-PROMs and low-PROMs postoperatively.

Compartment	Exercise	Flexion range (°)	High-PROMs (%)	Low-PROMs (%)	Mean difference	P-value
Medial	Lunge	0-30	51.1 ± 5.3 (n=4)	50.2 ± 5.1 (n= 18)	1	0.594†
		30-60	48 ± 4.2 (n=6)	50 ± 5 (n=20)	-2	0.387†
		60-90	39.2 ± 3.6 (n=7)	39.4 ± 4.2 (n= 21)	-0.2	0.435†
		fROM (Extension→ Flexion)	-25.6 ± 5.7 (n=7)	-19.6 ± 8.4 (n=20)	-6	0.130†
	FE	0-30	47.4 ± 3.5 (n=8)	49.3 ± 4.7 (n=20)	-1.9	0.318‡
		30-60	48.6 ± 3.6 (n=8)	52 ± 3.8 (n=22)	-3.4	0.037‡
		60-90	39.1 ± 5.6 (n=8)	41.1 ± 3 (n=21)	-2	0.220‡
		fROM (Flexion→ Extension)	+14.5 ± 7.9 (n=8)	+14.9 ± 8.8 (n=22)	0.4	0.912‡
	STS	0-30	48.6 ± 4.7 (n=8)	50.9 ± 7.2 (n=21)	-2.3	0.406‡
		30-60	47.6 ± 2.8 (n=8)	50.9 ± 4 (n=21)	-3.3	0.043‡
		60-90	39.6 ± 4.5 (n=8)	40.9 ± 4.1 (n=21)	-1.3	0.466‡
		fROM (Flexion→ Extension)	+13.5 ± 5.4 (n=8)	+15.1 ± 8.2 (n=21)	1.5	0.633‡
Lateral	Lunge	0-30	46.4 ± 3.6 (n=4)	47 ± 8.6 (n=18)	-0.6	0.898‡
		30-60	43.4 ± 3.3 (n=6)	46.2 ± 7.3 (n=20)	-2.8	0.378‡
		60-90	33.1 ± 1.4 (n=7)	35.1 ± 5.5 (n=21)	-2	0.132‡
		fROM (Extension→ Flexion)	-28.8 ± 4.7 (n=7)	-21.6 ± 10.4 (n=21)	-7.2	0.091‡
	FE	0-30	48.6 ± 2.7 (n=8)	45.6 ± 4 (n=20)	3	0.063‡
		30-60	46.9 ± 1.1 (n=8)	46.8 ± 5 (n=22)	0	0.992‡
		60-90	33.6 ± 2.9 (n=8)	34.5 ± 5.3 (n=21)	-1	0.634‡
		fROM (Flexion→ Extension)	+24.1 ± 8.9 (n=8)	+20.8 ± 13.3 (n=22)	-3.3	0.765†
	STS	0-30	48.5 ± 4.7 (n=8)	49.7 ± 5.9 (n=21)	-1.2	0.602‡
		30-60	46.2 ± 3.2 (n=8)	46.9 ± 4.7 (n=21)	-0.7	0.694‡
		60-90	35.6 ± 2 (n=8)	35.9 ± 5.3 (n=21)	-0.3	0.866‡
		fROM (Flexion→ Extension)	+19.5 ± 8.3 (n=8)	+21.3 ± 9.7 (n=21)	1.8	0.653‡

AP, anteroposterior. TKA, Total Knee Arthroplasty. PROMs, patient-reported outcome measures. FE, flexion-extension. STS, sit-to-stand. fROM, full range of motion (represents the difference in percentage position between the endpoint and the starting point of the exercise: a negative value represents posterior translation and a positive value anterior translation). °, Degrees. %, Percentage. ‡, Independent Student T-Test. †, Mann-Whitney U-Test.

The kinematic pattern during the STS exercise mirrored that of the FE exercise. There was a trend for a more anterior femoral position during the fROM in the low-PROMs group, but only statistically significant in the mid-flexion range (high-PROMs: 47.6% (SD, 2.8); low-PROMs: 50.9% (SD, 4); $p = 0.043$). The AP translation was similar between both groups ($p = 0.633$).

Lateral compartment

No significant difference in kinematic patterns was observed between the high-PROMs and low-PROMs clusters across all three flexion ranges for the lateral compartment, irrespective of the exercise performed.

Post-cam engagement

The flexion angle at which the post-cam engagement occurred was not different between the low-PROMs and high-PROMs group during both open-chain and closed-chain exercises (closed-chain: $p = 0.110$; open-chain: $p = 0.090$) (Table IV).

DISCUSSION

Although numerous studies have investigated kinematic patterns in pTKA patients, a critical research gap exists in linking these patterns to PROMs, and no studies have yet addressed kinematics in rTKA patients. Given the increasing incidence of rTKA, its generally inferior outcomes, and the limited understanding of the factors influencing these outcomes, there was a pressing need for further exploration of kinematics in rTKA patients. The primary finding of this study demonstrated that, in the medial knee compartment, patients with low PROMs exhibited a more anterior femoral position across the entire range of motion,

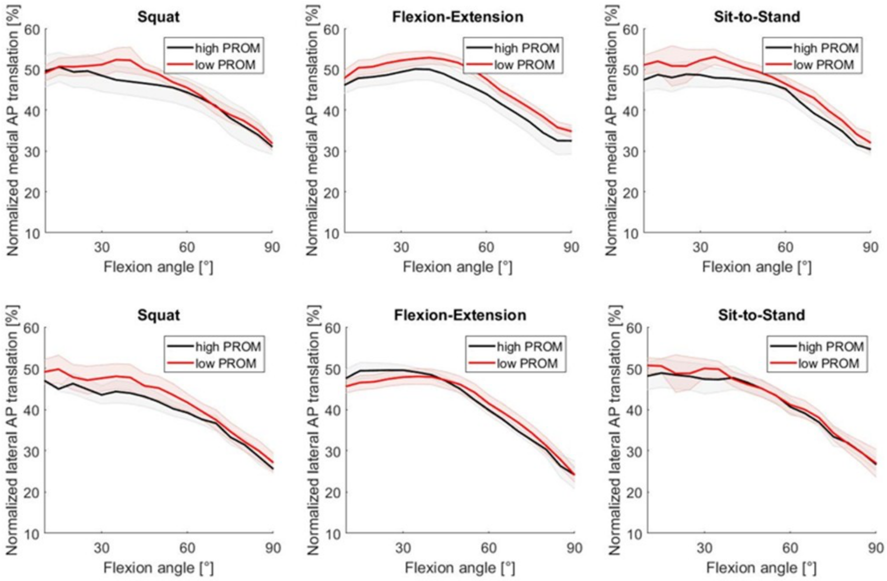


Fig. 4 — AP translation of the lateral (superior row) and medial condyles (inferior row) for the high-PROMs group (black) and the low-PROMs group (red), during three exercises, with respect to the flexion angle. The line represents the mean value, and the shaded area denotes the 95% confidence interval. AP translation is expressed as a percentage based on the tibial reference frame. An asterisk (*) indicates statistically significant differences between groups. PROMs, patient-reported outcome measures. %, Percentage. °, Degrees.

Table IV. — Comparison of post-cam engagement revision TKA patients with high-PROMs and low-PROMs postoperatively.

Exercise	High-PROMs (°)	Low-PROMs (°)	P-value
Closed-Chain	52.8 ± 9.8 (n=8)	46.2 ± 9.8 (n=22)	0.110‡
Open-Chain	49 ± 9.4 (n=8)	42.6 ± 8.6 (n=22)	0.090‡

TKA, Total Knee Arthroplasty. PROMs, patient-reported outcome measures. °, Degrees. ‡, Independent Student T-Test.

with the most pronounced and statistically significant difference observed in the mid-flexion range. In contrast, no association was found between PROMs and AP translation in the lateral compartment.

Anteroposterior translation

Progressive femoral rollback is essential for achieving maximal knee flexion by reducing the risk of posterior hard- or soft-tissue impingement between the femur and the polyethylene insert[17,18]. Both groups in this study demonstrated an adequate and comparable posterior femoral rollback during both closed-chain and open-chain exercises. Nevertheless, the low-PROMs group had a more anterior femoral position compared to the high-PROMs group, reducing the quadriceps lever arm and impairing knee extension efficiency by requiring a higher amount of muscle forces[12,29]. This is particularly concerning as TKA patients, especially those undergoing revision surgery, experience prolonged quadriceps strength reduction following surgery[30-33]. Furu et al. identified a close relationship between quadriceps strength, physical function, and patient satisfaction, suggesting that diminished quadriceps efficiency and strength may contribute to the lower PROM scores[12,34].

Posterior femoral translation reduces patellofemoral loading[35]. The more anterior femoral position in the low-PROMs group may lead to increased patellofemoral loading, which is particularly relevant in activities like kneeling, where joint contact pressures can be up to 245% higher than in unloaded conditions[35]. Several authors have linked elevated patellofemoral pressures to onset of anterior knee pain[35].

It is noteworthy that the anterior femoral position in the medial compartment was statistically significant exclusively within the mid-flexion range during STS and FE exercises. Near full extension, the congruence between the tibial and femoral components primarily governs knee kinematics. In deeper flexion, the post cam mechanism, once engaged, exerts a substantial influence on the kinematic pattern. Therefore, we hypothesize that the mid-flexion range is more susceptible to the influence of additional factors on the kinematic pattern, such as the soft tissue conditions. Further consideration is necessary to fully understand the effect size of the presented data. The 3% difference in AP position in the medial compartment between high- and low-PROMs is noteworthy. This is particularly relevant considering that total AP translation spans from a maximum anterior point of approximately 50% (tibial center due to post-cam engagement) to a maximum posterior point of approximately 30%, resulting in translation occurring across roughly 20% of the tibial surface[12]. As such, the 3% difference constitutes approximately 15% of the total AP excursion. This magnitude is comparable to findings by Van Onsem et al., where differences of 2 and 5 percentage points in AP position were associated with significant differences in PROMs after primary TKA[12]. Furthermore, the effect sizes were large during both the FE and the STS exercises, with Cohen's d values of 0.93 and 0.89 respectively, indicating substantial and clinically meaningful differences between groups. During the lunge exercise, the low-PROMs group tended to have a more anterior femoral position, although this difference did not reach statistical significance. This may be attributed to the limited sample size of patients with available data within the mid-flexion range for the lunge exercise.

In a similar study involving primary TKA patients, Van Onsem et al. demonstrated a difference between high-PROMs and low-PROMs patients only during closed-chain exercises, but not during open-chain exercises. This was attributed to the fact that most activities of daily living are performed under weight-bearing, closed-chain conditions[12]. Conversely, our study was able to demonstrate a difference during the open-chain FE movement. A possible explanation for this discrepancy is that the revision population is more complex and less forgiving, leading to inferior outcomes, which may also manifest during open-chain exercises.

In contrast to the medial compartment, no significant differences were observed between high- and low-PROM patients in the lateral compartment, which may reflect its greater biomechanical adaptability. Numerous studies of native knee kinematics have shown that the lateral compartment exhibits a larger AP translation during FE compared to the medial compartment, a motion pattern known as "medial pivoting"[14]. This kinematic asymmetry results in a relatively constrained and stable medial compartment, whereas the lateral compartment demonstrates increased mobility, potentially allowing it to better accommodate biomechanical alterations. These kinematic observations correspond with findings from coronal laxity studies, which underscore the critical role of medial compartment stability. Medial laxity is known to induce aberrant, non-physiological knee kinematics, whereas lateral laxity exerts minimal influence and is considered physiological in the native knee across both extension and flexion[37]. This difference in laxity helps explain why the lateral compartment is more adaptable to changes in knee movement.

Post-cam engagement

The moment of post-cam engagement did not exhibit a statistically significant difference between high-PROM and low-PROM patients, although there was a tendency for earlier post-cam engagement in the low-PROM group. In the native knee, the posterior cruciate ligament becomes functional beyond 50° of flexion, guiding posterior femoral rollback and contributing to normal kinematics, which is generally associated with greater patient satisfaction[38]. In contrast, early post-cam engagement may indicate joint space overstuffing, which has been associated with decreased ROM, increased contact stresses and accelerated polyethylene wear in previous studies[39]. Moreover, early engagement could contribute to symptoms such as anterior knee pain, possibly due to altering of patellofemoral kinematics. These biomechanical changes could explain the lower PROM scores observed in this group. However, values reported in the literature range from 50 to 90 degrees of flexion and are highly dependent on implant design, making it difficult to assess the clinical relevance of the slightly earlier post-cam engagement in the low-PROMs group[40,41].

Limitations

Several potential limitations should be acknowledged. First, the use of two different constraints may serve as a potential confounder, though this reflects the need for higher constraints in the revision population to manage bone defects and ligamentous insufficiencies. However, prior to data analysis, kinematic comparisons between CCK and PS implants in this study population demonstrated no significant differences, as both inserts share identical sagittal profiles for post and cam, resulting in similar posterior femoral rollback initiated by the post-cam engagement[27]. This consistent kinematic behavior justifies the inclusion of both constraint types in the overall study population. Second, it is important to note that our findings are applicable to a single revision TKA system and may not be generalizable to other revision implant systems. Third, although the sample size was small, this is typical for such intensive studies, and the group sizes algin with those in similar published studies[12]. Although the post hoc power was limited (58.5%), the observed effect size for the primary outcome was large (Cohen's d = 0.93) and the result statistically significant, suggesting a potentially meaningful difference. As one of the first studies to explore this outcome in a revision TKA population, the findings remain clinically relevant but should be interpreted with caution and confirmed in larger cohorts. Moreover, some patients were excluded from specific analyses due to incomplete motion capture or suboptimal image quality at certain flexion angles. This was addressed by transparently reporting the number of patients included in each analysis throughout the manuscript. Additionally, no correction for multiple testing was applied due to the exploratory nature and small sample size, which could reduce statistical power.

Furthermore, other factors influencing revision TKA outcomes were not considered. Additionally, the kinematic analysis was performed early postoperatively, though Palm-Vlasak et al. reported that TKA kinematics stabilize by 12 weeks postoperatively[42,43]. Finally, handrail support was available during the closed-chain exercises if needed. While its use was limited and provided only for safety, it could have influenced kinematic outcomes by reducing joint forces and muscular demand.

Future perspectives

Despite these limitations, this is the first study to offer valuable insights into the kinematic patterns of revision arthroplasty patients and their association with PROMS. This study demonstrates that PROMs are sensitive to variations in kinematic patterns[18]. This is promising, as radiographic kinematic exams may serve as a novel clinical tool, enabling surgeons to correlate knee mechanics with patient outcomes and clinical progress[42]. Nevertheless, studies investigating the association between kinematics and PROMs are still in its early stages[12]. Further investigation is required, both for research purposes and for the potential implementation of this approach in clinical practice[12], with particular emphasis on alternative measurements such as axial rotation and varus-valgus movements.

CONCLUSION

This study provides valuable insights into the kinematic patterns of revision TKA comparing patients with high and low PROMs. The findings demonstrate that, in the medial knee compartment, patients with low PROMs exhibited a more anterior femoral position across the entire range of motion, with the most pronounced and statistically significant difference observed in the mid-flexion range. In contrast, no association was found between PROMs and AP translation in the lateral compartment or the moment of post-cam engagement. Further investigation is needed to better understand the relationship between kinematic variations and PROMs, and to facilitate the translation of these findings into clinical practice.

Funding: The research leading to these results received funding from the Fonds Wetenschappelijk Onderzoek – Vlaanderen (FWO) under Grant Agreement No T001620N.

Acknowledgements: The authors thank Jocelyn Castille for his assistance in the data collection.

Conflict of interest: All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

REFERENCES

1. Klug A, Gramlich Y, Rudert M, Drees P, Hoffmann R, Weißenberger M, et al. The projected volume of primary and revision total knee arthroplasty will place an immense burden on future health care systems over the next 30 years. Knee Surgery, Sports Traumatology, Arthroscopy 2021;29:3287–98. https://doi.org/10.1007/s00167-020-06154-7.
2. Brown LR, Clement ND, MacDonald DJ, Breusch SJ. The survivorship of the link endo-rotational hinge total knee arthroplasty: 5–12-year follow-up of 100 patients. Arch Orthop Trauma Surg 2019;139:107–12. https://doi.org/10.1007/s00402-018-3064-0.
3. Shichman I, Askew N, Habibi A, Nherera L, Macaulay W, Seyler T, et al. Projections and Epidemiology of Revision Hip and Knee Arthroplasty in the United States to 2040-2060. Arthroplast Today 2023;21. https://doi.org/10.1016/j.artd.2023.101152.
4. Batailler C, Foissey C, Fary C, Naaim A, Servien E, Lustig S. Similar kinematic patterns between revision total stabilized (TS) and primary posterior stabilized (PS) knee prostheses: a prospective case–controlled study with gait assessment. Knee Surgery, Sports Traumatology, Arthroscopy 2022;30:2714–22. https://doi.org/10.1007/s00167-021-06591-y.
5. Stroobant L, Ackerman T, Vermue H, Bouzezza O, Arnout N, Van Onsem S, et al. Revision Knee Arthroplasty in a Tertiary Center: Infection Remains the Leading Cause For Primary Revisions, while Aseptic Loosening Led Causes for

Re-Revisions. J Arthroplasty 2025. https://doi.org/10.1016/j.arth.2025.02.045.

6. Saleh KJ, Dykes DC, Tweedie RL, Mohamed K, Ravichandran A, Saleh RM, et al. Functional outcome after total knee arthroplasty revision: A meta-analysis. Journal of Arthroplasty 2002;17:967–77. https://doi.org/10.1054/arth.2002.35823.
7. Baker P, Cowling P, Kurtz S, Jameson S, Gregg P, Deehan D. Reason for revision influences early patient outcomes after aseptic knee revision knee. Clin Orthop Relat Res 2012;470:2244–52. https://doi.org/10.1007/s11999-012-2278-7.
8. Greidanus N V., Peterson RC, Masri BA, Garbuz DS. Quality of Life Outcomes in Revision Versus Primary Total Knee Arthroplasty. J Arthroplasty 2011;26:615–20. https://doi.org/10.1016/j.arth.2010.04.026.
9. Hardeman F, Londers J, Favril A, Witvrouw E, Bellemans J, Victor J. Predisposing factors which are relevant for the clinical outcome after revision total knee arthroplasty. Knee Surgery, Sports Traumatology, Arthroscopy 2012;20:1049–56. https://doi.org/10.1007/s00167-011-1624-8.
10. Quinn J, Jones P, Randle R. Clinical Outcomes Following Revision Total Knee Arthroplasty: Minimum 2-Year Follow-up. CiOS Clinics in Orthopedic Surgery 2022;14:69–75. https://doi.org/10.4055/cios20206.
11. Broberg JS, Naudie DDR, Lanting BA, Howard JL, Vasarhelyi EM, Teeter MG. Patient and Implant Performance of Satisfied and Dissatisfied Total Knee Arthroplasty Patients. Journal of Arthroplasty 2022;37:S98–104. https://doi.org/10.1016/j.arth.2021.10.024.
12. Van Onsem S, Verstraete M, Van Eenoo W, Van Der Straeten C, Victor J. Are TKA Kinematics During Closed Kinetic Chain Exercises Associated with Patient-reported Outcomes? A Preliminary Analysis. Clin Orthop Relat Res 2020;478:255–63. https://doi.org/10.1097/CORR.0000000000000991.
13. Banks SA, Catani F, Deckard ER, Mahoney OM, Matsuda S, Meneghini RM, et al. Total Knee Arthroplasty Kinematics Predict Patient-Reported Outcome Measures: Implications for Clinical Kinematic Examinations. Journal of Arthroplasty 2024;39:S224–9. https://doi.org/10.1016/j.arth.2024.02.014.
14. Alesi D, Marcheggiani Muccioli GM, Roberti di Sarsina T, Bontempi M, Pizza N, Zinno R, et al. In vivo femorotibial kinematics of medial-stabilized total knee arthroplasty correlates to post-operative clinical outcomes. Knee Surgery, Sports Traumatology, Arthroscopy 2021;29:491–7. https://doi.org/10.1007/s00167-020-05975-w.
15. Clary CW, Fitzpatrick CK, Maletsky LP, Rullkoetter PJ. The influence of total knee arthroplasty geometry on mid-flexion stability: An experimental and finite element study. J Biomech 2013;46:1351–7. https://doi.org/10.1016/j.jbiomech.2013.01.025.
16. Pizza N, Di Paolo S, Zinno R, Marcheggiani Muccioli GM, Agostinone P, Alesi D, et al. Over-constrained kinematic of the medial compartment leads to lower clinical outcomes after total knee arthroplasty. Knee Surgery, Sports Traumatology, Arthroscopy 2022;30:661–7. https://doi.org/10.1007/s00167-020-06398-3.
17. Bellemans J, Vandenneucker OH, Surgeon O, Moemans A, Victor J, Banks S, et al. THE JOURNAL OF BONE AND JOINT SURGERY Fluoroscopic analysis of the kinematics of deep flexion in total knee arthroplasty INFLUENCE OF POSTERIOR CONDYLAR OFFSET. vol. 84. 2002.
18. Hodge PE, Rabak OJ, Perriman DM, Scarvell JM, Smith PN, Lynch JT. Are Kinematics an Indicator of Outcome After Total Knee Arthroplasty? Journal of Arthroplasty 2024;39:343-349.e1. https://doi.org/10.1016/j.arth.2023.08.010.
19. Banks SA, Harman MK, Bellemans J, Hodge WA. Making Sense of Knee Arthroplasty Kinematics: News You Can Use. 2003.
20. Jensen AJ, Flood PDL, Palm-Vlasak LS, Burton WS, Chevalier A, Rullkoetter PJ, et al. Joint Track Machine Learning: An Autonomous Method of Measuring Total Knee Arthroplasty Kinematics From Single-Plane X-Ray Images. Journal of Arthroplasty 2023;38:2068–74. https://doi.org/10.1016/j.arth.2023.05.029.
21. Grood ES, Suntay WJ. A Joint Coordinate System for the Clinical Description of Three-Dimensional Motions: Application to the Knee. J Biomech Eng 1983;105:136–44. https://doi.org/10.1115/1.3138397.
22. Van Der Straeten C, Witvrouw E, Willems T, Bellemans J, Victor J. Translation and validation of the Dutch New Knee Society Scoring System©. Clin Orthop Relat Res 2013;471:3565–71. https://doi.org/10.1007/s11999-013-3149-6.
23. de Groot IB, Favejee MM, Reijman M, Verhaar JAN, Terwee CB. The dutch version of the knee injury and osteoarthritis outcome score: A validation study. Health Qual Life Outcomes 2008;6. https://doi.org/10.1186/1477-7525-6-16.
24. M. Versteegh M, M. Vermeulen K, M. A. A. Evers S, de Wit GA, Prenger R, A. Stolk E. Dutch Tariff for the Five-Level Version of EQ-5D. Value in Health 2016;19:343–52. https://doi.org/10.1016/j.jval.2016.01.003.
25. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee Injury and Osteoarthritis Outcome Score (~00~)-Development of a Self-Administered Outcome Measure. vol. 78. 1998.
26. Scuderi GR, Bourne RB, Noble PC, Benjamin JB, Lonner JH, Scott WN. The new knee society knee scoring system. Clin Orthop Relat Res, vol. 470, Springer Science and Business Media, LLC; 2012, p. 3–19. https://doi.org/10.1007/s11999-011-2135-0.
27. Stroobant L, Vermue H, Jacobs E, Arnout N, Van Onsem S, Banks SA, et al. Similar kinematic patterns in posterior-stabilized and condylar constrained knee prostheses in revision knee arthroplasty: a prospective cohort study. J Orthop 2025;64:153–62. https://doi.org/10.1016/j.jor.2025.04.004.
28. Mooi E, Sarstedt M. A Concise Guide to Market Research. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011. https://doi.org/10.1007/978-3-642-12541-6.
29. Khasian M, Sharma A, Fehring TK, Griffin WL, Mason JB, Komistek RD. Kinematic Performance of Gradually Variable Radius Posterior-Stabilized Primary TKA During Various Activities: An In Vivo Study Using Fluoroscopy. Journal of Arthroplasty 2020;35:1101–8. https://doi.org/10.1016/j.arth.2019.10.053.
30. Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps Strength and the Time Course of Functional Recovery After Total Knee Arthroplasty. 2005.
31. Stevens-Lapsley JE, Balter JE, Kohrt WM, Eckhoff DG. Quadriceps and hamstrings muscle dysfunction after total knee arthroplasty. Clin Orthop Relat Res 2010;468:2460–8. https://doi.org/10.1007/s11999-009-1219-6.
32. Yoshida Y, Mizner RL, Ramsey DK, Snyder-Mackler L. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. Clinical Biomechanics 2008;23:320–8. https://doi.org/10.1016/j.clinbiomech.2007.10.008.
33. Alnahdi AH, Zeni JA, Snyder-Mackler L. Quadriceps strength asymmetry predicts loading asymmetry during sit-to-stand task in patients with unilateral total knee arthroplasty. Knee Surgery, Sports Traumatology, Arthroscopy 2016;24:2587–94. https://doi.org/10.1007/s00167-015-3827-x.
34. Furu M, Ito H, Nishikawa T, Nankaku M, Kuriyama S, Ishikawa M, et al. Quadriceps strength affects patient satisfaction after total knee arthroplasty. Journal of Orthopaedic Science 2016;21:38–43. https://doi.org/10.1016/j.jos.2015.10.002.
35. Lynch JT, Perriman DM, Scarvell JM, et al. The influence of total knee arthroplasty design on kneeling kinematics: a

prospective randomized clinical trial. Bone Joint J. 2021;103-B(1):105-112 https://doi.org/10.1302/0301-620X.103B1.BJJ-2020-0958.R1
36. Heyse TJ, Becher C, Kron N, Ostermeier S, Hurschler C, Schofer MD, et al. Patellofemoral pressure after TKA in vitro: Highly conforming vs. posterior stabilized inlays. Arch Orthop Trauma Surg 2010;130:191–6. https://doi.org/10.1007/s00402-009-0920-y.
37. Stroobant L, Vermue H, Jacobs E, Arnout N, Sadones C, Van Onsem S, et al. Extension stress radiographs for coronal laxity assessment in revision TKA: high reliability and increased valgus laxity in this population. Arch Orthop Trauma Surg 2025;145. https://doi.org/10.1007/s00402-025-05882-0.
38. Arnout N, Vanlommel L, Vanlommel J, Luyckx JP, Labey L, Innocenti B, et al. Post-cam mechanics and tibiofemoral kinematics: a dynamic in vitro analysis of eight posterior-stabilized total knee designs. Knee Surgery, Sports Traumatology, Arthroscopy 2015;23:3343–53. https://doi.org/10.1007/s00167-014-3167-2.
39. Sekeitto AR, McGale JG, Montgomery LA, Vasarhelyi EM, Willing R, Lanting BA. Posterior-stabilized total knee arthroplasty kinematics and joint laxity: A hybrid biomechanical study. Arthroplasty 2022;4:53. https://doi.org/10.1186/s42836-022-00153-4.
40. Arnout N, Vanlommel L, Vanlommel J, Luyckx JP, Labey L, Innocenti B, et al. Post-cam mechanics and tibiofemoral kinematics: a dynamic in vitro analysis of eight posterior-stabilized total knee designs. Knee Surgery, Sports Traumatology, Arthroscopy 2015;23:3343–53. https://doi.org/10.1007/s00167-014-3167-2.
41. Mihalko WM, Lowell J, Higgs G, Kurtz S. Total Knee Post-Cam Design Variations and Their Effects on Kinematics and Wear Patterns. Orthopedics 2016;39. https://doi.org/10.3928/01477447-20160509-14.
42. Banks SA, Catani F, Deckard ER, Mahoney OM, Matsuda S, Meneghini RM, et al. Total Knee Arthroplasty Kinematics Predict Patient-Reported Outcome Measures: Implications for Clinical Kinematic Examinations. Journal of Arthroplasty 2024;39:S224–9. https://doi.org/10.1016/j.arth.2024.02.014.
43. Palm-Vlasak LS, Smith J, Harvey A, Gupta A, Banks SA. Posterior cruciate-retaining total knee arthroplasty exhibits small kinematic changes in the first postoperative year. Knee Surgery, Sports Traumatology, Arthroscopy 2023;31:914–21. https://doi.org/10.1007/s00167-022-07027-x.