Clinical Biomechanics 100 (2022) 105824

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Comparison of the in-vivo kinematics of three different knee prosthesis designs during a step-up movement

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ARTICLE INFO

Keywords:
Total knee arthroplasty
Kinematics
Radiostereometric analysis
Knee prosthesis design

ABSTRACT

Background: There is no consensus on the importance of the kinematics of the prosthetic joint for the clinical outcome after total knee arthroplasty. A 3-armed randomized controlled trial was done to determine and compare the in vivo kinematics of a posterior cruciate-retaining and two posterior cruciate-sacrificing (Anterior-Stabilized and Posterior-Stabilized) prosthetic designs from the same total knee arthroplasty system. Since the anterior-stabilized and posterior-stabilized designs are posterior cruciate ligament-sacrificing designs, we hypothesized they would have similar contact-point kinematics. Further, we hypothesized that the cruciate-retaining design would have contact-point kinematics different from the anterior-stabilized and the posterior-stabilized designs, but comparable to a native knee.
Methods: Thirty-nine patients with a well-functioning total knee arthroplasty one year postoperatively underwent kinematic analysis of a weight-bearing step-up movement under fluoroscopic recording. Model-based radiostereometric analysis was used to determine anteroposterior contact-point translations and rotations through the movement path to assess knee kinematics.
Findings: The cruciate-retaining and anterior-stabilized groups' medial and lateral contact-points displayed similar paradoxical posterior translations during step-up in the magnitude of 7 and 2 mm, respectively. In contrast, the posterior-stabilized group's contact-points translated anteriorly by 4 and 10 mm throughout the movement and were significantly more posterior than the cruciate-retaining and the anterior-stabilized groups from >100° to 40° of flexion. The femur rotated internally with all designs.
Interpretation: The cruciate-retaining and anterior-stabilized designs displayed similar contact-point translation patterns during a step-up movement. Only the posterior-stabilized design showed a pattern comparable to native knees. Conversion from a cruciate-retaining to an anterior-stabilized design because of posterior cruciate ligament insufficiency will not change knee kinematics.

1. Introduction

One of the unresolved topics in total knee arthroplasty (TKA) is the effectiveness of the prosthesis in reproducing physiological kinematics comparable to a healthy native knee (Arnout et al., 2015; Dennis et al., 2003a). Implant design is one factor that influences post-TKA kinematics. However, there is still no consensus on the relationship between joint kinematics and TKA outcomes (Arnout et al., 2015). Non-physiological kinematics might result in impaired knee function due to reduced range of motion (RoM), paradoxical sagittal femorotibial translation or loss of femoral axial rotation (Angerame et al., 2019; Dennis et al., 2003b). Abnormal kinematics may also lead to increased polyethylene wear (Bourdon et al., 2021). Five percent of new TKAs fail within ten years, and about half for biomechanical reasons (Khan et al., 2016).

Healthy knee kinematics are complex, with a combination of rolling and gliding motions of the femoral condyles and tibial rotation (Smith et al., 2003). The posterior cruciate ligament (PCL) contributes to knee kinematics by preventing posterior translation of the tibia, contributing to femoral rollback during flexion and the "screw-home" mechanism in extension. Various attempts have been made to design implants that maintain normal kinematics after TKA. The decision to retain or sacrifice

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https://doi.org/10.1016/j.clinbiomech.2022.105824
Received 24 June 2022; Accepted 15 November 2022
Available online 17 November 2022

the PCL during TKA remains a controversial issue. Advocates of PCL-retention argue that the PCL provides more natural knee kinematics, improves proprioception, and enhances stability (Broberg et al., 2020a; Chalidis et al., 2011). Those who favour sacrificing the PCL claim that it allows for better ligament balancing, a more straightforward surgical procedure, reduced tibiofemoral loads and more predictable kinematics (Broberg et al., 2020a). Clinical evidence suggests that if the PCL is sacrificed, knee function can be improved with PCL-substitution (Harato et al., 2008). There are two ways to substitute PCL function; either with a central polyethylene post on the tibial insert and a transverse cam on the femoral component in the posterior-stabilized (PS) TKA or with a more congruent tibial insert, anterior stabilized (AS), characterized by a higher anterior wall and deeper trough compared to the standard cruciate-retaining (CR) insert. Some clinical studies have reported no difference in functional or radiographic outcomes between AS and PS inserts after TKA (Scott, 2018; Sur et al., 2015). Others have concluded that AS designs result in significantly less posterior femoral rollback, less anteroposterior stability and inferior patient-reported outcomes than PS inserts (Fritzsche et al., 2018; Han and Kang, 2020). However, evidence regarding AS designs is lacking. This dynamic, radiostereometric study aimed to compare the joint kinematics of AS, CR and PS designs of the same knee replacement system in a step-up movement from deep flexion to full extension. We hypothesized that an AS design would not significantly alter the contact kinematics compared to a PS design. Further, we hypothesized that the CR design would have contact kinematics different from AS and PS designs but resemble a native knee. Although previous in vivo studies have reported on the kinematics in different TKA implant designs (Banks et al., 1997; Broberg et al., 2020a; Cardinale et al., 2020; Cates et al., 2008; Jang et al., 2019), to our knowledge, none has investigated CR, PS and AS designs from the same manufacturer in a prospective randomized clinical trial.

2. Methods

This study is part of a larger prospective, randomized clinical trial comparing clinical outcomes of CR, AS and PS options of the same primary TKA system. The original study was conducted between March 2017 and January 2020 and included 216 patients. Eligible patients to the main study had primary osteoarthritis, varus or valgus deformity ≦15°, intact PCL, age between 45 and 77 years, body mass index <35 kg/m^2 and American Society of Anesthesiologists score of I or II. Exclusion criteria were: 1) prior anterior cruciate ligament surgery, 2) impaired collateral ligaments, 3) flexion <90°, 4) flexion contracture >10°, 5) peripheral neuropathy, 6) malignancy, 7) patients who did not speak Norwegian, 8) rheumatic disease and 9) previous osteotomy.

We used the primary Legion TKA system (Smith & Nephew, USA), which offers CR, AS and PS options. The CR and AS options entail identical tibial and femoral components but different designs of the tibial insert. The AS insert is a sagitally-curved tibial insert with vertically prominent anterior and posterior lips intended to provide stability for an insufficient or resected PCL.

The PS design has a typical cam-and-post mechanism to replace the role of the PCL in preventing anterior translation of the femur, still allowing for femoral rollback.

All participants provided informed consent before surgery. All procedures were carried out under spinal anaesthesia without a tourniquet. We used, in all cases, a mechanical alignment and measured resection with a femur-first technique. A medial parapatellar arthrotomy was used, and the patella resurfaced in all cases. A bony island and PCL-retractor protected the PCL during surgery. After resection of the tibial plateau, the PCL's integrity was assessed visually, by palpation and with trial components in place using the posterior drawer test. Patients with an intact PCL were randomly allocated to one of the three implant designs (CR, AS or PS). Patients with a compromised PCL underwent a routine cruciate-substituting TKA outside the study protocol. The post-operative care and rehabilitation were identical for the three groups.

Two independent physiotherapists, blinded to the study design, measured the knee RoM using a goniometer 12 months postoperatively. Patients completed the Knee injury and Osteoarthritis Outcome Score (KOOS) preoperatively and 12 months postoperatively.

To be included in the present radiostereometric substudy, eligible patients had to report no knee pain, have KOOS subscores >80 on the Pain, Symptoms, ADL and QOL subscales and > 60 on the Sport/Rec subscale 12 months postoperatively, and be capable of the step-up movement needed for the fluoroscopic procedure. In vivo knee kinematics were assessed for 39 consecutive patients from the three randomized groups, 13 with each implant design.

The patients' preoperative x-rays and x-rays taken one year after TKA were examined for measurements of hip-knee-ankle angle (HKA), medial proximal tibial angle (MPTA), mechanical lateral distal femoral angle (mLDFA) and posterior tibial slope; these parameters were compared between the groups.

2.1. *Fluoroscopy and kinematics*

All 39 patients underwent kinematic evaluation a minimum of 12 months after TKA using an Adora DRFI flat-panel fluoroscopy system (15 frames/s). Before data acquisition, patients received thorough instructions and performed the step-up task 2–3 times to gain comfort with the setup. Evaluations were done without shoes, and balance railings ensured patient safety. Patients placed their non-operated foot on the ground, their operated knee 30 cm from the detector and their operated foot on a 50 cm high staircase. Standardized positioning was ensured with built-in laser guidance. Then, under fluoroscopic surveillance, patients put weight on their operated knee and stepped up.

Recordings were in DICOM format, and each frame was separated into high-quality BMP grayscale images. Model-based RSA software was used to analyze the data (RSA*core* Leiden, The Netherlands). Three-dimensional (3D) computer-aided design (CAD) models for the Legion knee prosthesis (tibial and femoral components) were obtained from the manufacturer (Smith & Nephew, USA). The CAD models were superimposed on their respective projections in the two-dimensional (2D) fluoroscopy images (Fregly et al., 2005); 3D in vivo kinematics were also extracted from the 2D images (Mahfouz et al., 2003).

Data were analyzed from flexion (> 90°) to full extension in 20° intervals. We calculated the contact point positions of the medial and lateral femoral condyles with respect to the tibial plateau based on the minimum joint space width from the fluoroscopy data (van Ijsseldijk et al., 2012). Using these contact points, we also calculated the internal and external femoral rotation during the movement.

A coordinate system on the tibial plateau was created using the center point of the tibial baseplate in the mediolateral (x-axis) / anteroposterior (z-axis) direction and on the upper surface of the tibial baseplate (y = 0). Contact point positions anterior to the center point were defined as positive and posterior contact point positions as negative. The main parameter of interest was the anterior-posterior displacement of the contact points, defined as the shortest distance between the tibial metal baseplate and the medial and lateral condyle of the femur.

2.1.1. *Ethics*

The Regional Ethics Committee (2016/1981) approved the study, and it is registered at ClinicalTrials.gov (NCT03059927).

2.1.2. *Statistics*

A power analysis determined the number of study patients needed. A phantom study from our clinic showed a standard deviation (SD) of 0.37 mm for zero motion in the z-plane. A clinically significant group difference was a mean difference of 1 mm translation. Therefore, nine patients were needed in each group with an estimated SD of 0.37, a type 1 error rate of 5%, and a power of 80%. Allowing for dropouts, we included 13 patients per group, similar to other kinematic studies (Cates et al., 2008; Klemt et al., 2022).

Descriptive statistics were used to summarize sample characteristics. Normality was assessed with the Kolmogorov-Smirnov test. Mann-Whitney U, Kruskal-Wallis, independent sample *t*-tests, ANOVA and Pearson's chi-squared test were used as appropriate to compare groups. All analyses were two-sided and statistical significance was defined as $p < 0.05$. Statistical analyses were performed using IBM SPSS software, version 28.0 (IBM Corp, Armonk, NY, USA).

3. Results

Patient demographics (Table 1) and KOOS subscores preoperatively and at one year did not differ significantly between the three groups (Fig. 1).

At 1-year follow-up, flexion was significantly better in the PS group than in the CR and AS groups (Table 2). A comparison of the HKA angle, MPTA, mLDFA and posterior tibial slope did not show any statistically significant difference between the groups (Table 2).

3.1. Locations of contact points

Medial and lateral contact point translation patterns were determined for each group during the step-up movement. Figs. 2 and 3 show that the medial and lateral contact point lines of the CR and AS groups overlap. We found no statistically significant differences between the CR and AS groups in how the contact points translated during step-up.

The medial contact points in the PS group (Fig. 2) exhibited more posterior contact than the CR and AS groups throughout early flexion at >100° ($P = 0.0003$), 80° ($P < 0.001$), 60° (P < 0.001) and 40° (P < 0.001). The PS, CR and AS groups showed similar contact points from <40° of flexion ($P = 0.7$) to full extension ($P = 0.2$). In both the CR and AS groups, the medial contact points moved posteriorly approximately 7 mm throughout the movement (Fig. 2); hence a paradoxical translation compared with a healthy, unoperated knee. In the PS group, the medial contact points moved anteriorly approximately 4 mm from >100° to 60°, but from 60° to full extension, there was just a slight anterior movement of the contact points.

The lateral contact points showed a similar trend (Fig. 3). The PS group had more posterior contact points than the CR and AS groups throughout early flexion at >100° ($P < 0.0003$), 80° ($P < 0.001$), 60° (P < 0.001) and 40° ($P = 0.045$). All three groups showed similar contact point positions from 40° ($P = 0.5$) to full extension ($P = 0.3$). In the PS group, the lateral contact point moved anteriorly around 10 mm from >100° to 40° of flexion and remained relatively constant from 40° to full extension, moving only slightly anteriorly. The lateral contact points of the CR and AS groups moved only slightly posteriorly, around 2 mm throughout the motion. The PS group's lateral contact points translated the most. However, the medial contact points moved in opposite directions: posteriorly for the CR and AS groups versus anteriorly for the PS group. As a result, the PS group's lateral contact points translated the most, while those of the CR and AS groups moved slightly (Figs. 2 and 3).

In full extension, the medial and lateral contact points of all three groups ended up at almost the same relative positions, approximately 5 mm posterior to the tibial plateau's center point.

Table 1
Baseline characteristics for the three implant groups.

	CR (*n* = 13)	AS (n = 13)	PS (n = 13)	*P*-value
Age, mean (SD)	68 (5)	69 (4)	67 (5)	0.5
Body mass index, mean (SD)	28 (4)	27 (3)	29 (4)	0.7
Male/Female distribution, n/n	9/4	6/7	8/5	
Operated right side	8	9	9	
Days from surgery to fluoroscopy exam, mean(SD)	504 (98)	504 (109)	485 (80)	0.8

CR, cruciate-retaining; AS, anterior-stabilized; PS, posterior-stabilized.

There was an internal femoral rotation (external tibial rotation) throughout the step-up motion, with no significant group differences (Fig. 4).

4. Discussion

This study compared the in vivo kinematics of CR, AS, and PS designs of the same primary TKA system during a step-up movement using model-based dynamic RSA. We examined two PCL-sacrificing designs (AS and PS) and one PCL-preserving design (CR). Our main finding was that the PS design showed different contact point translations than the CR and AS designs. PS TKA had significantly more posterior tibiofemoral contact position for both medial and lateral condyles than CR and AS TKA from >100° to 40°. The PS group experienced *anterior* translation of the contact points of both condyles, more *laterally* than medially, resulting in internal rotation of the femur with respect to the tibia. In contrast, the AS and CR groups experienced *posterior* translation of the contact points of both condyles, but *more medially* than laterally, thus also resulting in internal rotation of the femur. Despite the differences in contact point translations of the PS design compared to the CR and AS designs, due to the direction and differences in the magnitude of the medial and lateral contact point translations, the resulting femoral axial orientation was the same in all three designs. All three designs showed a progressive internal rotation of the femoral component relative to the tibia during extension. The screw-home mechanism, associated with normal knee function, was present in all three designs, consistent with several other studies (Belvedere et al., 2017; Okamoto et al., 2014). The translation pattern for the PS group, but not the AS or CR groups, resembles native knee kinematics (Komistek et al., 2003).

Iwamoto et al. (Iwamoto et al., 2021) compared in vivo kinematics of CR and AS designs and found no significant difference between them. Unlike us, they examined the patients during deep knee flexion and not a step-up movement. Other studies have shown contact point translation patterns for the CR design similar to our findings (Okamoto et al., 2014; Victor et al., 2005). Victor et al. (Victor et al., 2005) studied the Genesis II TKA (Smith&Nephew, USA) and found progressive anterior contact point translation during flexion for the CR design, but the displacement pattern for the PS differed.

A pre-condition for CR TKA is that the PCL is fully functioning. However, some studies have demonstrated that the PCL in osteoarthritic knees is histologically abnormal, questioning this assumption (Akisue et al., 2002; Arbuthnot et al., 2011). Our kinematic analysis showed that the AS design mimicked the CR design. A few studies compared the outcome of a PCL-retaining TKA in patients with and without a PCL (Dion et al., 2019; Misra et al., 2003). Misra et al. (Misra et al., 2003) conducted a prospective randomized controlled trial with five-year follow-up where they compared resection with retention of the PCL when using a standard PCL-retaining TKA. They found no significant group differences regarding pain relief, RoM, strength or stability. A recent study (Dion et al., 2019) of 677 CR TKAs (540 retained intact PCL, 24 partially recessed PCL at the femoral side, and 113 completely excised PCL) reported no significant difference in clinical outcomes among the three groups, although there was significant variability in TKA types within each group. Dennis et al. (Dennis et al., 2003a) showed that even different models of the same type of implant could have different knee kinematics. A CR insert from another manufacturer might differ in depth, the anterior lip's prominence, or the posterior lip's size/presence, which can alter kinematics.

Both the AS and PS designs sacrifice the PCL, but they address substitution differently. With the PS design, the PCL is resected off the femur and removed with some intercondylar bone, whereas with AS design the PCL is often recessed or excised off the tibia and might remain attached to the posterior capsule, which might impact the knee's stability. Our primary hypothesis was that AS and PS designs would have similar contact point translation since they are PCL-sacrificing designs. The AS design's mean medial and lateral contact point translation was

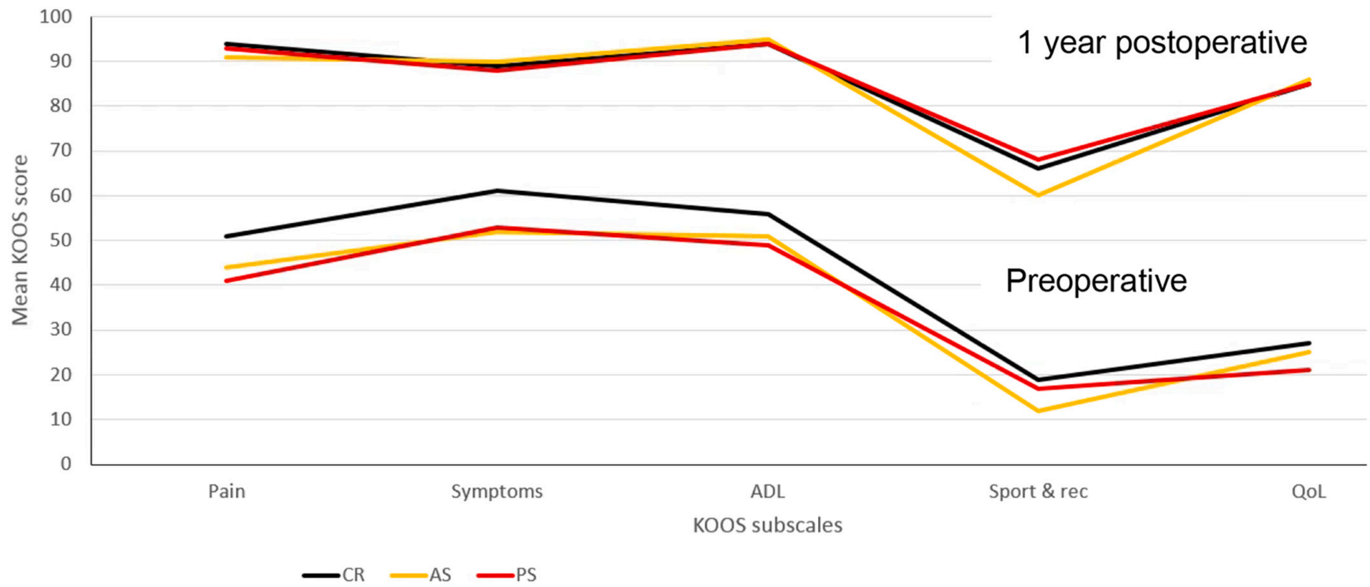

Fig. 1. KOOS profiles before and one year after TKA for the three implant designs.

Table 2
Pre- and postoperative knee alignment parameters and range of motion one year after total knee arthroplasty.

Parameters	CR	AS	PS	P-value
Flexion at one year, mean (°) (SD)	120 (7)	124 (4)	129 (7)	<0.05[a]
Extension at one year, mean (°) (SD)	-2 (3)	-2 (3)	-1 (2)	
HKA preoperative, mean (°) (SD)	5.9 (4.8)	5.0 (6.4)	6.8 (3.6)	0.7
HKA at one year, mean (°) (SD)	1.4 (1.8)	2.6 (2.1)	2.0 (1.8)	0.3
PTS[b] preoperative mean (°) (SD)	84.3 (6.3)	84.5 (3.6)	82.8 (4.8)	0.6
PTS[b] at one year, mean (°) (SD)	87.8 (3.9)	86.6 (2.3)	86.7 (2.7)	0.6
MPTA[c] preoperative, mean (°) (SD)	86.8 (2.9)	86.1 (2.1)	85.6 (2.9)	0.5
MPTA[c] at one year, mean (°) (SD)	87.7 (0.8)	87.3 (1.7)	87.2 (0.8)	0.5
mLDFA[d] preoperative, mean (°) (SD)	89.3 (2.5)	88.3 (3.4)	88.8 (2.2)	0.7
mLDFA[d] at one year, mean (°) (SD)	90.3 (2.3)	91.1 (2.1)	91.3 (1.7)	0.4

CR, cruciate-retaining; AS, anterior-stabilized; PS, posterior-stabilized; HKA, hip- knee- ankle angle; PTS, posterior tibial slope; MPTA, Medial proximal tibial angle; mLDFA, mechanical lateral distal femoral angle.

[a] Statistically significantly different from CR and AS ($p = 0.002$ and $p = 0.009$, respectively).

[b] Angle formed between the vertical line of the tibial anatomical axis and the tibial plateau tangent in the sagittal plane.

[c] Medial angle between the tangent to the tibial plateau and the mechanical axis of the tibia.

[d] Lateral angle between the distal femoral joint line and the mechanical axis of the femur.

significantly different from the PS group from 100° to approximately 40–50° of flexion. However, from 40-50° to full extension, the pattern was similar for the three designs. We believe the contact point pattern of the PS design is a result of the cam-and-post mechanism: the cam engages the post at around 40° of flexion (Banks et al., 1997), and drives

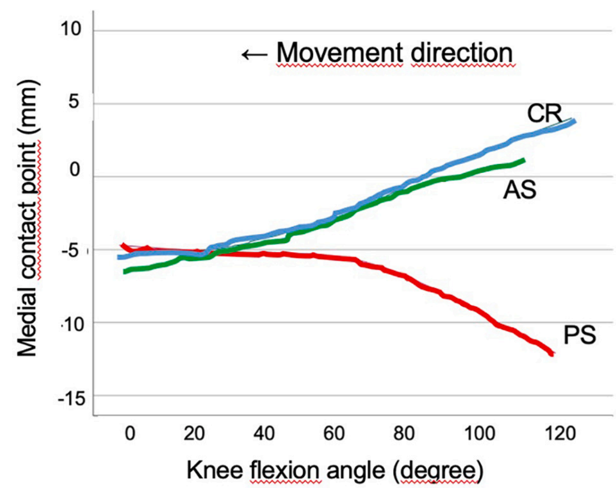

Fig. 2. Medial contact point motion plotted against knee flexion angles for the CR, AS and PS groups.

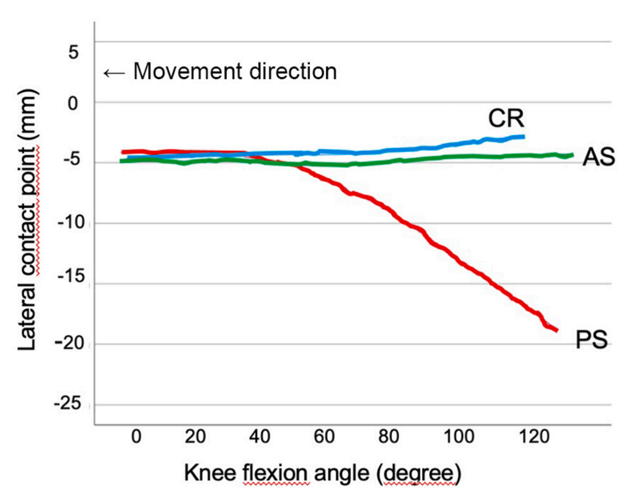

Fig. 3. Lateral contact point motion plotted against knee flexion angles for the CR, AS and PS groups.

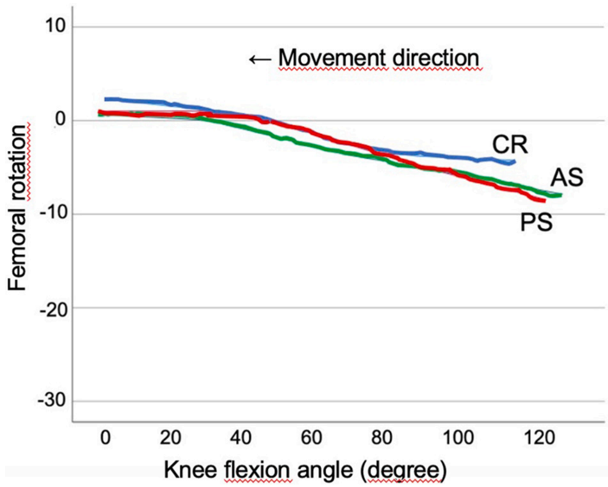

Fig. 4. Axial rotation of the femur with respect to the tibia for the CR, AS and PS groups. Negative and positive values correspond to external and internal rotation, respectively.

the femorotibial contact points posteriorly during further knee flexion, preventing anterior sliding of the contact points. This mechanism (femoral rollback) enables deeper flexion. Our results agree with other studies that suggest that the cam-and-post mechanism engages between 40° and 100° of flexion (Broberg et al., 2020b; Mihalko et al., 2016).

Multiple in vivo, weight-bearing, fluoroscopic analyses have indicated that natural knee kinematics are challenging to obtain after TKA (Dennis et al., 2001; Dennis et al., 2003a). In addition, combined kinematic abnormalities (decreased femoral rollback, paradoxical anterior femoral translation, reverse axial rotational patterns, and femoral condylar lift-off) typically are present (Dennis et al., 2001; Dennis et al., 2003a). All patients included in the present study were satisfied with their knees and had good RoM. However, our data showed that patients in the AS and CR groups had contact point kinematics different from a natural knee during step-up. In contrast, the PS group showed contact point translation and axial rotation that was more like a native knee. Moreover, we found significantly better RoM in the PS group compared to the AS and CR groups. This finding is consistent with several studies that report better RoM with PS design than CR or AS designs (Bercik et al., 2013; Hirsch et al., 1994; Li et al., 1995).

Several study limitations need to be considered. First, we analyzed only a step-up movement, as few studies have analyzed knee joint kinematics during such movement (Li et al., 2013; Okamoto et al., 2014). However, retrospectively, including a step-down movement would have yielded a more comprehensive kinematic investigation. Second, all patients had knee prostheses from the same manufacturer. Thus, the study findings may not be generalized to different TKA systems since other implant models, even of the same kind, can have different knee kinematics (Dennis et al., 2003a). However, limiting this study to one implant design nullified the influence of varying implant model designs on kinematics. More long-term follow-up studies of different implant models are required for more general conclusions. Third, we recruited well-performing patients to observe the impact of the prosthesis design, but this sample is not necessarily representative of the entire clinical population receiving these TKA designs.

Despite these limitations, our study provided valuable insight into the in vivo kinematics of three different TKA designs during weight-bearing step-up activity.

Study strengths were the precise kinematic measurements using a validated methodology, a standardized step-up movement and a consistent surgical technique.

5. Conclusion

TKA with either a CR or an AS design fails to restore physiological joint kinematics during step-up loading, in contrast to a PS design. The PS design provides a contact- point translation like the native knee during a step-up movement.

Funding

This work was supported by the Regional Health Board Southeast [grant number 2018103].

The study was funded by the Regional Health Board Southeast [grant number #2018060] and the Research Council of Norway [grant number #287816]. None of the funders was involved in the study at any time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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