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J-curve design total knee arthroplasty: the posterior stabilized shows wider medial pivot compared to the cruciate retaining during chair raising

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Abstract

Purpose Which total knee arthroplasty (TKA) design represents the better solution to restore a correct knee biomechanics is still debated. The aim of this study was to compare posterior stabilized (PS) and cruciate retaining (CR) version of the same TKA design (femoral component with an anatomic sagittal radius—J-curve design) by the use of dynamic Roentgen stereophotogrammetric analysis (RSA). The hypothesis was that the two models influence differently in vivo knee kinematic.

Methods A cohort of 16 randomly selected patients was evaluated 9 months after surgery: Zimmer PERSONA® was implanted, eight with CR design and eight with PS design. The kinematic evaluations were performed using a Dynamic RSA (BI-STAND DRX 2) developed in our Institute, during the execution of the sit-to-stand motor task. The motion parameters were obtained using the Grood and Suntay decomposition and the low-point kinematics methods.

Results PS TKA lateral femoral compartment had a wider anterior translation (17 ± 2 mm) than the medial one (11 ± 2 mm), while the two compartments of CR TKA showed a similar anterior translation (medial: 9 ± 2 mm/lateral: 11 ± 2 mm). T test for comparison between CR and PS TKA of antero-posterior translation showed a statistically significant difference ($p < 0.05$) in the flexion range between 15° and 40°. The CR prosthesis did not anteriorly translate during flexion. The PS design translated anteriorly showing a roll-forward mechanism during extension from 80° to 18° of flexion and a posterior translation from 18° to 0°. The same significant differences ($p < 0.05$) between the PS and CR groups were found comparing the low-point positions of the femoral condyles in the range of flexion between 25° and 40° for the medial compartment and between 15° and 25° for the lateral compartment.

Conclusions Dynamic RSA was able to investigate for the first time in vivo the kinematic behaviour of PS and CR version of the same TKA J-curve design. PS type showed a medial pivot during sit-to-stand motion task, while the CR type showed a cylindrical movement. Further studies are needed to evaluate the impact of different TKA designs on clinical results.

Level of evidence IV.

Keywords TKA · Posterior stabilized · Cruciate retaining · Dynamic RSA · Kinematics · Biomechanics

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Abbreviations

ACL	Anterior cruciate ligament
AEC	Automatic exposure control
AP	Anterior/posterior
BMI	Body mass index
fps	frames per second
FU	Follow-up
HIPAA	Health Insurance Portability and Accountability Act
OA	Osteoarthritis
PCL	Posterior cruciate ligament
PS	Posterior stabilized
CR	Cruciate retaining
RSA	Roentgen stereophotogrammetric analysis
TKA	Total knee arthroplasty

Introduction

Many new total knee arthroplasty (TKA) designs have been developed during years and the modern ones have nowadays reached in 83% of the cases a survival rate up to 25 years [1]. However, more than 20% of patients are still not satisfied in terms of pain relief and clinical improvement [2]. Which design represents the better solution to restore a correct knee biomechanics is still debated. The role of posterior cruciate ligament (PCL) in TKA and the level of constraint given by the polyethylene insert appears to be one of the most crucial topic [3–6]. The cruciate retaining (CR) design preserves the posterior cruciate ligament (PCL) and its role of primary stabilizer in antero-posterior translations, influencing joint stability and kinematics [7]. This implant disadvantage is that the surgical balance of the PCL is not always easy and that sometimes the ligament can result insufficient. On the contrary, in posterior stabilized (PS) prosthesis, the PCL is resected and substituted with a "Post and Cam mechanism" which should avoid paradoxical anterior translation of the femur during knee flexion (roll-forward) and allow a greater range of motion (ROM) [8–10]. To evaluate joint kinematics in vivo, under weight-bearing conditions, Roentgen stereophotogrammetric analysis (RSA) appears to be one of the most accurate techniques (based on the principles of optical photogrammetry) through the measurement of micromotions between two rigid bodies in three-dimensional space [11]. The purpose of the present study was to compare the biomechanical behaviour of two different prosthetic models, CR and PS version of a multi-radius J-curve design using a model-based dynamic RSA that had already shown to be able to asses TKA biomechanical properties [12]. This work is focused on the PERSONA® (Zimmer Inc, Warshaw, Indiana, USA) which has been highlighted as one of the best TKA designs in meeting the morphological variability of the distal femur across the global population [13]. The

PERSONA® CR femoral condyle shape is asymmetric and the posterior lateral part results lower than the medial one. This asymmetry matches the polyethylene insert improving its congruency. The PS femoral condyles, on the contrary, are symmetric and the polyethylene insert shape was developed to facilitate the postero-lateral contact with the femoral component to allow an easier roll-back. The hypothesis of the present study was that a different biomechanical behaviour would be present between the PS and the CR types during chair raising, a weight bearing, in vivo motor task that exemplifies common activities of daily living.

The clinical relevance of the present study is that, understanding biomechanical behaviour of different TKA design we could better understand the impact of the design on the clinical results.

Materials and methods

Patient selection

The number of patients was defined starting from a power analysis. The two populations T test was considered with a $p < 0.05$. The standard deviation of the two populations was set to 3 mm in AP translations, as reported in the literature [4, 14, 15]. The true difference of means was set to 5 mm. The power value was 0.9. On the basis of this analysis, the number of patients resulted eight subjects per prosthesis design and a total number of 16 subjects.

Thus, a cohort of 16 randomly selected patients was evaluated in this study. The randomization was carried out using a random numbers generator available on the website of Italian National Health System (https://www.servizi.regione.emilia-romagna.it/generatore/). This software generated 16 casual numbers within the interval (1, 45), which were used to select the patients from the waiting list for TKA between January and December 2015.

The inclusion criteria were: (1) age 50–90 years, (2) severe radiographic osteoarthritis (Kellgren–Lawrence grade > 3), and (3) patients scheduled for a primary TKA.

The exclusion criteria were: (1) previous corrective osteotomy on the affected lower limb, (2) post-traumatic arthritis, (3) severe preoperative valgus deformity (hip knee ankle angle > 10°), (4) BMI > 40 kg/m^2, (5) rheumatoid arthritis, (6) chronic inflammatory joint diseases, (7) patients with a pre-pathological abnormal gait (amputated, neuromuscular disorders, poliomyelitis, developmental dysplasia of the hip), (8) severe ankle osteoarthritis (Kellgren–Lawrence > 3), (9) severe hip osteoarthritis (Kellgren–Lawrence > 3), (10) previous total hip or ankle replacement, and (11) unwilling to take part in study and providing HIPAA authorization.

All patients were recruited after signing an informed consent. This study obtained the approval of the Ethics Committee

of the IRCCS Rizzoli Orthopaedic Institute (IRB statement: 0012645 approved 2014/04/03).

Computerized randomization was conducted to allocate them in a proportion of 1:1 either to "PS group" or "CR group".

The patients were divided into groups according to the prosthesis models.

Eight PS: five males, three females, six right knees, two left knees, mean age 68 years (95% CI 50–86), average BMI 30.

Eight CR: two males, six females, two right knees, six left knees, mean age 67 years (95% CI 55–79), average BMI 26.

Motor task

Patients were evaluated at 9-month follow-up (FU). The motor task evaluated for this study was the sit-to-stand: from the sitting position, the patient stands up. The used chair was made of a radiolucent material and had a height of 40 cm. Before starting the acquisition, the position of the image detector was adjusted according to the patient height to centre the knee in the field of view of the detector. The motor task was not standardized, to maintain the natural movement of the body of the patient. The motion test was performed three times. In the first and the second, the patient gain comfort with the experimental setup (no X-ray exposure), in the third, data were acquired (X-ray exposure).

Dynamic RSA

The RSA analysis was performed using an RSA device (BI-STAND DRX 2) developed in IRCCS Rizzoli Orthopaedic Institute, with the collaboration of ASSING (ASSING Group, Rome, Italy). The RSA device has two X-ray tubes (RTM 101HS, IAE, Milan, Italy) and two digital flat panels (PIXIUM RF4343, Thales Electron Devices S.A, Vélizy-Villacoublay, France). The two beamlines were positioned perpendicular to each other, as showed in Fig. 1.

The beamlines are synchronized to acquire two contemporary set images with a frame rate of eight frame for seconds (fps). The X-ray equipment was set at 70 kV, 125 mA, with AEC enabled at the image centre. During the acquisition, a solid-state dosimeter (Unfors Multi-O-meter 510L, Unfors RaySafe AB, Billdal, Sweden) was posed at the beam centre. The total measured dose was 3.0 ± 0.1 mGy. After motor task, the images of the calibration box (50 kV, 50 mA) were acquired to perform the data analysis and 3D reconstruction of the RSA scene.

Data analysis

The RSA images were processed using MATLAB® (R2016a, The MathWorks Inc., Natick, MA, USA) using the Model-Based RSA (MBRSA) algorithms [16–18] (Fig. 2).

Fig. 1 Beamlines setup used for the dynamic RSA evaluations of the patients

The output of the image processing was a 3D reconstruction of the movement of femur and tibia. The kinematical quantitative data for each patient were calculated using the Grood and Suntay decomposition [19, 20] and the contact areas between femur and tibia (low point).

The reference systems associated to femur and tibia are shown in Fig. 3.

The X-axis was chosen from medial to lateral direction and used to evaluate the flexion angle. The Y-axis was orientated from posterior to anterior direction and used to evaluate the anterior–posterior translations. The Z-axis was directed perpendicularly with respect to the other axes (Fig. 3).

Statistical analysis

The accuracy of the Dynamic RSA system was 1 mm for translations and 1° for rotations. The analyzed populations were so variable that the evaluated standard deviations were 4 mm and 4°. For this reason, the uncertainties associated to the results were evaluated according to the JCGM100 definition [21]. Thus, uncertainties of 1.4 mm and 1.4° have to be considered for all data in the following section. The groups (PS and CR) were compared to evaluate statistically significant differences during the motor task between the different prosthesis models. The comparison was performed using T test ($p < 0.05$). The T test was applied by pairing the kinematic data according to the normalized time. In this way, significant differences can be detected in specific moments of the motor task.

The compared kinematical parameters were: anterior/posterior translations, and the lowest point position of the femoral condyles (medial/lateral) with respect to the tibial component.
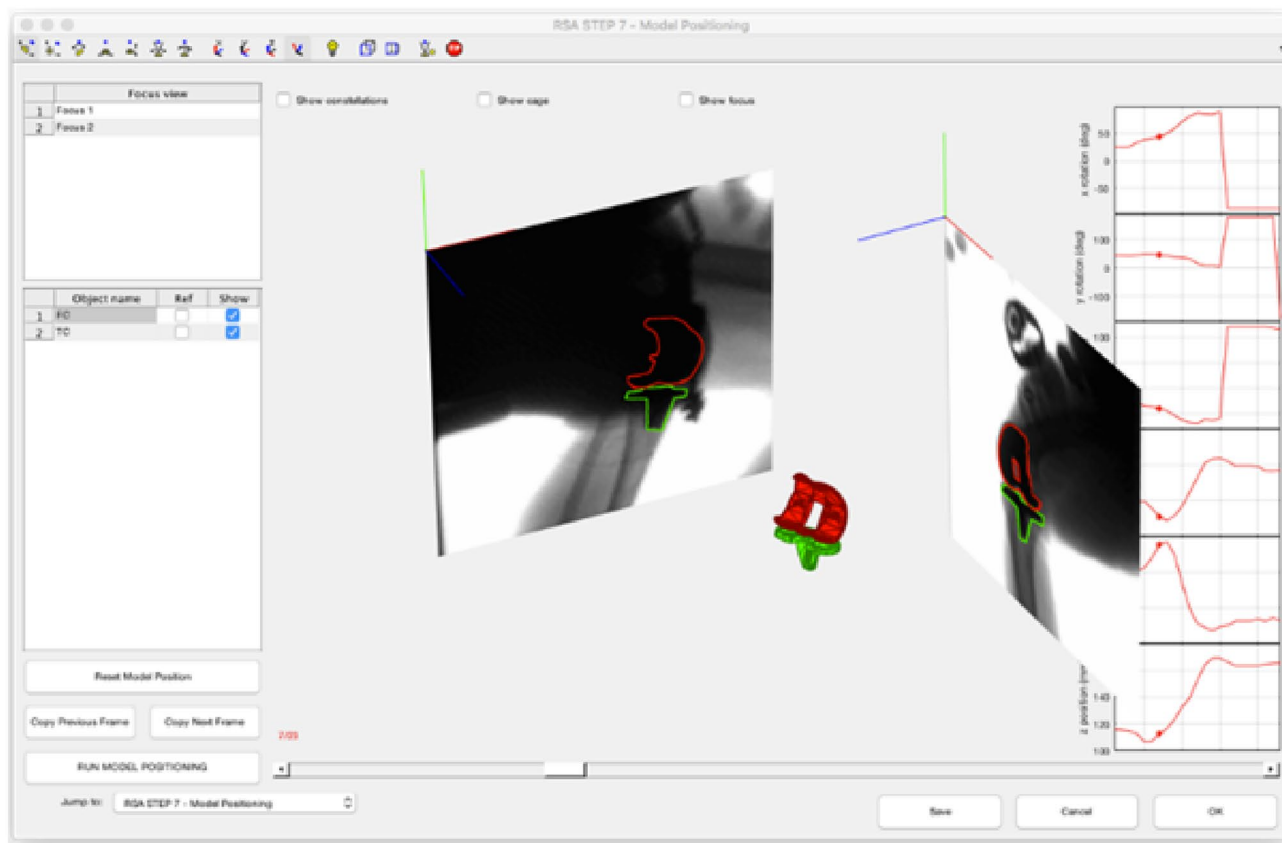
Fig. 2 Screenshot of the model-based positioning software used to process the RSA data. A PS model is shown

Results

Regarding the anterior/posterior translation of the femur with respect to the tibia, a statistically significant difference between the two groups ($p < 0.05$) has been found between 15° and 40° of knee flexion with a translation difference from 5.1 ± 1.4 mm at 18° to 2.4 ± 1.4 mm at 40° (Fig. 4).

Moreover, the PS model shows an anterior translation, from -3.1 ± 1.4 mm to 5.4 ± 1.4 mm during the movement between 80° and 18° of knee flexion and a posterior movement, from 5.4 ± 1.4 mm to 0.9 ± 1.4 mm, from 18° to 0° of knee flexion. On the contrary, the CR model does not show any significant translation during the whole motor task, and ranges from -1.4 ± 1.4 mm to a maximum of 0.9 ± 1.4 mm.

Regarding the low-point kinematic of the medial compartment of the femur with respect to the tibia, a statistically significant difference ($p < 0.05$) has been found between 25° and 40° of knee flexion, with differences from 3.0 ± 1.4 mm to 3.8 ± 1.4 mm (Fig. 5).

Regarding the low-point kinematic of the lateral compartment of the femur with respect to the tibia, a statistically significant difference ($p < 0.05$) was found between 15° and 25° of knee flexion, with differences from 2.0 ± 1.4 mm, to 3.8 ± 1.4 mm (Fig. 6).

A comparison of the low-point ranges between PS and CR models is represented in Fig. 7 and in Table 1.

The internal–external (IE) and varus–valgus (VV) rotations did not show any statistically significant difference between CR and PS models.

Discussion

The most important finding of the present study is that the PS model of a J-curve TKA design showed wider medial pivoting compared to the CR model in the described setting using Dynamic RSA. During years, a great number of knee prosthesis design have been proposed, always with the goal to resemble as much as possible the normal knee motion and to achieve satisfactory clinical result for the patients. One of these new TKA is the PERSONA® which peculiarity is the femoral component with an anatomic sagittal radius (J-curve design). The PERSONA® CR type femoral condyle shape is asymmetric, and its lateral side is thinner than the medial one.

The PERSONA® PS type on the other hand, has symmetric femoral condyles. Even though this specific prosthesis have been already studied in terms of clinical

Fig. 3 Position of the femoral and tibial reference systems used in the RSA processing
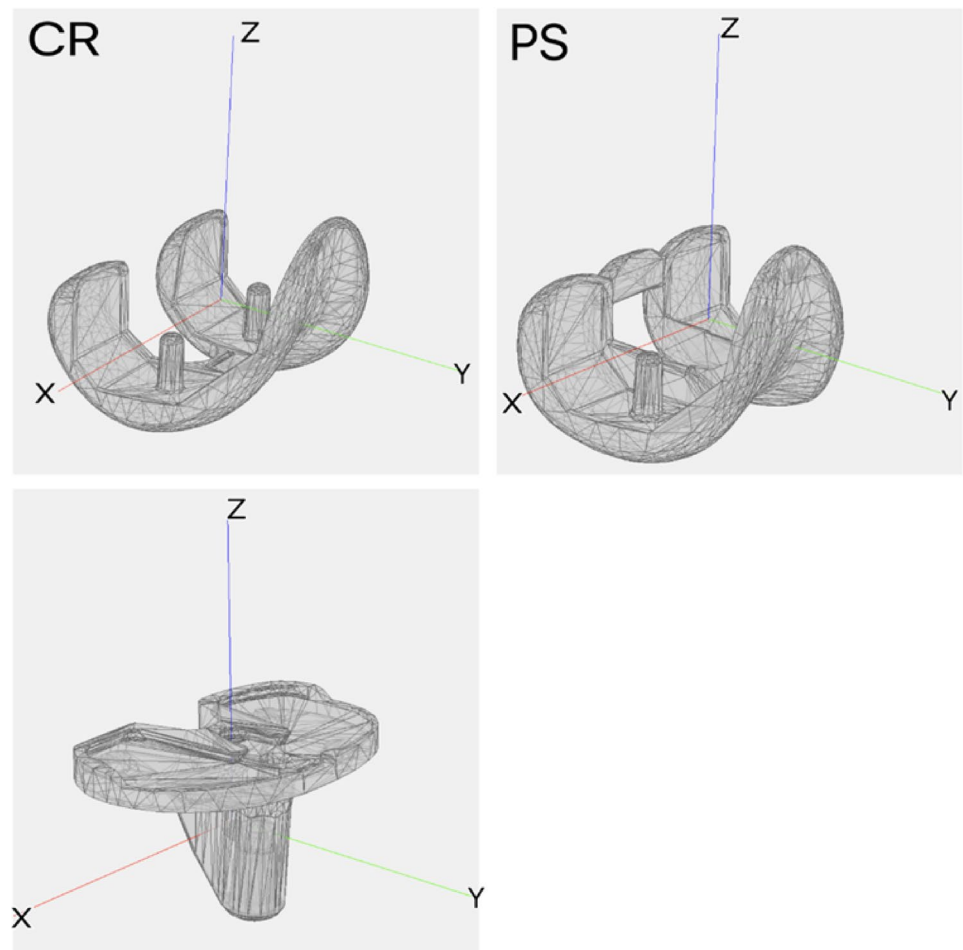
outcomes [14, 22], and femoral component fit [13] to the authors' knowledge, its kinematical features have never been investigated in vivo during the execution of motor tasks simulating activities of daily living.

The differences found in this study were statistically significant in terms of AP translation and low-point contact areas. Those parameters are the most affected by the presence or absence of the PCL as an AP translational stabilizer of the joint [23].

Concerning AP translations, the significant difference occurred in the range from 40° to 10° of flexion. The CR design seems not to translate and remains substantially in the same position during the whole range of extension (Fig. 4). The different prosthetic types and the functionality of the PCL can explain the different translation pattern. PS TKA femoral component, indeed, has a roll-forward movement during extension and, when the post engages the cam, the constraints make the femur slide backward in the final part of the extension, avoiding anterior luxation. Otherwise, the spared PCL in the CR TKA was not able to induce a similar anterior translation.

Focusing on low-point kinematic, it was possible to understand better the medial and lateral compartment behaviours. Figures 5 and 6 show that the CR TKA lateral compartment had an anterior translation slightly greater than the medial side. The difference between the medial and lateral side translation of the PS TKA femoral component was more significant. Therefore, if both prostheses performed a medial pivot, it resulted more evident for the PS group. This difference can be ascribed to polyethylene shape of the CR design which is highly congruent to femoral condyles, avoiding anterior paradoxical translation but also limiting the movement of the two compartments.

However, the overall behaviour of both PS and CR TKA agrees with the normal knee motion as described by Komistek et al. [24]. Using uniplanar fluoroscopy during sit-to-stand, they found an anterior translation of femorotibial contact areas, greater for the lateral compartment than the medial one. Our results were, also, in line with a Banks and Hodge [25] study which collected 213 TKA knees. The patients performed stair stepping under fluoroscopic control. They found that the PS TKAs analyzed had
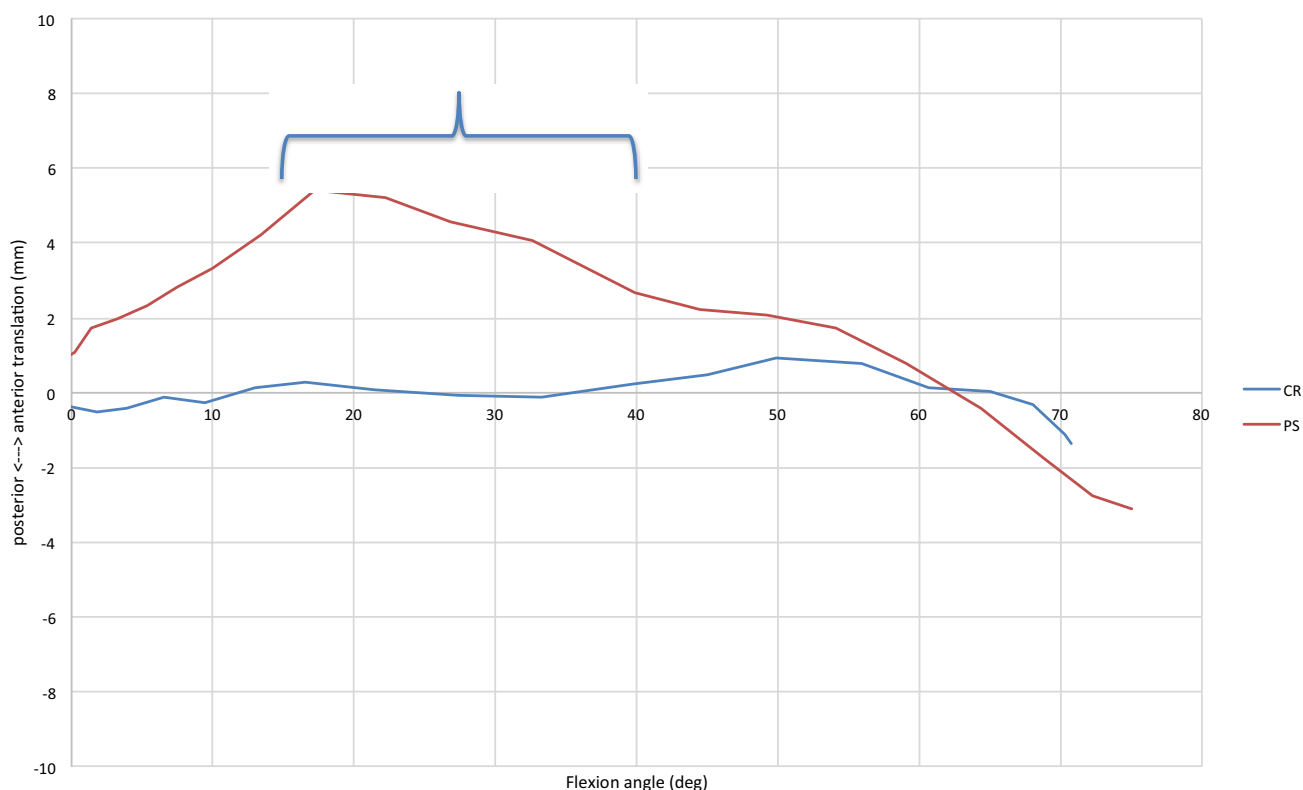
Fig. 4 Plots of the anterior/posterior displacements of the PS and CR models. Bracket indicates the significant difference range

a medial centre of rotation (75%) while in CR TKAs it was lateral (63%).

In addition, Carvalho [26] found a significantly lower femoral roll back in terms of AP translation, in CR prosthesis than in PS prosthesis, in a fluoroscopic model-based study on 38 knees.

However, the kinematical pattern observed in this study appears in contrast with other different comparative studies of CR and PS designs [27, 28]. Yoshiya's work, during weight-bearing deep knee bend, found that CR TKA performed a significant anterior shift of both medial and lateral side between 30° and 60° of flexion. On the contrary, PS TKA compartments remained almost constant throughout the range of motion [28].

Banks et al. [27] conducted an in vivo analysis with uniplanar fluoroscopy on a stair climb task that exhibited significantly lower ranges of femoral condylar translation for PS group, than PCL-retaining TKAs which also showed a larger lateral condylar translations with respect to the medial condyle. The authors explained these findings stating that the PCL exerted greater medial constraint when fully maintained.

Most of the differences found in the literature with the results presented in the present study could be due to PCL. This ligament alone, in fact, seemed not able to give enough constraint and induce a medial pivot in CR group as wide as in PS group. This is supported by Tang et al. [5] who evaluated the intra-articular forces in PS and CR TKA. They showed that PCL distributed forces more equally on medial and lateral sides whereas the presence of the post and cam mechanism facilitated the medial pivot and avoided paradoxical AP translations.

If there is accordance, in the literature, about the ability of PS and CR prosthesis to regain a good function [5, 29] and a long-lasting survivorship [1, 9, 30–32], biomechanical issues are still present. Not unique results are reported in the literature in terms of AP stability and roll-back mechanism, the majority did not find statistically significant differences [31, 33]. Baier et al. [34] reported only a slight mid-flexion instability in CR group, which did not occur in this study. Other studies detected a paradoxical femoral translation at low flexion angles for both PS and CR TKAs [35, 36], which was not observed in this study.

It is clear that different kinematic results can be obtained with different examination conditions. In vitro studies have the advantage to analyse fewer factors to evaluate the knee movement. On the other hand, in vivo studies can describe the movement in usual daily conditions. The disadvantage is the number of variables that affect the knee kinematics.
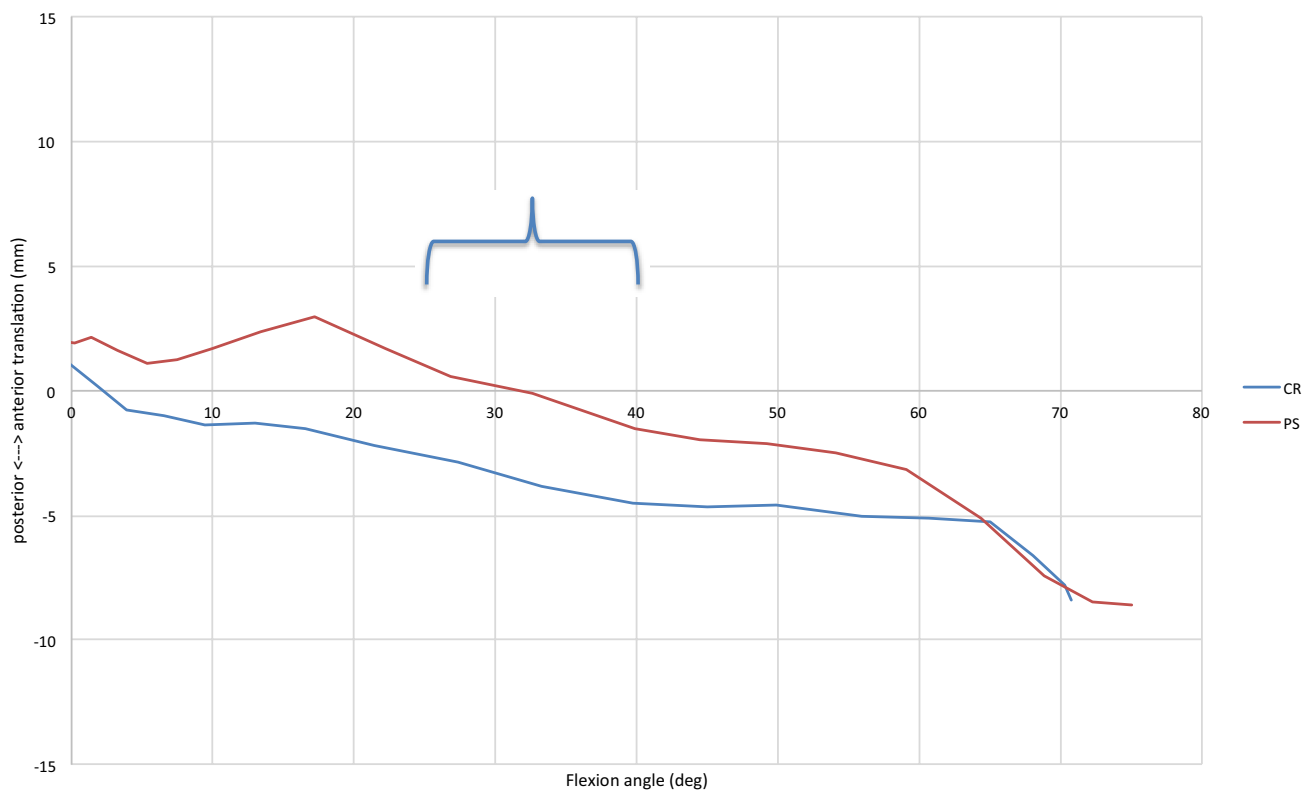
Fig. 5 Plots of the low-point positions of the femoral medial compartment of the PS and CR models. Bracket indicates the significant difference range

Then the implants studied in the literature have diverse features than the PERSONA® TKA. This could be one of the reasons why such different kinematical pattern is demonstrated. In fact, as confirmed by various authors, different geometrical solutions used by different TKA designs affected the kinematical behaviour of operated knees [7, 37].

The present study revealed some important limitations.

First, the motors task performed is not strictly standardized and so reproducible. The reason is that we wanted the patient to perform the movement in the most natural condition. But for this, some patients may had started the movement with a more pronounced external rotation of the knee, and so contact patterns and translations could be influenced by the initial position of the femur relative to the tibia. Due to this, to compare the data of every patient, the data were normalized, thus all the movements started and ended at the same time (see "Materials and methods" for details).

Another limitation concerns the relationship between the ratio of absorbed radiation dose and the numbers of frame per second. To reduce patient's exposure to radiation, the number of frames per second had to be set a priori, resulting in a limitation of the potential of the instrument.

Third, dynamic RSA evaluation was performed only after surgery, so it was not possible to compare joint kinematics before and after implant. It must be said that this was not an aim of the study: joint kinematics of an arthritic knee is not as the native one and also, involving the use of radiations, it was decided to avoid an excessive exposure.

Further studies are needed to understand the correlation between kinematical behaviour and clinical outcomes.

The clinical relevance of the present study is that understanding biomechanical behaviour of different TKA design we could better understand the impact of the design on the clinical results.

Conclusions

Model-based dynamic RSA proved to be an effective tool in comparing kinematical features of the PS and the CR types of a J-curve TKA. In particular, a statistically significant difference in terms of AP translation and low-point femoral contact areas has been detected between this specific PS and CR TKA. The PS model had a medial pivot movement during knee extension, while the CR model performed a more cylindrical movement. This derives from the specific shape of the CR prosthesis polyethylene which is highly congruent with the femoral component.
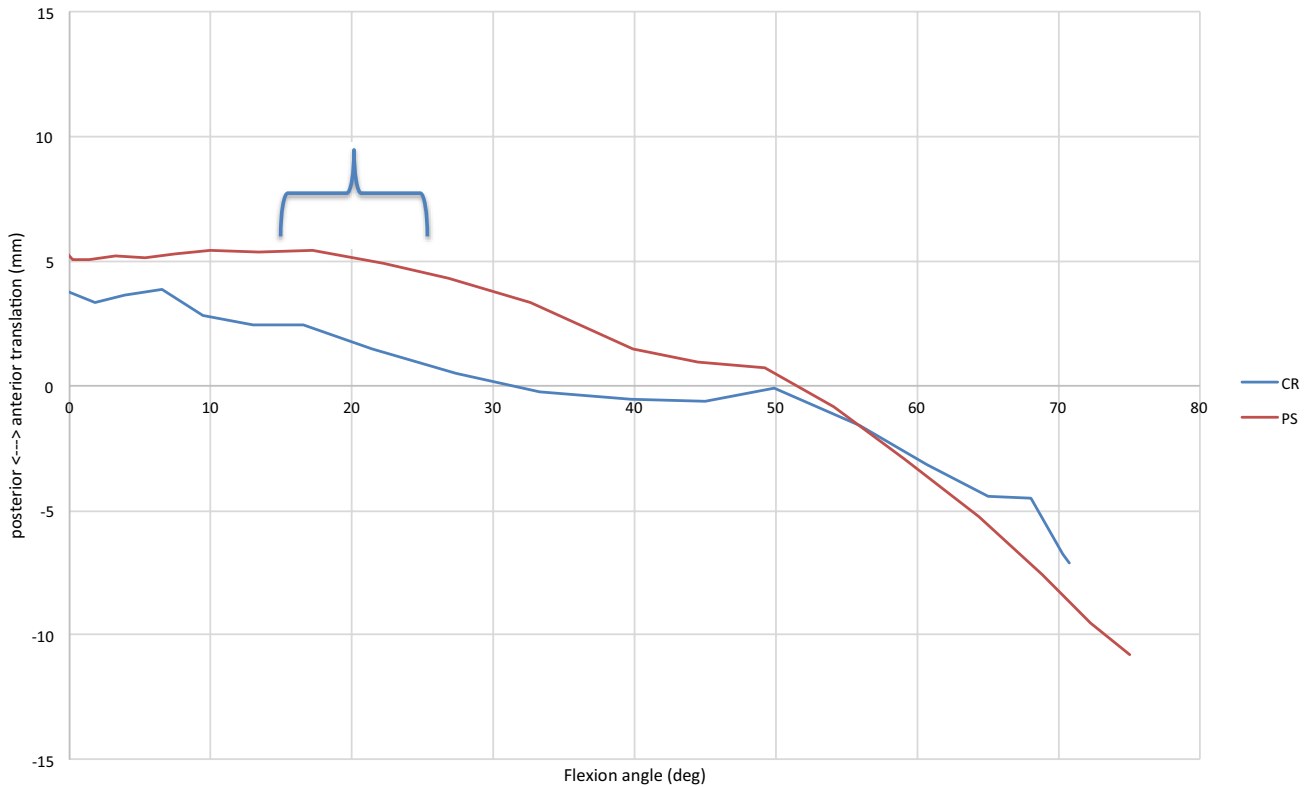
Fig. 6 Plots of the low-point positions of the femoral lateral compartment of the PS and CR models. Bracket indicates the significant difference range

Fig. 7 Plots of the low-point kinematic during the sit-to-stand of the PS and CR models
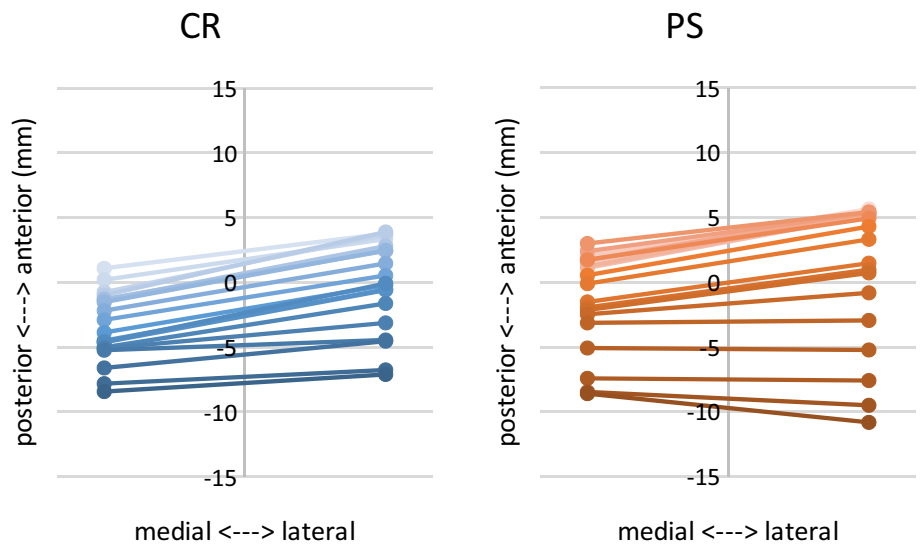

Table 1 Ranges of medial and lateral compartment low-point translations of PS and CR models

	Medial min–max (range)	Lateral min–max(range)
CR (mm)	-8.4 ± 1.4 to 1.1 ± 1.4 (9 ± 2)	-7.1 ± 1.4 to 3.8 ± 1.4 (11 ± 2)
PS (mm)	-8.6 ± 1.4 to 2.1 ± 1.4 (11 ± 2)	-10.8 ± 1.4 to 5.7 ± 1.4 (17 ± 2)

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study obtained the approval of the Ethics Committee of the IRCCS Rizzoli Orthopaedic Institute (IRB statement: 0012645 approved 2014/04/03).

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