Plain Radiographs Underestimate the Asymmetry of the Posterior Condylar Offset of the Knee Compared With MRI

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Abstract

Background Restoration of posterior condylar offset (PCO) during total knee arthroplasty is essential to maximize range of motion, prevent impingement, and minimize flexion instability. Previously, PCO was determined with lateral radiographs, which could not distinguish the asymmetries between the femoral condyles. MRI can independently measure both medial and lateral PCO.

Questions/purposes The purpose of this study is to determine the normal PCO of the knee, to establish the differences in medial and lateral PCO, and to compare PCO measurements obtained from radiographs versus those obtained from MRI.

Methods We identified 32 patients without a history of prior knee pathology who had both plain radiographs and

MRI scans of the same knee performed. The PCO was measured on lateral radiographs and compared with MRI measurements using a novel three-dimensional protocol.

Results By MRI, the mean medial PCO was 29 (± 3) mm and the mean lateral PCO was 26 (± 3) mm; both values were greater ($p < 0.001$ and $p = 0.03$, respectively) than the mean radiographic PCO of 25 (± 2) mm. The medial PCO, as measured by MRI, was significantly greater than the lateral PCO ($p < 0.001$).

Conclusions Plain radiographs underestimate PCO as well as the asymmetry of the medial and lateral PCO compared with MRI. This discrepancy is the result of both articular cartilage thickness and the anatomic differences between medial and lateral condyles. Designers of knee prostheses and instrumentation should take these differences into account.

Level of Evidence Level II, diagnostic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

The concept of restoration of the posterior condylar offset (PCO) of the knee during TKA to maximize ROM and avoid impingement was originally described by Bellemans et al. [2]. In their study, PCO was defined as “the maximal thickness of the posterior condyle, projected posteriorly to the tangent of the posterior cortex of the femoral shaft” as measured on true lateral radiographs [2]. Subsequent studies have shown that restoration of the relationship between the posterior articular surface of the femur and the femoral shaft is essential to preventing impingement, improving knee kinematics, maximizing ROM, and minimizing flexion instability [1, 14–16, 20, 21].

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

Each author certifies that he or she, or a member of his or her immediate family, has no funding or commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.

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Fig. 1 Photograph demonstrating the asymmetry of the PCOs of the medial and lateral femoral condyles.

During TKA, restoration of the PCO can be accomplished through prosthesis design, appropriate sizing, and position and rotation of the femoral component. Most current prosthetic knee designs do not account for differences in sizes between the medial and lateral femoral condyles (Fig. 1) and thus require surgeons to properly rotate the femoral component and perform the appropriate ligament releases [4, 9, 13, 24]. Proper femoral component rotation has been shown to be important in minimizing patellar complications and knee instability after TKA [11, 18]. Optimally, the femoral component should be rotated parallel to the transepicondylar axis of the femur. Lakstein et al. [12] reported femoral component internal rotation as a major cause of knee dysfunction in patients who required revision TKA. In addition, femoral component malrotation has been shown to be associated with coronal plane instability [19].

Traditional methods for measuring PCO rely on perfect lateral plain radiographs of the knee and do not take into account articular cartilage thickness or imperfections in radiographic technique. In fact, Clarke [5] demonstrated significant variability in the thickness of the articular cartilage of the posterior condyles in his study examining cartilage resected during primary TKA. He found that the mean cartilage thickness was 1.7 mm (range, 0–4 mm) on the posterior medial femoral condyle and 2.0 mm (range, 0–5 mm) on the posterior lateral femoral condyle [5].

In contrast to radiographs, we believe that MRI can visualize articular cartilage and eliminate imprecisions related to magnification and obliquity, allowing for precise, independent measurements of the true PCO of each femoral condyle.

Therefore, the purposes of this study were (1) to determine the normal PCO of the medial and lateral femoral condyles in normal, nonarthritic knees; (2) to examine differences between the medial and lateral PCO; and (3) to compare PCO measurements obtained from plain radiographs versus those obtained from MRI.

Patients and Methods

Before data collection, a power analysis was performed to determine the minimum number of patients that needed to be included in the study to detect a minimum clinically important difference of 2 mm. It was calculated that 17 patients were needed in each study group (radiograph and MRI).

Using our institutional online searchable radiology database, we identified patients between the ages of 20 and 40 years who had both plain radiographs and MRI scans of the same knee performed at our institution between March 2010 and February 2012. We selected only patients between age 20 and 40 years so as to minimize the likelihood of age-related degenerative joint disease in our study population. We excluded patients with a history of arthritis, deformity, dysplasia, osteochondral defect, fracture, or surgery about the knee; patient history was determined by examining office and inpatient progress notes, operative reports, and radiology reports. A total of 32 patients met our inclusion criteria during the period in question. This study population included 16 men and 16 women with an overall mean age of 31 years. The ethnicities of these individuals were as follows: 14 whites, 13 blacks, three Hispanics, and two Asians.

Using the lateral plain radiographs for these 32 patients, the PCO was measured using the technique previously described by Bellemans et al. [2]. In brief, we first drew a tangent line along the posterior cortex of the femoral shaft. A second line that was parallel to the first line and intersected the most posterior aspect of the femoral condyles was then drawn. The perpendicular distance between those two lines was then measured to determine the PCO of the knee. In addition, the cranial-caudal height of the patella was measured at the level of the anterior cortex (Fig. 2A); this value was used as a normalizing measurement to compare PCO measurements obtained from radiography with those obtained from MRI. All radiography measurements were performed digitally using our online Picture Archiving and Communication System and using the same computer terminal with the same high-resolution monitor.

For the MRI measurements, we designed a novel three-dimensional (3-D) protocol to precisely determine the PCO of both the medial and lateral femoral condyles. We used 3-D reconstructions of three-dimensional SPACE (Spatial

Fig. 2A–B (A) Representative lateral radiograph demonstrating measurement of the cranial-caudal height of the patella at the level of the anterior cortex. This value was used as a normalizing measurement to compare PCO measurements obtained from radiography with those obtained from MRI. (B) Representative sagittal MRI cut demonstrating measurement of the maximum cranial-caudal height of the patella at the level of the anterior cortex.

and Chemical-shift Encoded Excitation) proton density-weighted isovoxel MRI sequences with fat saturation to perform this technique. Articular cartilage is clearly visible on these proton density sequences because it is intermediate in signal; the high signal joint fluid and low signal subchondral cortex provide excellent contrast [3]. A multiplanar viewing platform (TeraRecon, Foster City, CA, USA) was used to create default orthogonal axial, sagittal, and coronal planes. First, we identified the axial cut that demonstrated the surgical transepicondylar axis of the femur (green line in Fig. 3A). Using that axial slice, we rotated the plane of the coronal images to be parallel to the transepicondylar axis and the plane of the sagittal images to be perpendicular to the transepicondylar axis (Fig. 3A, blue line = sagittal plane, green line = coronal plane). Using a single sagittal image through the center of the femoral shaft, the plane of the oblique images was angled to parallel the posterior cortex of the femoral shaft. In effect, this creates an oblique coronal plane that represents the posterior femoral cortex tangent line propagated medially and laterally along a line that parallels the transepicondylar axis. On sagittal images, the perpendicular distance between the position of this plane (Fig. 3B, red line) and the most posterior aspect of the medial femoral condyle (Fig. 3B, magenta line) was measured yielding the medial PCO value. The same technique was then repeated for the lateral PCO (Fig. 3C–D). Using the same sagittal images used to obtain the PCO values, we measured the articular cartilage thickness at the most posterior aspect of the femoral condyle. Finally, we measured the maximum cranial-caudal height of the patella at the level of the anterior cortex (Fig. 2B); this value was used as a normalizing measurement to compare PCO measurements obtained from radiography with those obtained from MRI.

The PCO measurements obtained from the lateral plain radiographs were then normalized to the PCO

measurements obtained from MRI using the patellar height as a normalizing value. Statistically, we compared the medial PCO with the lateral PCO obtained by MRI, and we compared the radiographic PCO measurements with the MRI PCO measurements using two-tailed paired t-tests. To evaluate the importance of articular cartilage thickness, we added the measured articular cartilage thickness on MRI to the radiographic PCO measurements and once again compared these values with the MRI PCO measurements using two-tailed paired t-tests.

Results

There is wide variability in PCO in the normal, nonarthritic knee (Table 1). Using MRI, the mean medial PCO was $30 (\pm 4)$ mm (range, 23–38 mm) in men versus $28 (\pm 3)$ mm (range, 22–32 mm) in women, and the mean lateral PCO was $27 (\pm 3)$ mm (range, 21–33 mm) in men versus $26 (\pm 3)$ mm (range, 21–32 mm) in women.

There is also significant asymmetry between the PCO of the medial femoral condyle and the PCO of the lateral femoral condyle. Using MRI, the mean medial PCO for all patients was $29 (\pm 3)$ mm (range, 22–38 mm), and the mean lateral PCO for all patients was $26 (\pm 3)$ mm (range, 21–33 mm) (Table 1). The medial PCO, as measured by MRI, was significantly greater than the lateral PCO in our study population ($p < 0.001$). In addition, the medial PCO was greater than the lateral PCO in all patients but one. The mean ratio of medial PCO to lateral PCO was $1.12 (\pm 0.08)$ (Table 1). Therefore, the medial PCO is on average 12% larger than the lateral PCO.

Plain radiographs underestimate the PCO in normal, nonarthritic knees compared with MRI. The mean PCO on lateral plain radiographs was $25 (\pm 2)$ mm. The radiographic PCO was less than the MRI medial PCO in all

Fig. 3A–D (A) Representative axial cut of a knee MRI demonstrating the surgical TEA of the femur (green line) and a line perpendicular to the TEA intersecting the most posterior aspect of the medial femoral condyle (blue line). (B) A sagittal cross-section demonstrating the medial PCO (green line), which is the perpendicular distance between a line drawn along the posterior aspect of the femoral shaft (red line) and a parallel line intersecting the most posterior aspect of the medial femoral condyle (magenta line). (C) Representative axial cut of a knee MRI demonstrating the surgical TEA of the femur (green line) and a line perpendicular to the TEA intersecting the most posterior aspect of the lateral femoral condyle (blue line). (D) A sagittal cross-section demonstrating the lateral PCO (light blue line), which is the perpendicular distance between a line drawn along the posterior aspect of the femoral shaft (dark blue line) and a parallel line intersecting the most posterior aspect of the medial femoral condyle (green line).

patients and was less than the MRI lateral PCO in 20 of 32 patients (63%). Using two-tailed paired t-tests, the medial and lateral PCO measurements from MRI were both significantly ($p < 0.001$ and $p = 0.03$, respectively) greater than the corresponding PCO measurements from radiographs. The mean thickness of the articular cartilage as measured on MRI at the most posterior aspect of the respective condyles was $2.3 (\pm 0.4)$ mm at the medial femoral condyle and $1.9 (\pm 0.4)$ mm at the lateral femoral condyle (Table 2). After adding the corresponding articular cartilage thicknesses to the radiographic PCO measurements, these total values were still significantly less than the MRI PCO measurements at the medial femoral condyle ($p < 0.001$) but not at lateral femoral condyle ($p = 0.1$).

Discussion

Restoration of PCO during TKA is essential to improving knee kinematics, maximizing ROM, and minimizing flexion instability [1, 14–16, 20, 21]. Bellemans et al. [2] found

that a reduction of the PCO by 1 mm after TKA decreased knee flexion by 6.1° . Massin and Gournay [15] found that a 3-mm decrease in PCO after TKA could reduce knee flexion by 10° before the occurrence of tibiofemoral impingement. Although the clinical significance of restoring the PCO during TKA is incompletely defined, if the goal of TKA design is to reproduce normal anatomy and kinematics, then appropriate measurement of the normal PCO is necessary for prosthesis and instrumentation design. Despite improvements in surgical technique and prosthetic design, “physiologic” TKA kinematics remain elusive [7, 8]. Thus far, the asymmetry of the anatomy has not been well appreciated. Designers of knee prostheses and instrumentation need reliable measurements to help reproduce normal anatomy, and therefore the “normal” anatomy must be defined and the accuracy of these measurements is of critical importance.

There are several limitations to this study. First, our study population was small and thus susceptible to sampling bias. All imaging studies were obtained at one urban tertiary care medical center. Therefore, the bone-articular

Table 1. Comparisons of various measurements of PCO

Patient number	Radiograph PCO (mm)	MRI medial PCO (mm)	MRI lateral PCO (mm)	MRI medial PCO:lateral PCO ratio
1	28	38	33	1:14
2	27	31	27	1:14
3	28	29	28	1:05
4	23	32	25	1:31
5	27	31	29	1:08
6	24	31	32	0:97
7	22	32	28	1:13
8	24	27	26	1:04
9	28	32	27	1:17
10	26	32	27	1:17
11	24	30	28	1:07
12	27	29	27	1:10
13	25	26	24	1:11
14	23	31	28	1:11
15	26	35	27	1:29
16	27	28	25	1:12
17	22	23	21	1:14
18	27	35	30	1:15
19	21	22	21	1:01
20	23	27	24	1:09
21	24	27	24	1:11
22	27	28	27	1:04
23	28	29	28	1:04
24	25	29	25	1:17
25	27	27	23	1:17
26	25	30	24	1:22
27	26	28	25	1:14
28	22	28	25	1:14
29	24	24	22	1:08
30	23	29	28	1:02
31	25	29	22	1:33
32	23	29	28	1:03
Mean	25	29	26	1:12
SD	2	3	3	0:08

PCO = posterior condyle offset.

relationships demonstrated in our study cannot be widely generalized to all patient populations. Larger study populations are needed to further delineate the anthropomorphic differences in PCO across sexes and/or ethnicities. Second, our study only evaluated nonarthritic knees, and thus, the results may not be applicable to arthritic knees requiring TKA. Because the importance of restoring “normal” anatomy during TKA continues to be emphasized, we sought to define the “normal” anatomy in patients without arthritis in this study. Future studies should evaluate PCO in patients with arthritis and may take advantage of

Table 2. Differences between articular cartilage thicknesses

Patient number	MRI MFC articular cartilage thickness (mm)	MRI LFC articular cartilage thickness (mm)
1	2.2	1.7
2	2.5	2.1
3	1.6	1.5
4	2.4	2.0
5	1.8	1.5
6	2.8	2.5
7	2.1	2.0
8	3.1	2.5
9	1.7	1.6
10	2.1	1.6
11	1.9	1.8
12	2.4	1.8
13	2.9	2.0
14	2.6	2.5
15	3.1	2.8
16	2.7	2.5
17	2.0	1.7
18	1.9	1.5
19	2.1	1.7
20	2.5	2.1
21	2.3	2.2
22	2.6	2.1
23	1.9	1.4
24	2.8	2.5
25	2.5	2.3
26	1.8	1.5
27	2.0	1.8
28	2.3	2.1
29	2.6	2.0
30	1.6	1.6
31	1.8	1.3
32	2.1	1.6
Mean	2.3	1.9
SD	0.4	0.4

MFC = medial femoral condyle; LFC = lateral femoral condyle.

intraoperative measurements during primary TKA. Third, measurements of bone-articular relationships in presurgical knees may not be applicable to relationships between the bone and the artificial articular surface after TKA. However, the measures of PCO were taken using the transepicondylar axis as a reference point to enhance clinical relevance. Thus, although the significance of the relationships is unknown, these measurements are necessary for prosthesis and instrumentation design when the goal is to reproduce normal knee anatomy. Fourth, our study reports only absolute measurements for PCO.

A followup study will focus on determining relative measurements for PCO, including ratios of PCO to femoral width and to AP height, in a larger patient population.

There are also notable weaknesses in the techniques used in this study. First, although all radiographs were performed by members of our radiology department using a standard protocol with a radiographic magnification marker, subtle differences in technique and leg position were detected, possibly as a result of the fact that the same technician did not perform all of the studies. These differences could potentially lead to biased results. Second, we have yet to perform a validation study to document the accuracy or reproducibility of the MRI measurement technique used. This is an important limitation of the present study. Future studies will be aimed at validating (1) the accuracy of our technique in both cadaveric and living subjects; and (2) the reproducibility of our technique by evaluating intra- and interobserver variability. Third, we are lacking a validation study that justifies using patellar height as a normalizing measurement. Establishing the accuracy and reproducibility of this technique will certainly be the goal of a future study.

This study shows there is wide size variability in the PCO of the normal, nonarthritic knee. Using MRI, the mean dimensions showed great variability and the SD in these values exceeded 10% of the values themselves. These results illustrate the complex anatomy of the knee articulation necessary for physiologic motion. Knee flexion occurs through space along 6 degrees of freedom through simultaneous flexion, rotation, and translation. This motion is guided by the cruciate ligaments and the asymmetric articular surface geometry of the medial and lateral tibial plateaus [23]. However, current knee designs universally sacrifice the anterior cruciate ligament and do not take into account the normal asymmetry of the posterior femoral condyles. Perhaps because of these differences, current TKA designs still generate nonphysiologic, paradoxical motions, and the reproduction of normal, physiologic knee kinematics has been elusive [17, 22]. If the ultimate design goal of TKA is achievement of normal knee kinematics, it is conceivable that reproduction of the normal surface geometry will help.

Our results also show there is significant asymmetry between the medial and lateral posterior condylar offsets in the normal, nonarthritic knee. In all but one, the medial femoral condyle posterior articular surface was more posterior than the lateral femoral condyle posterior articular surface. Using paired comparisons, the medial PCO was significantly greater than the lateral PCO in our study population. The medial PCO was on average 12% larger than the lateral PCO. Of course, these results only pertain to the knee with normal articular cartilage and may not pertain to the arthritic knee, particularly the valgus knee,

which typically has posterolateral cartilage loss, or the varus knee with chronic ACL insufficiency, which typically has posteromedial cartilage loss. In this study, we measured PCO using the transepicondylar axis (TEA) as a reference point to translate our results to the procedure of TKA and prosthesis design. Ideally, during TKA, the femoral component should be rotated parallel to the TEA of the femur to minimize patellar maltracking and instability [11, 18]. However, most femoral components currently available are symmetric in terms of the AP dimension of the medial and lateral condyles. Thus, when the standard symmetric femoral component is externally rotated, the PCO is increased more on the lateral side than on the medial side. Ishii et al. observed this reversal of the posterior articular surface offset relationship in a CT-based study involving 109 knees. Before surgery, the medial PCO was significantly larger compared with the lateral PCO, but after surgery, the lateral PCO was significantly larger compared with the medial PCO [10]. This decrease in medial PCO after TKA is typically compensated for by an asymmetric (perpendicular) tibial resection in which more bone is removed from the medial tibia than from the lateral tibia; this allows the surgeon to create a rectangular flexion gap. However, what remains unclear is the effect of changing the relative sizes of the medial and lateral PCO on knee kinematics when the lengths of the collateral ligaments remain constant. The implications of failing to reproduce the normal asymmetry in PCO are unknown. Clarke and Hentz [6] also found that after TKA, PCO increased by 2.8 mm in men and by 1.3 mm in women and that compromises in sizing were often required with unisex implants, particularly in female patients. Consequently, current prosthesis design and instrumentation do not allow for anatomic reproduction of the PCO of the knee.

We found that lateral plain radiographs significantly underestimate PCO, particularly at the medial femoral condyle, when compared with MRI. One explanation for this discrepancy is the fact that measurements based on radiographs do not take into account the thickness of the articular cartilage. Because articular cartilage adds to the thickness of the posterior condyle and plays an important role in knee kinematics, its thickness should be replaced when performing a TKA. Clarke [5] confirmed this discrepancy by measuring the articular cartilage thickness of resected posterior femoral condyles intraoperatively during TKA. Furthermore, another explanation for the discrepancy between radiographic PCO measurements and MRI PCO measurements is that the former is heavily dependent on technique. A true lateral radiograph requires both the medial and the lateral femoral condyles to be perfectly aligned. In reality, a true perfect lateral radiograph depends on perfect rotation and is rarely obtained. Therefore, the accuracy of measurements based on this

imaging modality may be limited. This pitfall is supported by the fact that even after adding the measured articular cartilage thicknesses to the radiographic PCO values, plain radiographs still significantly underestimate the PCO of the medial femoral condyle compared with MRI. Conversely, PCO measurements based on MRI are not subject to the same restrictions in technique, because slight changes in rotation can be corrected for using our novel three-dimensional measuring technique.

In this study, we developed a technique to measure the PCO by MRI. We found that plain radiographs significantly underestimate the size of the femoral condyles when compared with MRI scans. In the normal knee, the medial PCO is larger than the lateral PCO; in contrast to measurements made on plain radiographs, our MRI-based approach allows evaluation of this important difference. If future knee designs look to save both cruciate ligaments or to become asymmetric to reproduce normal surface geometries, precise measurement of PCO will be critical to the sizing of knee prostheses and instrumentation. Therefore, we recommend that the designers of these products use MRI scans when developing such devices.

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