Anatomical Assessment of the Distal Femur and Tibia for Optimal Femoral Rotational Alignment in Total Knee Arthroplasty

Chong Bum Chang, M.D.1,2, Sang Cheol Seong, M.D.1, Sahnghoon Lee, M.D.1 and Myung Chul Lee, M.D. 1

1Department of Orthopedic Surgery, Seoul National University College of Medicine, Seoul, 2Department of Orthopedic Surgery, Seoul National University Bundang Hospital, Seongnam, Korea

Purpose: This study aimed 1) to identify the rotational axis of the femur that provides a balanced 90° flexion space in TKA, 2) to assess the changes in the flexion space in deep flexion, and 3) to assess the changes in rotational alignment, with using the posterior condylar axis (PCA) as a guide, and as the changes are related to asymmetric cartilage erosion of the posterior condyle.

Materials and Methods: The axial MR images of the distal femur in knee extension and the coronal images of the distal femur and the entire tibia at 90 and 130° were examined in 40 healthy adults.

Results: The clinical transepicondylar axis (TEA) provides a balanced 90° flexion space on average. The balanced flexion space in 90° became an asymmetrical space with relative narrowing of the medial side in 130°. Every 1 mm of asymmetrical cartilage erosion between the posterior condyles changed the femoral rotation by approximately 1° when using the PCA as a guide.

Conclusion: This study suggests that the clinical TEA is the rotational reference that provides a balanced flexion space. When using the PCA as a rotational reference, a surgeon should consider the potential change in the rotational angle that is caused by asymmetrical cartilage erosion.

Key Words: Total knee arthroplasty, Femoral component rotation, 90 degree flexion gap, 130 degree flexion gap, Asymmetrical cartilage erosion

INTRODUCTION

Rotational alignment of the femoral component is an important surgical factor for successful total knee arthroplasty (TKA).2-5,8,16,18,19 Since an anatomical study demonstrated that the average tibial slope in the frontal plane was 3° of varus versus the mechanical axis of the tibia,3,9 external rotation of the femoral component relative to the posterior condylar surface has been regarded as reasonable rotational alignment to create a rectangular flexion gap when using the classic bone resection method. In addition, some degrees of external rotation of the femoral component is well known to be critical to prevent patellofemoral complications such as lateral tracking, subluxation and patellar component...
However, there’s controversy in the literature regarding the amount of external rotation and the ideal anatomical axis for optimal rotational alignment of the femoral component. The contemporary movement toward the concept of a fixed flexion-extension axis began with TKA, and the fixed axis was reported to closely approximate the epicondylar axis; thus, the transepicondylar axis (TEA) has attracted attention as an ideal rotational reference that provides functional kinematics. Furthermore, several authors also reported that the TEA most consistently recreates a balanced flexion gap. Nevertheless, two different TEAs, i.e. the surgical TEA and the clinical TEA, have been described in the literatures. Although more than 3° of discrepancy between the two TEAs was reported, controversy still exists regarding the relative merits of the two TEAs, in terms of which one is more optimal. Because of the traditional 3° external rotation of the femoral component stemming from the previous anatomical study, the posterior condylar axis (PCA) is generally believed to be the reasonable and practical reference axis, which also has been thoroughly integrated into instrumentation systems. However, several studies have demonstrated that 3° external rotation relative to the PCA is not sufficient with respect to both achieving a balanced flexion gap and physiologic patellofemoral tracking. In addition, its reliability has been questioned due to individual variations of the posterior femoral condyle and the anatomical changes of the condyles in arthritic knees. Among the anatomical changes of the posterior femoral condyle, it is our anecdotal experience that asymmetrical cartilage erosion in varus osteoarthritis, that is, the complete loss of cartilage on the medial femoral condyle with preservation of cartilage on the lateral femoral condyle, is the commonest finding during TKA. For this type of case, as many total knee replacement systems provide PCA guides which have two bars that rest on the medial and lateral posterior condyles to set the rotational angle, we expected more external rotation of the femoral component than the setting angle of the PCA guides.

Rotational alignment of the femoral component during deep knee flexion is another concern. Deep knee flexion after TKA has become a major challenge because more patients wish to continue sports and leisure activities that require an adequate range of motion. Many studies have been performed to identify the optimal rotational references that ensure a balanced flexion space at 90° of flexion, yet little information is available on optimal rotational alignment for the flexion space during deep knee flexion.

This study had three goals: 1) To assess the relationships between the femoral component rotation reference axes in normal subjects, and to identify the axis that provide a balanced flexion space at 90° flexion; 2) To assess the changes in the flexion space at 130° flexion for determining the optimal rotational alignment in deep knee flexion; 3) To assess the changes in rotational alignment related to asymmetric cartilage erosion of the posterior condylar surfaces when the PCA is used as a rotational reference.

MATERIALS AND METHODS

Forty normal knees in 20 female and 20 male healthy volunteers were evaluated using MRI (1.5 Tesla, Symphony, Siemens Medical Solutions, Erlangen, Germany). None of the subjects had a history of knee trauma or infection or any obvious knee deformity. The male subjects had a mean age of 22.1 years (range: 20 to 24 years), a mean weight of 68.2 kg (range: 58 to 86 kg), a mean height of 173.6 cm (range: 164 to 184 cm). The female subjects had a mean age of 25.8 years (range: 23 to 31 years), a mean weight of 51.4 kg (range: 42 to 66 kg), a mean height of 162.5 cm (range: 157 to 173 cm). We obtained axial MR images by using a custom knee coil with the knees in full extension, while obtained the coronal MR images of the whole length of the tibia with the distal femur at 90 and 130° of knee flexion.
flexion by using a body coil. During the whole examination, the flexion angle of the knee was controlled using a goniometer by one of the authors. The MR images at 90 and 130° of knee flexion were obtained using the following protocol: two signals were acquired using the coronal T1-weighted spin echo (SE) mode (repetition time msec/echo time msec, 750/20) with a 2-mm section thickness over a 400-mm field of view (adjusted according to leg length), and a 512×512 matrix.

The measurements were subsequently carried using the digital images on a 21-inch LCD monitor (ME315L; Totoku, Nagaoka, Japan) with employing M-view™ ver. 4.0 (Marotech, Seoul, Korea), the working software of the picture archiving and communication system (PACS). One of the study’s authors performed all the measurements and the intra-observer reliability of the obtained measurements was assessed by repeating the measurements three times at weekly intervals. The average angles of the three measurements between the individual axes were regarded as the true values.

This study was approved by the institutional review board of the hospital.

1. Evaluation of relationship between the femoral rotational axes and the flexion space at 90 degrees

To determine which axis most consistently provides a balanced flexion space at 90° flexion, the angles between the four femoral axes, i.e. the clinical and surgical TEAs, the anteroposterior axis of the distal femur (AP axis) and the PCA, and the line perpendicular to the tibial mechanical axis (p-TMA), which is parallel to the tibial cutting plane in conventional TKA, were measured on the images acquired at 90° of knee flexion. To define the p-TMA, the mechanical axis of the tibia was drawn first as a line connecting the center of the talus and the center of the intercondylar eminences of the tibia, and then the line perpendicular to the tibial mechanical axis was drawn from the medial edge of the medial tibial plateau (Fig. 1A, B).

2. Evaluation of difference in the flexion space between 90 and 130 degrees of knee flexion

To evaluate changes in the flexion space during deep knee flexion, we measured the angles between the clinical TEA and p-TMA at 130° of knee flexion (Fig. 2). By comparing this data with that acquired at 90° flexion, we assessed the change in rotational alignment on further flexing the knees from 90 to 130°.
3. Evaluation of the changes on the rotational alignment determined by the PCA due to asymmetric cartilage erosion

To assess the rotational alignment changes related to asymmetrical cartilage erosion of the posterior femoral condyles, which is expected in varus osteoarthritis, we measured the angle between the clinical TEA and the PCA with assuming complete erosion of the articular cartilage on the posterior part of the medial femoral condyle with preservation of the lateral femoral condyle cartilage (Fig. 3A, B). We then calculated the amount of rotational angle change relative to the differences of the eroded cartilage thickness between the medial and lateral femoral condyles when the PCA was used as a reference axis.

4. Reliability tests and statistical analysis

The intra-rater reliability for all measurements was assessed using the intraclass correlation coefficient (ICC) and found that the measurements agreed well (ICC = 0.77~0.89). Student’s t-test was used to determine whether the angles between the rotational references in the male group were different with those in the female groups. In addition, paired t-test was used to examine the significance of changes in the angle of the clinical TEA vs. the p-TMA between 90° and 130° of knee flexion in each gender. All the statistical analysis was performed using SPSS ver. 12.0 (SPSS Inc., Chicago, IL, USA).

RESULTS

Among the evaluated axes, the clinical TEA most consistently showed a parallel relationship with the p-TMA at 90° of knee flexion, which means a balanced flexion space at 90°. The mean angles between the clinical TEA
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နာစာအင်အထိမ်းအင်စီ တီးစီး အသစ် တချက် ၁ ချက် ၁၀ ချက် ၂၀၁၀ အကြိုရပ်စီ

and the p-TMA were 0.8° (range: −2.2 to 2.7, SD: 1.3), in the men and 0.4° (range: −2.0 to 4.3, SD: 1.8) in the women (the plus value indicates that the clinical TEA requires external rotation to adopt a position parallel to the p-TMA). The average angles between the posterior condylar axis (PCA) and the p-TMA were 5.1° in the men and 6.6° in the women (Table 1).

Compared with the relationship at 90° flexion, the clinical TEA was significantly internally rotated relative to the p-TMA during deep knee flexion (p<0.001 in both gender), which means that relative medial flexion space narrowing occurred compared to the lateral flexion space. The mean angles of internal rotation were 2.3° in the men and 2.0° in the women (Table 2).

When assuming the presence of expected asymmetrical cartilage erosion on the posterior condyles in varus osteoarthritis, the average changes of the clinical TEA/PCA angles were 1.9° in both genders (Table 3); the measured average thicknesses of the cartilage on the posterior part of the medial femoral condyle on the MR imaging was 1.8 mm in the men and 1.6 mm in the women. Therefore, a 1mm difference of cartilage erosion of the posterior condyles causes a change of 1.1° of rotation in the men and 1.2° in the women when using a PCA guide with two bars that rest on the medial and lateral posterior condyles to set the femoral component rotation. Based on the amount of change, the calculated average angles between the PCA and the p-TMA that were expected in varus osteoarthritis were 3.3° in the men and 4.7° in the women (Table 3).

Table 1. The Angles between the Line Perpendicular to the Tibial Mechanical Axis and the Four Femoral Rotational Axes at 90 Degrees of Flexion

<table>
<thead>
<tr>
<th>Reference axis</th>
<th>Male</th>
<th>Female</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD (range))</td>
<td>Mean (SD (range))</td>
<td></td>
</tr>
<tr>
<td>cTEA†</td>
<td>0.8° (1.3° (−2.2 to 2.7°))</td>
<td>0.2° (2.2° (−5.6 to 4.3°))</td>
<td>0.335</td>
</tr>
<tr>
<td>sTEA†</td>
<td>3.9° (1.3° (1.5 to 5.9°))</td>
<td>4.0° (2.1° (−0.7 to 6.9°))</td>
<td>0.982</td>
</tr>
<tr>
<td>PCA†</td>
<td>5.1° (1.6° (1.7 to 8.2°))</td>
<td>6.6° (2.2° (1.4 to 10.5°))</td>
<td>0.020</td>
</tr>
<tr>
<td>p-AP axis†</td>
<td>0.9° (2.6° (−4.8 to 5.0°))</td>
<td>0.2° (2.8° (−5.0 to 6.0°))</td>
<td>0.434</td>
</tr>
</tbody>
</table>

SD: Standard deviation, cTEA: Clinical transepicondylar axis, sTEA: Surgical transepicondylar axis, PCA: Posterior condylar axis, p-AP axis: Perpendicular line to the anteroposterior axis of the femur.

*The p-value with statistical significance (p<0.05) are shown in bold. †The plus value indicates that each axis requires external rotation to be set parallel to the line perpendicular to the tibial mechanical axis.

Table 2. The Relationship between the Perpendicular Line of the Tibial Mechanical Axis and the Clinical TEA as the Knee Flexed is from 90 Degrees to 130 Degrees

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD (range))</td>
<td>Mean (SD (range))</td>
<td></td>
</tr>
<tr>
<td>90° flexion*</td>
<td>0.8° (1.3° (−2.2 to 2.7°))</td>
<td>0.2° (2.2° (−5.6 to 4.3°))</td>
<td>0.335</td>
</tr>
<tr>
<td>130° flexion*</td>
<td>3.1° (1.0° (0.0 to 4.2°))</td>
<td>2.2° (2.4° (−3.1 to 8.4°))</td>
<td>0.171</td>
</tr>
<tr>
<td>Amount of change†</td>
<td>2.3° (0.7° (1.1 to 3.8°))</td>
<td>2.0° (0.6° (1.2 to 4.1°))</td>
<td>0.211</td>
</tr>
</tbody>
</table>

SD: Standard deviation.

*The plus value indicates that the clinical TEA requires external rotation to be set parallel to the line perpendicular to the tibial mechanical axis, †The changes are statistically significant (p<0.001 in both genders).
Table 3. Comparison of Angles between the Clinical TEA and the PCA, and the PCA and the Line Perpendicular to the Tibial Mechanical Axis (p-TMA) before, and after Assuming Asymmetrical Cartilage Erosion on Posterior Condyles Expected in Varus Osteoarthritis

<table>
<thead>
<tr>
<th>Variables</th>
<th>Male</th>
<th>Female</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD (range)</td>
<td>Mean</td>
</tr>
<tr>
<td>cTEA vs. PCA</td>
<td>4.3°</td>
<td>1.2° (2.3~6.2°)</td>
<td>6.5°</td>
</tr>
<tr>
<td>Adjusted cTEA vs. PCA†</td>
<td>2.4°</td>
<td>1.2° (0.5~4.1°)</td>
<td>4.6°</td>
</tr>
<tr>
<td>Amount of change</td>
<td>1.9°</td>
<td>0.3° (1.2~2.4°)</td>
<td>1.9°</td>
</tr>
<tr>
<td>PCA vs. p-TMA</td>
<td>5.1°</td>
<td>1.6° (1.7~8.2°)</td>
<td>6.6°</td>
</tr>
<tr>
<td>Adjusted PCA vs. p-TMA‡</td>
<td>3.3°</td>
<td>1.6° (−0.7~5.5°)</td>
<td>4.7°</td>
</tr>
</tbody>
</table>

SD: Standard deviation, cTEA: Clinical transcondylar axis, PCA: Posterior condylar axis.
*The p-value with statistical significance (p<0.05) are shown in bold. †The angle between the cTEA and the PCA measured on the axial MR imaging assuming complete erosion of the articular cartilage on the posterior part of the medial femoral condyle with preservation of the lateral femoral condyle cartilage. ‡The calculated average angles between the PCA and the p-TMA based on the amount of change between the cTEA and the PCA.

DISCUSSION

Despite that there is more than 3° of discrepancy between the two TEAs9), it’s still debatable which is the more reproducible and functional axis, i.e., the clinical or the surgical TEA2,7,10,12,18,28,31,32). Regarding the functional aspect of the patellofemoral joint, Akagi et al. suggested that the clinical TEA might be closer to the functional axis for patellofemoral articulation because the average AP axis is perpendicular to the clinical TEA2,28), which was also confirmed in our previous study9). Concerning the flexion gap, some authors have reported that the surgical TEA most consistently recreates a balanced flexion gap, based on the intraoperative measurement data21), whereas others have demonstrated that the clinical TEA has a parallel relationship with the line perpendicular to the tibial mechanical axis, which corresponds with our results18,23).

Our assessments of the MR images acquired at 130° of flexion implies that even a symmetrical flexion space at 90° changes to become asymmetrical with narrowing of the medial flexion gap relative to the lateral gap for TKA. We found a similar phenomenon by comparing the measurements of the medial and lateral flexion gaps at 90 and 130° in 20 osteoarthritic patients (36 knees), who participated in another rotational alignment study with performing TKA. The obtained measurements showed that a flexion space that’s balanced at 90° becomes asymmetric with narrowing of the medial flexion gap at 130° of flexion (mean: 2.7 mm, SD: 1.2 mm, range: 1~6 mm)8). Having reviewed the available data, we are concerned that aligning the femoral component to the surgical TEA potentially aggravates such an imbalance with the knee in deep flexion, which might lead to excessive stress on the medial side of the tibial insert after TKA, or this requires excessive medial soft tissue release that’s more than physiologic tension, and this might lead to flexion instability after TKA. Taken together, aligning the femoral component to the clinical TEA, rather than the surgical TEA, would be advantageous in terms of restoration of patellofemoral kinematics and balancing the flexion gap not only at 90° but also in deep flexion during TKA.

Traditionally, 3° of external rotation relative to the PCA is generally regarded as reasonable rotational alignment to create a rectangular flexion gap when using the classic bone resection method20). In contrast, Tang et al. found that the medial inclination of the tibial plateau in Chinese patients was greater than the commonly reported 3°, suggesting that the tibial slope in
Fig. 4. Photograph showing the resected distal femur of a patient with varus osteoarthritis. Complete loss of cartilage on the medial femoral condyle (arrow) with preservation of cartilage on the lateral femoral condyle (arrow head) was observed.

the frontal plane might be race dependent\textsuperscript{29}. We also found that the mean external rotation of 6.6° in women and 5.1° in men relative to the PCA provides a rectangular flexion gap at 90°, which are 2 or 3° more degrees of external rotation compared to the traditional 3° relative to the PCA. However, we found that, approximately, every 1 mm of asymmetrical cartilage erosion can change the femoral rotation by 1° when using a PCA guide. Considering the majority of the patients warranting TKA have advanced varus OA of the knee, which would have erosion of the cartilage on the medial posterior condyle with relatively intact lateral condyle (Fig. 4), a surgeon can expect that aligning component rotation using a PCA guide in these patients caused more external rotation relative to the setting angle of the PCA guides. In view of this finding, conventional 3° of external rotation relative to the PCA would be close to an optimal angle in advanced varus OA of the knee, which is conducive to setting the femoral-component rotation closer to the clinical TEA.

We believe that the data presented by this study is useful for determining the optimal rotational alignment of the femoral component, and especially in an Asian population. However, as there are considerable individual deviations, these anatomic variations should be considered when treating individual knees. To assess the rotational profile of the individual knees before TKA, MRI or computed tomography would be the most useful tools. However, routine use of these methods has its drawbacks, which include high cost and/or radiation. Instead, the use of recently developed axial radiographs, which allow measurement of the angle between the PCA and TEA\textsuperscript{16,27}, might be a practical alternative method to assess the rotational profile of the individual knees. Nevertheless, as the axial radiographs only provide the angle between the TEA and the PCA as a bony geometry, operative information on the asymmetrical cartilage erosion should be considered when final rotational angle was determined during TKA.

Several limitations should be noted in this study. A major limitation involved that our study was conducted in the young healthy volunteers, thus the results may be different from those in the osteoarthritic patients. However, our another study found that the relationship among the rotational axes in the osteoarthritic patients was almost identical with the results in this study\textsuperscript{8}). Furthermore, most related studies which have been performed in Asian countries have reported similar relationships of rotational axes with our study\textsuperscript{1,2,17,21,28,29,31,32}). Thus, our findings would not be unique in young healthy subjects. Another limitation is that we did not consider mechanical alignment during our study. Although our study subjects had no significant deformity of their lower limbs (mean anatomic tibiofemoral angles: valgus 4.2°, SD: 1.7, range: valgus 1° to 7°), as individual variations in the tibial and femoral mechanical alignments may influence the flexion gap conditions, consideration of the mechanical alignments might provide additional information. Finally, intra-observer reliabilities of the measurements in this study were satisfactory, but as one examiner carried out all measurements, we cannot comment on inter-observer reliability.
CONCLUSION

Our study suggests that the clinical TEA, rather than the surgical TEA, would be the rotational reference provides a more balanced flexion space not only in 90° but also in deep knee flexion. When using the PCA as a rotational reference, a surgeon should consider the potential change in the rotational angle caused by asymmetrical cartilage erosion.

REFERENCES

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인공 슬관절 전치환술 시 적절한 대퇴 치환물의 회전 정렬을 위한 원위 대퇴골과 경골의 해부학적 고찰

장종범1,2, 성상철1, 이상훈1, 이명철1

목적: 본 연구는 1) 인공 슬관절 전치환술 시 균형잡힌 90° 굴곡 간격을 위한 대퇴 회전 정렬의 축과, 2) 90°와 130° 굴곡에서의 균극 간격 사이의 변화 및 3) posterior condylar axis (PCA) 이용 시 후방 대퇴골의 비 대칭적 연골 소실에 의한 대퇴 회전 정렬의 변화를 알아보고자 하였다.

대상 및 방법: 건강한 성인 40명의 원위 대퇴골의 축상면 자기공명영상과 90° 굴곡 및 130° 굴곡 위에서의 원위 대퇴골과 경골 전장의 관상면 자기공명영상 등을 이용, 분석하였다.

결과: 임상적 transepicondylar axis (TEA)가 평균적으로 균형잡힌 90도 굴곡 간격을 얻을 수 있는 축이었으며, 90°에서 균형잡힌 굴곡 간격은 130°에서는 대퇴의 회전 정렬이 외측으로 증가하여 상대적으로 좁아지는 비대칭적인 간격이 되었다. PCA를 이용한 회전 정렬은 약 1mm당 약 1°의 변화가 생겼다.

결론: 임상적 TEA는 균형잡힌 굴곡 간격을 얻는데 유리한 대퇴 회전 정렬 축임을 시사하며, PCA를 이용하여 대퇴 치환물의 회전 정렬을 정할 때, 외측 구획의 연골 소실 상태의 차이에 따라 회전 정렬이 변할 수 있음을 고려해 야 한다.

색인 단어: 인공 슬관절 전치환술, 대퇴 치환물의 회전 정렬, 90° 굴곡 간격, 130° 굴곡 간격, 비대칭적 연골 마모