Abnormal Axial Rotations in TKA Contribute to Reduced Weightbearing Flexion

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Abstract

Background Previous in vivo fluoroscopy studies have documented that axial rotation for patients having a TKA was significantly less than those having a normal knee. In fact, many subjects having a TKA experience a reverse axial rotation pattern where the femur internally rotates with increasing flexion. However, no previous studies have been conducted to determine if this reverse axial rotation pattern affects TKA performance.

Questions/purposes The purposes of this study were: (1) Do normal and reverse axial rotation patterns of a TKA

affect the maximum flexion angle postoperatively? (2) Does the axial rotation angle of the knee at maximum flexion during weightbearing impact the magnitude of the maximum flexion achieved in weightbearing?

Methods One hundred twenty patients having TKA, previously analyzed under in vivo conditions using fluoroscopy and a three-dimensional model-fitting software package, were further evaluated to determine if reverse axial rotation patterns limit weightbearing TKA flexion. In this retrospective cohort, we identified 58 patients who had a normal axial rotation pattern (greater than 15° normal rotation). Sixty-two patients experienced greater than 3° of reverse axial rotation, defined as internal rotation of the femur relative to the tibia.

Results Patients having a normal axial rotation achieved greater weightbearing knee flexion than those with reverse axial rotation (115° versus 109°, $p = 0.02$). Additionally, patients with greater than 3° of normal axial rotation at maximum flexion had more flexion than those with less than 3° of normal axial rotation at ending flexion (115° versus 107°, $p < 0.001$).

Conclusions These findings show reverse axial rotation and a smaller magnitude of normal axial rotation reduce weightbearing knee flexion. This is likely the result of increased posterior movement of the lateral condyle and is an important consideration in future implant designs.

Level of Evidence Level III, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

One of the authors certifies that he (DD), or a member of his or her immediate family, has or may receive payments or benefits, during the study period, an amount greater than USD 1,000,001 from DePuy, Inc (Warsaw, IN, USA).

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Introduction

No currently available TKA consistently reproduces kinematic patterns observed in the normal knee [13, 14]. Along

with the inability to provide native kinematics, most patients having a TKA also fail to achieve full function when compared with a sex- and age-matched control group [18]. More importantly, weightbearing knee flexion is significantly reduced compared with passive flexion and only a small subset of patients undergoing TKA obtain more than 120° flexion in a weightbearing deep knee bend [6, 19].

In the normal knee exhibiting a normal rotation pattern, the tibia rotates externally relative to the femur during extension and internally relative to the femur with flexion [4]. In a deep knee bend activity, the tibia of a normal knee axially rotates an average of 28° internally relative to the femur (normal rotation) to reach deeper flexion angles [4, 12]. During the same activity, a TKA will display much less axial rotation with less than 4° for most types of implants [4]. Some patients having a TKA even exhibit a reverse rotation pattern, where the tibia rotates externally relative to the femur during a deep knee bend with increasing knee flexion.

Currently, the demographic of patients undergoing TKA is changing to include more people from Asian or Middle Eastern cultures, who place higher importance on obtaining deep flexion [7]. Additionally, younger patients who may require deeper flexion for an active lifestyle are opting for TKA [11, 16]. Therefore, a successful implant must enable patients to reach deep flexion angles during weightbearing activities such as a deep knee bend. If future implants seek to enable deeper flexion angles, it is important to understand the effect of kinematics on maximum flexion angle. In this study, the kinematics of interest are the axial rotation pattern (start-to-finish axial rotation angle change) of a TKA and the angle of the femoral component relative to the tibial component at maximum flexion.

The objective of this study was to determine if these factors influence weightbearing knee flexion. Specifically, we sought to determine: (1) whether normal and reverse axial rotation patterns of a TKA affect the maximum flexion angle postoperatively; and (2) does the axial rotation angle of the femoral component relative to the tibial component at maximum flexion impact the magnitude of the maximum flexion?

Patients and Methods

This study involved reviewing more than 500 TKAs that were previously analyzed in multiple fluoroscopic studies; patients were included in this report if they demonstrated greater than 15° of normal axial rotation or more than 3° of reverse axial rotation [4, 5, 17] during a weightbearing deep knee bend. All patients in this study had Knee Society scores greater than 90 and were considered well functioning. It was determined that 120 TKAs qualified for this

study and they were reanalyzed to determine maximum flexion and axial rotation. These 120 TKAs were then divided into one of two cohorts based on whether they displayed more than 15° of normal rotation or more than 3° of reverse rotation. For clarity, reverse rotation is reported as a negative number. Because our goal for this study was to determine if axial rotation patterns affected weightbearing knee flexion, two distinctly different bounds were chosen. The first bound represented a normal rotation greater than 15° because the normal knees in our previous studies had at least 15° of axial rotation [5, 9]. The second bound represented reverse rotation, which was chosen to be at least −3° to ensure a clear distinction from no rotation.

Then, the maximum flexion angle was compared between the cohorts to determine if reverse rotation corresponds to lower maximum weightbearing knee flexion angles. A post hoc power analysis of the study population showed a power of 0.85 with a beta value of 0.15 for detecting differences in average maximum flexion of 4° or more using a significance criterion of 0.05. This value was chosen because smaller differences (and perhaps even larger differences) are likely to be unimportant in terms of patient satisfaction [8].

Sixty-one TKAs were placed in the first cohort because they displayed reverse rotation of more than 3°. Of these 61 TKAs, 35 were fixed-bearing and 26 were mobile-bearing. They can be broken out as follows: 11 PS mobile, 14 PS fixed, 18 PCR fixed, nine PCR mobile, six PCS mobile, and three ACL-R. The remaining 58 TKAs were placed in the second cohort because they displayed greater than 15° of normal rotation. Forty of the TKAs in the normal group were fixed-bearing, whereas 18 were mobile-bearing. These can be broken out as follows: five PS mobile, 34 PS fixed, five PCR fixed, five PCR mobile, eight PCS mobile, and one ACL-R fixed. One patient was excluded from the reverse rotation cohort because the maximum flexion angle (48°) was an outlier more than 2 SDs from the mean.

Additionally, two other cohorts were constructed based on the femoral component angle relative to the tibial component at maximum flexion. Patients with greater than 3° of normal rotation at maximum flexion were placed in the high-ending axial rotation cohort. Those patients with less than 3° of normal rotation or reverse rotation at maximum flexion were placed in the low-ending axial rotation cohort. Of the 119 included patients, 76 were placed in the high-ending axial rotation cohort with 43 subjects in the low-ending axial rotation cohort. The maximum flexion angle was compared between the cohorts to find if high-ending axial rotation corresponds with increased maximum flexion. The power of this comparison was 0.87 for finding differences of 4° in average maximum flexion using a significance criterion of 0.05 based on a post hoc power analysis.

All 120 patients had surgery at least 6 months before their gait analysis was performed. Additionally, all TKAs

Fig. 1 The TKA on the left has an ending reverse rotation θ of -5° , whereas the TKA on the right displays a normal ending rotation ϕ of 15° . The horizontal line represents a neutral position with 0° axial rotation.

analyzed were considered clinically successful with Hospital for Special Surgery scores above 90 and without ligamentous laxity or pain. The knee implants considered in this study included NexGen PCR (Zimmer Inc, Warsaw, IN, USA), Hermes ACR (Ceraver, Paris, France), Advance Medial Pivot PCR (Wright Medical Technology, Inc, Arlington, TN, USA), Genesis PCR (Smith & Nephew, Inc, Memphis, TN, USA), LCS AP Glide (DePuy Orthopaedics, Inc, Warsaw, IN, USA), LCS Rotating Platform (DePuy Orthopaedics, Inc), LPS Flex PS (Zimmer Inc), LCS Meniscal Bearing PCR (DePuy Orthopaedics, Inc), Sigma PS (DePuy Orthopaedics, Inc), Sigma PS RP (DePuy Orthopaedics, Inc), LPS Flex PS RP (Zimmer Inc), Sigma PCR RP (DePuy Orthopaedics, Inc), Journey BCS (Smith & Nephew, Inc), Hermes PS FB (Ceraver), and Kyocera Bi-Surface (Kyocera Corporation, Kyoto, Japan).

The in vivo kinematics of these patients had been evaluated using fluoroscopic recordings in conjunction with three-dimensional (3-D) to two-dimensional (2-D) registration. The registration method matched the CAD model to its fluoroscopic image at full extension and maximum flexion using a previously published simulated annealing algorithm. This method has been shown to produce less than 0.5 mm of 3-D translation error and less than 0.5° rotational out-of-plane error [15]. For each subject, the 3-D orientation of the femoral and tibial TKA components was noted at full extension and maximum flexion.

To measure the axial rotation, the start-to-finish angle change of the femur relative to the tibia was considered. To find this angle change, the location of the medial and lateral tibiofemoral contact point is located at both full extension and maximum flexion. The contact points are assumed to be the most inferior points on the medial and lateral femoral condyles in the tibial reference frame. Lines are then drawn connecting the two initial contact points as well as the two final contact points. The angle at which these lines intersect each other (as measured in custom 3-D visualization and analysis software) is the start-to-finish axial rotation angle change. The ending axial rotation angle was recorded as the angle between this line at maximum flexion and a line connecting the midpoint of the medial and lateral

polyethylene articulating surfaces (Fig. 1). Maximum flexion was initially measured directly from the fluoroscopic recording with a goniometer and finalized on the computer after completing 3-D to 2-D registration. All surgeries were performed with the standard surgical technique by experienced surgeons.

The means of the normal and reverse axial rotation cohorts were compared as well as the high-ending axial rotation and low-ending axial rotation cohorts with a one-tailed Welch's t-test. This test is appropriate because it applies for heteroscedastic samples, and the alternative hypothesis states less axial rotation corresponds with lower maximum flexion angles or low-ending axial rotation. To ensure the validity of the t-test, a Shapiro-Wilk test was used to verify if flexion angles were normally distributed. All statistical analyses were performed using JMP software (SAS Institute Inc, Cary, NC, USA).

Results

The reverse rotation cohort displayed an average axial rotation of -6.6° with a SD of 3.2° . The maximum and minimum rotations were -3.3° and -15.1° , respectively. The normal rotation cohort averaged 18.1° of axial rotation with a SD of 3.1° . The maximum and minimum external rotations were 26.9° and 15.0° , respectively. The reverse rotation cohort had an average maximum of flexion with 109.3° with a SD, maximum, and minimum of 14.7° , 150° , and 80° , respectively (Table 1). The normal cohort averaged 114.8° of flexion. The maximum flexion and minimum flexion were 147° and 90° , respectively, with a SD of 14.0° . The maximum flexion angles in the normal cohort and reverse rotation cohort were both normally distributed according to the Shapiro-Wilk test (normal rotation $p = 0.31$; reverse rotation $p = 0.15$). During the deep knee bend maneuver, TKAs displaying less than -3° of reverse axial rotation angle change had lower maximum flexion angles than those with greater than 15° of normal rotation ($p = 0.019$). Therefore, axial rotation pattern does influence weightbearing knee flexion.

Table 1. The data for each cohort is shown along with p values for the relevant tests

Cohort	Number	Average $\pm$ SD	Fixed-/mobile-bearing	p value
Normal rotation	58	114.8° $\pm$ 14.0°	40/18	0.0003
Reverse rotation	61	109.3° $\pm$ 14.7°	35/26	
HR	76	115.1° $\pm$ 15.5°	49/27	
LR	43	106.6° $\pm$ 10.9°	26/17	

HR = high-ending axial rotation; LR = low-ending axial rotation.

Fig. 2 Maximum flexion is plotted against ending axial rotation. The dashed line represents the division between the high-ending axial rotation and low-ending axial rotation cohorts.

The average ending axial rotation for the high-ending axial rotation cohort was 12.5° with a SD, maximum, and minimum of 6.3°, 31.3°, and 3.1°, respectively. The low-ending axial rotation cohort had an average ending axial rotation of −4.4°. The maximum and minimum were 2.79° and −20.5°, respectively, whereas the SD was 4.7°. The high-ending axial rotation cohort averaged 115.1° of flexion with a SD, minimum, and maximum of 15.5°, 80°, and 150°, respectively (Table 1). The low-ending axial rotation cohort averaged 106.6° of flexion. The maximum and minimum flexions were 133° and 84°, respectively, with a SD of 10.9° (Fig. 2). Based on a Shapiro-Wilk test, maximum flexion angles were normally distributed for the low-ending axial rotation and high-ending axial rotation cohorts (high-ending axial rotation $p = 0.37$; low-ending axial rotation $p = 0.16$). The high-ending axial rotation cohort had higher maximum flexion than the low rotation cohort ($p < 0.001$). Therefore, patients exhibiting a high-ending rotation angle experienced greater weightbearing flexion than subjects having a low-ending axial rotation angle.

Discussion

In attempting to understand the metrics that predict maximum flexion, the relationship between maximum flexion

and axial rotation patterns during a deep knee bend must be understood. The evidence presented strongly supports the premise that normal axial rotation and high-ending axial rotation correspond with greater maximum knee flexion. In this study, we found that knees with greater than 15° of normal axial rotation obtain deeper flexion than those with more than 3° of reverse rotation. It has been hypothesized that this reverse rotation pattern may limit TKA flexion as a result of the anteriorization of the lateral condyle [3]. Additionally, we found that knees with an ending normal axial rotation of greater than 3° obtained deeper flexion than those knees that had less normal-ending axial rotation or reverse-ending axial rotation.

It is important to acknowledge the limitations of this study. First, the selective criteria did not account for implant design, surgeon, or surgical technique but pertained directly to axial rotation patterns. Therefore, differences in implant design, composition (ie, different ratios of PCR, posterior-stabilized, mobile- and fixed-bearing designs), and the influence of the surgeon regarding the cohorts provide possible confounding factors. Additionally, this study analyzed only start-to-finish axial rotation change and ending axial rotation angle. It did not consider axial rotation variation through flexion. Whether the axial rotation occurs primarily in early flexion, late flexion, or uniformly throughout flexion may play an

important role in predicting maximum flexion. Another possible limitation is that the cohorts consisted of different designs of TKAs. The different composition of the cohorts may indicate that certain implant designs lead to both reverse axial rotation and decreased flexion. This may show a flaw with certain implant designs, but analyzing the performance of different implant designs is beyond the scope of this study. This was an initial study to determine if axial rotation influences weightbearing flexion. Unfortunately, the number of subjects in this study for each implant type was too small to determine if implant design affects flexion. However, further analyses will be conducted in followup studies to determine other influencing factors. Even with different implant designs in each group, the correlation between normal axial rotation and higher knee flexion was clearly revealed, because again the goal of this study was to determine if axial rotation patterns influence weightbearing flexion, which is clinically significant because present-day patients desire higher knee flexion.

We have previously shown four types of knee rotation can occur during deep knee bend. These involve normal axial rotation, no rotation (where the knee behaves like a hinged joint), reverse rotation, and a variable rotation pattern where the first three types of rotation are all present at different phases of the deep knee bend [4]. Our initial question for this study pertained to whether axial rotation patterns affected weightbearing knee flexion, which was proven to occur, in this study. Reverse rotation patterns limited flexion, whereas normal rotation patterns seemed to position the lateral condyle more posterior, leading to more posterior clearance in deep flexion. In the normal knee, the lateral condyle has been shown to translate posteriorly, whereas the medial condyle remains relatively stationary for a small group of subjects analyzing knee flexion up to 90° [10]. This increased posterior translation resulted in an average of 16.5° normal rotation during a deep knee bend activity [4]. Other studies revealed that axial rotation for the normal knee is, on average, greater than 27° when analyzing knee kinematics up to maximum knee flexion

[6, 18]. In fact, at least 19% of TKAs (all types) showed reverse rotation during a multicenter analysis analyzing over 1000 knees [4].

The second question addressed in this study pertained to if a higher ending rotation angle led to greater weightbearing knee flexion compared with subjects experiencing a lower ending rotation angle, which did occur in this study because high-ending axial rotation resulted in deeper knee flexion.

In understanding the significance of these results, it is important to understand the mechanism by which low-ending axial rotation prevent flexion. As a TKA rotates, the lateral condyle is positioned more posteriorly, but lesser axial rotation anteriorizes the lateral condyle, leading to impingement between the femoral component and polyethylene [6]. To avoid this impingement, high-flexion polyethylene has been designed with posterior polyethylene lips, which recess downward [1]. Alternatively, increased posterior translation of the lateral condyle, as documented for the normal knee, also increases posterior clearance of the thigh and the calf, allowing for greater weightbearing knee flexion.

In conclusion, normal rotation patterns and high-ending axial rotation angles correlated to higher knee flexion. It is unclear if axial rotation is the only factor affecting the lateral condyle position, so it might be beneficial to conduct followup studies incorporating not just the change in axial rotation, but also condylar contact positions both at full extension and maximum knee flexion. As stated previously, the normal knee lateral condyle rolls posteriorly with increasing flexion, but patients undergoing TKA experience very erratic and variable patterns as pertained to the lateral condyle [2]. Ensuring that the lateral condyle is positioned more posterior in deeper flexion leads to greater posterior clearance, allowing for increasing knee flexion. In contrast, if the lateral condyle shifts anterior with flexion, posterior impingement occurs, leading to decreased weightbearing knee flexion. Also, it must be clearly stated that it is possible for a knee to display reverse rotation while translating posteriorly or to rotate normally while

Fig. 3 Two right knee TKA implants are shown in deep flexion. The TKA on the left had an axial rotation of $\theta = -3^\circ$ while translating posteriorly. The TKA on the right had an axial rotation of $\phi = 15^\circ$ while translating anteriorly. The amount of translation and rotation is such that the lateral condyle has translated the same amount in the AP directions for each knee.

translating anteriorly. If the magnitude of the translation and rotations were correct, the lateral condyle could translate equivalent amounts for both normal and reverse rotation (Fig. 3). Although reverse rotation TKAs flex less in general, it is difficult to predict what would happen in the described scenario. Therefore, additional research must be done to indicate whether the rotation or the lateral condyle translation is the more important predictor. However, in this study, both normal rotation and high-ending axial rotation lead to beneficial condyle translation. Therefore, they appear to be critical, regardless of which parameter is the more important predictor of deep knee bend maximum flexion.

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