Intraoperative Passive Kinematics of Osteoarthritic Knees before and after Total Knee Arthroplasty

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ABSTRACT: Total knee arthroplasty is a successful procedure to treat pain and functional disability due to osteoarthritis. However, precisely how a total knee arthroplasty changes the kinematics of an osteoarthritic knee is unknown. We used a surgical navigation system to measure normal passive kinematics from 7 embalmed cadaver lower extremities and in vivo intraoperative passive kinematics on 17 patients undergoing primary total knee arthroplasty to address two questions: How do the kinematics of knees with advanced osteoarthritis differ from normal knees?; and, Does posterior substituting total knee arthroplasty restore kinematics towards normal? Osteoarthritic knees displayed a decreased screw-home motion and abnormal varus/valgus rotations between $10°$ and $90°$ of knee flexion when compared to normal knees. The anterior–posterior motion of the femur in osteoarthritic knees was not different than in normal knees. Following total knee arthroplasty, we found abnormal varus/valgus rotations in early flexion, a reduced screw-home motion when compared to the osteoarthritic knees, and an abnormal anterior translation of the femur during the first $60°$ of flexion. Posterior substituting total knee arthroplasty does not appear to restore normal passive varus/valgus rotations or the screw motion and introduces an abnormal anterior translation of the femur during intraoperative evaluation. © 2006 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 24:1607–1614, 2006

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INTRODUCTION

Total knee arthroplasty (TKA) is a successful surgical procedure used to treat the pain, disability, and loss of motion associated with osteoarthritis (OA). Previous studies have used computational models[1-4] and anatomical investigations[5-7] to examine the kinematics of the knee following TKA. Kinematics following TKA have also been assessed intraoperatively using navigation systems[8] and postoperatively using gait analysis,[9] fluoroscopy[10-15] and dynamic radiostereometry.[16-19]

The tibiofemoral kinematics following TKA may be different from the motions of normal knees and from the expectations associated with a specific prosthetic design.[20] For example, abnormal anterior translation of the femur in early flexion during weightbearing activities has been reported from cine fluoroscopy studies.[10,12,13,21] Weightbearing experiments provide insight into knee motions during functional activities, but make it difficult to separate the influence of prosthesis design and surgical technique from those of the large forces from muscles and the external environment. Nozaki and colleagues[14] speculated that fluoroscopy experiments involving patients with posterior cruciate retaining TKAs performing step-up and deep knee bend motion trials yielded different patterns of anterior–posterior (AP) femoral translation in part because of different external and muscular forces in the two different motions. Thus, the source of the abnormal kinematics following TKA remains unknown.

Postoperative knee kinematics are influenced by the preoperative clinical–pathological condition.[22-25] Therefore, the abnormal kinematics observed following TKA could be influenced by the kinematics of the advanced OA knee. However,

little information exists[26] on tibiofemoral kinematics of advanced OA knees. While gait analysis has provided insight into knee moments and compensatory gait mechanics associated with OA,[27–31] accurately measuring the 6 degree-of-freedom kinematics of the bones with skin-mounted markers is challenging because of substantial skin motion relative to the bones.[32] Thus, how the kinematics of patients with severe osteoarthritis differ from normal remains unclear. It is also unclear how the kinematics of advanced OA knees change as a result of TKA. Because knee motion following TKA depends on the preoperative condition, understanding the kinematics of OA knees, and how a total knee arthroplasty changes those kinematics, could lead to improved implant design and surgical techniques.

In this study, we used a surgical navigation system to characterize intraoperatively the passive kinematics of knees with advanced OA, before and after TKA. The navigation system allowed accurate measurement of kinematics by direct attachment of reference frames to the femur and tibia. Data collected with this system enabled us to address two questions: How do the passive kinematics of OA knees differ from normal knees?; and, Does posterior substituting TKA restore the kinematics of a knee with advanced OA towards normal?

METHODS

Seventeen male patients (average age, 64.2 years; range, 52–81 years) undergoing primary TKA for treatment of advanced OA participated. Based on the Knee Society Clinical Rating System,[33] the patients had an average preoperative knee score of 29.8 (range, 5–48) and an average function score of 50.8 (range, 0–60). The radiographic level of OA was classified using the Kellgren–Lawrence Rating System.[34] All patients had tricompartmental OA; average scores for the medial, lateral, and patellofemoral compartments were 3.6, 2.9, and 3, respectively. Preoperatively, patients had intact anterior and posterior cruciate ligaments, but none presented with normal menisci due to previous meniscectomy or degeneration. Internal review board approval and informed consent were received for this study.

We measured intraoperative passive knee kinematics with a surgical navigation system.[35] This system has a linear accuracy of <2 mm[36] and a worst-case angular accuracy, in the transverse plane, of about $1.25°$.[37] After exposing the knee and inflating the tourniquet with the knee flexed, the surgeon attached passive optical reference frames (Traxtal Inc., Toronto, Ontario, Canada) from the navigation system onto the medial side of the distal femur and proximal tibia.

The surgeon established anatomic coordinate systems in the femur[38] and tibia[39] (Fig. 1). To establish the femoral coordinate system, the surgeon first circumducted the femur to locate the center of the femoral head[40] and then used a calibrated optical stylus from the navigation system to identify the anterolateral attachment point of the posterior cruciate ligament (the origin of the femoral anatomic coordinate system)[38] and the medial and lateral epicondyles. We defined the vector connecting the center of the head to the origin of the femoral coordinate system as the superior–inferior axis. The cross-product of the superior–inferior axis with an axis between the epicondyles defined the AP axis. The cross-product of the AP axis with the superior–inferior axis formed the medial–lateral axis and completed the orthogonal femoral coordinate system. To establish the tibial coordinate system, the surgeon used the stylus to locate the midpoint of the tibial spines (the origin of the tibial coordinate system), the most medial and lateral points on the plateau, and the most medial and lateral aspects of the malleoli. The midpoint of the malleoli was used as the center of the ankle,[36] and the superior–inferior axis in the tibia was the vector between the center of the ankle and the origin. The cross-product of the superior–inferior axis with a vector defined from the lateral point to the medial point on the plateau formed the AP axis. The cross product of the AP axis with the superior–inferior axis formed the tibial medial–lateral axis and completed the orthogonal coordinate system.

The surgeon manipulated the knee through two cycles of flexion and extension. The flexion movement began by initially supporting the foot posteriorly to record the position of full extension. While supporting the foot with an open palm, the surgeon used his opposite hand to gently lift the thigh, flexing the hip and knee. As the hip reached $90°$ of flexion, the thigh was supported, and the foot was released so that gravity flexed the knee to its final point of flexion. The reverse procedure was used to extend the knee. During this motion, the navigation system recorded the position and orientation of the optical reference frame fixed to the femur with respect to the optical reference frame fixed to the tibia.

After cementing the final prosthetic components (Zimmer Nexgen® Legacy Posterior Cruciate Substituting Knee, Zimmer Inc., Warsaw, IN), the surgeon recorded the passive knee kinematics using the procedure described above. The reference frames were then removed and the surgery completed.

Because implant alignment influences TKA kinematics,[1,4,7] the surgeon recorded the orientation and direction of all bone cuts with a calibrated plate probe prior to cementing the components. The navigation system was only used to record surgical technique and not to assist in aligning components with respect to axes calculated by the system. The bone cut information was used to identify outliers in alignment that might have influenced kinematics. Femurs were cut in $0.0° \pm 1.8°$ (mean $\pm$ SD) of mechanical axis varus, $0.2° \pm 2.4°$ of flexion, and $3.1° \pm 3.6°$ of external rotation relative to the transepicondylar axis. Tibias were cut in $0.1° \pm 1.7°$ of valgus and $1.4° \pm 2.9°$ of posterior slope relative to the tibial mechanical axis. We measured the final cut planes

Figure 1. The definitions of anatomic coordinate systems for the right leg. The superior–inferior axes (z-axes) follow the mechanical axes of the femur and tibia. The AP axes (y-axes) are directed out of the page. The x-axes complete the right-hand ruled coordinate system and are directly medially.

and not actual component orientation; the cement mantle might have slightly altered the final alignment of the components.

We calculated the 6 degree-of-freedom kinematics of the knee from the data recorded during the motion cycles. We assessed femoral translation by measuring the displacement of the origin of the anatomic femoral coordinate system with respect to the origin of the anatomic tibial coordinate system. Angular motion was calculated with the procedure described by Grood and Suntay.[41] The translation and rotation data then were fitted with quintic splines that were evaluated at every 1° of flexion.

To compare our results to normal knee kinematics and to verify the ability of our navigation system to characterize kinematics accurately, we recorded passive knee kinematics from seven embalmed cadaver lower extremities using the same methodology. Cadaver specimens were used to eliminate the inherent difficulty and invasiveness of using our navigation system on healthy volunteers.

We examined three characteristics of knee kinematics as a function of knee flexion: varus/valgus rotation, AP translation of the femur on the tibia (femoral rollback),[9] and external tibial rotation with knee extension (the so-called screw-home motion).[42] We performed statistical analyses on the kinematics of OA and normal knees between 10° to 90° of flexion. This limited range of motion was common to both groups due to flexion contractures in some patients and limited flexion in the cadaver legs. We defined the screw-home motion as the angular displacement of the femur about the mechanical axis of the tibia (the z-axis of the tibia anatomic reference frame, Fig. 1) and used the Student's t-test to compare the magnitudes of screw-home motions between OA and normal knees. We used repeated measures analyses of variance (ANOVA), using the flexion angle as the repeated parameter, to detect significant differences in femoral AP translation and varus/valgus rotations between OA and normal knees. We used the preoperative malalignment of the limb in the frontal plane at 10° of flexion as a factor in our analysis after identifying that the pattern of valgus/valgus rotations was related to the preoperative malalignment. No relationship existed between preoperative alignment and screw-home motion or AP translation. Varus and valgus alignments were defined as mechanical axis varus or valgus alignments of $>2°$, respectively. We defined neutral alignment as $<2°$ of either mechanical axis varus or mechanical axis valgus alignment, based on comparing the range of limb alignment that was considered as neutral alignment in the Knee Society Rating System[33] with normal limb anatomy. The range 10° to 90° of knee flexion was again used to examine the kinematics of knees following TKA and normal knees. We used repeated measures ANOVA to detect significant differences in varus/valgus rotations and femoral AP translation. When a significant effect was present, we subsequently performed multivariate ANOVA and Scheffe's post hoc tests. We used the Student's t-test to determine differences in frontal plane alignment at 10° of flexion and to compare screw-home motions in knees following TKA and normal knees. For all statistical tests, the significance level was set at $\alpha = 0.05$.

RESULTS

At 10° of knee flexion, 10 subjects presented with mechanical axis varus alignment $(9.9° \pm 2.3°)$, 5 in neutral alignment $(1.7° \pm 1.2°$ varus), and 2 in

valgus alignment ($3.7°$ and $5.8°$). The preoperative varus/valgus alignment of the OA knees did not persist at greater knee flexion angles, as all OA knees trended towards slight varus alignment in deep flexion (Fig. 2). Motion patterns for different types of OA knees (varus, valgus, or neutral alignment) were significantly different from each other and from normal knees ($p < 0.0001$). Normal knees consistently trended from neutral alignment into slight varus alignment in mid flexion; no normal knee deviated from this pattern ($p = 0.38$). Following TKA, the alignment of the mechanical axis at $10°$ of flexion ($0.9° \pm 2.2°$ valgus) was different ($p < 0.02$) from normal knees ($1.3° \pm 2.2°$ varus), but not from $0°$ of mechanical axis alignment ($p = 0.11$). Between $10°$ and $60°$, we observed significant differences ($p < 0.05$) in varus/valgus angles between knees following TKA and normal knees. The knees following TKA trended towards slight varus alignment in deep flexion (Fig. 3). Throughout the range of flexion, no systematic relationship of varus/valgus rotation angle with flexion was present in any knee following TKA, resulting in a motion pattern significantly different from normal knees and from other knees following TKA ($p < 0.001$).

The magnitude of the screw-home motion was $10.1° \pm 4.2°$ in normal knees. We found significantly less screw-home motion in OA knees ($4.9° \pm 4.1°$) than normal knees ($p = 0.01$). The screw-home motion in knees following TKA was not restored to normal. We found less screw-home

Figure 3. Varus ($+$) or valgus ($-$) rotations for knees following TKA and normal cadaver knees over a range of flexion. The error bars represent 1 standard deviation. Normal rotations are not restored following TKA.

motion in knees following TKA ($2.1° \pm 4.0°$) than in the normal knees ($p < 0.001$). Also, the screw-home motion following TKA was significantly less than the screw-home motion in the OA knees ($p < 0.05$).

No difference in femoral AP motion was found between OA and normal knees ($p = 0.24$). In both, the femur translated posteriorly on the tibia in flexion $> 40°$, producing the classic femoral rollback motion (Fig. 4). AP femoral translation was significantly different in the knees following TKA compared to normal knees ($p < 0.001$). Following TKA, the femur translated anteriorly on the tibia until approximately $60°$ of flexion before beginning a posterior translation (Fig. 5).

DISCUSSION

The purposes of this study were to characterize the passive kinematics of OA knees and determine whether TKA restores the kinematics towards normal. We found that posterior cruciate substituting TKA corrected frontal plane malalignment observed in OA knees in extension. However, the procedure did not restore normal varus/valgus rotations with flexion or a normal screw-home motion. Further, TKA introduced an abnormal anterior femoral translation in early flexion that was not present in OA knees with normal cruciate ligament function. To reach these conclusions, we compared the passive kinematics from OA knees and knees following TKA to normal kinematics obtained from embalmed cadaver specimens. Because embalming changes biomechanical

Figure 2. Varus ($+$) or valgus ($-$) rotations for OA knees compared to normal cadaver knees over a range of flexion. The diamonds represent the mean rotation angle for normal knees; the error bars represent 1 standard deviation.

Figure 4. Anterior (+) or posterior (−) translation of the femur with respect to the tibia in OA knees compared to normal cadaver knees. The error bars represent 1 standard deviation.

properties of soft tissues, it was necessary to ensure that data from the embalmed specimens represented normal kinematics. Thus, we compared the results of our normal embalmed kinematics to results from previous researchers who used fresh-frozen specimens. Our normal varus/valgus rotations and AP femoral translations with increasing flexion were within 1 standard deviation of the results of Wilson and colleagues.[43] The magnitude of the screw-home motion in our study was less than their motion, but similar to those of Nagao and colleagues,[44] Markolf and colleagues,[45]

Figure 5. Anterior (+) or posterior (−) translation of the femur with respect to the tibia in knees following TKA compared to the normal cadaver knees. The error bars represent 1 standard deviation. TKA induces an abnormal anterior translation of the femur in early flexion.

and Shoemaker and colleagues.[46] These comparisons provide confidence in our measurement system and the normal knee kinematics used as a basis for comparison.

Our results suggest differences between varus/valgus rotations in normal knees, OA knees, and knees following TKA. Wilson and colleagues[43] reported that varus/valgus angles were coupled to flexion angle in normal knees. We agree, as we observed the same relation. We observed a similar relationship in OA knees, but this relationship was related to the preoperative alignment and was different from the motion pattern seen in normal knees. A reason for this difference could be the presence of osteophytes and abnormal ligaments in OA knees that influenced varus/valgus rotations. These findings contrast with those of Saari and colleagues,[26] who did not find differences between varus/valgus rotations of OA and normal knees. We did not observe that varus/valgus rotations were coupled to flexion angle following TKA.

Varus/valgus rotations following TKA may be related to bone cuts and soft tissue releases. The femurs were cut in about $0°$ of mechanical varus and $3°$ of external rotation relative to the transepicondylar axis. The former would explain correction of frontal plane varus alignment in full extension; the latter could explain why the knees trended towards slight varus in deeper flexion. Knee kinematics are also influenced by ligament and other soft tissue forces. Only one patient received a release of the medial soft tissues to correct an imbalance following removal of osteophytes, so soft tissue releases were unlikely to have influenced postoperative kinematics.

Our observation of a limited screw-home motion $(4.9° \pm 4.1°)$ in the OA knees is consistent with the findings of other researchers. Saari and coworkers[26] reported that OA knees displayed a mean $0.05°$ of screw-home motion at $50°$ of flexion when compared to a reference position in maximum extension. Nagao and colleagues[44] reported that grade III OA knees displayed significantly less screw-home motion $(0.5° \pm 3.6°)$ than normal knees $(8.3° \pm 3.2°)$ between $20°$ of flexion and full extension. These results differ from those of Koga,[47] who observed a reversed screw-home motion in OA knees.

We did not observe the screw-home motion following TKA. The screw-home motion has been attributed to the function of the ACL and to asymmetry between the medial and lateral femoral condyles. Thus, it is not surprising that an implant that does not preserve the ACL and has symmetric condyles did not induce this motion pattern.

Previous work reported a limited screw-home motion following TKA,[48,49] although Ishii and coworkers[50] observed a screw-home motion in posterior cruciate substituting knees under weightbearing motions.

The femur translated anteriorly with flexion until approximately 60° of knee flexion in every patient following TKA. Abnormal anterior translation is a potentially deleterious factor that contributes to a decreased quadriceps moment arm, decreased maximal knee flexion,[13] and possibly accelerated polyethylene wear associated with the cyclic sliding motion.[51] Our results are consistent with other reports of anterior femoral translation in posterior cruciate substituting knees. While Dennis and colleagues[12] reported posterior femoral rollback in 100% of subjects with a posterior cruciate substituting TKA, they also reported an abnormal anterior femoral translation of the medial condyle from 30° to 60° of flexion. Li and coworkers[5] reported anterior translation of the medial femoral condyle from 0° to 60° of flexion while using a robotic testing device to examine the passive motion of the same implant that was used in our study. The cam–spine interaction is designed to occur at approximately 75° of flexion in this particular implant,[5] and this interaction likely contributed to the posterior femoral translation in deep flexion.

The measurement of AP translation is affected by the choice of femoral coordinate system. Assuming that the geometry of the femoral component was different from that of the native femoral condyles, the average center of rotation (for flexion) and the location of the femoral coordinate system with respect to the tibial coordinate system could change following TKA. Therefore, translation of the origin of the femoral reference frame could have been influenced by the offset between the chosen anatomic coordinate system and the instantaneous center of rotation following TKA. The origin of the femoral coordinate system was displaced on average 2.2 mm anteriorly and 1.8 mm distally from its preoperative position with respect to the tibia when the knee was in full extension. Also, the instantaneous center of rotation was displaced on average 1.6 mm posteriorly and 0.7 mm proximally relative to the preoperative instantaneous center of rotation. Assuming purely planar motion, these changes account for about 4.1 mm of anterior displacement over a 60° range of flexion compared to the OA knee. For the 15 mm of anterior translation observed in early flexion following TKA, these changes account for about 27% of the observed total anterior translation.

To ensure that the recorded anterior femoral translation following TKA was the result of a change in passive kinematics and not an artifact created by the changes in the location of the femoral anatomic reference frame and the average instantaneous center of rotation, we compared the anterior translation of the most distal point on the femoral condyles following TKA against the translation of the most distal point on the femoral condyles in the OA knee. We found that, from 10° to 60° of flexion, the distal medial femoral condyle translated an average of 11.0 mm more anteriorly following TKA. Similarly, the distal lateral condyle translated an average of 13.6 mm more anteriorly. These findings corroborate our conclusion of increased femoral translation following TKA during passive motion.

Postoperative kinematics are influenced by joint geometry, ligaments and other soft tissues, and potentially large muscle forces. Of these factors, the surgeon can alter the soft tissue balance and joint geometry intraoperatively. Assessment of muscle activation and forces from the external environment are not feasible intraoperatively. The best that a surgeon can do intraoperatively is to assess the passive motion of the joint and the effects of joint geometry, ligaments, and soft tissues on this motion.

By measuring passive kinematics, the influence of TKA and implant design on the motion of the joint can be assessed without the influence of large external or muscle forces. Our study of passive kinematics yielded similar patterns of abnormal anterior femoral translation in early flexion to those observed with gait analysis[52] and cine-fluoroscopy,[10,12,13,21] suggesting that joint geometry and passive structures play an important role in postoperative kinematics. However, the active, weightbearing, kinematics following TKA are likely different than the passive kinematics recorded intraoperatively. Future work is needed to examine the relationship between intraoperative passive kinematics recorded with a navigation system and postoperative active kinematics recorded with gait analysis or cine-fluoroscopy. When such a relationship is understood, using a navigation system to measure intraoperative passive kinematics may provide immediate intraoperative feedback to the surgeon to make changes that could potentially improve the functional outcome.

This study represents the results of only one experienced arthroplasty surgeon using one particular posterior cruciate substituting implant. Different surgeons using different implants may yield

different results. Future work should examine the differences in kinematics in posterior cruciate retaining designs as well as implants that have rotating tibial platforms.

Our results suggest that while TKA corrects frontal plane malalignment, it does not restore normal passive varus/valgus rotations throughout flexion. We did not observe the screw-home motion in OA knees or in knees following TKA during passive motion, so it appears that this particular implant design does not restore this motion. OA knees displayed a femoral rollback motion similar to normal knees, but knees following posterior cruciate substituting TKA consistently displayed an abnormal anterior femoral translation during the first 60° of flexion. In every knee, normal AP translation was present prior to TKA, and this normal motion was replaced by the potentially deleterious anterior femoral translation following the procedure. These data suggest that this abnormal anterior translation is not the result of preoperative kinematics, but may be influenced by the removal of the cruciate ligaments and implantation of the prosthesis.

ACKNOWLEDGMENTS

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