# Averaging Different Alignment Axes Improves Femoral Rotational Alignment in Computer-Navigated Total Knee Arthroplasty

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**Background:** Computer navigation systems generally establish the rotational alignment axis of the femoral component on the basis of user-defined anatomic landmarks. However, navigation systems can also record knee kinematics and average alignment axes established with multiple techniques. We hypothesized that establishing femoral rotational alignment with the use of kinematic techniques is more accurate and precise (repeatable) than the use of anatomic techniques and that establishing femoral rotational alignment by averaging the results of different alignment techniques is more accurate and precise than the use of a single technique.

**Methods:** Twelve orthopaedic surgeons used three anatomic and two kinematic alignment techniques to establish femoral rotational alignment axes in a series of nine cadaver knees. The axes derived with the individual anatomic and kinematic techniques as well as the axes derived with six combination techniques—i.e., those involving averaging of the alignments established with two of the individual techniques—were compared against a reference axis established with computed tomography images of each femur.

**Results:** The kinematic methods were not more accurate (did not have smaller mean errors) or more precise (repeatable) than the anatomic techniques. The combination techniques were accurate (five of the six had a mean error of <5°) and significantly more precise than all but one of the single methods. The percentage of measurements with <5° of error as compared with the reference epicondylar axis was 37% for the individual anatomic techniques, 30% for the individual kinematic techniques, and 58% for the combination techniques.

**Conclusions:** Averaging the results of kinematic and anatomic techniques, which is possible with computer navigation systems, appears to improve the accuracy of rotational alignment of the femoral component. The number of rotational alignment outliers was reduced when combination techniques were used; however, they are still a problem and continued improvement in methods to accurately establish rotation of the femoral component in total knee arthroplasty is needed.

Obtaining proper rotational alignment of the femoral component during total knee arthroplasty is a challenging step that influences the success of the procedure. Errors in femoral rotational alignment can lead to problems with tibiofemoral kinematics[1], improperly balanced soft tissues and instability[2-6], increased shear forces on the patellar component[1,6,7], and patellofemoral complications[8-11].

The posterior condylar axis[12], the anteroposterior axis (the so-called Whiteside line)[5,13], and the epicondylar axis[14,15] have been used to establish femoral component rotation, but identification of these axes with use of bony landmarks on the distal part of the femur is highly variable[16-19]. There is still debate regarding whether a computer navigation system does[20,21] or does not[15,16] improve rotational alignment of the femoral

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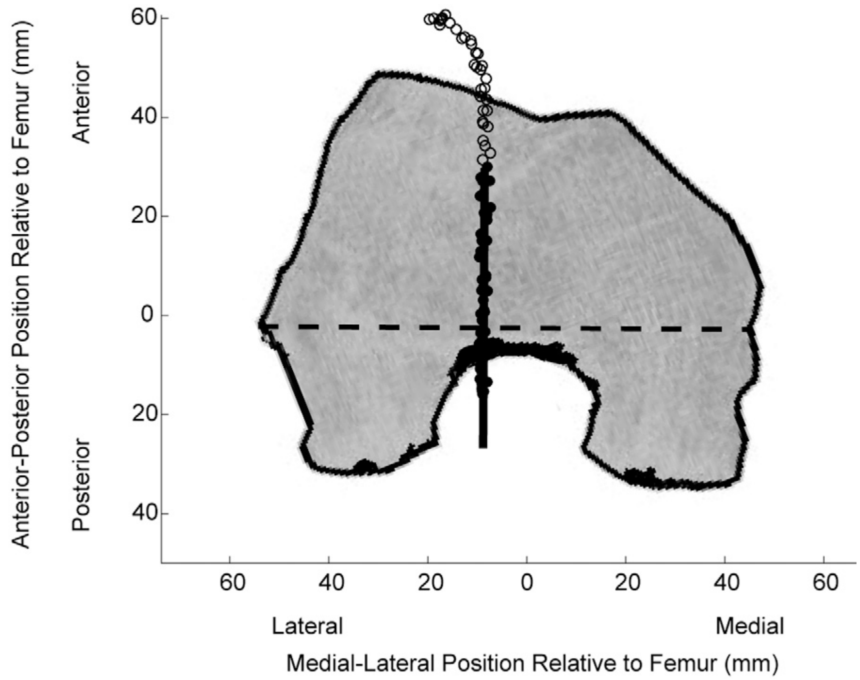


Fig. 1

Illustration of the patella tracking technique. The circles represent all of the points recorded by the navigation system, but only the solid circles, which represent points within 30 mm of the center of the knee, were used to establish the rotational alignment axis (solid line). The dotted line represents the epicondylar axis.

component. Some commercial navigation systems use the passive motion of the osteoarthritic knee to guide rotational alignment of the femoral component[22,23]. Others establish femoral rotational alignment by averaging the alignment axes[20,24] determined with two different techniques. It remains unclear whether these alternative approaches improve femoral rotational alignment.

In this study, we investigated the variability of techniques used to establish femoral rotational alignment during total knee arthroplasty. We examined anatomic techniques, which rely on localization of bony landmarks, and kinematic techniques, which use the relative motion of the bones to define axes. We hypothesized that establishing femoral rotational alignment with kinematic techniques is more accurate and precise (repeatable) than using anatomic techniques, and that establishing femoral rotational alignment by averaging the results of different alignment techniques is more accurate and precise than using a single technique.

## Materials and Methods

We assessed, in a series of nine fresh-frozen cadaver lower extremities, the variability of anatomic and kinematic techniques that are used to establish femoral rotational alignment axes. We performed an a priori power analysis by assuming a standard deviation of 7.0° for the techniques[16,17]. With this assumption, 108 measurements with each technique were required to achieve an a priori statistical power of 0.83 to detect a 3.5° difference between techniques.

The nine cadaver specimens contained all structures distal to the femoral head. The femur of each specimen was bolted to a custom-built platform that allowed approximately 120° of knee flexion. The knees were exposed with use of a standard anterior midline incision and a standard medial parapatellar arthrotomy. After the capsule of each knee was opened, exposing the distal part of the femur and the proximal part of the tibia, a hole was drilled into the femoral medullary canal to simulate an initial step of a total knee arthroplasty.

Twelve orthopaedic surgeons (eight with a practice specializing in total joint arthroplasty, two with other specialty interests, and two total joint arthroplasty fellows) participated in this study. Each surgeon used three anatomic techniques to establish rotational alignment axes for each specimen. The surgeons first established the transepicondylar axis by directly digitizing the epicondyles[22] with an optically tracked stylus from an image-free navigation system (the "digitized epicondyles technique"). Similarly, the surgeons used the optical stylus to identify two points along the sulcus of the femoral trochlea to establish the Whiteside line (the "Whiteside line technique") as well as to identify the most posterior point on the medial and lateral femoral condyles to establish the posterior condylar axis (the "posterior condyles technique").

Each surgeon also used two computer-navigation-assisted kinematic techniques to establish the femoral rotational alignment axis. The patella tracking technique involved tracking of the position of the patella in the trochlear groove of the femur

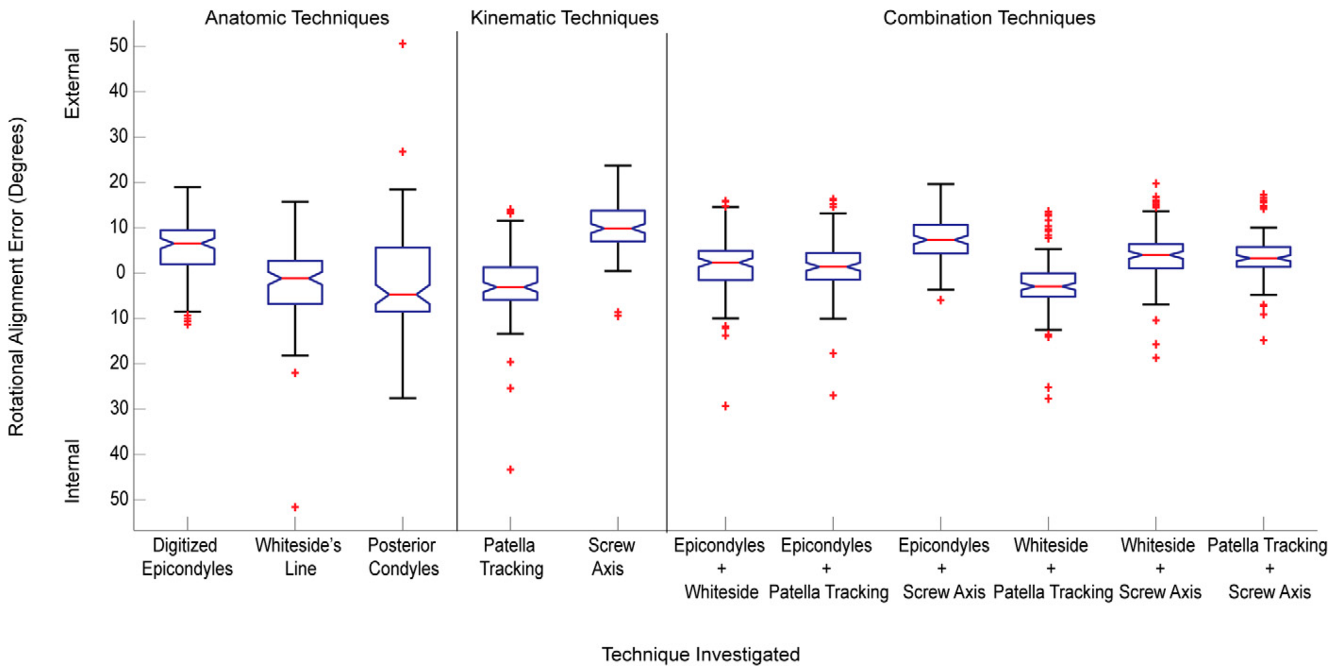


Fig. 2

Box-and-whisker plot of the errors in rotational alignment for the three anatomic, two kinematic, and six combination alignment techniques. The horizontal line across each box represents the median error. The box edges represent the upper and lower quartiles of the data. The + symbols represent data outliers that lie at a distance of more than 1.5 times the length of the box from either end of the box. The whiskers represent the range of data that are not considered outliers.

as the knee joint was passively flexed and extended. The surgeons first reduced the patella into the trochlea and then reapproximated the medial retinaculum with sharp surgical towel clips. Next, they pressed the sharp end point of the optical stylus from the navigation system into the anterior surface of the patella and flexed and extended the knee joint from approximately 0° to 120°. Because the lower-limb specimens were disarticulated at the hip, there was minimal tension in the quadriceps tendon. To simulate the resting tension of the quadriceps tendon, large sutures were sewn into the quadriceps tendon, and a member of the research team applied traction to the tendon. To match the direction of passive tension that the rectus femoris would produce, the researcher aligned the sutures to cross anterior to the lateral edge of the femoral head. This tension kept the patella reduced in the trochlear groove while the knee was flexed and extended. While the knee was being passively flexed and extended, the navigation system recorded the position of the end point of the stylus with respect to an optical tracker attached to the femur, thereby recording the three-dimensional path of translation of the patella in the trochlear groove (Fig. 1). This collection of points was then projected into the transverse plane, and a line was fit to the collected points that were within a 30-mm anterior-posterior window of the center of the knee[25]. Most problems with patellar tracking are thought to occur between full extension and 20° of knee flexion[26], so a 30-mm anterior-posterior window of the center of the knee ensures that only points that represent the patella properly tracking in the trochlear groove are used. The orientation of this projected line established an anterior-posterior axis for rotational alignment.

The so-called screw axis was obtained by calculating the average axis of rotation during passive motion of the knee[27,28]. To implement this technique, the surgeons slowly flexed and extended the knee joint from approximately 0° to 120° while supporting the tibia with an open palm. During this motion, the navigation system recorded the position and orientation of an optical tracker attached to the tibia with respect to an optical tracker attached to the femur. We calculated a series of instantaneous kinematic screw axes during this motion according to the procedure described by Bottema and Roth[29]; the screw axis was collected only when it corresponded to at least 5° of rotation, as this magnitude reduces the need for data filtering[30]. The average orientation of these screw axes defined a medial-lateral alignment axis.

We investigated six combination techniques, which were performed by averaging the results of two of the four previously described alignment techniques. We included combinations that have previously been used by navigation systems to establish femoral rotational alignment[20,24].

The alignment error was defined as the angle between the axis established by the surgeon, or the axis derived with a combination technique, and a reference axis for each specimen. Prior to the experimental portion of this study, we obtained a series of axial computed tomography scans of the femoral head of each cadaver specimen and from approximately 5 cm proximal to the femoral epicondyles to just distal

**TABLE I Errors in Femoral Rotational Alignment with Respect to the Surgical Epicondylar Axis**

| Technique | Alignment Error (Mean and Standard Deviation)* *(deg)* |
|---|---|
| Digitized epicondyles | 5.4 ± 7.1 |
| Whiteside line | −2.3 ± 8.8 |
| Posterior condyles | −2.5 ± 10.9 |
| Patella tracking | −2.6 ± 7.7 |
| Screw axis | 10.5 ± 5.7 |
| Digitized epicondyles and Whiteside line | 1.5 ± 6.6 |
| Digitized epicondyles and patella tracking | 1.4 ± 6.4 |
| Digitized epicondyles and screw axis | 7.9 ± 5.3 |
| Whiteside line and patella tracking | −2.5 ± 6.5 |
| Whiteside line and screw axis | 4.1 ± 5.9 |
| Patella tracking and screw axis | 3.9 ± 5.4 |

*Positive values represent external rotation.

to the tibial tubercle with use of a 24-cm field of view, 100 kVp, 120 mAs, and a 1-mm slice thickness. An experienced musculoskeletal radiologist (G.E.G.) established a reference surgical epicondylar axis by using medical image processing and visualization software (3D-Doctor; Able Software, Lexington, Massachusetts) to identify the prominence of the lateral epicondyle and the sulcus of the medial epicondyle on a series of images of each specimen[14]. The images were then segmented to produce a three-dimensional model of each bone. After all of the surgeons had participated, approximately 50 points on the femoral head and approximately 400 points on the distal part of the femur were digitized on each cadaver specimen with the navigation system; these points were used to register the three-dimensional models to the physical cadaver specimens with an iterative closest-point algorithm[31]. Because two of the axes identified by the surgeons were primarily oriented in the anteroposterior direction (the Whiteside line and the axis derived with the patella tracking technique) and the remaining three were directed primarily in the mediolateral direction, we used different reference axes for different techniques to avoid offsets of approximately 90°. We defined the error associated with the digitized epicondyles, posterior condyles, and screw axis techniques as the angle between the axis established by the surgeon and the reference surgical epicondylar axis for each specimen. The error for the Whiteside line and patella tracking techniques was defined as the angle between the surgeon-defined axis and an axis rotated 90° from the reference surgical epicondylar axis. The error for the combination techniques was determined by averaging the errors for the two methods used in each combination technique.

We assessed the precision of each method on the basis of its standard deviation, and we used the Levene test to evaluate homogeneity of variance among the methods and to detect significant differences in the standard deviations between methods. After identifying unequal variances of the techniques, we used the Kruskal-Wallis test to assess accuracy (as compared with the computed-tomography-derived reference axes) and to identify significant differences between methods. The Tamhane T2 test was used to further investigate significant results. The level of significance was set at $\alpha = 0.05$.

## Results

The kinematic methods were not more accurate (as indicated by the mean error) or precise (as indicated by the standard deviation of the mean errors) than the anatomic techniques. We found that 37% (120) of the 324 anatomic axes and 30% (sixty-five) of the 216 kinematic axes were rotated <5° from the reference axis (Fig. 2). The Whiteside line, posterior condyles, and kinematic patella tracking techniques were significantly more accurate than the digitized epicondyles and kinematic screw axis techniques ($p < 0.001$) (Table I). The kinematic screw axis technique was the most precise ($p = 0.02$) but least accurate ($p < 0.001$) single technique (Table I). There was no significant difference ($p = 0.636$) between the standard deviation of the kinematic patella tracking technique and that of the anatomic digitized epicondyles technique. The posterior condyles technique was the least precise.

The combination techniques were accurate and more precise than all but one of the single methods. Fifty-eight percent (375) of the 648 axes derived with combination techniques were rotated <5° from the reference axis, and five of the six combination techniques had a mean error of <5°. When we just considered the six combination techniques, we found that the combined digitized epicondyles and Whiteside line techniques and the combined digitized epicondyles and patella tracking techniques had a mean error of <2° and were more accurate than any of the other combination techniques ($p < 0.02$). When we collectively investigated all eleven alignment techniques in the study, post hoc comparisons demonstrated that the performance of these two combination techniques was not different ($p < 0.08$) than that of the anatomic posterior condyles technique and two additional combination techniques: the combined Whiteside line and screw axis techniques and the combined patella tracking and screw axis techniques. However, we were unable to determine a difference between the performance of the posterior condyles technique and the performance of those four combination techniques because of the large standard deviation of the posterior condyles technique; this anatomic technique was the least precise technique in the entire study ($p < 0.001$). The combination techniques and the "screw axis" technique were the most precise, and their standard deviations were not different from each other ($p = 0.654$).

## Discussion

No single alignment technique provided the most accurate rotational alignment and the best precision (smallest standard deviation). The combination techniques improved the accuracy of rotational alignment and were among the most precise. We found that incorporating data from various sources reduced the rotational alignment error associated with a single technique. We believe that this is not simply a function of increasing the number of data points; increasing the number of measurements with a single technique would likely result in the same error, since some surgeons are more accurate with certain techniques than others[16]. It is difficult to use the human eye to calculate kinematic axes and synthesize them with other data sources, but computer-based navigation systems can accomplish these tests and this represents an advantage over traditional techniques.

Although combining techniques improved accuracy, precision was still a problem. Only 58% of the axes derived with the combination techniques were rotated <5° from the reference axis. There is little clinical information relating magnitudes of femoral rotational malalignment to failure and rates of revision of total knee arthroplasties[1,4,6-8,32]. Studies relating rotational alignment to complications, failures, and revisions in association with different component designs are needed to address this question.

The present study revealed a high standard deviation for femoral rotational alignment, which is consistent with our previous results[16], although some details in the present study were different from those in our prior study. These differences could be due to the different implementation of two of the techniques. The Whiteside line technique was carried out before distal femoral resection in the current study and after distal femoral resection in our previous study. Both are clinically relevant, as some surgeons determine rotational alignment before resecting the distal part of the femur[33]. Posterior condylar alignment was determined with use of a stylus in the current study, but a commercial alignment jig was used in the previous investigation. In addition, different surgeons participated in each study, and techniques for determining anatomic rotational alignment appear to be influenced by an individual surgeon's skill and preferences[16].

The patella tracking technique is introduced in this paper. Because the lower limbs were disarticulated at the hip, we had to simulate the tension of the knee extensor mechanism, and this potentially affected the results derived with this technique. However, our results with the patella tracking technique were within 1° of results calculated in a previous radiographically based study[26]. We have used the patella tracking technique for patients undergoing total knee arthroplasty with none of the difficulties that were caused by the use of the disarticulated specimens. We are investigating this promising technique further.

None of the specimens had severe deformity, and only two of them showed signs of early, mild osteoarthritis. Therefore, the results of the kinematic techniques in this study may be different from what would be found in osteoarthritic knees[25]. The anatomic techniques may also be affected by osteoarthritis. Difficulty in accurately establishing the rotational alignment of the femoral component has been demonstrated in osteoarthritic knees[17,20,34] and cadaver knees[13,16,35-37], suggesting that the variability of alignment may not be primarily related to the disease but to challenges with visualizing the appropriate landmarks and with geometry, as a small linear error in identifying anatomic landmarks can lead to a large change in rotational alignment[38].

The learning curve for the use of computer-navigation systems[22,39] is associated with technical details of the system and with integrating new equipment into an established surgical procedure. It is unlikely that this learning curve influenced the results of the present study as the trackers were installed and the calibrations were performed by the research staff. Axes were established in the same order for each specimen, but there were no trends in alignment errors as the surgeons progressed through the study. We did not detect any substantial difference between the fellows' and attending surgeons' performances or between the surgeons of varying experience or specialization.

There is debate surrounding the so-called gold-standard alignment axis for establishing rotational alignment of the femoral component. We chose to use the epicondylar axis as studies have associated undesirable postoperative outcomes with not aligning the component parallel to this axis[1,6,7]. Other alignment axes have been suggested[13,40]. Regardless of the reference axis selected, it is reasonable to suggest that high variability in alignment may lead to unpredictable surgical outcomes, and it is desirable to develop new techniques to reduce this variability to improve surgical reconstructions.

In this study in which multiple surgeons defined more than 100 alignment axes with each technique, we found that four combination techniques (the digitized epicondyles and Whiteside line methods, the digitized epicondyles and patella tracking methods, the Whiteside line and screw axis methods, and the patella tracking and screw axis methods) were accurate and reduced the number of rotational alignment outliers. These combination techniques were superior to any individual kinematic or anatomic technique for establishing femoral rotational alignment. However, precision, as reflected by the standard deviation and the number of outliers, continues to be a problem. As computer-navigation technology moves forward, further research and development should focus on improving accuracy and precision across multiple surgeons. ■

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