Distal Femoral Rotation Correlates With Proximal Tibial Joint Line Obliquity: A Consideration for Kinematic Total Knee Arthroplasty

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ABSTRACT

Background: We hypothesized that there is a correlation between the distal femoral rotation and proximal tibial joint line obliquity in nonarthritic knees. This has significance for kinematic knee arthroplasty, in which the target knee alignment desired approximates the knee before disease.

Methods: Fifty computed tomography scans of nonarthritic knees were evaluated using three-dimensional image processing software. Four distal femoral rotational axes were determined in the axial plane: the transsepicondylar axis (TEA), transcondylar axis (TCA), posterior condylar axis (PCA), and a line perpendicular to Whiteside’s anterior-posterior axis. Then, angles were measured relative to the TEA. Tibial joint line obliquity was measured as the angle between the proximal tibial plane and a line perpendicular to the axis of the tibia.

Results: There was a strong positive correlation between PCA-TEA and tibial joint line obliquity ($r = 0.68, P < .001$) as well as TCA-TEA and tibial joint line obliquity ($r = 0.69, P < .001$). In addition, the tibial joint line obliquity and TCA-TEA angles were similar, $3.7 \pm 2.2^\circ$ (mean ± standard deviation) and $3.5 \pm 1.7^\circ$, respectively (mean difference, $0.2^\circ \pm 0.2^\circ; P = .369$).

Conclusion: Both PCA-TEA and TCA-TEA strongly correlated with proximal tibial joint line obliquity indicating a relationship between distal femoral rotational geometry and proximal tibial inclination. These findings could imply that the native knee in flexion attempts to balance the collateral ligaments toward a rectangular flexion space. A higher tibial varus inclination is matched with a more internally rotated distal femur relative to the TEA.

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The concept of restoring knee joint line obliquity to a few degrees of varus in total knee arthroplasty (TKA) using the “anatomic” method was first proposed by Hungerford et al [1]. In the past, this analogous concept, termed “kinematically aligned” TKA has been revisited despite the excellent survivorship of classical mechanically aligned TKA [2]. This could be partly driven by the high number of patients who remain dissatisfied after undergoing TKA, reported to be up to 20% [3–5] and the belief that restoration to a neutral mechanical alignment in TKA may not suit periacicular soft tissues throughout the range of motion [6]. In contrast to the classically aligned TKA, the surgical goal of kinematic TKA is not the attainment of a neutral limb alignment. Instead, the emphasis is placed on the soft tissue and restoration of alignment to the prearthritic state.

Proximal tibial joint line obliquity has been reported to vary from $0.1^\circ$ to $5.4^\circ$ and within a population there is variability around this average [1,7–10]. A number of surgical techniques have been proposed to restore and orientate the patient’s native knee joint line. Examples include application of patient-specific guides developed from preoperative magnetic resonance imaging (MRI) of

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the knee and setting the proximal tibial cut at an arbitrary 2° to 3° of varus [11–14]. Due to a lack of consensus on technique, goals, and an inherent variability of tibial joint line obliquity, it may be difficult to attain kinematic alignment which is predicated on the alignment before the arthritic process. Furthermore, determining what this alignment was before the disease when performing kinematic TKA is not straightforward.

Distal femoral geometry has been extensively studied, especially with recent advances in three-dimensional (3D) imaging [15–18]. There are at least 5 distal femoral rotational reference axes described: transcondylar axis (TCA) [16], posterior condylar axis (PCA) [1,19], anatomic and surgical transepicondylar axes (TEA) [20–22], and Whiteside’s anterior-posterior axis (WAP) [23]. These axes were described for the purpose of femoral component rotational alignment during knee implantation. However, the literature does not specifically examine the relationship between these and tibial geometry. Nonetheless, a relationship has been reported in relation to femoral component malrotation [24] and in patients with anterior cruciate deficiency [25].

This study sought to explore the relationship of references axes of the distal femoral rotation to that of the proximal tibia. We hypothesized that there is a correlation between the 2 in the normal knee. This has implication to kinematic reconstruction in knee replacement, in which the target knee alignment desired approximates the knee before disease.

Materials and Methods

We analyzed computed tomography (CT) scans of 50 lower limbs from 50 patients using 3D analysis software, Mimics version 14.0 (Materialise Inc, Belgium). Before commencement of this study, ethics approval was obtained from the medical research ethics committee of our institution. Patients who had CT angiograms of bilateral lower limbs for vascular disease or injury with no radiologic evidence of osteoarthritis were included in our study group. We selected patients aged 55 and older as this is the age-group of patients who typically undergo TKA in our center. These CTs with a 0.75-mm slice thickness included the hip, knee, and ankle joints. Our population consists of descendants from various regions of Asia. Chinese descendants (East Asia), Indian descendants (South Asia), and the Malays (South East Asia) made up 38%, 34%, and 28% of the study population, respectively.

Aligning the Femur

In order to attain reliable measurements with good reproducibility, a standard frame of reference was established for both the femur and tibia before measurement. The femur was aligned in the coronal and sagittal planes by firstly identifying its anatomic axis. This axis is defined as a best-fit line to the endosteal medullary tube of the femoral shaft (Fig. 1). Subsequently, the femur was rotationally aligned to its TCA, an axis which has been previously described [16]. The TCA is a line that connects the centers of best-fit spheres to the marked surfaces of the posterior condyles of the femur (Fig. 2A).

Once the femur was aligned in the coronal and sagittal planes as well as rotationally, 4 distal femur reference axes were then identified and marked: surgical TEA, PCA, and WAP.

The surgical TEA is a line that connects the most prominent point of the posterior epicondyle and the medial epicondyral sulcus (Fig. 2B and C). This is the reference axis from which angular measurements were made for the other axes. The PCA is a line which is tangent to the posterior aspect of both femoral condyles. This was derived by identifying the most posterior part of the femoral condyles in the sagittal plane (Fig. 2D). The WAP was identified by a best-fit plane to the deepest part of the trochlear groove. This is described in further detail in Figure 3A and B.

Aligning the Tibia

Alignment of the tibia has been described in detail in a previous study [26]. The tibia was first aligned to its anatomic axis (TAAx) in the coronal and sagittal planes. The TAAx is a line that connects the center of the ankle and the center of the proximal tibia. The center of the ankle was derived by fitting a sphere to the combined marked surfaces of the articular portion of the medial and lateral malleoli and the tibial plafond (Fig. 4A-C). The center of the proximal tibia was derived by projecting a locus of center points of the endosteal medullary tube of the proximal tibia to the surface of the tibial plateau (Fig. 5). Once aligned in the coronal and sagittal planes, the tibia was then rotationally aligned to the tibial centroid axis (TCAx). The TCAx is a line connecting 2 centroids, which were calculated by the software from marked surfaces of the medial and lateral tibial plateau (Fig. 6A and B). From these marked surfaces, a best-fit plane, the proximal tibial plane (PTP), was derived to measure tibial joint line obliquity (Fig. 7).

Measurements

In the axial plane, all 3 measurements of rotational axes (TCA, PCA, and WAP) were made in reference to the TEA (Fig. 8A-C). For the Whiteside’s line measurement, a line perpendicular to the WAP was developed (WAPa) and the angle between WAPa and TEA was then measured (WAPa-TEA, Fig. 8C). A positive value denotes that the axis of interest is externally rotated relative to the TEA. A negative value denotes the opposite.

In the coronal plane, tibial joint line obliquity was measured as the angle between the PTP and a line perpendicular to the axis of the tibia, TAAx (Fig. 8D). A positive value denotes varus inclination whereas negative value denotes valgus inclination.

The entire process of aligning, identification of axes and measurements was repeated in 20 subjects by the author and a coauthor, who performed these independently.
Considering 5% marginal error and 80% power of study, a statistical power analysis indicated that a minimum sample size of 46 subjects was needed to detect the mean of outcome variables. This calculation was performed using G*Power software, Germany (version 3.1.9.2). All analyses were performed using SPSS 21.0 (IBM, Chicago, IL). Statistical significance was defined as \( P < .05 \).

**Statistical Analyses**

Fig. 2. (A) Transcondylar axis (TCA) is defined as a line that connects the center of spheres best fitted to the medial and lateral condyles of the femur; (B-C) Surgical transepicondylar axis (TEA) was derived by connecting the medial epicondylar sulcus (B) and the most prominent point of lateral epicondyle; (D) posterior condylar axis (PCA) is a line tangent to the posterior aspect of both femur condyles. This was derived by identifying the most posterior part of the femoral condyles in the sagittal plane. Once these points were marked, a plane was fitted. In the axial view, this plane is seen as a line.

Fig. 3. (A-B) Whiteside's anterior-posterior axis (WAP) was derived by marking the deepest part of trochlear groove followed by developing a best-fit plane to it.
Variables were compared and examined with the appropriate statistical tests.

The Pearson correlation coefficient ($r$) was used to determine the relationship between PCA-TEA, TCA-TEA, and WAPa-TEA with tibial joint line obliquity. An $r \geq 0.5$ is considered strong positive correlation, $r \geq 0.3$ and <0.5 moderate positive correlation and $r < 0.3$ weak positive correlation [27]. Intraobserver and interobserver reliability were determined using intraclass correlation coefficient (ICC). An ICC value of $>0.80$ is considered excellent correlation, 0.61 to 0.80 good, 0.41 to 0.60 moderate, and <0.40 poor [28].

**Results**

There were 31 males (62%) and 19 females (38%), with a mean age of 64 years old. The PCA was $1.9^\circ \pm 1.8^\circ$ (mean ± standard deviation) internally rotated to the TEA, whereas the TCA was $3.5^\circ \pm 1.7^\circ$ internally rotated to the TEA. The WAPa was $4.4^\circ \pm 3.5^\circ$ externally rotated to TEA. The tibial joint line obliquity was on average $3.7^\circ \pm 2.2^\circ$ (Table 1).

There was significant difference in TCA-TEA between male and female ($P < .01$), but there was no significant difference observed in other variables for gender and ethnicity. The mean difference
between the TCA-TEA and tibial joint line obliquity was not significant (mean difference, 0.2° ± 0.2°; \( P = .369 \)).

There was a strong positive correlation between PCA-TEA and tibial joint line obliquity (\( r = 0.68, P < .001; \text{Fig. 9} \)). There was also a strong positive correlation between TCA-TEA and tibial joint line obliquity (\( r = 0.69, P < .001; \) Fig. 10). The correlation between WAPa-TEA and tibial joint line obliquity was weak and statistically not significant (\( r = -0.140, P = .331 \)).

For PCA-TEA, TCA-TEA, WAPa-TEA, and tibial joint line obliquity, the intrarater ICC was excellent at 0.885 (95% confidence interval [CI], 0.535-0.971), 0.940 (95% CI, 0.760-0.985), 0.925 (95% CI, 0.697-0.981), and 0.964 (95% CI, 0.91-0.983), respectively.

For PCA-TEA, TCA-TEA, WAPa-TEA, and tibial joint line obliquity, the interrater ICC was excellent at 0.805 (95% CI, 0.506-0.923), 0.805 (95% CI, 0.508-0.923), 0.924 (95% CI, 0.807-0.970), and 0.968 (95% CI, 0.92-0.987), respectively.

Discussion

Our study is based on 3D reconstructed CT images of healthy knees. CT has been considered as the imaging modality of choice for determining distal femur and proximal tibial bony geometry. It was reported in previous studies as a robust method to determine distal femur and proximal tibial reference axes precisely [18]. Similar to long leg radiographs and MRI, the usage of CT has its drawbacks. Without proper orientation of the images on CT scan, visualization of bony landmarks such as the medial and lateral epicondyle of the femur is difficult. Also, variations in limb positioning particularly rotation may have significant impact on defining the geometry and the measurement of angular relationships. Therefore, utilization of a 3D computer planning software to align the bone anatomically to a frame of reference is essential and has high reliability as well as low interobserver error for measurement of angles between one axis relative to another [16,18,31].

Previous studies have reported larger mean angles of PCA-TEA ranging from 4.7° to 5.8° in Indian and Chinese populations [29,32]. In a CT scan-based study by Berger et al [21], PCA was found to be 3.5° ± 1.2° (mean ± standard deviation) internally rotated to the TEA in osteoarthritic knees. However, Jabalameli et al [30] who studied 108 Iranian osteoarthritic knees using single axial CT images found that the mean angle of PCA-TEA was 1.6° ± 1.7°, which is almost similar to what we measured in normal knees (1.9° ± 1.8°).
Our result for the mean angle of TCA-TEA is $3.5^\circ \pm 1.7^\circ$ with a significant difference for gender ($P < .01$). Although there is significant difference between males and females for the TCA-TEA, further study needs to be carried out to arrive at a concrete conclusion. Iranpour et al [16] in their study reported the mean angle of TCA-TEA as $2.5^\circ \pm 2.5^\circ$ whereas Victor et al [31] reported a mean angle of $0.21^\circ \pm 1.77^\circ$ in nonarthritic knees. This discrepancy may be attributed to the smaller sample size by Victor et al and the method of measurement, especially inappropriate identification of the medial epicondyle. Demographic factors between study populations such as ethnicity may also be part of the reason.

We found that the mean tibial joint line obliquity in our sample population was $3.7^\circ \pm 2.2^\circ$ and this is consistent with the reported values from previous studies [1,6,33]. Prior studies have also been performed in Asians. Tang et al [10] studied 50 normal Chinese subjects using weight-bearing anterior-posterior radiographs and found that the mean tibial joint line obliquity was $5.4^\circ \pm 2.5^\circ$ for women and $4.9^\circ \pm 2.3^\circ$ for men. Khattak et al [8] studied 59 healthy Pakistani subjects and reported tibial joint line obliquity of $3.4^\circ \pm 2.2^\circ$ and $1.4^\circ \pm 3.2^\circ$ in males and females, respectively. This is comparable to our result.

The major findings of this study were that, in normal healthy adult knees, tibial joint line obliquity in the coronal plane strongly correlated with both the femoral PCA and TCA (relative to the TEA) in the axial plane, respectively. In other words, the more varus the tibial plateau inclination is in the coronal plane, the more internally rotated TCA and PCA is in relation to the TEA in the axial planes. Interestingly, there is almost no difference between the TCA-TEA

![Fig. 8. (A-C) Determination of distal femur axes angles relative to the TEA: TCA-TEA, PCA-TEA, and WAPa-TEA. (D) Tibial joint line obliquity is the angle between the PTP and a line perpendicular to the TAA.]
angle and tibial joint line obliquity (mean difference, 0.2° ± 0.2°). These findings could imply that the native knee in flexion attempts to balance the collateral ligaments toward a rectangular flexion space. A higher tibial varus inclination is matched with a more internally rotated distal femur relative to the TEA.

Previous reports of tibial joint line obliquity in relation to PCA-TEA are in agreement with our findings, namely those of Yau et al [25], who studied a group of 99 young healthy asymptomatic Chinese volunteers with anterior cruciate ligament deficiency. The MRI scan-based measurements showed there is an association of posterior condylar angle with tibial joint obliquity. The posterior condylar angle was 5° ± 2° and the knee was 5° ± 3° medially inclined (r = 0.391, P < .05). A similar finding has been shown in a cadaveric study of 60 knees by Pagnano and Hanssen [24].

Our study is the first to establish the relationship of distal femoral axes to tibial joint obliquity in nonarthritic knees using 3D reconstructed CT, showing strong positive correlation of tibial joint line obliquity to PCA-TEA. Also, our study is the first to show strong and consistent correlation of tibial joint line obliquity to TCA-TEA. In addition, as mentioned above, the tibial joint line obliquity is similar in magnitude to TCA-TEA with the means of 3.7° ± 2.2° and 3.5° ± 1.7°, respectively.

The implications of our findings in kinematic TKA are as follows. Kinematic TKA has gained interest recently as an alternative alignment goal in a hope to improve patient’s pain and satisfaction. The goal is to restore patient’s knee joint to prearthritic or native state. However, the means for determining the patient’s prearthritic knee joint remains unclear. Some advocate using patient-specific guides [11–13] whereas others suggest cutting the proximal tibia by comparing the thickness of lateral and medial tibia plateau after compensating for cartilage wear, bone loss, and kerf thickness [14]. Our results show that, in normal knees, tibial joint line obliquity is closely related to TCA-TEA and there is a strong correlation between tibial joint line obliquity and PCA-TEA as well. The findings are relevant to our objective which is to approximate the desired knee alignment to the native state during kinematic TKA. Conceptually, it provides some direction on the inclination magnitude for the proximal tibia cut for kinematic TKA. Our data show that tibial joint line obliquity approximates the angle TCA-TEA. This can be determined using 3D analysis software preoperatively or by referring to the PCA-TEA angle intraoperatively.

Our data provide basis for an alternate or adjunct method for the joint replacement surgeon to determine the appropriate proximal tibial cut orientation during kinematic TKA especially when native tibial joint line obliquity cannot be estimated due to excessive wear. Previous literature has reported that the posterior condyles of the femur are spared in arthritic knees [34], which makes it reliable for measurement to approximate the proximal tibial cut. Tibial joint line angle in the prearthritic knee, on the other hand, is significantly smaller in varus knee and significantly larger in valgus knee [34]. This is further supported by Victor et al [31] who reported a nonsignificant correlation of posterior condylar line to coronal alignment of lower limb.

Limitations

A limitation of our study is that patients are recruited from a single geographical location. Our results may not be similar to other populations. Further study will be needed to confirm that this anatomic relationship is consistent across other populations.
Our main finding is a strong correlation between tibial joint line obliquity and femoral rotational geometry. Although this can potentially guide surgeons in accurately restoring prearthritic alignment during TKA, the following will limit its practical usage. Firstly, the magnitude of tibial joint line obliquity and rotational measurements are small. Secondly, locating the surgical TEA and making measurements intraoperatively can be inaccurate. In addition, the execution of these small magnitude angular cuts would prove challenging using conventional methods and instrumentation. Finally, this study cannot address the clinical implications of our findings. Furthermore, joint geometry is only one of several other variables such as ligament laxity and muscle action which affects tibiofemoral kinematics. Thus, studying the outcome of kinematic TKA would require taking all these variables into consideration.

Conclusion

Proximal tibial joint line obliquity correlates with distal femoral rotational geometry. In addition, the tibial joint line obliquity and TCA-TEA angles are similar, $3.7^\circ \pm 2.2^\circ$ and $3.5^\circ \pm 1.7^\circ$, respectively. These findings shed light on the relationship between distal femoral rotation and tibial joint line obliquity in the normal knee and explain to some degree the anatomic variability.

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