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The effect of distal femur bony morphology on in vivo knee translational and rotational kinematics

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Abstract

Purpose—Tibio-femoral kinematics are clearly influenced by the bony morphology of the femur. Previous morphological studies have not directly evaluated relationships between morphology and knee kinematics. Therefore, the purpose of this study was to examine the relationship between distal femur bony morphology and in vivo knee kinematics during running. It was hypothesized that the posterior offset of the transcondylar axis would be related to the magnitude of anterior/posterior tibio-femoral translation and that the rotational angle of the transcondylar axis would be related to the magnitude of internal/external knee rotation.

Methods—Seventeen contralateral (uninjured) knees of ACL-reconstructed patients were used. Distal femoral geometry was analyzed from 3D-CT data by determining the anteroposterior location (condyle offset ratio—COR) and rotational angle (condylar twist angle—CTA) of the femoral transcondylar axis. Six degree-of-freedom knee kinematics were obtained during running using a dynamic stereo radiograph system. Knee kinematics were correlated with the femoral morphologic measures (COR and CTA) to investigate the influence of femoral geometry on dynamic knee function.

Results—Significant correlations were identified between distal femur morphology and knee kinematics. Anterior tibial translation was positively correlated with the condyle offset ratio ($R^2 =$

0.41, $P < 0.01$). Internal tibial rotation was positively correlated with the condylar twist angle ($R^2 = 0.48$, $P < 0.01$).

Conclusions—Correlations between knee kinematics and morphologic measures describing the position and orientation of the femoral transcondylar axis suggest that these specific measures are valuable for characterizing the influence of femur shape on dynamic knee function.

Level of evidence—III.

Keywords

Bony morphology; In vivo knee kinematics; Dynamic stereo radiograph (DSX) system; Transcondylar axis

Introduction

Knee kinematics are clearly influenced by bony morphology. Variation of femoral condyle morphology has been associated with anterior cruciate ligament (ACL) injury risk [9, 10, 19, 42] and is a factor for proper fitting of total knee arthroplasty (TKA) implants [8, 31]. Knee kinematics vary considerably between individuals during in vivo dynamic activity [48, 49], and it is reasonable to suggest that bony morphology might influence knee motion. However, little is known about how anatomic variation of the femur affects in vivo knee kinematics.

The transcondylar axis is the most common mechanical axis, which is set based on the bony geometry of the posterior condyles [6, 20, 24, 30, 34, 43, 48, 49, 51], and has been referred to as the “flexion facet center” or the “geometrical center axis” since it describes the axis of rotation (for unloaded cadaver knees) during the knee flexion of 10° or more [23]. This axis moves away from the center of flexion to the posterior in extension (less than 10° of flexion), when the flexion axis is aligned with the more anteriorly positioned “extension facet center”. This posterior shift of the transcondylar axis toward extension is associated with the anterior translation of the tibia relative to the femur [24]. Since the knee is typically near extension at heel strike during walking or running, this posterior shift would occur during a period of rapidly applied, high-magnitude loads, and the magnitude of the shift could have important implications for cartilage and ligament loading.

The second most common mechanical axis described for the distal femur is the transepicondylar axis, which runs through both medial and lateral epicondyles [10, 24, 29, 36, 37, 53]. Tibial rotation during flexion has similar trend of internal rotation based on both mechanical axes, but the range of tibial rotation is larger when calculated based on the transcondylar axis [24]. The condylar twist angle (CTA), defined as the angular difference between these two axes [52], varies considerably across individuals and may impact the magnitude of knee rotation.

The effects of the mechanical axes position and angle on functional knee kinematics should be evaluated during physiologically relevant loading. Dynamic stereo radiograph (DSX) can provide high-accuracy in vivo tibio-femoral kinematics during dynamic and functional activities [47–49] and is therefore well suited for this application.

The goals of this study were to examine the anteroposterior location and the rotational angle of the transcondylar axis within the femur and to compare it to in vivo knee kinematics during full weight-bearing dynamic activity for uninjured limbs. It was hypothesized that the posterior offset of the transcondylar axis would be related to the magnitude of anterior/posterior tibio-femoral translation and that the angular difference between the transcondylar

and transepicondylar axes would be related to the magnitude of internal/external knee rotation.

Materials and methods

Data already available from a previous IRB-approved ACL reconstruction study were employed for this analysis. Computed tomography (CT) scans and knee kinematics were obtained for the contralateral (uninjured) knees of seventeen ACL reconstruction patients (35 ± 12 years; 9 men and 8 women). CT scans included high-resolution slices from 10 cm above to 10 cm below the joint line, along with single slices through femoral head and ankle joint to establish long bone axes. As described elsewhere and reviewed briefly below, the knee CT scans were reconstructed into three-dimensional (3D) bone models of the tibia and femur for morphological measurements, and the location and the rotational angle of the femoral transcondylar axis were measured by 3D-CT analysis. The tibial anterior/posterior translation and internal/external rotation during downhill running were measured using the DSX system, as previously reported [47–49].

3D-CT measurements

The 3D-CTs of the femur were segmented and analyzed using 3D imaging software (Geomagic Studio 10, Geomagic Inc., Research Triangle Park, NC).

Condyle offset ratio (COR)—The condyle offset ratio (COR) is defined as the anteroposterior location of the transcondylar axis. Firstly, the articular surface area was extracted manually using the Geomagic angularity detection tool. Spheres were fitted to the regions of the medial and lateral posterior condyles between the top of the intercondylar notch and the posterior end (Fig. 1a, b). The transcondylar axis was defined as the line connecting the centers of both best-fit spheres (Fig. 1c). Next, the long axis of the femur was defined by fitting a cylinder to a section of the femoral shaft between 10 and 15 cm from the distal end (Fig. 1d). The condyle offset was calculated as the perpendicular distance between the transcondylar axis and the long axis of the femur (Fig. 1e). To normalize the condyle offset to femur size, the condyle offset ratio (COR) was calculated by dividing the condyle offset by the average radius of the two best-fit condyle spheres.

Condylar twist angle (CTA)—The two most common medial/lateral axes used for anatomic descriptions of the distal femur and knee kinematics studies are the transcondylar axis (as described above) and the transepicondylar axis, which connects the medial and lateral femoral epicondyles. The condylar twist angle (CTA) is defined as the angle between these two axes [52]. Clinically, the transepicondylar axis is defined as the line that connects the most prominent points of medial and lateral epicondyles [13, 35, 52]. The procedure to calculate the transepicondylar axis from 3D-CT is as follows. First, a temporary medial–lateral axis was defined by connecting a line between the centroid points of the medial and lateral condyle contact areas at 0 degree knee flexion, defined as the most distal area of the articular surface in the direction of femoral long axis (Fig. 2a, b). Then, a cutting plane perpendicular to this axis was translated medially and laterally to identify the most prominent areas of the both epicondyles (Fig. 2c). Lastly, the transepicondylar axis was defined by the line connecting the centroid points of the most prominent areas (Fig. 2d). The condylar twist angle (CTA) was then measured by projecting both axes (transcondylar and transepicondylar) onto a horizontal plane perpendicular to the long axis of the femur (Fig. 2e).

In vivo kinematics

Kinematics were evaluated during downhill running on a treadmill at a moderate speed (2.5 m/s) with 10° downward slope. Three trials were carried out for each subject. For each trial, kinematics data were collected from shortly before foot strike through midstance for one step of the tested leg (approximately 0.5 s duration).

Knee kinematics were assessed with a dynamic stereo radiograph (DSX) system [47–49]. The DSX system consisted of two gantries (each containing a 150-kW radiography source, 40-cm image intensifier, and 4-Mpixel digital video system), configured to provide two beams parallel to the ground with an inter-beam angle of 60°. Radiographic studies were performed using 90-kVp, 150-mA, and 1-ms pulsed exposures, at a frame rate of 150 Hz. Biplane images were collected for a total of 0.5 s, resulting in 75 image pairs per trial.

A model-based tracking technique was used to align 3D-CT bone models to the radiographic image pairs, defining the anatomical coordinate system and providing knee kinematics, as previously described [2]. Anatomic coordinate systems were defined from 3D bone models as described previously [48, 49]. Femoral origin was defined as the midpoint between the centers of the medial and lateral condyles. The vector from femoral origin to tibial insertion was defined and expressed in the tibial anatomical coordinate system. Thus, anteroposterior translation occurred along the tibia anatomical x-axis. This coordinate system was selected for translations because it was both orthogonal and fixed to the tibia with the anteroposterior and mediolateral axes approximately parallel to the tibial plateau. Tibio-femoral rotations were calculated using the conventions described by Grood and Suntay [17]. This kinematics measurement system has been previously used and is capable of evaluating in vivo joint motion with an accuracy of within ± 0.1 mm [47–49].

Typical examples of the measurement are shown in Figs. 3 and 4. The tibia moved anteriorly and rotated internally relative to the femur around heel strike. The most anterior and the most internally rotated tibial position was observed during the interval from 0 to 0.1 s after heel strike. For this analysis, anterior tibial translation range was determined as the distance from the most posterior to the most anterior position relative to the femur, while the internal tibial rotation range was calculated as angle from the most external to the most internal rotation.

Statistical analysis

Correlations between the morphological and kinematics measures were determined by linear regression analysis. The level of statistical significance was set at $\alpha = 0.05$. Statistical calculations were performed using PASW Statistics 18 (formerly SPSS Statistics, SPSS Inc, Chicago, IL). Post hoc power of these statistical tests were also calculated using G*Power 3.1 when a significant difference or relationship was not observed.

Results

The COR was significantly larger in women than men ($P < 0.05$; Table 1). The tibial anteroposterior translation around heel strike is shown in Fig. 5. The anterior tibial translation range was 8.9 ± 1.2 (range 6.6–12.0) mm. A fair correlation was observed between the COR and the anterior tibial translation range ($R^2 = 0.41$, $P < 0.01$; Fig. 6). Larger COR was associated with larger anterior tibial translation range after heel strike. A good correlation between COR and anterior tibial translation range was found for male subjects ($R^2 = 0.57$, $P < 0.05$), but not for women (n.s., power = 0.78) (Fig. 7).

The condylar twist angle (CTA) has no significant difference between genders (n.s., power = 0.49; Table 1). The tibial rotation around heel strike is shown in Fig. 8. The internal tibial

rotation range was $9.4 \pm 3.4^\circ$ (range $2.1\text{--}15.3^\circ$). The CTA was moderately correlated with internal tibial rotation range ($R^2 = 0.48$, $P < 0.01$; Fig. 9), with larger CTA associated with larger internal rotation range.

The relationship between the CTA and the internal tibial rotation range was highly significant in women ($R^2 = 0.81$, $P < 0.01$), but not in men (n.s., power = 0.76) (Fig. 10).

Discussion

The most important finding of the present study was that there were specific relationships between the femur geometry and tibio-femoral kinematics. Specifically, the condyle offset ratio (COR) was related to tibial anteroposterior translation, while the condylar twist angle [52] was related to knee axial rotation.

This study showed that knees with larger COR tend to have greater anterior tibial translation during a stressful dynamic task (downhill running), while those with larger CTA have greater internal rotation. Given that the tibial anterior translation and internal rotation induce the tensile stress on the ACL [32, 33], these findings suggest that individuals with larger COR and/or larger CTA might generate higher ACL stresses and be more dependent on ACL function to maintain joint stability.

Differences between genders of both bony morphology and knee kinematics have been often reported [1, 7–9, 18, 31, 50, 52]. The results of this study suggest that the interactions between morphology and kinematics also differ between genders. A relationship between COR and tibial anteroposterior translation was identified in men but not in women. Conversely, the relationship between CTA and tibial rotation was significant in women but not in men. These results strongly suggest that morphological variation may be an important determinant of kinematic knee function, though a larger sample size might be needed to fully characterize the effects of gender on these morphology–kinematics relationships.

Bony anatomy has often been considered as a factor contributing to ACL injury risk [5, 9, 19, 42], but its effect on tibio-femoral kinematics has been unknown. A notable exception is posterior inclination of the tibial plateau, which has been identified as a risk factor for ACL injury [18, 46]; this hypothesis is supported by studies demonstrating increased anterior tibial translation associated with larger tibial slope [11, 14]. Studies focusing on the intercondylar notch size as a predictor of ACL injury risk (particularly in women) provided mixed results, with some studies finding a relationship [9, 19, 42, 45], while others have not [1, 7, 27]. In the meantime, no relationships between intercondylar notch dimension and knee kinematics have been reported. This study is the first to report a definitive relationship between femoral geometry and in vivo knee kinematics, which could be used for evaluating the risk of ACL injury and determining optimal treatment (e.g., identifying potential copers or non-copers [39]) based on individual anatomical variation.

Rotation is a critical component of knee kinematics, not only for ACL pathology [32, 33, 38, 48, 49] but also for TKA implant design and placement [3, 4]. Thus, morphological factors affecting rotation could have value for optimizing the treatment of ACL injury and designing TKA procedures. Larger range of the internal rotation during knee flexion was calculated based on the transcondylar axis than the transepicondylar axis [24]. The current study showed that increased angle between the two axes was related to greater tibial internal rotation. Since CTA is larger in women [52, 53] (who are at higher risk for ACL injury [16]), further research into the potential role of its effects on knee rotation, ACL strain and further injury risk are warranted.

A limitation of the study is that we investigated only two of many factors that could affect in vivo knee kinematics. Ligament injuries surely alter knee kinematics, [15, 26, 30, 41] though a recent report demonstrated that the early reconstruction after ACL injury could avoid the alteration of in vivo knee kinematics [22]. Healthy knee function can be affected by loading conditions [12, 20, 25], muscle force [21, 28], and activities [29, 34, 50]. Subjects were tested under a controlled loading environment to minimize the influence of these other factors. In addition, the investigated knees were contralateral healthy knees in ACL-reconstructed patients, whereas uninjured subjects might be preferable as control. However, the contralateral knee in the ACL-deficient/reconstructed patient has often used as a normal control [48, 49], since they have similar kinematics to the normal subject [24, 40, 41]. Also the femoral bony morphology is not different between ACL injured and contralateral knees [44]. There is, however, a possibility of bias with this sample, since individuals who have undergone ACL reconstruction (and were by inference at high risk of ACL injury) may have different morphology on average than an uninjured population.

The relationship between femoral bony morphology and in vivo knee kinematics should be acknowledged to assess the ACL injury risk and to design a knee replacement implant for the better in vivo knee kinematics.

Conclusions

The location and orientation of the transcondylar axis were significantly related to knee kinematics during a high-load functional activity. These relationships appear to be different between men and women, though further research is necessary to fully characterize gender effects. These results are the first to establish specific links between femoral morphology and in vivo dynamic knee function and may contribute to the development of a mechanistic basis for predicting ACL injury risk.

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Fig. 1.
Definition of the condyle offset

Fig. 2.
Definition of the condylar twist angle (CTA)

Fig. 3.

Example of the tibial anteroposterior translation during 0.1 s around heel strike. Plus means anterior direction. The distance from the most posterior position to the most anterior position of the tibia relative to the femur was defined as anterior tibial translation range

Fig. 4.

Example of the tibial rotational angle during 0.1 s around heel strike. Plus means internal rotation. The internal tibial rotation range was calculated as the angle from the most external to the most internal rotation of the tibia relative to the femur

Fig. 5.
The tibial anteroposterior translation during 0.1 s around heel strike (time = 0.0). Plus means anterior direction. Average and ± 1 standard deviation

Fig. 6.

The relationship between anterior tibial translation during 0.1 s around heel strike and condyle offset ratio (COR)

Fig. 7.
The relationship between anterior tibial translation range during 0.1 s around heel strike and condyle offset ratio (COR) in each gender

Fig. 8.
The tibial rotation during 0.1 s around heel strike (time = 0.0). Plus means internal rotation.
Average and ± 1 standard deviation

Fig. 9.
The relationship between tibial internal rotation range during 0.1 s around heel strike and the condylar twist angle (CTA)

Fig. 10.

The relationship between tibial internal rotation range during 0.1 s around heel strike and the condylar twist angle (CTA) in each gender

Table 1

3D-CT measurement results

	Overall	Male	Female	Gender difference
Condyle offset ratio (COR)	1.03 ± 0.13 (range 0.81–1.24)	0.92 ± 0.10	1.09 ± 0.18	$P < 0.05$
Condylar twist angle (CTA)	5.4 ± 2.0° (range 2.4–8.5°)	5.5 ± 2.0°	5.3 ± 2.1°	n.s. Power = 0.49