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The Transepicondylar Axis Approximates the Optimal Flexion Axis of the Knee

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The traditional understanding of knee kinematics holds that no single fixed axis of rotation exists in the knee. In contrast, a recent hypothesis suggests that knee kinematics are better described simply as two simultaneous rotations occurring about fixed axes. Knee flexion and extension occurs about an optimal flexion axis fixed in the femur, whereas tibial internal and external rotations occur about a longitudinal rotation axis fixed in the tibia. No other translations or rotations exist. This hypothesis has been tested. Tibiofemoral kinematics were measured for 15 cadaveric knees undergoing a realistic loadbearing activity (simulated squatting). An optimization technique was used to identify the locations of the optimal flexion and longitudinal rotation axes such that simultaneous rotations about them could best represent the measured kinematics. The optimal flexion axis was compared with the transepicondylar axis defined by bony landmarks. The longitudinal rotation axis was found to pass through the medial joint compartment. The optimal flexion axis passed through the centers of the posterior femoral condyles. No significant difference was found between the optimal flexion and transepicondylar axes. To an average accuracy of better than 3.4 mm in translation, and 2.9° in orientation, knee kinematics were represented successfully by simple rotations about the optimal flexion and longitudinal rotation axes. The optimal flexion axis is fixed in the femur and can be considered the true flexion axis of the knee. The transepicondylar axis axis, which is identified easily by palpation, closely approximates the optimal flexion axis.

Knee kinematics historically have been analyzed in the sagittal plane using the method of instantaneous centers of rotation.[2,6,18,19] These centers are found to move within the femur during the flexion cycle suggesting that there is no single fixed axis of flexion. The instantaneous centers of rotation method, however, is only applicable to purely planar motion. Any out of plane movements will introduce errors.[13,17] The motion of the knee is known to include components out of the sagittal plane. In particular, tibial internal and external rotations as high as 20° typically are reported during flexion and extension.[2,10,11] Conclusions based on instantaneous centers of rotation results therefore should be treated with caution.

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More rigorous kinematic studies have used the helical axis method. This is a three-dimension extension of the instantaneous centers of rotation method, and is fully applicable to knee kinematics with no restrictions.[18] Helical axis studies report that the instantaneous axis of rotation undergoes translations and changes in orientation during the flexion cycle.[2,4,10,15,16,18] This is interpreted as evidence that the knee does not rotate about any fixed axis.

This conclusion was challenged by the anatomic studies of Elias et al[5] who found that the posterior portions of the femoral condyles are circular in profile and superimpose when viewed along a line passing through the collateral ligament origins. This suggests that the femur must flex about a fixed axis passing through the condyle centers.

More recently, Hollister et al[8] argued that knee kinematics can be described simply as two simultaneous rotations occurring about bony fixed axes. The optimal flexion axis (referred to as the FE axis in their work) is fixed in the femur and passes through the posterior femoral condyles. The longitudinal rotation axis is fixed in the tibia and is approximately parallel to its long axis. This implies that there are two distinct and fundamental components of knee motion essentially corresponding to flexion and extension (rotation about the optimal flexion axis) and internal and external rotation of the tibia (rotation about the longitudinal rotation axis). Proper positioning of the optimal flexion and longitudinal rotation axes is critical. They are not necessarily perpendicular nor are they aligned with the conventional anatomic planes. When the axes are located properly, all motions of the knee can be accounted for by simultaneous rotations about them. What conventionally is considered anteroposterior (AP) translation of the tibia, for example, can be accounted for as a rotation about the tibial longitudinal rotation axis. If this hypothesis proves accurate, then the optimal flexion axis can be considered the true flexion and extension axis of the knee. Likewise, the longitudinal rotation axis is the true axis of internal and external tibial rotation.

Hollister et al[8] based their conclusions on the results of in vitro experiments in which unloaded knee specimens were cycled manually through their passive range of motion. The fixed axes were identified by means of a mechanical axis finder operated in a trial and error manner. The position of a pointer was adjusted until it was aligned with one of the knee's fixed axes as evidenced by it undergoing only pure rotation with no translation.

Passive knee motions, however, may not be the same as those experienced during common loadbearing activities. The extensor mechanism and the hamstrings cross the joint and apply substantial loads to the tibia. Compressive joint loads may tend to seat the medial femoral condyle in the sulcus of the medial plateau, thereby reducing its mobility. Compressive load is known to increase the joint's stiffness in rotation[7] and in shear.[14]

The first objective of this work was to evaluate whether the kinematics of knees undergoing a realistic loadbearing activity (squatting) can be represented accurately by rotations about two bony fixed axes. Rather than a mechanical axis finder, a mathematical modeling technique developed by the authors,[3] called the compound hinge model, was used to identify the optimal flexion and longitudinal rotation axes. This provided an objective means for identifying fixed axes, and allowed for meaningful error quantification.

The second objective was to compare the location of the optimal flexion axis with the transepicondylar axis. The transepicondylar axis is defined anatomically as the line passing through the apexes of the medial and lateral femoral epicondyles. It is identified easily intraoperatively and during routine examination. Previous work suggests that the optimal flexion axis coincides with the transepicondylar axis.[5,8] If so, this will provide a means for readily identifying the optimal flexion axis of the knee.

MATERIALS AND METHODS

In Vitro Testing

Fifteen fresh frozen, whole leg human anatomic specimens (average age, 58.5 years; range, 29–77 years) were tested in a loading jig designed to simulate a loadbearing squatting activity (Fig 1). All legs were examined grossly and radiographically, and appeared normal. The quadriceps extensor mechanism, the biceps femoris, and the semimembranosus muscle bellies were dissected free approximately 10 cm proximal to their insertions and were sutured to loading straps. Intermedullary rods were cemented into the distal tibia and femoral neck and then were fixed to the jig's ankle and hip joints, respectively. Both joints provided all rotational degrees of freedom and were positioned in the anatomically correct locations. The hip joint remained stationary, whereas the ankle joint was free to translate along vertical rails, allowing knee flexion and extension to occur. Flexion cycles were activated by a servomotor that controlled the quadriceps load. Body weight was simulated by a 100–N static load applied to the ankle joint in an upward direction. A second static load of 30 N was divided equally between the semimembranosus and biceps femoris to simulate hamstrings muscle activity. This combination of loads caused the quadriceps force to reach as high as 1000 N during flexion.

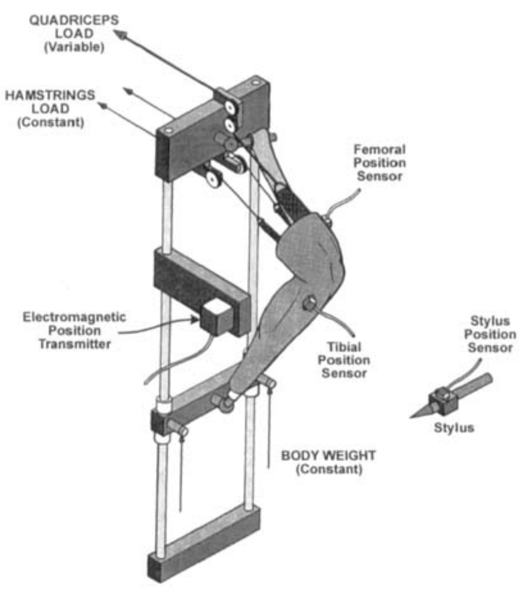

Fig 1. Schematic of loading jig. Hip and ankle joints provided all rotational degrees of freedom. Tibiofemoral kinematics were measured by electromagnetic position sensors. Constant body weight and hamstrings loads were applied, while flexion cycles were activated by varying the quadriceps load. The stylus was used to digitize bony landmarks.

The 6° freedom kinematics of the tibia and femur were measured using electromagnetic position sensors, one rigidly mounted to each bone (Flock of Birds, Ascension Technology, Colchester, VT). To eliminate interference, all metallic components of the jig were constructed of nonmagnetic 300 series stainless steel. An additional position sensor was configured as a stylus and used to digitize landmarks.

Flexion cycles were performed quasistatically at a rate of approximately one cycle per minute. Each specimen initially was preconditioned by performing at least 10 complete cycles. Kinematic data were collected at 10 Hz for three consecutive cycles, each ranging from full extension to at least 100° flexion. The most prominent points on the medial and lateral femoral epicondyles were identified by palpation and were digitized. These points were confirmed by dissection to be within the origin sites of the medial and lateral collateral ligaments, respectively. The joint capsule was opened, and the articular surface contours of the femoral condyles were examined. The regions that experience tibiofemoral contact (the posterior aspects of the condyles) were digitized.

Location of FE and Longitudinal Rotation Axes

The compound hinge model was used to perform the kinematic analysis and to identify the optimal flexion and longitudinal axes locations.[3] This method shares some similarities with the optimization scheme of Lewis and Lew,[12] although theirs does not attempt to model two distinct axes. Any three-dimensional motion can be described in terms of six components, three rotations, and three translations. In the compound hinge model this is written,

$$K = \Theta_{OF} + \Theta_{LR} + R_{\Theta} + R_X + R_y + R_Z$$

Where: K = Complete three-dimensional motion

Θ_{OF} = Rotation about the optimal flexion axis

Θ_{LR} = Rotation about the longitudinal rotation axis

R_Θ = Residual rotation
R_X, R_Y, R_Z = Residual translations

Varying the locations of the optimal flexion and longitudinal rotation axes will affect how the knee motion is divided into components. The central postulate of the compound hinge model is that when the optimal flexion and longitudinal rotation axes are positioned properly, all of the residual components will remain constant, or unchanged, during the entire flexion cycle. That is, no displacements will occur in these components. Knee kinematics then can be described simply by the rotations, Θ_{OF} and Θ_{LR}.

In reality, the residuals are not likely to remain exactly constant, but instead will undergo small displacements. These are quantified by the terms ΔR_X, ΔR_Y, ΔR_Z, and ΔR_Θ,

$$\Delta R_X = R_{X\max} - R_{X\min}$$

By evaluating the magnitude of these residual displacements, the accuracy of the compound hinge model, and hence the accuracy of assuming fixed axes, can be assessed.

For each specimen, one extension cycle over the flexion range of 90° through 5° was selected for analysis. An objective function, W, was calculated,

$$W = \Delta R_X^2 + \Delta R_Y^2 + \Delta R_Z^2 + (\Delta\Delta R_\Theta/360)^2$$

The constant, 360, is a weighting factor used to quantify the importance of errors in angulation relative to error in translation. The choice of 360 essentially means that an angular error of 1° will be considered as important as a translation error of 1 mm.

Using a computer based optimization technique, the positions of the optimal flexion and longitudinal rotation axes for each specimen were adjusted until the residual displacements (as summarized by W) were minimized.

Comparison of Optimal Flexion Axis and Transepicondylar Axis

For each specimen, the transepicondylar axis was constructed by passing a line through the digitized medial and lateral epicondyle points. Two parallel sagittal planes were established perpendicular to the optimal flexion axis (Fig 2). These were located such that the medial plane contained the medial epicondyle point, and the lateral plane contained the lateral epicondyle point. For statistical analysis, the medial and lateral planes were treated independently. The Hotelling's T^2 test was performed to determine whether the average location of the epicondyle point differed from the optimal flexion axis location. Hotelling's T^2 test is a two-dimensional equivalent of the Student's t test.[9] If a significant difference was found ($p < 0.05$) in either the medial or lateral sagittal planes, then the transepicondylar axis would be proven to be different than the optimal flexion axis.

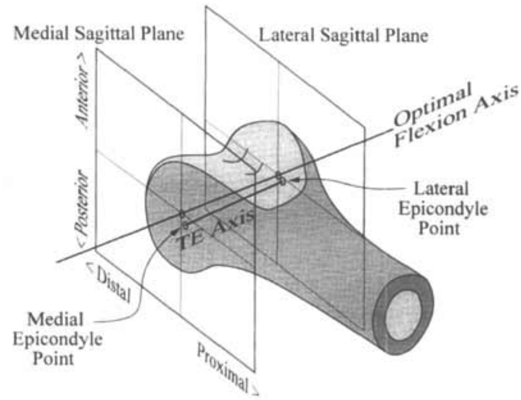

Fig 2. Schematic showing method of comparing the optimal flexion axis with the transepicondylar axis (TE). The in plane distance between the epicondyle point and the optimal flexion axis was evaluated in the medial and lateral sagittal planes.

RESULTS

Optimal flexion and longitudinal rotation axes were identified successfully for all specimens. The optimal flexion axis was found in all cases to pass through the posterior femoral condyles. When viewed along the optimal flexion axis, the digitized contours of both condyles appeared circular in profile and were superimposed (Fig 3). The centers of the best fit circles for each lay close to the optimal flexion axis. The distance between the condyle center and the optimal flexion axis averaged 2.8 mm (± 1.2 mm) for the medial side and 3.1 mm (± 1.8 mm) for the lateral side. The radius of the lateral condyle was an average of 12.5% (±2.3%) smaller than the medial condyle.

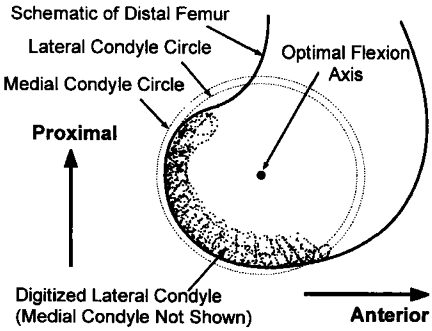

Fig 3. Example of digitized points on lateral femoral condyle as viewed along optimal flexion axis. Condyle is circular in profile with center on optimal flexion axis. Best fit circles for lateral and medial condyles are shown.

The longitudinal rotation axis was aligned approximately with the mechanical axis of the tibia in all cases. They were nonparallel by an average of 3.1°. No preferential orientation for this angular deviation was found. The longitudinal rotation axis passed through the medial plateau in 13 of 15 specimens (Fig 4). This indicates that the tibia typically undergoes internal and external rotation about the medial joint compartment. The magnitude of rotation about the longitudinal rotation axis was approximately 15° throughout the flexion cycle (Fig 5).

The magnitudes of the residual displacements averaged 3.4 mm (± 1.9 mm) for the three translations, and 2.9° (± 1.4°) for rotation.

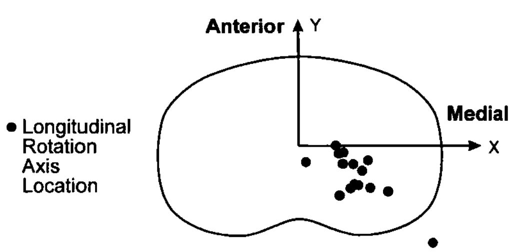

Fig 4. Schematic of tibial plateau showing longitudinal rotation axis location for each specimen. Each axis is aligned approximately parallel with the tibia's mechanical axis. To facilitate comparison, the AP and mediolateral dimensions of each specimen were normalized to those of the tibial outline illustrated.

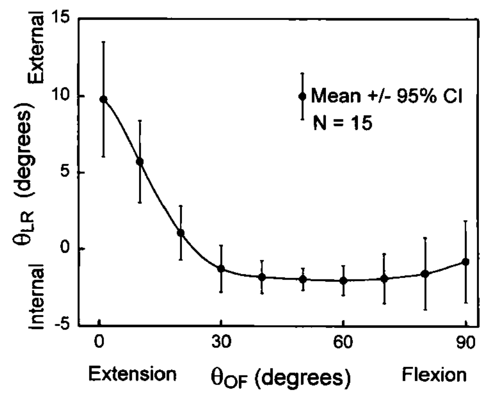

Fig 5. Graph of rotation about longitudinal rotation axis (θ_{OF}). Mean and 95% confidence interval (CI) shown for 15 specimens. Analogous to tibial internal and external rotation versus flexion.

The location and orientation of the anatomically defined transepicondylar axis was found to closely approximate the optimal flexion axis (Fig 6). In the medial sagittal plane, the average position of the medial epicondyle point was 0.2 mm posterior and 0.14 mm distal to the optimal flexion axis. The standard deviations of the epicondyle point distributions were ± 2.4 mm in the AP direction, and ± 2.7 mm in the proximodistal direction. In the lateral plane, the average epicondyle position was 0.2 mm posterior and 0.6 mm distal to the optimal flexion axis. The corresponding AP and proximodistal standard deviations were ± 2.7 mm and ± 2.9 mm, respectively. The optimal flexion and transepicondylar axes were nonparallel by an average of 2.9° (± 1.2°). This angular deviation showed no preferential orientation. The Hotelling's T^1 test found no statistically significant difference between the optimal flexion axis and the transepicondylar axis.

DISCUSSION

This work shows that the knee has two primary axes of rotation that essentially are fixed in bone. The optimal flexion axis

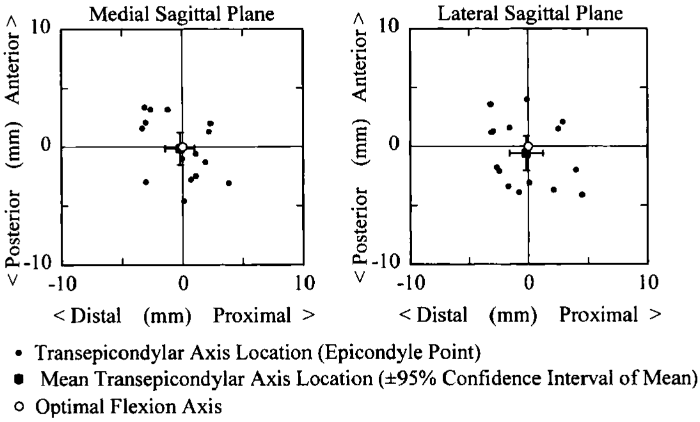

Fig 6. Scatterplots showing the medial and lateral sagittal plane locations of the transepicondylar axes (digitized epicondyle points) relative to the optimal flexion axis for each of the 15 experimental specimens. The mean transepicondylar axis location with 95% confidence interval of the mean also is shown. (See also Figure 2.)

passes through the centers of the femoral condyles, whereas the longitudinal rotation axis is parallel to the mechanical axis of the tibia and passes through the medial joint compartment.

As expected, to account precisely for the measured knee kinematics, the optimal flexion and longitudinal rotation axes cannot be truly fixed in bone. Using the compound hinge model for kinematic analysis provides a meaningful estimate of the errors induced by assuming fixed axes. The residual displacements quantify the amount that the optimal flexion axis would have to move within the femur to account exactly for the measured knee motions. Alternatively, they quantify the maximum error incurred by assuming fixed axes. Residual displacements averaging 3.4 mm in translation and 2.9° in rotation were found. These values are small when compared with the size of the knee, and the 85° range of flexion considered. One also can compare these results to those of the instantaneous centers of rotation, and helical axis methods. Instantaneous centers are reported to move 15 to 20 mm throughout the flexion cycle,[17-19] whereas helical axes are reported to translate 10 to 15 mm and undergo changes in orientation on the order of 30° to 45° throughout the flexion cycle.[2,4,10,11,15,16,18] For most purposes, the residual displacements in the compound hinge model can be neglected and the optimal flexion and longitudinal rotation axes assumed to be fixed.

The calculations of optimal flexion axis location were based solely on the measured knee kinematics. Subsequent comparison with anatomic data showed that the optimal flexion axis was compatible with the anatomic structure of the joint. The optimal flexion axis passes through the centers of the posterior femoral condyles, which appear circular in profile when viewed along the axis. This orientation is 5° to 10° away from the conventional sagittal plane normally, running posteriorly and distally from medial to lateral. Because the optimal flexion axis coincides with the transepicondylar axis, it also passes through the femoral epicondyles and the origins of the collateral ligaments. Thus, the collateral ligaments are isometric regarding knee flexion.

The location of the optimal flexion axis reported here agrees closely with that of the FE axis reported by Hollister et al.[8] Less agreement was found for the longitudinal rotation axis. Their longitudinal rotation axis passed close to the center of the tibial plateau, near the insertion of the anterior cruciate ligament. In the current work, the longitudinal rotation axis was located close to the sulcus of the medial tibial condyle in most specimens. The difference is likely attributable to the presence of compressive joint load in the current study, which tends to center the medial femoral condyle in the sulcus of the medial plateau. Hollister et al[8] did not include a compressive load or muscle forces in their work.

At both extremes of the flexion cycle, the knee does not rotate about the optimal flexion axis. In full extension through hyperextension, the anterior, noncircular portions of the femoral condyles come into contact with the anterior horns of the menisci and the tibial plateau. This is an integral part of the terminal screw home mechanism that causes the knee to lockout. The point at which lockout begins is variable between knees, but generally is less than 5° flexion. In deep flexion, beyond approximately 90°, the femur undergoes posterior translation which is not consistent with a fixed flexion axis. This may be necessary for the shaft of the femur to clear the posterior rim of the tibial plateau. In addition, the most posterior aspects of the femoral condyles, which contact the tibia beyond 90° flexion, are no longer circular. Many of the specimens in this study could not be flexed beyond 100° because of limitations of the loading jig. Thus, the kinematics of deep flexion were not investigated fully. The optimization routine was limited to considering the 5° through 90° flexion range when calculating optimal flexion and longitudinal rotation axes locations.

The concept of two bony fixed axes, formalized by the compound hinge model, should not be viewed as contradicting previous kinematic analyses. Methods that treat kinematics only in the sagittal plane cannot account properly for the fully three-dimensional motion that is known to exist. Panjabi et al[13] calculated that the errors incurred by assuming planar motion could reach as high as 28 mm. This fully explains the apparent discrepancy between the instantaneous centers of rotation results and the current results.

Helical axis analyses, which are known to be mathematically exact,[18] show a moving axis of rotation.[2,4,10,11,15,16,18] This does not contradict the current work. The helical axis method attempts to account for all knee motion as occurring about a single axis. When only one rotation axis is allowed, it is necessary for that axis to move during flexion. When two distinct axes of rotation are allowed, however, it is possible for those axes to remain fixed in bone. This is the fundamental insight provided by the compound hinge model.

Many authors[1,6] have observed femoral rollback during flexion. This is described as a posterior translation of the tibiofemoral contact point. Such motion largely can be accounted for by a rotation of the tibia about its longitudinal rotation axis. The tibia typically rotates internally during flexion (Fig 5). Because the longitudinal rotation axis is located on the medial side of the joint, this will cause a relatively large posterior translation of the lateral femoral condyle with respect to the lateral tibial condyle. At the same time, the medial femoral condyle will undergo a relative small, possibly anterior, translation. When knee motion is viewed on lateral radiographs, the rotation of the tibia is not easily appreciated. Thus, the motion of the lateral compartment of the joint often is attributed to an overall posterior translation of the femur relative to the tibia. Differential motion of the medial and lateral compartments, however, more properly should be attributed to a rotation of the tibia about its longitudinal rotation axis.

The location of the optimal flexion and longitudinal rotation axes were identified in this work by kinematic analysis, a process that typically is not available in most settings. Two excellent estimates of the optimal flexion axis are readily available, however. The posterior femoral condyles can be visualized on a lateral radiograph. When they are viewed so that they superimpose, the optimal flexion axis will be perpendicular to the view and will pass through the condyle centers. Alternatively, the transepicondylar axis can be used as an estimate of the optimal flexion axis. The transepicondylar axis can be identified by either palpation or direct visualization. The transepicondylar axis has the important advantage of not being defined by the articular surfaces. It therefore can be used to estimate the original optimal flexion axis in knees that have undergone severe degeneration.

By analyzing the kinematics of knees undergoing a realistic loadbearing activity, this study has shown that knee motions can be represented accurately as rotations about two bony fixed axes. This represents a subtle, yet important change in the understanding of knee kinematics. Many previous works have concluded that there is no fixed axis of knee rotation. The recognition that the optimal flexion and longitudinal rotation axes remain essentially fixed in their respective bones should provide insight into many areas of knee research, including the design of prosthetic components.

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