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The Axes of Rotation of the Knee

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Knee motion is believed to occur about a variable flexion–extension (FE) axis perpendicular to the sagittal plane and a longitudinal rotation (LR) axis. The authors used a mechanical device to locate the FE and the LR axes of six fresh anatomic specimen knees. The motion of points on the LR axis produced circular, planar paths about the fixed FE axis. Magnetic resonance (MR) images in planes perpendicular to the FE axis showed a circular profile for the femoral condyles. The FE axis is constant and directed from anterosuperior on the medial side to posteroinferior on the lateral side, passing through the origins of the medial and lateral collateral ligaments and superior to the crossing point of the cruciates. The LR axis is anterior and not perpendicular to the FE axis, the anatomic planes. This offset produces the valgus and external rotation observed with extension. The implications of two fixed offset axes for knee motion on prosthetic design, braces, gait analysis, and reconstructive surgery are profound.

Kinematics of the knee has been described as occurring about a variable flexion–extension (FE) axis located in the posterior femoral condyle and about an independent tibial rotation axis. This theory of knee kinematics is based on the works of several investigators[2,3,22] whose studies were later reviewed by Fick,[5] Strasser,[20] and Steindler.[19] This variable FE axis theory was derived from both anatomic and kinematic studies done in the sagittal plane.

The Reuleaux method,[15] a planar technique that determines the center of rotation, has been used to study knee motion.[1,6,17,18,22] This center of rotation analysis is extremely sensitive to perspective and experimental design errors. These studies have been criticized by Panjabi *et al.*[14] because improper experimental design gives inaccurate results.[1,6,17,18] The "circles of uncertainty" within which each of the centers of rotation would lie with 95% confidence were calculated to be 2.84 cm for the Frankel *et al.*[6] study and 6.28 cm for the Smidt study.[17] This large variation makes it difficult to draw conclusions about normal knee kinematics. Soudan and Auderkercke[18] demonstrated the limitations and inaccuracies of using Reuleaux analysis for nonplanar data and pointed out that it is necessary to know the plane of motion prior to applying this method. Because the plane of motion is perpendicular to the axis of rotation, the location of the axis must be known before applying planar kinematic techniques.

Fick[5] reviewed the photographic studies of Braune and Fischer[2] and the radiographic study of Zuppinger[22] and analyzed the three-dimensional shape of the femoral condyles. He believed that the results of these studies were compatible with a fixed, oblique FE axis, which is inclined posteriorly and distally from medial to lateral, with an additional independent axis for tibial rotation.[5] Elias *et al.*[4] found isometric points on the distal femur, which suggested fixed FE axes located in the posterior femoral condyles along lines

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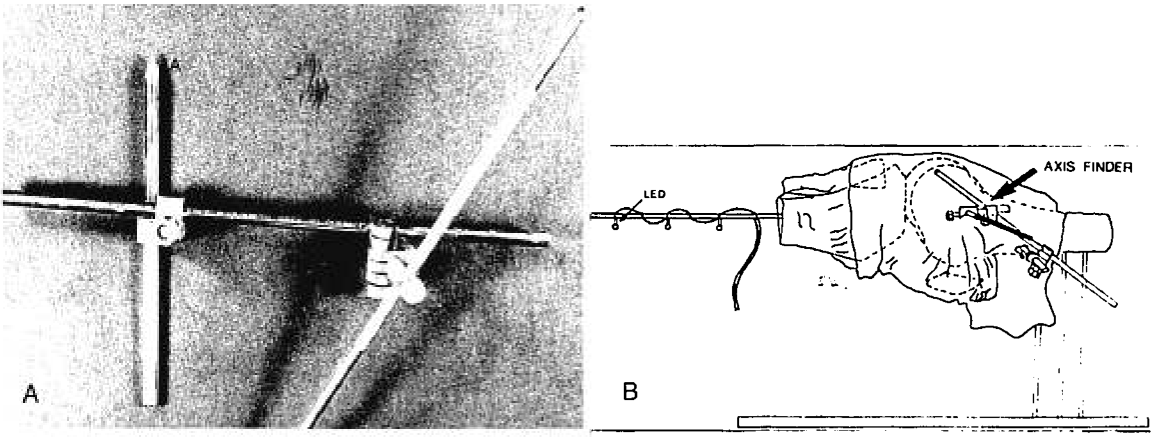
connecting the collateral and cruciate ligaments. In contrast to previous investigations,[3,19,20] they found that posterior femoral condyles have a circular contour when sectioned perpendicular to lines joining these isometric points.

A major fault in previous studies of knee motion has been the inability to ascertain the location of the axes of rotation before performing kinematic analyses.[18] The purposes of this investigation were to locate the FE axis and the longitudinal rotational (LR) axis of the knee using a simple mechanical device, to evaluate the kinematics about these axes, and to demonstrate their anatomic correlation by magnetic resonance imaging (MRI) and dissection.

MATERIALS AND METHODS

A mechanical device, the axis finder (Fig. 1A), was used to locate the LR and FE axes. This device has previously been used to demonstrate the axes of rotation of the knees of living subjects.[10] The axis finder is based on the principle that a rod acts as an axle if attached to a rotating body in alignment with the axis of rotation. A rod placed in any other orientation will describe an arc as the body rotates. This device is a series of metal rods linked with universal joints allowing free positioning of a drill guide in space. A 4-mm × 25-cm Steinmann pin, which acts as the axle, is held in the drill guide. This device can only be used to locate an axis that is fixed throughout a joint's range of motion. It can locate only one axis at a time. In joints with more than one axis, the motion about each axis must be studied separately. This device can locate the axis of rotation of a hinge to within 1 mm and 1.5°.

Six fresh frozen, anatomic specimen knees were prepared, leaving approximately 20 cm of distal femur and 10 cm of proximal tibia. The skin and soft tissues around the knee were preserved. Incisions were made over the anterior aspects of the femur and tibia through which three 5-mm external fixator pins were inserted. The knee then was mounted with the femoral pins on a firm platform to find the LR axis (Fig. 1B). The tibia was moved passively through internal and external rotation, and the axis finder was adjusted until only rotation of the pin occurred. Less than 1 mm of motion at the end of the pin nearest the bone and 3 mm of motion at the distal end of the pin were allowed. The axis then was checked in various positions of flexion and extension and was found to be constant in all knees. Once the axis was found, the Steinmann pin was drilled into the tibia. The knees then were mounted with the three tibial pins, and the FE axis in the femur was found by adjusting the axis finder while the femur was moved through flexion and extension. When the FE axis had been located, it was checked in different positions of internal and external rotation. All knees had a position of longitudinal rotation that allowed complete flexion and extension without



FIGS. 1A AND 1B. (A) Axis finder: A mechanical device used to locate the axes of rotation. The pin on the left (A) is fixed to the bone. The pair of universal joints allows the drill sleeve (B) to be positioned freely in space. (B) Experimental setup: After the FE axis is found, the femur is mounted by pins in its anterior aspect to the platform. The LEDs are placed on the LR axis. The camera is aligned with and centered on the FE axis. The knee then is flexed, producing arcs.

movement about the LR axis. This position was near the end of external rotation about the LR axis. These procedures were recorded on video tape.

The femur was fixed to the platform, and a camera placed 3 m from the knee was centered on and aligned with the axis finder's femoral Steinmann pin. Three flashing light-emitting diodes (LEDs) that spanned a 20-cm distance were placed on the tibial Steinmann pin located on the LR axis. This minimized the effect of independent tibial rotation, allowing analysis of only the FE movements (Fig. 1B). The knee then was moved passively from extension to full flexion in internal, neutral, and external tibial rotation. The three arcs described by the three LEDs were recorded by time-lapse photography. The camera then was placed perpendicular to the axis with an end-on view of the femur, and the same movements were repeated.

Next, the femur was rigidly fixed by six pins to an adjustable platform mounted on a drill press. The specimen was drilled along the FE axis in the distal femur with a stiff 5.5-mm chrome-cobalt drill bit. The FE axis lies just under the epicondyles, and the irregularity of the cortical bone made accurate drilling difficult. Deformation of the bone and bending of the bit during drilling introduced the largest experimental error.

Location of the axes was documented by plain roentgenography in three planes and by MRI. The FE axis was parallel to the plate for the axis anteroposterior (AP) view and perpendicular to the plate for the axis lateral. An end-on view parallel to the FE axis also was obtained. Measurements of the location of the axes were obtained from each view. T1-weighted MR imaging using a 1.5-Tesla Picker scanner was performed (Picker International, Highland Heights, Ohio). Four-millimeter-thick MR sections, both parallel and perpendicular to the FE axis, were obtained. The specimens were dissected, and the relationship of the axes to the condyles and ligaments was demonstrated.

MATHEMATICAL ANALYSIS

Photographs of the LED paths and MR sections of both condyles were scanned with a Hewlett Packard Scanjet Plus (Hewlett Packard, San Jose, California) into an Apple Macintosh IIcx (Apple Computer, Cupertino, California). The images were processed using IMAGE (National Technical Information Service, Washington, D.C.). The LED paths were digitized, resulting in reference X and Y coordinates for each data point.

If the camera were aligned with the FE axis and the axis were constant, the arcs formed by the three LEDs would form three concentric circles. Arcs photographed in a plane other than the plane of motion would have a distorted shape. Because the three arcs appeared circular and concentric, numerical analysis was employed to find the center. The data set from each of the three arcs was entered into a nonlinear optimization program,[13] which determined the center of the concentric arcs by least squares fit. The optimization subroutine began with a user-supplied set of initial conditions for the three radii and their common center of rotation. These parameters were improved iteratively until a best fit to the data points was obtained, in which the subroutine minimized the least sum of squares error (F) between each arc's optimized radius and the distances from the common center coordinates to the corresponding arc's data points.

$$F = \sum_{i}^{n} (r_{opt} - r_i)^2$$

$$= \sum_{i}^{n} (r_{opt} - \sqrt{[(x_i - x_c)^2 + (y_i - y_c)^2]})^2$$

r_i = calculated radius
r_{opt} = optimized radius
x_i = data point x value
y_i = data point y value
x_c = circle center x value
y_c = circle center y value
n = number of data points

Data from concentric circular arcs would generate a common center and minimal residual error (the value of F at program termination). Noncircular or nonconcentric arcs would yield a higher residual error. Results from each set of arcs included a sum of the least squares error value (F), the coordinates of the best fit center (X_c, Y_c) of the optimized circle, and the size of the optimized radii (R_1, R_2, R_3) of the three constituent arcs. The percentage error was calculated from the F value and the optimized mean R values. A low percentage error would indicate that the arcs are parts of three concentric circles. The equation for the percentage error is as follows:

$$\text{Percentage Error} = \frac{100\sqrt{\frac{\sum_{i=1}^{n} (r_i - r_{opt})^2}{n}}}{r_{opt}}$$

r_i = calculated radius

r_{opt} = optimized radius

n = number of data points

The accuracy of the optimization routine was established by drawing three concentric 110° arcs with radii of 5.7, 4.5, and 3.2 cm. X and Y coordinates of the common center as well as data points chosen at 10°-increments along the arcs were digitized. Initial values for the center coordinates were 7.27 and 2.82. The program gave center coordinates of 7.24 and 2.82 with radii of 5.69, 4.42, and 3.16 (Table 1).

The accuracy of the entire method was tested by building a two-axis mechanical model, using a hinge that was offset 7° in the sagittal plane to simulate the FE axis. A second axis, which allowed 15° of internal and external rotation, was positioned anterior and perpendicular to the femoral hinge to simulate the LR axis.[12] The femoral component of the model was mounted on the frame. The LEDs were positioned on the LR axis and the camera was aligned with the FE axis, in a manner that was similar to the anatomic specimen experiment. The LED paths were recorded for 133° of FE motion. Nonlinear optimization of the arcs disclosed an F value of 0.028 and a percentage error of 0.52 (Table 1).

Three MR sections of both the medial and lateral condyle were evaluated for circularity. The meniscal impression was the anterior margin of the condylar curve. The posterior limit of the curve was the posterior end of the bearing surface excluding on average a 1-cm distance. The curve from each MR section averaged 120° of arc but represented different portions of the femorotibial contact surface. The central sections included a more posterior and the outer sections, a more anterior area of tibial contact. Points were digitized from the center of the cartilaginous rim of the posterior condyle. The arc of each MR section was analyzed separately using a nonlinear optimization routine similar to that described above. The F and percentage error were calculated for each curve. The distance from the determined center and the drill hole center for the FE axis was measured with the IMAGE software.

RESULTS

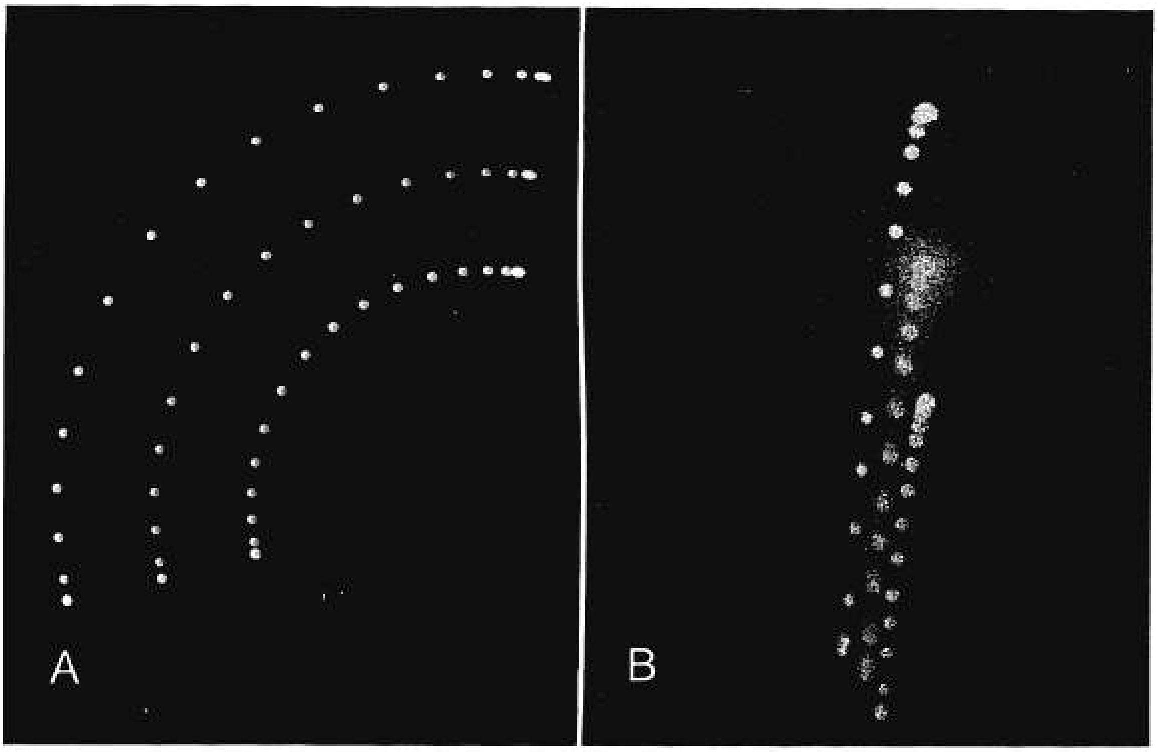
KINEMATIC RESULTS

The three LEDs produced concentric arcs when knee motion was recorded with the camera aligned along the FE axis (Fig. 2A). Nonlinear curve optimization for the three arcs for all six knees disclosed low F (0.01) and percentage error (0.60) values, indicating close fit to concentric circles. These values were similar to those obtained for a two fixed-axis model used to simulate knee motion.[12] Because the LEDs were placed on the LR axis, the effect of tibial rotation during knee flexion was minimized. Tibial internal and external rotation during flexion and extension resulted in arc pathways with similar F and percentage error values (mean F value 0.01, ± 0.002 standard deviation [SD]; mean percentage error value 0.70, ± 0.08 [SD]). Statistical analysis of the results using the Sign test[16] demonstrated no significant difference between the percentage error values obtained for the knees, the model, and the arc test ($p > 0.15$).

TABLE 1. Knee Kinematics Results: Nonlinear Optimization Routine

Knee	*F*	*R1*	*R2*	*R3*	*Mean R*	*% Error*
1	0.018	3.05	4.31	5.60	4.32	0.77
2	0.008	3.82	5.09	6.43	5.11	0.45
3	0.016	3.52	4.73	6.05	4.77	0.66
4	0.010	3.57	4.78	6.05	4.79	0.52
5	0.016	4.01	5.22	6.55	5.26	0.60
6	0.018	4.20	5.47	6.82	5.50	0.61
Model	0.028	6.28	8.07	9.86	8.07	0.52
Test (opt)	0.011	3.16	4.42	5.69	4.42	0.57
Test (actual)		3.20	4.50	5.70		

The low percentage error values indicate a high degree of circularity implying a fixed center. F, value at convergence; R1-3, radii of optimized circle; % Error, error from optimization estimating divergence from a circle; Model, fixed femoral and tibial axis, tibial rotation allowed and compensated; Test, three perfectly concentric circular arcs with similar radii to knee and model arcs; Test (opt), optimization results for three circular arcs drawn with radii R1, R2, R3; Test (actual), true radii of the test arcs.



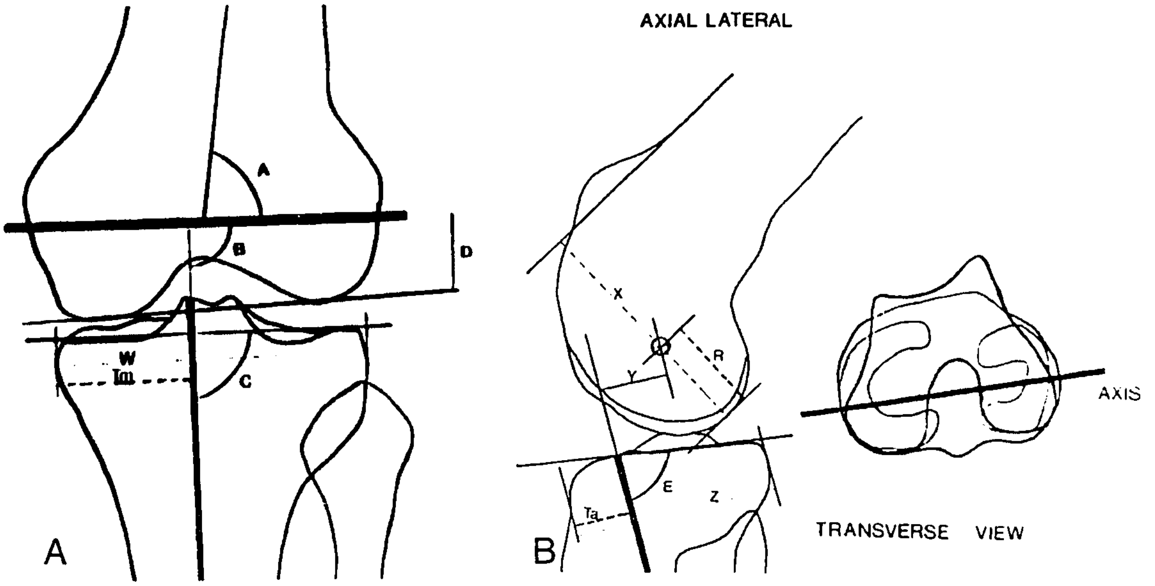
FIGS. 2A AND 2B. (A) The LED arcs obtained with the femur fixed and the camera aligned along the FE axis. (B) LED paths with camera aligned perpendicular to the FE axis.

Camera alignment perpendicular to the FE axis generated three linear trajectories (Fig. 2B), consistent with planar motion. Linear regression of the LED pathways from this perspective resulted in a mean regression value (R) of 0.973 ± 0.03 (SD) for the six knees.

ROENTENOGRAPHIC RESULTS

Measurements taken from AP and axial lateral roentgenographs and their average values are shown in Figures 3A and 3B and Tables 2 and 3. The tibial rotation axis averaged 47.5% of the width of the tibial plateau (W) from the medial side. On the axial lateral, the FE axis was 35% of the width of the distal femur. The radius of the posterior aspect on the medial femoral condyle was 22.8 mm. The angle between the most distal aspect of the femoral condyles and the FE axis averaged 4.3° on standard AP views with the knee in full extension. On plane views of the distal femur, it averaged 3.3°. This discrepancy in measurements is attributable to the superimposition of transition zone of the distal femur on the posterior femoral condyles; the plane views give a more representative relationship of the FE axis to the geometry of the posterior aspect of the femoral condyles.

From MR sections made in a plane perpendicular to the FE axis, the contour of the posterior femoral condyles appeared circular (Fig. 4). One hundred twenty degrees of the posterior condylar surface of three sections gave percentage errors of 1.59 ± 0.38 (SD) and 1.42 ± 0.45 (SD) for the medial and lateral condyles, respectively. This confirmed the circularity of the condylar surface. The optimized centers representing the location of the FE axes for all knees were found to differ from the drilled axes by a mean distance of 4.6 mm ± 0.14 (SD) mm. This primarily represents the errors associated with



FIGS. 3A AND 3B. (A) Diagrammatic representation of axes in AP view with axis parallel to the plate. A is the angle the FE axis makes with the shaft of the femur; B is the angle between the FE and LR axes in the AP plane. C is the angle between the LR axis and the tibial plateau. The distances D, W, and Tm are the distances between the FE axis and the joint surface, the AP width of the tibia, and the medial tibia and the LR axis, respectively. (B) Diagrammatic representation of axes in axial lateral view with x-ray beam parallel to the FE axis. E is the angle between the LR axis and the tibial plateau in the axial lateral plane; X is the distance between the anterior femoral shaft and the posterior-medial femoral condyle. R is the distance between the FE axis and the posterior-medial femoral condyle. Y is the perpendicular distance between the two axes. Z is the AP dimension of the tibia and Ta is the distance of the LR axis from the anterior tibia.

the drilling technique. The kinematic analysis was not affected by this error, because it was performed before the drilling.

The FE axis runs through the collateral ligament origins and superior to the intersection of the cruciate ligaments. The relationship of the axes to the collateral and cruciate ligaments demonstrated by the MRI sections was confirmed at dissection for all six knees. The FE axis passed through the origins of the medial collateral (MCL) and lateral collateral (LCL) ligaments in all knees dissected. The LR axis passed through the insertion of the anterior cruciate ligament (ACL) on the tibial plateau and was directed posteromedially in the proximity of the insertion of the posterior cruciate ligament (PCL) at the femoral notch. The length of the patellar groove ran perpendicular to the FE axis. When the FE axis was viewed end-on, the posterior femoral condyles were superimposed and appeared circular.

TABLE 2. Location of Axes of Rotation

Knee	*A*°	*B*°	*C*°	*D*°	*E*°
1	80	89	89	3.0	82
2	83	88	90	5.0	88
3	87	87	88	5.0	88
4	83	89	87	5.0	80
5	85	87	88	5.0	84
6	85	90	93	3.0	88
Mean	84	88	89	4.3	85
±SD	2.4	1.2	2.1	1.0	3.5

Measurements of the angles of the axes with the bones in the AP and axial lateral views.

DISCUSSION

Knee motion is thought to occur about a variable FE axis that is perpendicular to the

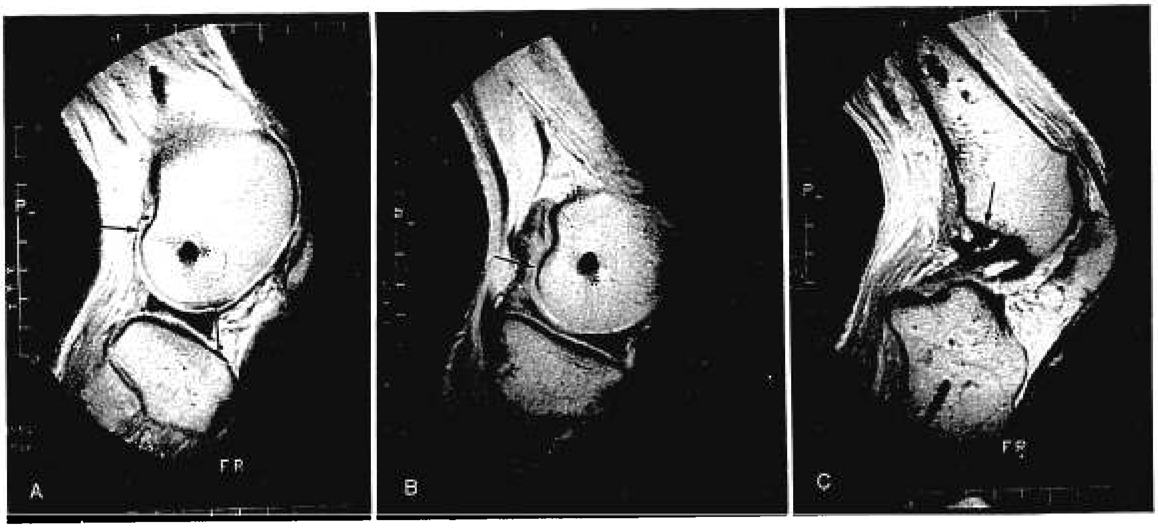
TABLE 3. Location of Axes of Rotation

	Tibial Axis			*Femoral Axis*
Knee	*Tm/W*	*Ta/Z*	*Y/W*	*R/X*
1	43.3	35.7	35.7	29.2
2	46.5	41.9	11.3	36.1
3	53.3	19.6	35.2	41.4
4	42.8	23.5	49.0	40.9
5	49.3	25.0	30.8	31.6
6	50.0	45.1	27.5	32.3
Mean	47.5	31.8	31.6	35.3
±SD	4.1	10.6	12.3	5.1

Location of the axes described as a percent of femoral and tibial dimensions. Tm/W, percentage ratio locating tibial axis on AP view; Ta/Z, percentage ratio locating tibial axis on axial lateral view; Y/W, percentage ratio depicting interaxial distance relative to tibial plateau width; R/X, percentage ratio locating femoral axis on axial lateral view.

sagittal plane and a tibial rotation axis, which is perpendicular to the tibial plateau. This theory is based on kinematic and anatomic investigations done in the sagittal plane.[1-3,5,6,8,17-22] These investigators assumed that the axes for knee FE motion are perpendicular to the sagittal plane.

Guidelines for the design of kinematic studies that use two-dimensional techniques to record three-dimensional joint motion have been listed by Panjabi *et al.*[14] A technique such as the Reuleaux method, which analyzes motion in one plane, requires a prior knowledge of the location and orientation of the axes of rotation of the joint, or perspective distortions will occur. Previous studies have not limited knee motion to a single plane.[1,2,6,17,18,21,22] Braune and Fischer[2] showed that one must allow motion at the hip to produce pure sagittal plane knee flexion and extension. This error has been continued in the work of others.[1,6,8,17,18,21,22] The early workers[2,3,5,22] noted the obligatory tibial internal rotation and varus motion that occurs with flexion. They did not realize, however, that these motions could be conjoint rotations occurring because the FE axis is not perpendicular to the sagittal plane. They regarded the nonsagittal components of knee



FIGS. 4A–4C. MRI sections perpendicular to FE axis. Note the circularity of the posterior femoral condyles. The letters FR are incidental. (A) Lateral condyle. (B) Medial condyle. The large hole next to the (*) indicates location where distal femur actually drilled. The anterior and posterior limits of the posterior aspect of the condyles mathematically analyzed are marked with arrows and the optimized center by (*). (C) The cruciate crossing point. The arrow indicates the location of the drilled FE axis.

FE motion as being insignificant and analyzed only sagittal plane motion. These investigators did not correct for the independent tibial rotation in their analyses. The Reuleaux method can only analyze motion about two axes if they lie parallel. The use of planar techniques to analyze motion about two axes that are not co-planar requires knowing the precise location of and movement about each axis, as well as complex mathematics, including perspective transformations.

In an anatomic study, Bugnion[3] described the location of the instant center path or evolute for the FE axis. He cut sections through the most prominent part of both femoral condyles and determined the radii of curvature for the condylar profile. The profile of the medial condyle subtended an arc of 194°, and the radius of curvature decreased from anterior to posterior. Critical review of his study discloses several problems. Although he described beautifully the obligatory internal tibial rotation that accompanies knee flexion, he was unable to account for it in his model. His sections were not cut perpendicular to the motion plane because he did not know the plane of knee FE motion. Furthermore, he attributed too much of the distal femoral surface to the tibiofemoral articulation.

In contrast, sections of the posterior medial condyle made perpendicular to a line passing through the isometric points have a circular contour.[4] Elias *et al.*[4] studied an arc of 120° and found an average radius of 21 mm. Magnetic resonance sections of the posterior femoral condyles made perpendicular to the current authors' FE axis also have circular contours. Plain roentgenographs of the knees in the current study gave an average radius of 22.8 mm for the posterior aspect of the medial condyle.

In this kinematic study, the effect of tibial rotation was minimized by placing the reference LEDs on the LR axis so that displacement of the LEDs out of the plane of FE motion would be negligible. The camera was aligned with and centered on the femoral FE axis to reduce perspective error.

Nonlinear optimization found the arcs of knee motion to be circular, with values in the same range as a model with fixed FE and LR axes.[12] The linear LED paths perpendicular to the axis show that the FE motion is planar, but the plane of motion is not the sagittal plane. The results in the current study differ from those of previous kinematic studies[1,2,6,17,18,21,22] because the current authors limited motion to the knee joint, located, and then aligned their camera with the FE axis to minimize the effects of independent tibial rotation. The study adheres to Panjabi *et al.*'s guidelines.[14]

The most sensitive method the authors used for locating the axes of rotation was the axis finder. Numerical analysis of the LED paths gave optimized values for the knee that were not statistically different than those for a fixed axis model or a drawn circle. The 1% error inherent in this planar technique can allow significant misalignment of the camera with the plane of motion. Precise verification of the axes' position requires accurate three-dimensional bone position data, such as those obtained from MRI studies or magnetic tracking devices. Modern three-dimensional kinematic analysis should be used instead of the Reuleaux or other planar techniques.

Both the current kinematic study and anatomic evaluation of the posterior femoral condyle by Freeman[7] have suggested a fixed FE axis related to the collateral and cruciate ligaments. The current study is similar to Inman's[11] work on the ankle, where a mechanical method demonstrated fixed, nonorthogonal axes for joints thought to have variable centers in sagittal-plane kinematic studies.

The FE axis is fixed in the distal femur and is directed posteroinferiorly from medial to lateral. The offset from the condylar surface averages 3° in the coronal and in the transverse planes. The portion of distal end of the femur that articulates with the tibia is a cone. The lateral condyle has a smaller radius of curvature than the medial condyle, and the lateral joint surface is closer to the FE axis. The medial and lateral articular surface of each condyle is rounded off to allow movement about the LR axis.

The LR axis is anterior and not perpendicular to the FE axis. It is fixed in the tibia and moves about the FE axis. The axis passes near the anterior cruciate insertion on the tibia and is directed posteromedially near the posterior cruciate insertion on the femur.

Classically, joint motion has been considered to occur about axes that lie in the anatomic planes, with separate perpendicular axes for FE, LR, and abduction–adduction (AA). If an axis of rotation is not perpendicular to the anatomic planes, the plane of motion will not be in an anatomic plane. Joint motion about an axis that is offset in two planes will include all three movements of FE, internal–external rotation, and AA, as Inman[11] demonstrated for the ankle joints.

The current study indicates that motion of the human knee occurs about two fixed nonorthogonal axes. This suggests that knee motion is pure rotation about these fixed axes. The FE axis is not in the coronal plane, nor is the LR in the sagittal plane. Motion about each axis includes varus–valgus, FE, and internal–external rotation. The major component of motion about the FE axis is flexion and extension, but conjoint varus and internal rotation occur with flexion because the axis is not perpendicular to the sagittal plane. This also accounts for the two types of tibial rotation noted by Bugnion.[3] One occurs about the independent LR axis and the other occurs as a consequence of flexion and extension about an offset FE axis.

Grood *et al.*[9] have demonstrated that the screw home mechanism occurs only if the tibia is initially internally rotated in flexion before the knee is extended. If the tibia is externally rotated, internal tibial rotation will occur with knee extension. The current authors believe that the screw home mechanism is a combination of the external rotation of the tibia with extension, caused by the obliquity of the FE axis and independent rotation about the LR axis. The amount of external rotation of the tibia with knee extension is dependent on the initial position of the knee about the LR axis and the degree of offset of the FE axis. In each specimen, there was one position of longitudinal rotation that allowed full flexion and extension with no movement about the LR axis.

The relationship of the cruciates to the two fixed axes suggests their isometry in the physiologic range of knee motion. This relationship of the axes to the cruciate ligaments is similar to that described for the ligaments of the ankle by Inman.[11] Both the MCL and LCL origins are about the FE axis of the knee. Their anatomy is more complex than the cruciates not only because they are dynamically stabilized but also because the LCL crosses the tibiofibular joint as well as the knee.

This model, with two fixed nonorthogonal axes, can explain the shape of the condyles, the location of the ligaments, and the obligatory tibial varus and internal rotation that occur with flexion. Because current prostheses, braces, models for gait, calculations of forces, and reconstructive surgery are based on a changing horizontal FE axis, the implications for the practitioner are profound. Further kinematic studies using accurate three-dimensional devices are needed to clarify the orthopedist's understanding of knee motion.

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