Three-Dimensional Morphology and Kinematics of the Distal Part of the Femur Viewed in Virtual Reality. Part II

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Part II

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The purpose of this exhibit is to demonstrate, with conventional and virtual images, the three-dimensional shape of the naturally asymmetric distal part of the femur, illustrating the cylindrical axis of the femoral condyles relative to the conventional (mechanical, anatomic, and epicondylar) axes of the lower limb and knee. The relationships between morphologically and experimentally determined rotation axes are illustrated. This study provides kinematic and morphologic validation for a single cylindrical flexion-extension axis of the knee. The clinical implications of a single flexion axis of the knee for alignment and soft-tissue balance in total knee arthroplasty, as well as the position and tension of a graft in anterior cruciate ligament reconstruction, are demonstrated with the aid of illustrations from the Visible Human Project at the National Library of Medicine as well as images from the University of Colorado Center for Human Simulation.

The morphologic shape of the distal part of the femur and its relation to the tibia and the patella dictate the kinematics of the knee. Work presented in an earlier American Academy of Orthopaedic Surgeons exhibit[1] demonstrated that the lateral tracking of the patella is reflected in the trochlear groove lying lateral to the mid-plane and oriented between the mechanical and anatomic axes of the femur in the coronal plane[2,3]. The posterior-lateral offset of the tibia relative to the femur in the normal knee and the external rotation of the tibia relative to the femur in the abnormal knee were also documented in the transverse plane[4-7]. The asymmetric cylindrical morphology of the femoral condyles posterior to the coronal plane, another morphologic feature of the distal aspect of the femur demonstrated in the earlier exhibit[1], dictates the location of the flexion-extension axis of the knee and drives the kinematics of the tibia relative to the femur.

These observations[1-7] on the relationship of distal femoral morphology to knee kinematics form the basis for additional studies presented in this scientific exhibit relating condylar geometry of the femur to the location and orientation of the flexion-extension axis of the knee. Recent work has suggested that when the plane in which knee flexion-extension motion occurs is identified, there is a single fixed axis perpendicular to that plane around which flexion and extension in the knee takes place[8-10]. This exhibit supports this observation by illustrating, with three different methodologies, that the asymmetric cylindrical features of the distal part of the femur dictate a single flexion-extension axis throughout a majority of the knee arc of motion. The purpose of this presentation is to document the location and orientation of this single axis of the condyles relative to the conventional mechanical, anatomic, and epicondylar axes.

The clinical significance of this work lies in its application to total knee arthroplasty and anterior cruciate ligament reconstruction. The function and longevity of these reconstructive procedures depends on the soft-tissue balance achieved and the kinematics imparted by the balance or imbalance of these soft tissues. This exhibit illustrates the morphologic relationship between the flexion axis and soft tissues of the knee.

Materials and Methods

The initial phase of this project involved the creation of a three-dimensional computer knee model to facilitate the identification of the plane of knee motion and the orthogonal axis of knee flexion. The Visible Human Data Set from the National Library of Medicine, containing one male cadaver (1877 cross sections at 1-mm intervals) and one female cadaver (5189 cross sections at 0.3-mm intervals), was accessed, and the data were segmented to extract the intracapsular structures of the knee. Subsequently, the more detailed three-dimensional morphology of the high-resolution knee from the University of Colorado Center for Human Simulation (2500 cross sections at 0.1-mm intervals) was segmented and used for this analysis (Fig. 1).

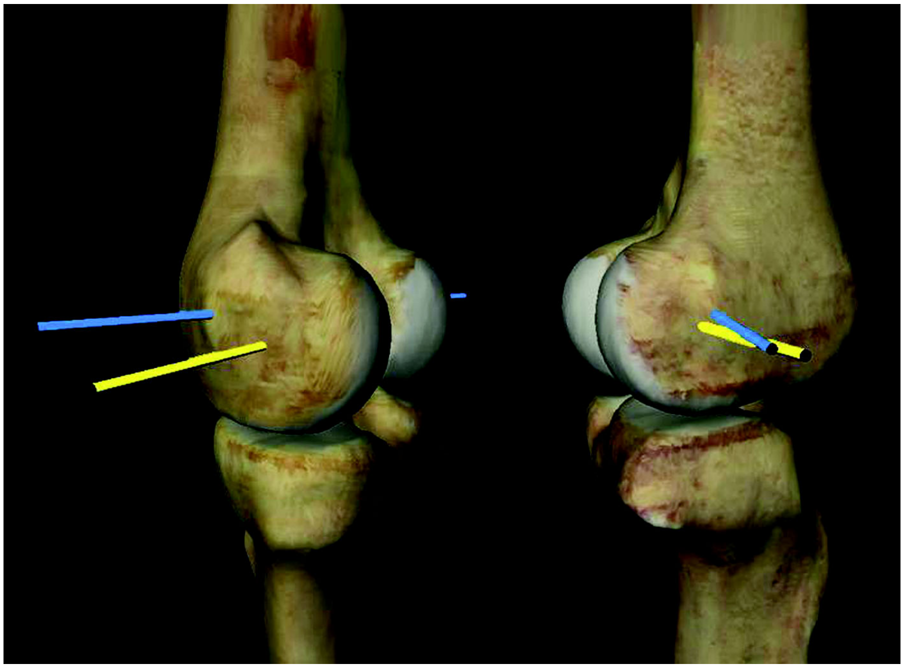

Fig. 1

Three-dimensional knee model constructed from the Visible Human database with epicondylar (blue) and cylindrical (yellow) axes described in the text.

The geometry of the femoral condyle was modeled as a cylindrical surface around which the tibia rotates in flexion and extension. A computer algorithm that was developed allowed the investigator to place a cylinder inside each femoral condyle of the Visible Human models and subsequently position and enlarge the cylinder in an iterative fashion until <1 mm of condylar bone remained outside the cylinder. A separate cylinder was created in the other condyle in an identical fashion (Fig. 2). The axes of the two cylinders were colinear, i.e., the axes of the two cylinders were the same line, despite the fact that the diameter of each cylinder was different. This "cylindrical axis" of the condyles defines the flexion axis about which the tibia moves, assuming constant contact of the tibial and femoral surfaces.

For the purpose of demonstrating this method to participants at this Academy exhibit, a second method for fitting the cylinders within the condyles was developed with use of a haptic device. The algorithm allowed the participant to touch the surface of the segmented femoral condyles of the Visible Human knee model in cyberspace while the computer gathered data points that corresponded to the condylar surface geometry. The computer was programmed to generate and position a cylinder within the condyle with the requisite 1-mm tolerance of remaining condylar bone outside the cylinder. After the creation of cylinders in both condyles, the computer generated the "cylindrical axis." On the basis of a visual inspection of the three-dimensional model by manipulating it in cyberspace, each participant confirmed that the condyles of the femur were well modeled by cylinders, i.e., the condyles are circular where they contact the tibia. This methodology was subsequently incorporated into an algorithm and technique with use of the surgical navigation system (Stryker Navi-

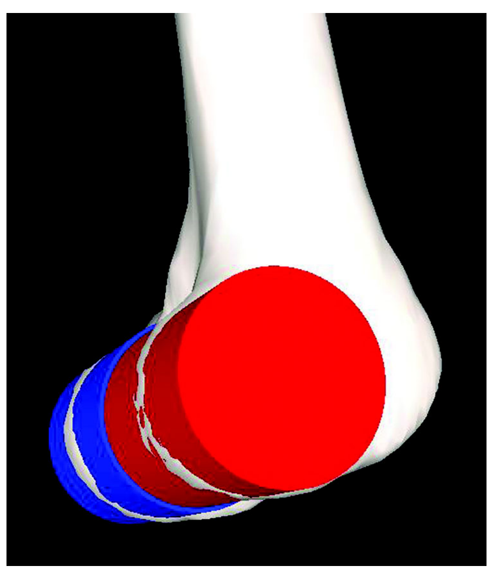

Fig. 2

Cylinders fit in the posterior condyles of the Visible Human femur.

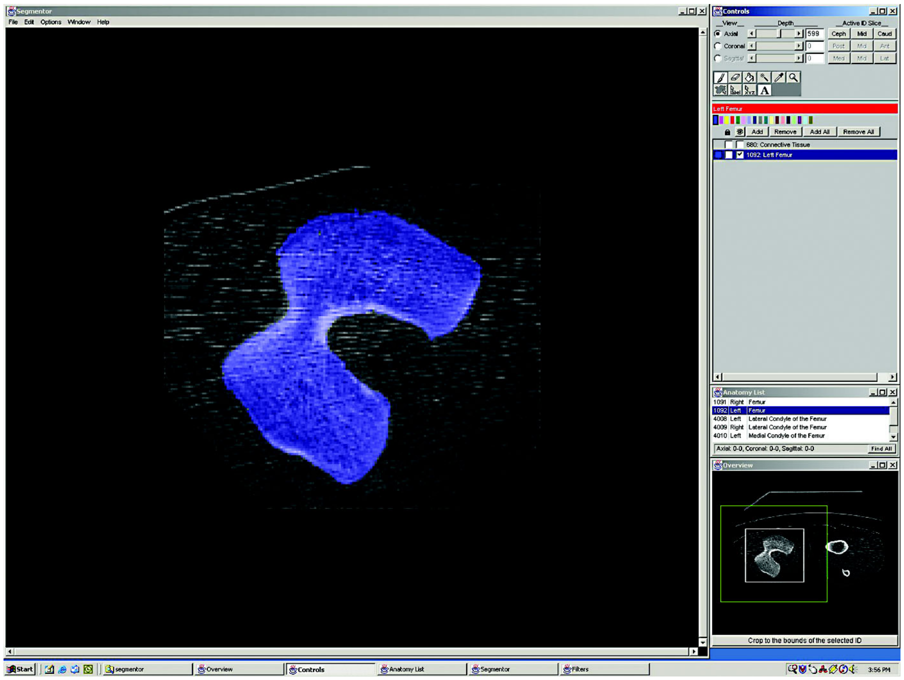

Fig. 3

Segmented computed tomographic slice of the femur (soft tissues removed).

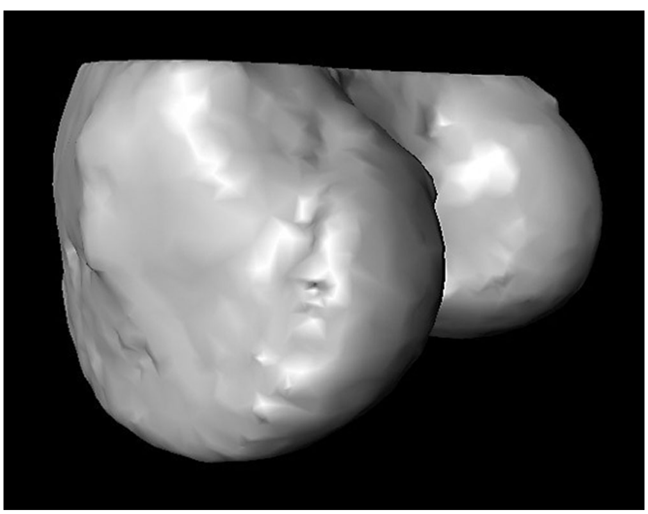

Fig. 4

Reconstructed three-dimensional knee from segmented computed tomographic data.

gation, Kalamazoo, Michigan) as described below.

The second phase of this project involved confirmation that the morphology of the femoral condyle that articulates with the tibia can be modeled as a cylinder. Three separate modalities were utilized in multiple specimens to demonstrate the cylindrical morphology.

Computed tomographic studies of ten cadaver knees (five pairs) were obtained. Each slice, measuring 0.5 mm thick, was segmented in a personal computer to extract the bone morphology of the specimen (Fig. 3). The bone architecture of the knee was reconstructed in three dimensions (Fig. 4). The cylinder-fitting algorithm described above was used to place

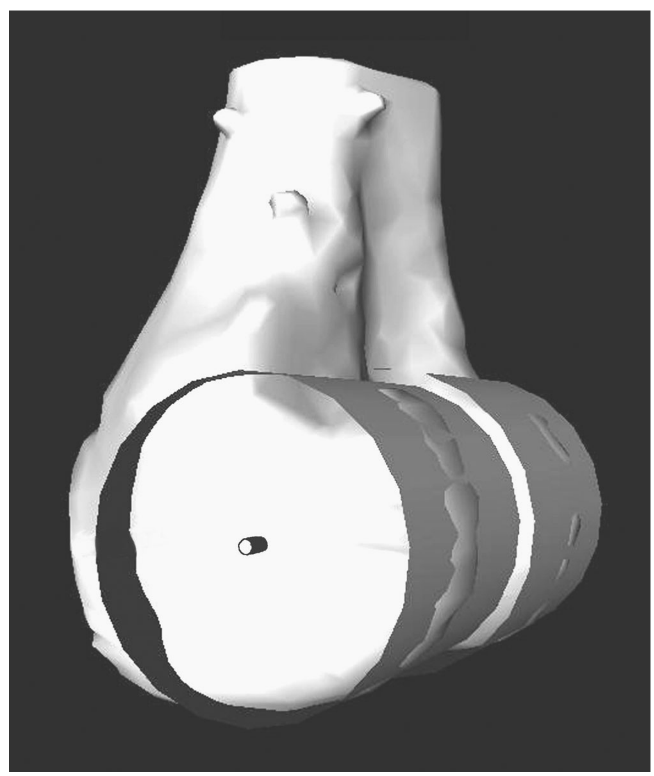

Fig. 5

Cylinders with common axis (lumps on the femur are fiducials described in the text).

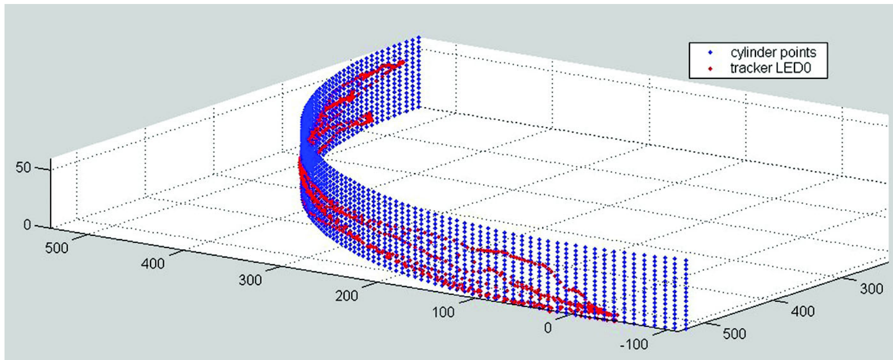

Fig. 6
Cloud of points created by surgical navigation, demonstrating cylindrical shape of femoral condyles. LED0 = light-emitting diode 0.

cylinders in both condyles and define the common axis (Fig. 5). The position of this axis relative to fiducial markers placed prior to the computed tomographic scan was determined.

The axis position was then obtained independently by functionally aligning the specimen in a six-degrees-of-freedom motion analysis apparatus[11] that was based on a floating coordinate system[12]. Once the specimen was aligned, the location of the functionally determined flexion axis was referenced to the fiducial markers. The specimen was also moved through a range of motion to confirm that the flexion axis of the knee demonstrated in the motion apparatus corresponded to the cylindrical axis defined by the cylinders in the three-dimensional computed tomographic scan.

Additional confirmation of the cylindrical morphology of the femoral condyles was obtained with use of an optical surgical navigation system (Stryker Navigation). The system measures and records the three-dimensional position of tracking devices fit with light-emitting diodes. The tracking devices can be fixed rigidly to the tibia and the femur and recorded in real time as the knee flexes and extends, or they can be attached to an instrumented stylus and passed over the condyles in a repetitive fashion to create a cloud of points. These points were entered into a personal computer with proprietary software designed to locate the center of each condyle. Analysis of these data revealed geometrically semicircular paths traced by the light-emitting diodes (Fig. 6). This finding indicates that a single fixed axis of rotation is present in the knee, and it can be determined analytically.

The third and final phase of the project demonstrated in this exhibit was a comparison of the cylindrical axis with other conventional reference "axes" of the knee (mechanical, anatomic, and epicondylar axes). Three independent observers each performed the cylinder-fitting routine twice in the computed tomographic data for the ten cadaver knees to demonstrate the reliability and reproducibility of the method. They also visually identified the medial and lateral epicondyles in conjunction with each cylinder fitting, allowing the computer to generate the corresponding epicondylar axis (Fig. 7). Since neither the cylindrical axis nor the epicondylar axis lies in a traditional plane, i.e., sagittal or coronal plane, and they are not coplanar with respect to each other, the angle between them was calculated as a measure of their difference. Computer-generated interactive animations were produced to illustrate the relationship of these axes to conventional (mechanical and anatomic) axes defining limb alignment (Figs. 8 and 9).

Results

A general consensus was obtained from the authors and participants of this exhibit that the condyles fit with cylinders were, by visual inspection with three-dimensional glasses, cylindrical in shape from approximately 20° to 120° of flexion. All individuals completing the cylinder-fitting exercise in this exhibit were in agreement that the cylinder closely approximated the posterior femoral condyles and accurately reflected the geometry of the specimen. This consensus applied to both the Visible Human database and the ten reconstructed three-dimensional computed tomographic models. There was also consensus among the authors and participants that the cylindrical axis and epicondylar axis

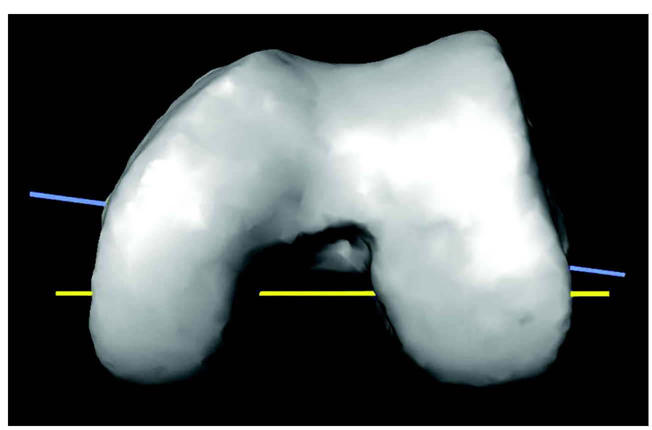

Fig. 7
Comparison of epicondylar (blue line) and cylindrical (yellow line) axes.

were not colinear. Furthermore, the planes passing perpendicular through the midpoint of the cylindrical and epicondylar lines were not coplanar; the plane perpendicular to the cylindrical axis contained the mechanical axis of the tibia, whereas the plane perpendicular to the epicondylar axis contained the mechanical axis of the femur. The center of the femoral head did not lie in the plane perpendicular to the cylindrical axis, and the center of the ankle did not lie in the plane perpendicular to the epicondylar axis.

The angle between the cylindrical axis and the epicondylar axis was documented by three independent observers

Fig. 8

The mechanical axis of the femur perpendicular to the epicondylar axis.

and is presented in Table I. The average angular deviation (and standard deviation) of the cylindrical and epicondylar

TABLE I Angle Between the Epicondylar Axis and the Cylindrical Axis in Five Pairs of Cadaver Knees

Pair	Right	Left
1	10.7°	7.6°
2	7.1°	14.2°
3	1.8°	1.1°
4	1.3°	9.0°
5	6.4°	8.1°

axes was 6.7° ± 4.3°. The range of angular deviation was 1.1° to 14.2°.

Discussion

The morphology of the distal part of the femur is a topic attracting considerable interest in the literature. A substantial amount has been written,

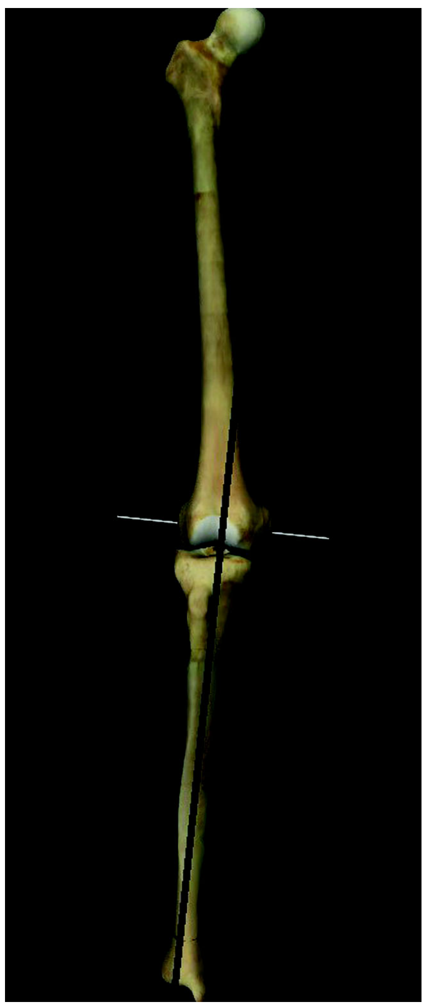

Fig. 9

The mechanical axis of the tibia perpendicular to the cylindrical axis.

dating back to the 1836 investigations of the Weber brothers[13]. Despite this attention, disagreement and controversy persist.

One source of controversy is the shape of the femoral condyles. Studies addressing femoral morphology have suggested that the femoral condyles display a circular profile from approximately 20° to 120° of flexion[1,8,13]. The anterior portion of the femur contacting the tibia in the first 20° of flexion and last 20° of extension also appears circular, but of a different radius than the posterior segment[8]. The Weber brothers were the first in a long list of investigators to document this circular profile of the condyles[13]. The illustrations in this exhibit, created with both the Visible Human database and the ten reconstructed three-dimensional computed tomographic scans, are consistent with this observation, i.e., the posterior femoral condyles are circular in profile. Furthermore, this study confirmed the previously documented asymmetry of the condyles, with the medial condyle demonstrating a larger radius of curvature than the lateral condyle[8].

The contrasting view of femoral morphology, and the source of controversy, is that the condylar radius of curvature is not constant. Fick first documented this perspective on femoral morphology in 1911 with his impression that the femoral condyle resembled a spiral, demonstrating a helical radius of curvature in which the radii of curvature increased regularly from anterior to posterior[14]. Fick introduced the term "evolving curve" with a shifting center[14] to describe what later investigators have referred to as the instant center of rotation in the knee. This perspective of knee morphology, promoted largely by mathematicians and engineers, is an effort to describe the knee in terms of a single axis of rotation projected with traditional Cartesian coordinates onto orthogonal planes. However, on the basis of more contemporary work[8-10], including the work presented in this exhibit with the use of a six-degrees-of-freedom motion analysis apparatus[11], the shift of the instant center of rotation appears to be an artifact created by insisting that all tibial-femoral motion occurs about axes in the femur. This shift of the instant center disappears and a single fixed flexion-extension axis remains when the tibia is allowed to rotate about a longitudinal axis[8-11] in the tibia and when anterior-posterior translation of the tibia relative to the femur is analyzed independently of flexion-extension.

The three-dimensional illustrations and analyses offered in this exhibit do not support this contrasting "instant center" view of knee morphology and kinematics. The three-dimensional reconstructions clearly demonstrate a constant radius of curvature of the posterior femoral condyles. The individuals participating in the cylinder-fitting exercise at this exhibit concurred with this observation. The mechanical testing of cadaveric specimens with the use of a six-degrees-of-freedom motion analysis apparatus[11] that was based on a floating coordinate system[12] confirmed this assessment. Allowing the tibia to rotate about a longitudinal axis in this apparatus and allowing the tibia to translate anteriorly and posteriorly while flexing and extending the knee demonstrated a single fixed axis of rotation in close proximity to the cylindrical axis. The application of a contemporary surgical navigation system to establish a cylindrical cloud of points from the condylar surface provided yet another confirmation of this observation.

Accepting that a fixed flexion-extension axis exists, a second source of controversy centers on the location of the axis. This exhibit provided morphologic illustration and kinematic analysis that the fixed axis is coincident with the axis of the cylinders most closely approximating the posterior surface of the condyles. The contrasting view is that the axis is coincident with the line joining the epicondyles of the distal part of the femur. The disparity of these two representations of the flexion-extension axis is illustrated in Figure 7 and quantified in Table I.

In one argument bearing on the choice of surrogate for the flexion axis, Geraghty et al. noted that the mechanical axes of the femur and tibia are rarely collinear[15]. The importance of this observation, borne out in three-dimensional images in this exhibit, is that the epicondylar line is perpendicular to the plane of the mechanical axis of the femur (Fig. 8), whereas the cylindrical axis is perpendicular to the plane of the mechanical axis of the tibia (Fig. 9). On the basis of this observation, it is apparent that the plane perpendicular to the mechanical axis of the proximal part of the tibia, referred to clinically as the "classical cut," is not parallel and bears no constant relationship to the epicondylar axis of the femur. This point has considerable relevance to balancing soft tissues in total knee arthroplasty, which is discussed below, and lends support to the selection of the cylindrical axis as the substitute for the flexion axis in the context of total knee arthroplasty.

A perhaps most compelling argument focuses on the observation that the tibia normally articulates with the femoral condyles such that it remains equidistant from the cylinder center but varies in distance from the epicondylar line throughout the entire range of motion. This implies that ligament length and tension are constantly changing or that the articular surfaces are compressing and distracting to accommodate motion about the epicondyles. Ligament length and tension as well as articular contact are unaffected by motion about the cylindrical axis.

The clinical relevance of the work presented in this exhibit is reflected in its impact on total knee arthroplasty. The morphology of the femur illustrated here should dictate the shape of a prosthetic implant. If the femoral component of a total knee prosthesis is geometrically similar to the normal distal part of the femur, the trochlear groove should be lateral to the midline and oriented between the anatomic and mechanical axes of the femur. The posterior condyles should be cylindrical in shape, with the medial condyle slightly larger in radius than the lateral. If the implant is geometrically similar, i.e., a single radius of curvature equal in size to the posterior femoral condyles, the soft tissues will remain equally balanced throughout the range of motion. The kinematics of the prosthetic knee, reflecting the normal tension in the soft-tissue sleeve, will approximate the kinematics of the otherwise normal, anterior cruciate ligament-deficient knee. The data and illustrations provided in this exhibit support the use of implants designed with a single radius of posterior curvature. Multiradius implants do not reflect the geometry of the distal part of the femur documented in this exhibit.

The clinical relevance of this work to total knee arthroplasty is also reflected in the selection of an axis for alignment of the implant. The axis selected by the surgeon will dictate the position of the implant and impact knee kinematics through balance, or imbalance, of the soft tissue and interaction of the extensor mechanism. If the implant is geometrically similar to the normal knee, i.e., a single radius of curvature equal in size to the posterior femoral condyles, and if it is positioned in the appropriate location and orientation relative to the flexion axis of the knee, the soft tissues will remain equally balanced throughout the range of motion. Kinematics of the knee approaching those of a normal knee will be imparted by tensions approaching normal in the soft-tissue sleeve.

By contrast, if the same implant with anatomic geometry is positioned off axis, the soft tissues will become lax or taut depending on the distance and direction of the implant from the flexion axis. If the surgeon compensates for the iatrogenic displacement of the axis from the anatomic location of the flexion axis by altering the size of the implant, e.g., selecting an implant with a larger radius of curvature, the soft tissues will again be unbalanced in specific portions of the flexion-extension arc. By way of illustration, if the axis is moved anteriorly and superiorly, and a larger implant is selected to fill the void created, the range of motion will likely decrease as the soft tissues become tight in terminal flexion and extension, where the implant pushes the tibia further from the anatomic flexion axis.

These observations of soft-tissue imbalance secondary to axis translation are compounded when the surgeon-selected axis is also rotated, i.e., it is moved further from the flexion axis on the one side than the other. For example, if the displacement of the implant is greater in any direction on the medial side than the lateral side, soft-tissue imbalance will be greater on the medial side. Although the soft tissues may be rebalanced with some time, attention, and surgical skill, the current practice of surgeons is to balance only in flexion and extension, leaving residual mid-range instability.

The contemporary practice of balancing a knee around the epicondylar axis requires cutting the tibia at 90° to its mechanical axis, the "classic cut." This alteration of the tibial surface articulating with the femur further compounds the complexity of restoring normal soft-tissue balance and kinematics because, as described above, the epicondylar line is perpendicular to the mechanical axis of the femur, not the tibia. As such, there is no constant or parallel relationship of the epicondylar axis to the plane perpendicular to the proximal part of the tibia. Restoring a symmetric flexion and extension space throughout the range of motion in the presence of this skewed relationship of the flexion axis to the cut surface of the tibia becomes an almost insurmountable three-dimensional challenge for the surgeon.

These observations of femoral morphology and axis location also have clinical relevance to ligament reconstruction. Restoring normal stability and kinematics to the knee in reconstructive surgery of the anterior cruciate and the posterior cruciate ligament requires accurate positioning and tensioning of the graft. This goal is not achieved when the axis of knee motion is assumed incorrectly or is altered. Graft placement must take into account the natural flexion-extension axis of the femur. Figure 7 demonstrates that the epicondylar axis is completely contained within the femur, whereas the cylindrical axis passes through the intercondylar notch. If the knee were actually rotating about the epicondylar axis, then the anterior cruciate ligament would be overly taut in extension and completely lax in flexion. This behavior does not match the published research on anterior cruciate ligament tension[16], strain[17], or length[18]. In contrast, a knee rotating about the cylindrical axis will lead to the reciprocating tension/strain patterns seen in the anteromedial and posterolateral bundles of the anterior cruciate ligament[17]. In order to achieve correct tension patterns of an anterior cruciate ligament graft over the range of flexion-extension, the surgeon must consider the relationship of the graft origin and insertion relative to the cylindrical axis when placing the bone tunnels.

Conclusions

The selection of an axis for the purpose of clinical reconstruction of the knee is not a trivial exercise. The consequences with respect to knee kinematics and longevity are considerable. Motion of the tibia about the femur is determined by articular geometry and ligament balance. Wear of the cartilage, or wear of the prosthesis, is dictated by the soft tissues controlling tibial contact with the femur. The goal of reconstruction is to restore knee kinematics and limit wear to promote longevity of the reconstruction. The selection of an axis is key to restoring the articular geometry and soft-tissue balance that determines knee kinematics, thereby limiting wear and ensuring longevity of the reconstruction. The studies and three-dimensional illustrations in this exhibit provide kinematic and morphologic validation for a single cylindrical flexion-extension axis of the knee. ■

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