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A New Device to Measure the Structural Properties of the Femur-Anterior Cruciate Ligament-Tibia Complex

Previous studies of biomechanical properties of femur-anterior cruciate ligament-tibia complex (FATC) utilized a wide variety of testing methodologies, particularly with respect to ligament orientation relative to loading direction. A new device was designed and built to test the anterior-posterior displacement of the intact porcine knee at 30 and 90 deg of flexion, as well as the tensile properties of the FATC at any loading direction and flexion angle. Tensile tests were performed with the knees at 30 and 90 deg of flexion with the loading direction along either the axis of the tibia (tibial axis) or the axis of the anterior cruciate ligament (ligament axis). The results showed that the stiffness, ultimate load and energy absorbed were all significantly increased when the FATC was tested along the ligament axis. This study demonstrates the importance of alignment in the evaluation of the biomechanical characteristics of the femur-ACL-tibia complex.

Introduction

The anterior cruciate ligament (ACL) has a very complex anatomy which enables it to perform an important role in guiding knee motion. As the knee undergoes flexion-extension, internal-external, and varus-valgus rotation, the length and orientation of the ACL change significantly. The broad attachments of the ACL to both the femur and the tibia allow various portions of the ligament to be relatively taut throughout a full range of knee motion. So, given a particular orientation of the knee, some collagen bundles of the ACL experience tension while other bundles are unloaded [1–4]. In addition, the orientation of the ACL changes with different knee positions [2]. Therefore, it is reasonable to assume that the tensile behavior of the ACL will depend on the orientation of the femur with respect to the tibia as well as the direction of applied load.

Previous studies of the biomechanical properties of the femur-ACL-tibia complexes (FATC) utilized knee orientations and loading directions which were poorly documented and seemingly arbitrary with respect to the ligament orientation relative to the direction of applied load. Thus, data are difficult to compare with one another. Viidik [5] investigated the structural properties of the FATC in rabbits with the knee in a fully extended position and with the femur, tibia, and ACL all aligned along the axis of the applied tensile load. Gupta et al. [6] used a similar experimental set up to test the FATC of canines, but with the tibia externally rotated 90 deg relative to the femur to eliminate the natural twist in the ACL. Noyes and Grood [7] tested the FATC of rhesus monkeys as well as young and old humans. In their study, the knee was placed in approximately 45 deg flexion and the loading axis was aligned with the axis of the ACL in the sagittal plane, but not in the frontal plane. Dorlot et al. [8] tested the canine FATC with knee flexion angle of 90 deg, but the loading axis relative to the ACL axis was not detailed.

Several authors have used a simulated anterior drawer loading to assess the failure properties of canine FATC [9–11]. Other investigators examined the structural properties of the FATC using various knee flexion angles and axes of tensile loading. Clancy et al. [12] tested the FATC of rhesus monkeys at 30 deg knee flexion with an unspecified ACL orientation. Cabaud et al. [13] studied the repair of ACLs in dogs and monkeys. Shino et al. [14] tested the canine FATC with the tibia aligned along the loading axis and the knee at 30 deg flexion. Yoshiya et al. [15, 16] tested canine FATC with the femur aligned along the loading axis and the knee flexed to 30 deg. Jackson et al. [17] used a knee flexion angle of 30 deg with the ACL aligned vertically along the direction of loading.

Alm et al. [18] in a study of the tensile strength of the dog ACL, found that the angle of tibial axial rotation had an effect on the strength and that the normal position resulted in the highest load. Recently, Figgie et al. [19] demonstrated that the angle of knee flexion had a significant effect on the structural properties of the canine FATC. When the FATC was stretched along the axis of the tibia, the load at failure decreased significantly with increasing angles of flexion. Our laboratory confirmed these findings [20]. We further demonstrated that the direction of applied tensile load also plays an important role in the structural properties of the FATC in rabbits.

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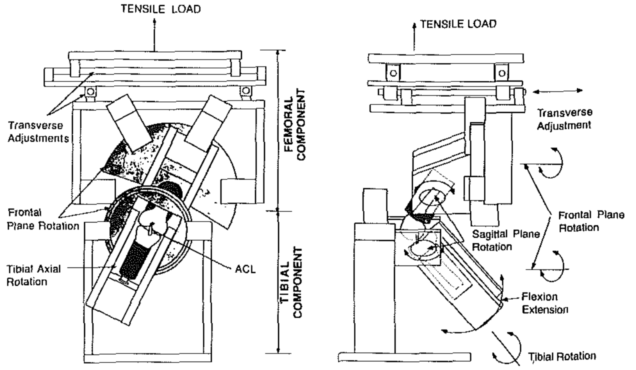

A. ANTERIOR-POSTERIOR VIEW B. MEDIAL-LATERAL VIEW

Fig. 1 Schematic diagram of the testing device designed to evaluate the structural properties of the Femur-ACL-tibia Complex (FATC)

Based on the above reports, it is apparent that there is a need to determine the effects of different loading conditions on the tensile properties of the FATC with specific regard to the direction of loading with respect to the ligament axis [21]. We propose a method of testing where the tensile load is directed along the anatomical axis of the ACL [22]. To do this, an apparatus has been designed for testing of knee specimens in which the orientation of the ACL can be precisely adjusted and aligned with respect to the direction of applied tensile load in both the frontal and sagittal planes. This device can also accommodate a full range of knee flexion angles. By visual examination, porcine knees have ACLs similar in size and anatomy to those of humans, and thus were studied at 30 and 90 deg of flexion. Testing was done with the tensile load applied either along the anatomical axis of the ACL (ligament axis) or along the long axis of the tibia (tibial axis).

Materials and Methods

Experimental Apparatus. A new device for testing knee specimens was designed and fabricated to evaluate the tensile properties of the FATC at any desired loading direction and knee flexion angle (Fig. 1A and 1B). In addition, the apparatus also allows for the testing of the anterior-posterior (A-P) displacement of the intact knee at any predetermined flexion angle (Fig. 2). These adjustments are accomplished by precise alignment of the apparatus and knee specimen before the tests.

The device consists of two major pieces: a femoral component and a tibial component. The femoral component permits femoral rotation in the frontal plane by means of a semicircular plate and clamp, and in the sagittal plane by a single transverse pivot and clamp (Fig. 1A and 1B). The entire femoral component can also be moved in the horizontal plane (transverse adjustments) by linear bearings on two sets of perpendicularly aligned shafts. These shafts are rigidly affixed to a support plate and load cell on the moving crosshead of an Instron testing machine. The tibial component also allows adjustments of the tibia in the frontal and sagittal planes using a semi-circular plate and transverse pivot, similar to that used in the femoral component. A shaft on rotary bearings to which the tibia and its mounting cylinder are attached, provides for unrestrained tibial axial rotation. Transverse plane motion of the tibial component is eliminated by rigidly fixing it to the base of the testing machine.

Together, the femoral and tibial components allow the knee to be secured at a wide variety of orientations relative to the axis of tensile loading. The linear bearing of the femoral component and changes in crosshead position permit alterations of the medial-lateral, anterior-posterior, and proximal-distal translations. The frontal and sagittal adjustments and the cylindrical clamps for both the femur and tibia permit alteration of knee flexion angle, internal-external and varus-valgus rotations. Given the versatility of the apparatus, adjustments are made possible in all six degrees of freedom for both tensile testing and A-P displacement testing.

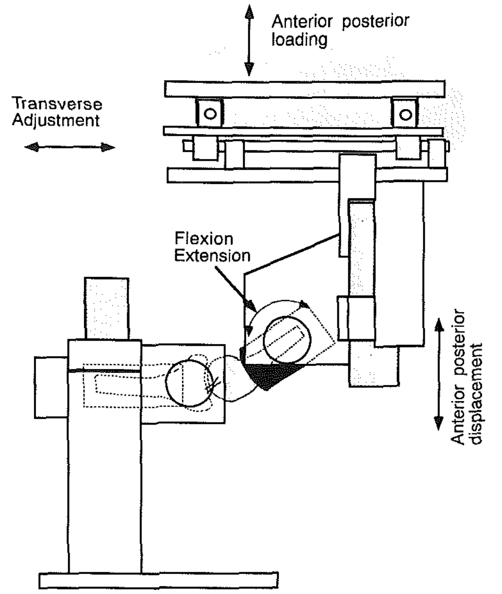

Fig. 2 The device used for anterior-posterior drawer testing of an intact knee. Medial-Lateral view of the knee is given.

Specimen Preparation. Twenty-four knees from young farm pigs (approximately 5 months of age and weighing 60 kg) were obtained fresh from a local meat packing house and frozen at −20°C for no more than one month before testing. Porcine knees were used because they were easily available and by visual examination had ACLs that were similar in length, attachment site, and fiber orientation to those of human knees (Fig. 3). Prior to testing, the specimen was thawed to room temperature, and then dissected free of muscular tissue, leaving the ligaments and joint capsule intact. The femur and tibia were cut to a length of 15 cm from the joint line, positioned within their respective thick-walled aluminum mounting cylinders and secured by means of two, 6 mm diameter transfixing bolts through each bone. The cylinders were made of solid aluminum with an outside diameter of 82 mm and an ovoid hole bored into the center to accommodate the shaft of the bone. The maximum and minimum wall thicknesses were 22 mm and 12 mm, respectively. The cylinders were placed as near the joint line as possible with the wider portion of the bone in contact with the cylinders. Each pair of bolts was separated by 5 cm and the bolt most proximal to the joint was located approximately 4 cm from the joint line. The specimen in its mounting cylinders was then secured into the femoral and tibial components by the device clamps. Physiologic saline was used to keep all the soft tissues moist throughout the entire test protocol, and the ambient temperature was controlled at 22°C.

Experimental Procedure

(*i*) *A-P Displacement Test.* A-P displacement tests were first performed on all the specimens. The knees were tested at both 30 and 90 deg of knee flexion, with the joint capsule and knee ligaments intact. The specimen was first placed into the apparatus in its neutral position with no external load applied. The tibia was placed in a horizontal position (aligned perpendicular to the axis of loading) and the femur was secured at a chosen angle of flexion with respect to the tibia (Fig. 2). The femur was allowed unrestrained proximal-distal and medial-lateral translations, however, femoral rotation was not permitted. The tibia was allowed unrestrained axial rotation, but

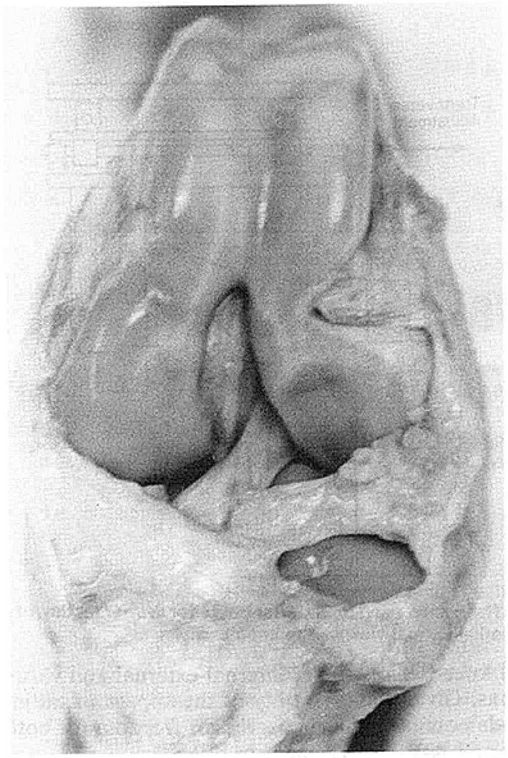

Fig. 3 A photograph of a typical porcine knee showing similarity of size and anatomy to that of a human knee

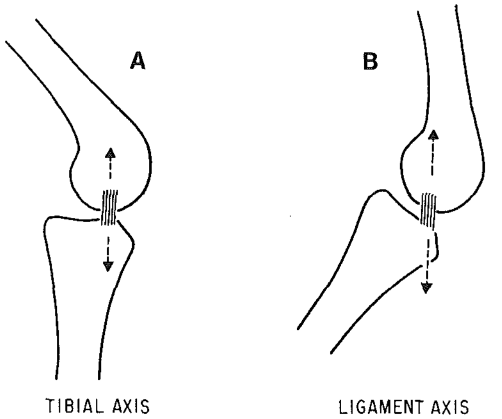

Fig. 4 Schematic diagram of FATCs of 30 deg knee flexion, demonstrating the difference in alignment for tibial and ligament axes during tensile testing

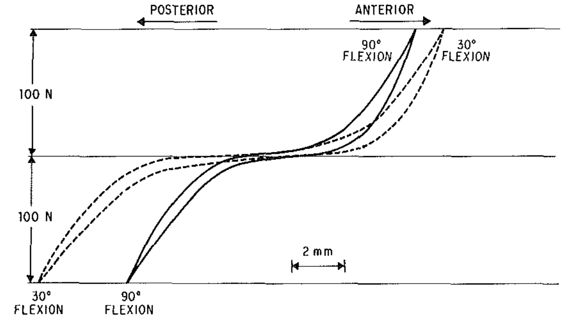

Fig. 5 Typical A-P displacement curves for a porcine knee tested at 30 and 90 deg knee flexion

other rotations and translations were restricted. A cyclic load of ±100 N was then applied to the femur in the A-P direction at a rate of 20 mm/min for 10 cycles. The varus-valgus knee rotation was restricted as it is very small during this test. The load versus displacement curves were recorded for both flexion angles.

(*ii*) *Tensile Testing.* Following A-P displacement testing, twelve FATC specimens underwent tensile testing at 90 deg and twelve at 30 deg of knee flexion. Half of the specimens at each flexion angle were tested with the axis of tensile load in the direction of the long axis of the tibia (tibial axis) (Fig. 4). All the knees to be tested along this axis were first placed into the apparatus with the knee structures intact. The tibia was positioned vertically along the direction of tensile load. All periarticular soft tissues except the ACL were then removed from the joint, leaving the FATC. The femur was then moved transversely in the anterior and medial direction, so that the femoral insertion of the ACL was directly over its tibial insertion, and in line with the applied tensile load.

The remaining half of the specimens were tested with the axis of loading along the anatomical axis of the ACL (ligament axis). For this group, the femur and tibia were required to be at an angle to the axis of loading in both the frontal and sagittal planes. All of the knees had the patella and fat pad removed to allow visualization of the ACL. After mounting the specimen in the device, adjustments were made in the femoral and tibial components such that the ACL as a whole was aligned vertically along a plumb line reference, and the ligament was directly beneath the load cell. All soft tissues except the ACL were then removed from the joint.

With the ligament aligned along its respective axes, all the clamps and bearings in the testing device were locked, restricting all degrees of freedom. Then, the cross-head of the testing machine was lowered so that the ACL was slightly buckled. A curved metal support plate was placed in contact with the femoral condyle to prevent premature failure at the femoral growth plate during tensile testing. A preload of 2.5 N was then applied. Each specimen was then preconditioned between 0.0 to 1.5 mm deformation at a rate of 20 mm/min for 10 cycles to settle the specimen in the clamp and obtain reproducible load-displacement characteristics. Subsequently, the specimen was loaded to failure at a rate of 20 mm/min. The load and crosshead displacement were recorded on a strip chart recorder. The maximum load, linear stiffness, and deformation and energy absorbed at maximum load were determined. The specimen displacement was later corrected to account for the stiffness of the testing device. The stiffness of the device was measured by bolting a stainless steel plate (2½cm × 2 cm × 6 cm) into the femoral and tibial cylindrical clamps. The stiffness was constant and was measured to be 508 N/mm for the entire range of tensile load used in this study (up to 2500 N).

Results

A typical nonlinear load versus displacement curve obtained during the 10th cycle of the A-P displacement testing of an intact knee is shown in Fig. 5. From this diagram, the A-P displacement was defined as the total displacement between the maximum anterior load (+100 N) and maximum posterior load (−100 N). The A-P displacement from the intact porcine knee was higher at 30 deg (12.0 ± 0.8 mm, mean ± SEM) than at 90 deg of flexion (10.6 ± 0.5 mm) ($p < 0.05$ paired t test). This trend is similar to that for human knees [25].

Typical load-displacement curves obtained during tensile testing of the FATC along the tibial and ligament axes are shown in Fig. 6. It can be seen that the ligament axis specimen has a steeper slope and higher peak load than the tibial axis specimen. The linear stiffness, taken as the slope of the load-deformation curve between 2 and 4 mm of deformation for all the FATCs is detailed in Fig. 7A. A two-way analysis of variance indicated that both the knee flexion angle and the direction of tensile load had a significant effect on the linear stiffness ($p < 0.001$). Specimens tested along the tibial axis had

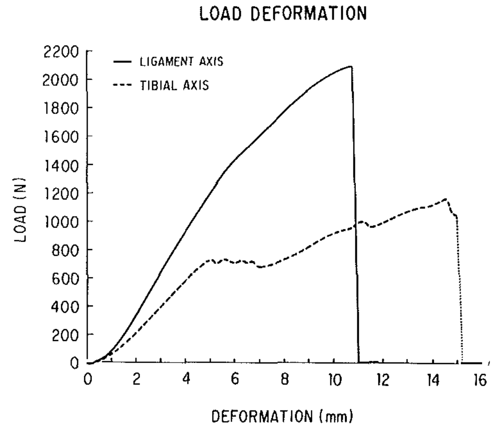

Fig. 6 Typical tensile load-deformation curves comparing the porcine FATCs tested along the tibial axis and ligament axis

a linear stiffness of 211 ± 86 N/mm at 30 deg of knee flexion, which was approximately 2 times higher than that for the specimens tested at 90 deg of knee flexion (108 ± 36 N/mm). Those specimens tested along the ligament axis had significantly higher linear stiffness values than those tested along the tibial axis. When tested along the ligament axis, however, the effect of flexion angle was not as great (299 ± 38 N/mm at 30 deg versus 229 ± 38 N/mm at 90 deg).

The direction of loading had a significant effect on the ultimate loads of the FATC, ($p < 0.05$), while the knee flexion angle did not ($p > 0.05$) (Fig. 7B). The mean values for specimens tested along the ligament axis were 1.8 and 2.1 times the ultimate loads of specimens tested along the tibial axis at 30 and 90 deg of knee flexion, respectively. The ultimate load values for specimens tested at 30 deg were higher than the ultimate load values for specimens tested at 90 deg of knee flexion for both the tibial and ligament axes. For specimens tested along the tibial axis, the flexion angle did not have a significant effect on ultimate load values (1,010 ± 300 N at 30 deg and 760 ± 350 N at 90 deg of knee flexion), while for specimens tested along the ligament axis, the effect of flexion angle was even less (1770 ± 320 N at 30 deg and 1620 ± 70 N at 90 deg).

Specimen deformation at maximum load was significantly affected by knee flexion angle ($p < 0.01$), but not by the loading axis ($p > 0.2$) (Fig. 7C). Specimens tested at 90 deg had values 58 and 52 percent higher than those tested at 30 deg of knee flexion for the tibial and ligament axis, respectively. Specimens tested along the tibial axis had deformation values 18 and 14 percent higher than those tested along the ligament axis for 30 and 90 deg of knee flexion, respectively.

The energy absorbed to failure (defined as the area beneath the load-deformation curve) was significantly affected by loading axis ($p < 0.05$) but not knee flexion angle ($p > 0.2$) (Fig. 7D). At a knee flexion angle of 30 deg, specimens tested along the ligament axis absorbed 50 percent more energy to failure compared to those tested along the tibial axis. Whereas, at a knee flexion angle of 90 deg, ligament axis tested specimens absorbed 87 percent more energy to failure than tibial axis tested specimens.

FATC failure modes were similar for specimens tested at 30 and 90 deg of knee flexion. Therefore, we compared the failure modes between the two loading axes. The predominant failure mode of specimens tested along the ligament axis was bony avulsion. Eighteen specimens (75 percent) failed by bony avulsion while the remaining six specimens (25 percent) experienced substance failure. Twelve specimens (50 percent) tested along the tibial axis failed by the ACL "peeling off" of the bone at the insertion site, ten (42 percent) failed by bony avulsion, and two (8 percent) failed by substance failure.

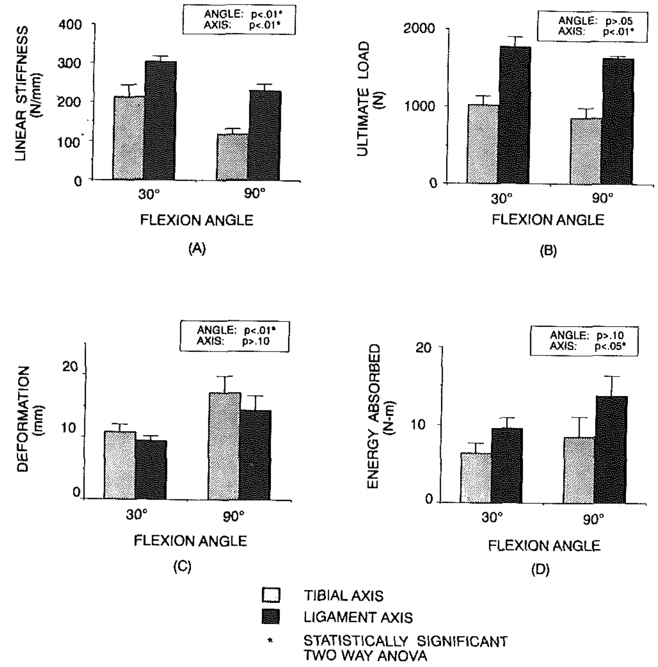

Fig. 7 Histograms of tensile properties obtained for the porcine FATCs as functions of axis of loading and angles of knee flexion. Two way analysis of variance (ANOVA) was used to compare the data statistically.

Discussion

The development of this testing device and a comparison between loading directions was an attempt to advance our knowledge of the tensile testing procedure for the anatomically complex anterior cruciate ligament. This testing device allows for the assessment of both the knee A-P displacement and FATC structural properties under a wide variety of loading conditions. The five multiplanar adjustments of both the tibia and femur allow precise orientation and alignment of the knees to be tested.

In this study, the versatility of such a device has been illustrated by using porcine knees. The loading conditions and flexion angles for knee A-P displacement testing were chosen to coincide with those of previous investigations as well as clinical knee displacement testing [21, 22]. Our findings of greater knee A-P displacement at 30 deg than at 90 deg of flexion are in agreement with these reports. Also, the displacement values for the porcine knees are similar to those reported in the in vitro studies of human knees [25] and are substantially higher than those in studies of canine [26] and goat knees [17].

FATC alignment relative to the tensile loading axis has been demonstrated to be important in the assessment of its structural properties. As fiber bundles of the ACL vary in length, the uniform tensile loading of every ACL fiber bundle along a single loading axis is not possible. When testing FATCs along the long axis of the ACL (ligament axis), we were able to apply the tensile load along the anatomical axis of the ACL, with the tibia and femur in their normal unloaded anatomical orientations. Such alignment may permit a larger proportion of fiber bundles of the ACL to be loaded simultaneously during tensile stretch, and as a result, these specimens obtained higher values of ultimate load and linear stiffness.

In contrast, tensile testing of the FATCs aligned along the tibial axis resulted in fewer fiber bundles of the ACL being loaded simultaneously during tensile stretch. As a result, the stiffness and ultimate loads of the FATC were lower than those tested along the ligament axis. Also, for specimens tested along the tibial axis, the differences in results obtained between 30 and 90 deg of knee flexion were more pronounced than the differences found among specimens tested along the ligament axis. At 90 deg knee flexion, the sequential failure of the fiber bundles allows the FATC to undergo a relatively larger deformation before failure. Therefore, for the tibial axis group, not only were a relatively small proportion of fiber bundles able to bear load at any one time, but the tensile force at the insertion site was directed in an abnormal angle with respect to the joint surface. This hypothesis may help to explain the differences between this study and our previous study using rabbits [20], in which the apparatus did not provide anatomical alignment in the frontal plane. Both studies demonstrate the dependence of structural properties on loading axis. However, the trend of the data as a function of knee flexion obtained from the porcine knee is different from that for the rabbit knee, particularly for those specimens tested along the ligament axis. Arguably, two-dimensional versus three-dimensional planar alignment may explain these differences.

In this study, we have been able to demonstrate that structural properties of the FATC are dependent on the direction of applied tensile load. Thus, it is essential that a detailed account of loading direction relative to the ACL, tibia and femur be included in all studies of this nature. The values for structural properties of the FATC obtained in previous studies in which the FATC was not tested along the ligament axis were less than what could have been attained. Shino et al. [14], for example, tested specimens with the ACL aligned along the tibial axis. One would expect that their reported data on the stiffness and ultimate load of FATC would be significantly lower than if the specimens were tested along the ligament axis. In view of the higher values of stiffness, ultimate load, and energy absorbed, we feel that to obtain the highest values of structural properties, tensile testing of FATC should be done with the load applied along the anatomical axis of the ACL. The adaptation of this approach with the use of appropriate clamping devices by all investigators would help to insure more comparable data on the structural properties of the femur-anterior cruciate ligament-tibia complex.

Acknowledgment

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