The Role of Fibers in the Femoral Attachment of the Anterior Cruciate Ligament in Resisting Tibial Displacement

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Purpose: The purpose was to clarify the load-bearing functions of the fibers of the femoral anterior cruciate ligament (ACL) attachment in resisting tibial anterior drawer and rotation. **Methods:** A sequential cutting study was performed on 8 fresh-frozen human knees. The femoral attachment of the ACL was divided into a central area that had dense fibers inserting directly into the femur and anterior and posterior fan-like extension areas. The ACL fibers were cut sequentially from the bone: the posterior fan-like area in 2 stages, the central dense area in 4 stages, and then the anterior fan-like area in 2 stages. Each knee was mounted in a robotic joint testing system that applied tibial anteroposterior 6-mm translations and 10° or 15° of internal rotation at 0° to 90° of flexion. The reduction of restraining force or moment was measured after each cut. **Results:** The central area resisted 82% to 90% of the anterior drawer force; the anterior fan-like area, 2% to 3%; and the posterior fan-like area, 11% to 15%. Among the 4 central areas, most load was carried close to the roof of the intercondylar notch: the anteromedial bundle resisted 66% to 84% of the force and the posterolateral bundle resisted 16% to 9% from 0° to 90° of flexion. There was no clear pattern for tibial internal rotation, with the load shared among the posterodistal and central areas near extension and mostly the central areas in flexion. **Conclusions:** Under the experimental conditions described, 66% to 84% of the resistance to tibial anterior drawer arose from the ACL fibers at the central-proximal area of the femoral attachment, corresponding to the anteromedial bundle; the fan-like extension fibers contributed very little. This work did not support moving a single-bundle ACL graft to the side wall of the notch or attempting to cover the whole attachment area if the intention was to mimic how the natural ACL resists tibial displacements. **Clinical Relevance:** There is ongoing debate about how best to reconstruct the ACL to restore normal knee function, including where is the best place for ACL graft tunnels. This study found that the most important area on the femur, in terms of resisting displacement of the tibia, was in the central-anterior part of the femoral ACL attachment, near the roof of the intercondylar notch. The testing protocol did not lead to data that would support using a large ACL graft tunnel that attempts to cover the whole natural femoral attachment area.

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The ideal outcome for an anterior cruciate ligament (ACL) reconstruction is to restore the native knee function, both the stability and kinematics. In single-bundle ACL reconstruction, it has been accepted that the femoral ACL graft tunnel should be placed close to the roof of the femoral intercondylar notch. However, studies of the outcome of ACL reconstruction in vitro[1,2] and in vivo[3,4] showed that such knees had sometimes retained abnormal instability. Rotational deficits were related to placing the ACL graft close to the roof of the femoral intercondylar notch.[5,6] Recently, therefore, techniques in which the ACL graft attachment is spread further across the anatomic attachment area have been used. These include anatomic double-bundle reconstruction of the anteromedial (AM) and posterolateral (PL) bundles[7] and "anatomic" (i.e., placed centrally in the ACL femoral attachment) single-bundle reconstruction procedures.[8,9]

It is implicit in these stages of evolution of ACL reconstruction that the exact site of the femoral attachment of the graft is most important. Noting this, researchers have recently performed anatomic and histologic work to understand the femoral ACL attachment in more depth. Early studies divided the ACL into AM and PL fiber bundles,[10] and their attachment areas are associated with ridges on the surface of the femur.[11] Mochizuki et al.[12] reported that the femoral attachment of the ACL has a dense, direct attachment of the ACL midsubstance fibers, as well as thin, membranous attachments of the fibers that spread out on the posterior condyle, termed "fan-like extension fibers." Hara et al.[13] confirmed that the dense midsubstance fibers attach to a narrow oval area on the lateral condyle. Iwahashi et al.[14] described that the direct insertion of the ACL was located in the depression between the resident's ridge and the articular cartilage margin on the lateral femoral condyle, whereas Sasaki et al.[15] reported that it was located at the anterior narrow part of the whole ACL insertion. Mochizuki et al.[16] reported that the posterior fan-like extension area remained adherent to the surface of the femur and was not aligned with the load when the knee was flexed. This observation suggested that these fibers may have a limited role.

There have been many studies of ACL reconstruction. Some created femoral tunnels in the direct attachment of the ACL midsubstance,[7,17] whereas others have recommended tunnels that include as much as possible of the attachment area, including the fan-like extension fibers.[11,18] This difference may be caused by a deficit in our knowledge on how the load carried by the ACL is transmitted to the femoral attachment. There have been studies in which the ACL was separated into 2 fiber bundles[19] or 3 fiber bundles,[20] but those did not use recent anatomic knowledge of the attachment morphology. Simply stated, we do not know which parts of the ACL, across the femoral attachment, are most important in resisting tibial displacements. If this were known, it would—for the first time—provide objective mechanical data to guide the femoral tunnel position in ACL reconstruction procedures if the objectives of the operation include the aim to try to reproduce the load transmission behavior of the natural ACL. To obtain more detailed knowledge, the ACL should be split into many small fiber bundles.[13]

The purpose of this study was to clarify the load-bearing functions of the fibers of the femoral ACL attachment in resisting tibial anterior drawer and rotation. It was hypothesized that most of the load transmitted by the ACL would not be in the attachment of the fan-like extension fibers but would be in the central relatively narrow area, where the dense midsubstance fibers of the ACL insert directly.

Methods

Specimen Preparation

Eight fresh-frozen cadaveric right knees without evidence of previous injury or surgery (mean age, 76.5 years; range, 67 to 91 years) were obtained with consent and permission from the London Riverside research ethics committee. The knees were stored at −20°C and thawed before use. Each knee was prepared on 1 day and kept overnight in a refrigerator, and the biomechanical experiment was completed the following day. The tibia and femur were cut approximately 15 cm from the joint line. The fibular head was transfixed to the tibia with 2 screws to maintain its anatomic position. The skin, musculature, patella, and central part of the posterior capsule were then removed so that the tibial and femoral shafts were exposed, leaving the knee ligaments intact. The tibia and femur were placed in 60-mm-diameter cylindrical steel pots and fixed with bone cement and screws. During the preparation and testing procedure, specimens were kept moist with wet tissue paper and water spray.

Partition of Femoral Attachment of ACL

Two transverse holes were created across the distal femur, avoiding the collateral ligament attachments and other stabilizing structures. The medial femoral condyle was separated with a reciprocating saw, starting between the cruciate ligaments and cutting proximally in the sagittal plane for 60 mm and then medially.[21]

The morphology and dimensions of the femoral ACL attachment were assessed on the lateral intercondylar surface. The outline of the attachment with the fan-like extensions was marked (Fig 1), on the basis of visual observation of the extent of the ACL fiber attachment area. The narrow, central, direct attachment area of the ACL midsubstance was identified by flexing and extending the knee with the ACL tensed. The directly attaching fibers remained tight when the knee was flexed and extended, passing straight to the bone attachment. The posterior fan-like extension fibers were tight when the knee was near extension but remained adherent to the surface of the femur when the knee flexed, causing a distinct folding of the ACL fibers at the boundary between the posterior fan-like extension and the central direct attachment areas, as illustrated in prior anatomic studies.[12,16] A similar process identified the boundary between the central direct fiber attachment area and the anterior fan-like extension area, in a deep fold between the bulk of the ACL and the wall of the intercondylar notch. These boundary lines were marked and were found to be straight and parallel, so another line could be drawn midway between them, along the central axis of the direct attachment area. Two more lines were drawn parallel to the central line, tangent to the outer edges of the attachment. Five parallel lines were drawn parallel to Blumensaat's line: 2 were tangent to the outer edges of ACL attachment, and then the other 3 were equally spaced between them so that the length of the central direct fiber attachment area was divided into 4 equal