

Anatomy, Biology and Biomechanics of Patellar Tendon Autograft Anterior Cruciate Ligament Reconstruction

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Summary: Autologous bone-patellar tendon-bone autograft is a common choice for anterior cruciate ligament reconstruction and from both biologic and biomechanical perspectives is well-suited for this purpose. A centrally harvested, 10 mm wide patellar tendon graft has an estimated initial load-to-failure of 2977 N, and interference screw fixation of associated bone blocks provides initial pull-out strength as high as 640 N. After reconstruction, both intraarticular and extraarticular portions of the graft experience significant changes. The intraarticular portion of the graft undergoes a prolonged histologic, morphologic, and structural evolution known as *ligamentization*. The extraarticular portion of the graft becomes rapidly incorporated into surrounding bone tunnels over the weeks after implantation. The use of biologics to accelerate this process holds promise. This review summarizes relevant data regarding the anatomy, biology, and biomechanics of the anterior cruciate ligament, patellar tendon, and anterior cruciate ligament reconstruction with autogenous bone-patellar tendon-bone graft. **Key Words:** Anterior cruciate ligament—Biology—Biomechanics—Ligamentization—Patellar tendon autograft.

The anatomy and biomechanics of the anterior cruciate ligament are complex, and regardless of technique or graft selection, the clinical ability to recapitulate normal anterior cruciate biomechanics has not yet been demonstrated in the literature. Nevertheless, among the multiplicity of graft selections available, the bone-patellar tendon-bone (BPTB) graft possesses several properties that make a favorable choice for anterior cruciate ligament reconstruction.

ANATOMY AND BIOMECHANICS OF THE NATIVE ANTERIOR CRUCIATE LIGAMENT

Anatomy

The anterior cruciate ligament (ACL) is an intraarticular, intrasynovial structure that comprises 2 bundles named for the location of their respective tibial attach-

ment sites: anteromedial and posterolateral.^{4,30} Collectively, the 2 bundles attach proximally along the posteromedial aspect of the lateral femoral condyle in a circular area measuring approximately 113 mm². The tibial attachment site is elliptical in shape with an average area of 136 mm² and is situated a mean of 15 mm posterior to the anterior border of the tibial articular surface, posterior to the attachment of the anterior horn of the medial meniscus and medial to the attachment of the anterior horn of the lateral meniscus (Fig. 1).^{30,34} Both the proximal and distal attachment sites of the ligament are considerably broader than its midsubstance, the cross-sectional area of which averages 40 mm².³⁴ The anteromedial and posterolateral bundles are not arranged in a simple linear fashion, but rotate externally around each other as they extend from the proximal femoral to the distal tibial attachment.⁷¹ Cadaveric sectioning studies with isolated preservation of the ACL demonstrate slight internal rotation of the tibia on the femur.⁷¹

The primary blood supply to the cruciate ligaments arises from the middle geniculate artery, which branches directly off of the popliteal artery and pierces the posterior capsule to form a periligamentous plexus (Figs. 2

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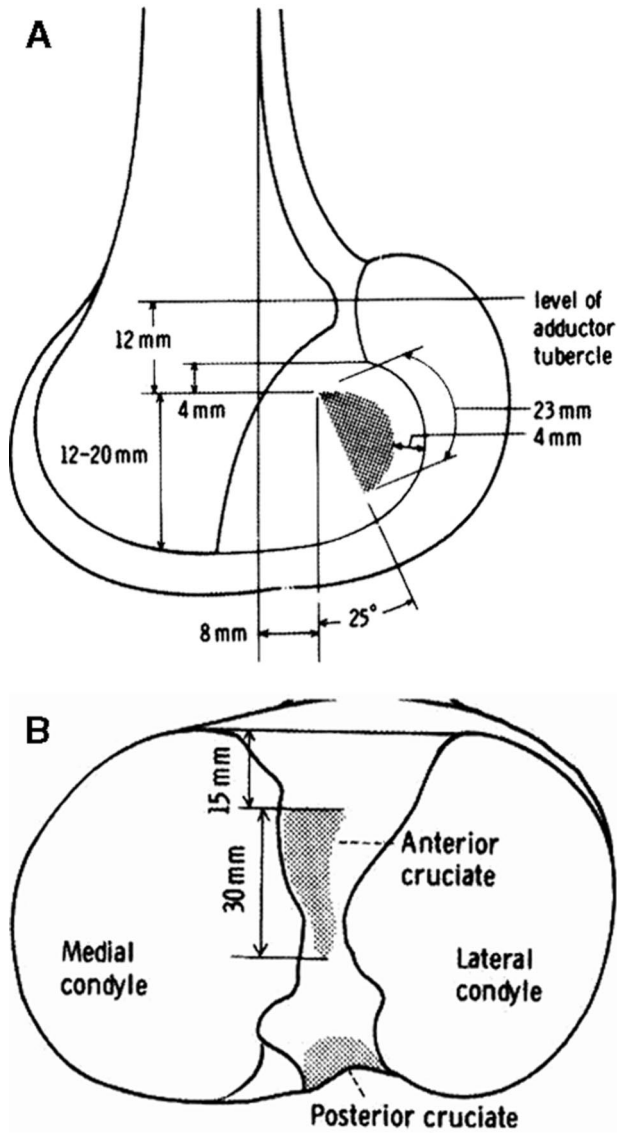


FIG. 1. (A) Diagram showing average dimensions for the femoral attachment of the anterior cruciate ligament. (B) Axial plane diagram of the tibial plateau showing average dimensions of both anterior cruciate and posterior cruciate ligaments. (Both images reprinted, with permission, from: Girgis FG, Marshall JL, Monajem ARS. The cruciate ligaments of the knee joint. *Clin Orthop* 106:216-231, 1975.).

and 3).⁴ Disruption of this periligamentous plexus gives rise to the hemarthrosis often present after acute injury to the ACL.

The posterior articular nerve, a branch of the posterior tibial nerve, provides innervation to the ACL.⁴⁶ In a manner analogous to the middle geniculate artery, the posterior articular nerve pierces the posterior capsule to form a periligamentous plexus. Furthermore, mechanoreceptors are found on the surface of the ligament,

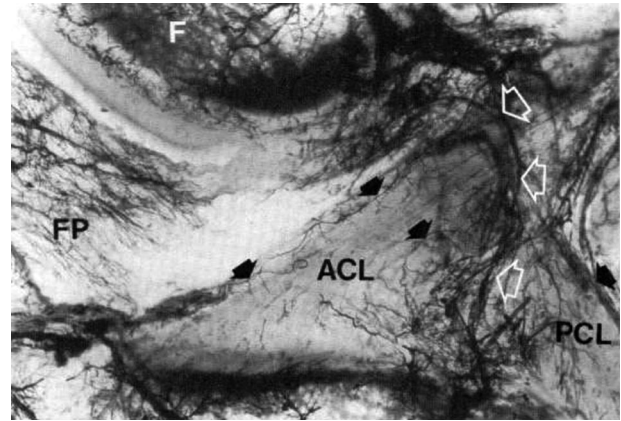


FIG. 2. Five-millimeter thick sagittal section of a human knee joint (Spalteholz technique) showing the vascularity of the anterior cruciate ligament. The ligamentous branch of the middle geniculate artery and its divisions (*open arrows*) can be seen supplying the periligamentous branches (*black arrows*) of the synovial covering of the anterior cruciate ligament (ACL). (F = femur; FP = fat pad; PCL = posterior cruciate ligament) (Reprinted, with permission, from: Arnoczky SP: Anatomy of the anterior cruciate ligament. *Clin. Orthop* 172:19-25, 1983).

arranged parallel to the course of the collagen fascicles, and clustered near the femoral attachment site.⁷⁴ These mechanoreceptors serve a presumptive proprioceptive role for the knee joint, facilitating muscular adaptation to



FIG. 3. Sagittal T2 FSE image depicting middle geniculate artery (*white arrow*) piercing the posterior capsule and branching to form periligamentous vascular plexus.

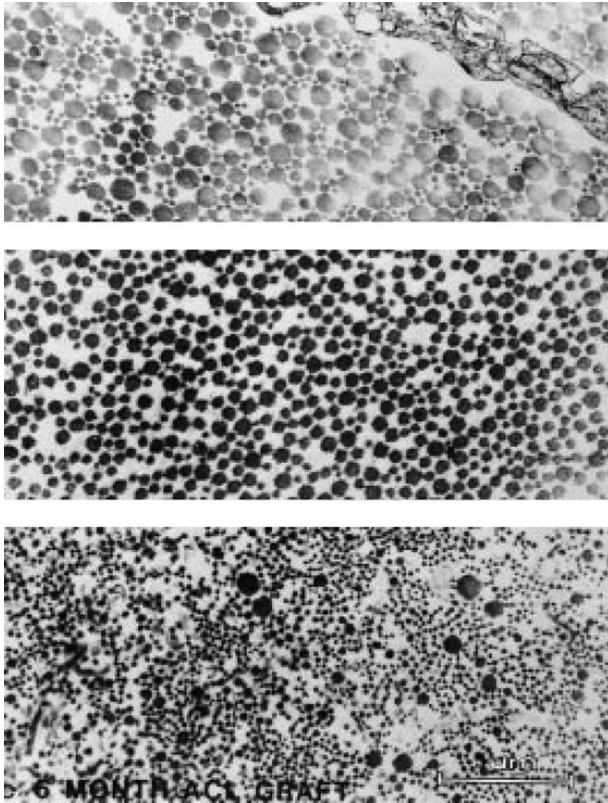


FIG. 4. Scanning electron microscopy. The first image shows the fibril composition of a normal patellar tendon. The second image shows the fibril composition of a normal anterior cruciate. The mean fibril diameter in the sample taken from the anterior cruciate ligament is smaller than that for the patellar tendon. The third image is that of a bone-patellar tendon-bone autograft 6-months after ACL reconstruction and depicts a mixed population of small and large fibril diameters. (Reprinted, with permission, from: Oakes, B.W.: Collagen ultrastructure in the normal ACL and in ACL graft. In: Jackson DW, ed. *The Anterior Cruciate Ligament. Current and Future Concepts*. Edited by. New York: Raven Press; 1993:214.)

movement and theoretically enhancing dynamic joint stability.⁷⁴

On a microstructural level, the ACL consists primarily of type I collagen in longitudinally arranged fibrils that increase in size from proximal to distal and range from 20 μm to 270 μm in diameter (Fig. 4).⁷ Small amounts of type III and type VI collagen are also present, particularly near the proximal and distal attachment sites. Both the proximal and distal attachment sites exhibit the four zones characteristic of “direct” ligament insertion: ligament, unmineralized fibrocartilage, mineralized fibrocartilage, and subchondral bone.³⁹ This transitional region between ligament and bone comprises a gradual change in stiffness that is thought to permit a more advantageous distribution of stress at the attachment sites than would

an “indirect” type of insertion that consists simply of direct soft-tissue attachment to bone (ie, Sharpey fibers).

The capacity of the anterior cruciate ligament to heal spontaneously is an area of increasing interest.⁵⁸ Despite the fact that the injured ACL exhibits a histologic healing response similar to that observed for other ligaments (eg, medial collateral ligament), consisting of inflammation, epiligamentous regeneration, proliferation, and remodeling, spontaneous healing of the ligament has rarely been observed experimentally or reported clinically (Fig. 5).^{49,58} Unlike other segments of dense connective tissue, a synovial cell layer with abundant α -smooth muscle actin-containing cells forms over the stump of the injured ACL, which may present a physical barrier to ligament healing.⁵⁸ An additional impediment to spontaneous healing is the fact that a fibrin scaffold, or post-traumatic clot, is not observed to form between torn ends of the ligament, perhaps because of the presence of fibrinolytic enzymes in synovial fluid.^{2,35}

Biomechanics

The ACL functions primarily to limit anterior translation of the tibia in relation to the femur, and secondarily to limit varus and valgus stress, and internal rotatory subluxation.⁵³ With respect to its role as a secondary restraint, sectioning studies with the knee in 5 degrees of flexion have shown the contribution of the ACL to be as high as 12% of the total restraining moment to valgus stress, its role diminishing with increasing flexion angles, and as high as 19.7% of the total restraining moment to varus stress, again its role decreasing with increasing flexion angles.³²

Fibers from the posterolateral and anteromedial bundles are thought to be recruited differentially as the knee moves through a full range of motion.²⁹ The posterolateral bundle of the ACL is thought to function as the principle restraint to anterior translation from 0 degrees to approximately 45 degrees of flexion, while the anteromedial bundle is thought to function as the principle restraint at higher flexion angles.²⁹ Based on in vitro studies, the anteromedial bundle has been observed to shorten from 0 degrees to 30 degrees of flexion, return to its baseline length from 30 degrees to 70 degrees of flexion, and lengthen from 70 degrees to 120 degrees of flexion.²¹ Conversely, the posterolateral bundle has been observed to reach maximum length with the knee in full extension and experience progressive shortening as the knee flexes, which together with the observed lengthening of the anteromedial bundle at high flexion angles supports the notions of differential recruitment and reciprocal function.²¹

Recently, however, the traditional view of the antero-

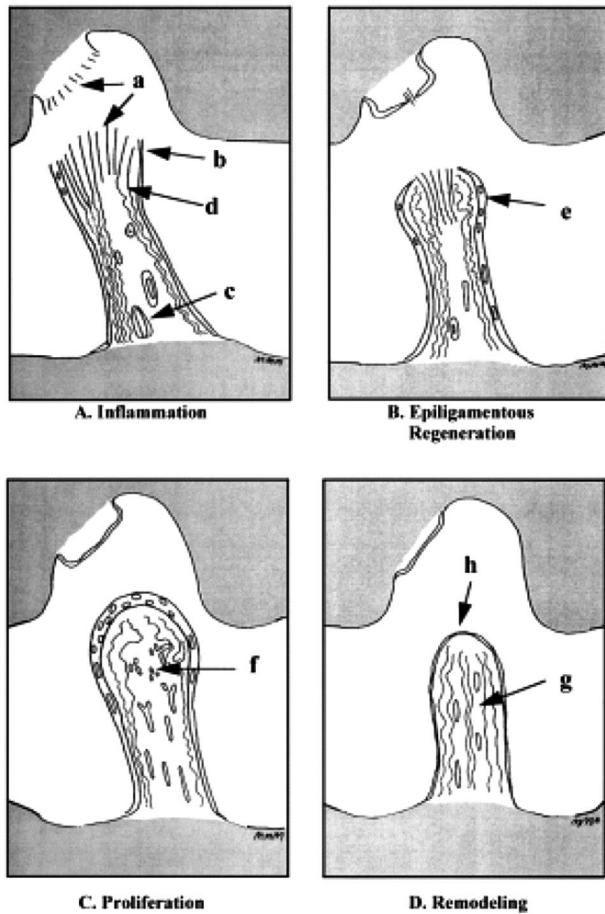


FIG. 5. Diagram illustrating the 4 histologic phases of healing observed for the torn anterior cruciate ligament. (A) The inflammatory phase shows mop-ends of the remnants (a), disruption of the epiligament and synovial covering of the ligament (b), intimal hyperplasia of the vessels (c), and loss of the regular crimp structure near the site of injury (d). (B) The epiligamentous regeneration phase, involving a gradual recovering of the ligament remnant by vascularized, epiligamentous tissue and synovial tissue (e). (C) The proliferative phase, with revascularization of the remnant with groups of capillaries. (D) The remodeling and maturation phase, characterized by a decrease in cell number density and blood vessel density (g) and by retraction of the ligament remnant (h). (Reprinted, with permission, from: Murray MM, Martin SD, Martin MD, Spector M. Histologic changes in the human anterior cruciate ligament after rupture. *J. Bone and Joint Surg* 82-A:1390, 2000.)

medial and posterolateral bundles acting reciprocally to limit anterior translation through a full range of motion has been challenged.⁵¹ In vivo data from Li and colleagues demonstrates shortening of both the anteromedial and posterolateral bundles as the knee moves from full extension to 90 degrees of flexion.⁵¹ The most significant decrease in length occurs in the posterolateral bundle, which was observed to shorten up to 14%. The most marked shortening occurs at flexion angles beyond

60 degrees. These findings support the role of the posterolateral bundle in limiting anterior translation at low flexion angles, and challenge the traditional notion that the anteromedial bundle reciprocates at higher flexion angles. A significant strength of this study is the fact that data were obtained during activity that permitted the dynamic tension provided by the hamstrings and extensor mechanism to be taken into account with respect to cruciate ligament behavior.

In vivo studies have shown muscular activation to significantly increase ACL strain. In particular, quadriceps activity produces a marked increase in ACL strain, most pronounced in full extension.⁹ Gastrocnemius activity has also been shown to increase ACL strain at low flexion angles, yielding a cumulative strain during co-contraction with the quadriceps that is significantly greater than that produced by the quadriceps alone.²⁷ Hamstring contraction decreases ACL strain at all flexion angles, but may not provide significant protection at very low flexion angles given the decrease in mechanical advantage experienced near full extension.¹¹

Beynon and colleagues have generated the most comprehensive characterization of in vivo strain experienced by the ACL. Using a Hall effect transducer implanted in the anteromedial bundle of the ACL, Beynon and colleagues directly measured strains during a wide variety of maneuvers.^{10,11,23-26} The highest recorded strains were during isometric quadriceps contraction (30 N/m extension torque) at 15 degree flexion, and approached 5%. Anterior shear loads applied at 30° of flexion (Lachman test) produced significantly greater strain than similar loads applied at 90 degrees of flexion (anterior drawer test), which correlates with the acknowledged superior clinical sensitivity of the Lachman test over the anterior drawer test in the detection of ACL injury. Limiting the clinical significance of these findings, however, is that strain measurements were isolated to the anteromedial bundle of the ACL. The findings of Li and colleagues suggest that studies limited to measurement of the anteromedial bundle are vulnerable to significant underestimation of the more relevant strains experienced by the posterolateral bundle.

In vitro studies have shown that the ACL has a load-to-failure as high as 2,160 N, a stiffness of 242 N/mm and is able to tolerate up to 20% strain before failure.^{16,28,63,77} The structural properties of the ACL, along with those of several tissues used as grafts for ACL reconstruction are listed in Table 1. The behavior of the load-displacement curve for the ACL has been shown to vary in response to several variables, including rate of load application, immobilization, and age. In particular, more energy is required to reach load-to-failure at high

TABLE 1. Ultimate Tensile Strengths of the Intact ACL And Various Graft Tissues

Graft	Ultimate Load-to-failure (N)	Reference
Bone-patellar-tendon-bone (10 mm)	2977	20
Quadriceps tendon (10 mm)	2352	73
Double-looped-semitendinosus-gracilis (equally tensioned)	4590	33
Intact ACL	2160	77

load rates versus slow load rates, brief periods of immobilization can result in significant decreases in load-to-failure and older individuals demonstrate a load-to-failure up to 3 times lower than that for young individuals.^{60–62}

ANATOMY AND BIOMECHANICS OF THE PATELLAR TENDON AND BONE-PATELLAR TENDON-GRAFT

Anatomy

The anatomy of the patellar tendon (PT) has been well-described.⁸ The PT has a broad, flat origin along the distal, anterior aspect of the patella. The apex of the distal pole of the patella corresponds to a point medial to the midpoint of the PT, limiting its usefulness as a landmark when harvesting the central one-third of the PT for ACL reconstruction. According to one cadaveric study, slightly over 60% of the PT width lies lateral to the apex of the distal pole. Fibers of the PT converge distally in the frontal plane, resulting in a tendon thicker distally than proximally. This fascicular convergence can result in a graft that narrows from proximal to distal if dissection along strict fascicular lines is used during graft harvest.

The PT receives its vascularity from the infrapatellar fat pad and surrounding patellar retinaculum via anastomoses from both the inferomedial and inferolateral geniculate arteries.⁵⁵ The anterior surface of the PT is supplied via retinacular tissues while the infrapatellar fat pad supplies the posterior surface of the PT (Fig. 6). The blood supply enters predominantly at the proximal and midportions of the tendon, and proximal and distal attachment sites of the tendon are relatively avascular.⁷²

Water constitutes approximately 70% of the wet weight of the PT, and collagen approximately 70% of the dry weight.⁵⁵ Over 90% of the collagen present in the PT is type I, with the remaining 10% comprising a distribution of types III, intravenously, V and VI. These collagen bundles are organized into large-diameter fibrils (>100 nm) with a characteristic crimp pattern that differs from that of the ACL. Of note is that proximal and distal attachments of the patellar tendon possess the same

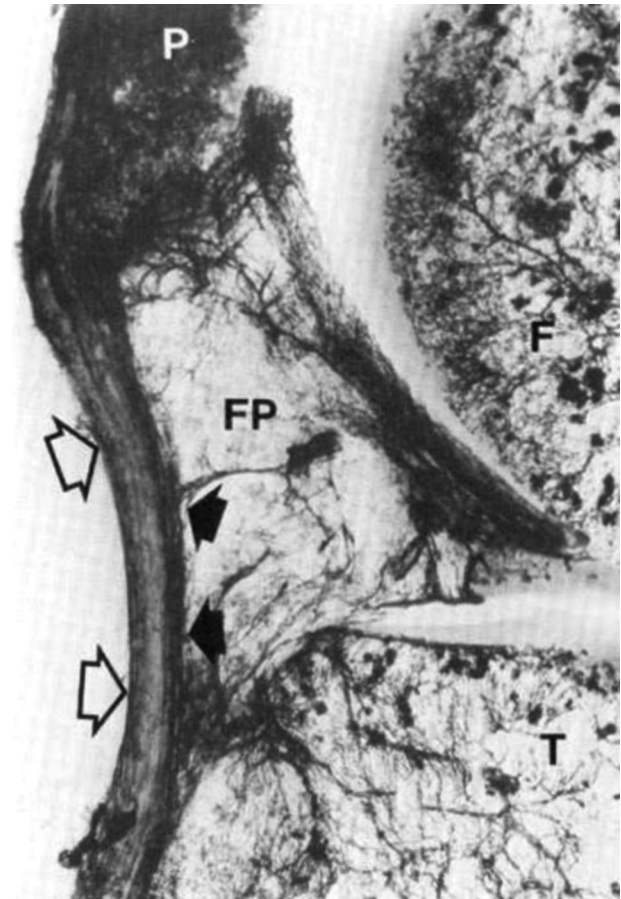


FIG. 6. Five-millimeter thick sagittal section of a human knee joint (Saplteholz technique) showing the vascular supply to the patellar ligament and infrapatellar fat pad (FP). The retinacular vessels (*open arrows*) overlie the patellar ligament and supply its anterior aspect, while vessels from the infrapatellar fat pad supply its posterior portion (*closed arrows*). These vessels originate at the proximal portion and midportion of the patellar ligament and course inferiorly on the posterior surface of the ligament. (P = patella; F = femur; T = tibia) (Reprinted, with permission, from: Arnoczky SP. Anatomy of the anterior cruciate ligament. *Clin Orthop* 172:19–25, 1983.).

direct insertional architecture as those of the ACL, and this architecture is preserved when BPTB is used as a graft for ligament reconstruction.^{18,19,52,79} Soft tissue grafts do not incorporate with this type of graduated interface.³¹ This may represent a biomechanical advantage of the BPTB graft over soft tissue grafts in terms of the ability to dissipate longitudinal and shear stresses in a manner more analogous to that of the native ACL.³⁹

Biomechanics

The PT routinely experiences high tensile forces. Simple activities of daily living such as ascending stairs are estimated to generate tensile forces in the PT over 3.2 times body weight, with even higher forces generated

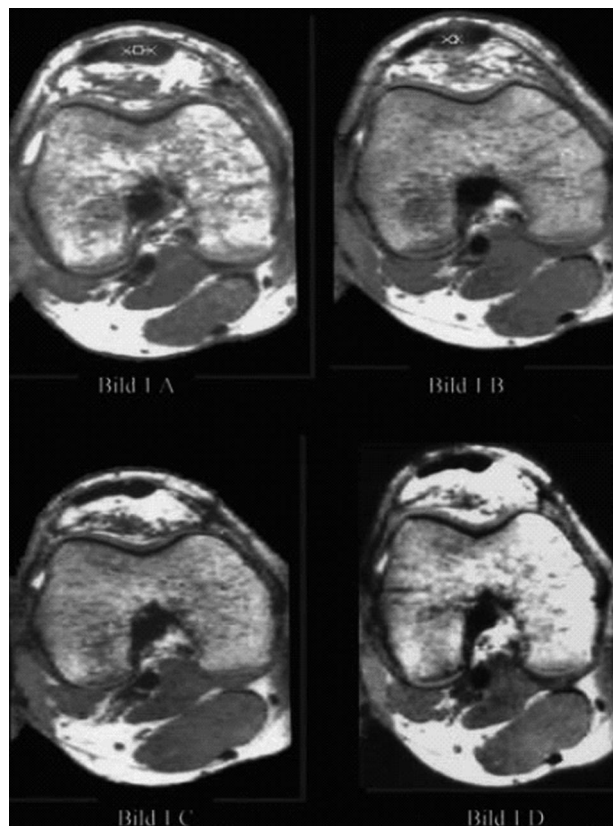


FIG. 7. Serial MRI studies illustrate healing of the patellar tendon graft donor site. Donor site gap measures 7 mm at 6 weeks (A), 2 mm at 6 months (B), and is completely healed at 27 and 71 months. A decrease in the thickness of the patellar tendon is also observed. The defect was not closed at the time of harvest. (Reprinted, with permission, from: Svensson M, Kartus J, Ejerhed L, Lindahl S, Karlsson J. Does the patellar tendon normalize after harvesting its central third? A prospective long-term MRI study. *Am J Sports Med* 32:36, 2004.).

during athletic activities.⁵⁹ The ultimate load-to-failure for a centrally harvested 10 mm PT graft has been measured as high as 2,977 N.²⁰

The fate of the defect left by harvesting the central portion of the PT has been an area of active investigation, particularly in the Scandinavian literature.^{42,45,76} Multiple long-term follow up studies using magnetic resonance imaging and ultrasound modalities indicate that even 6 to 10 years after harvest, though completely healed, the central area of the PT remains abnormal (Fig. 7).^{42,76} Histology of replacement tissue also differs significantly from normal PT in terms of cellularity and vascularity as far out as 2 years after harvest.⁴⁵ These morphologic abnormalities appear to be independent of whether the tendon defect was closed. What has been significantly correlated with closure of the harvest defect, however, is shortening of the PT, *patella infera*, and patellofemoral arthrosis.⁴¹

In addition to altered radiographic appearance and histology, canine models suggest that as far out as 12 months after harvesting the central portion of the PT, structural and material properties of the replacement tissue are significantly inferior to those of normal tendon tissue.^{14,50} These findings, along with those from the Scandinavian literature make it difficult to recommend reharvest of the central portion of the PT as a viable option in ACL reconstruction.

BIOLOGY OF GRAFTORPORATION

Healing of any ACL reconstruction must be considered along both the intraarticular and extraarticular portions of the graft. The intraarticular portion of the graft undergoes a process of donor cell necrosis, infiltration by local cell population and a series of morphologic, histologic, and vascular changes collectively termed "ligamentization."¹ Through this process the donor tissue gradually acquires structural and material properties similar to those of the native ACL, a process that may take up to 3 years in humans.^{1,69}

Ligamentization

The timeline for ligamentization to occur has been investigated extensively in a variety of animal models, but not been well-delineated in humans.^{12,15,19,40,47,57,79} Studies in humans are limited primarily to uncontrolled, observational designs.^{22,37,38,43,69,70} Nevertheless, in the absence of more rigorous data, the findings from these observational studies can provide a framework within which to consider the evolution of the graft tissue after transplantation. Rougraff and colleagues observed a 4-stage ligamentization process for human BPTB autografts.⁶⁹ This 4-stage process comprises an early "repopulation" stage that lasts until 2 months postreconstruction, a "rapid remodeling" stage from 2 until 10 months, a "maturation" stage from approximately 1 to 3 years and finally, a "quiescent" stage.

Stage I: Repopulation (0–2 months)

According to Rougraff's conceptual framework, ligamentization begins with repopulation days to weeks after reconstruction as intrinsic graft fibroblasts die and are replaced via migration of local fibroblasts into the transplanted tissue.^{48,69} In small animal models this process has been observed to be complete as early as 4 weeks postreconstruction.⁴⁸ Repopulation of the transplanted graft tissue with local fibroblasts results in hypercellularity of the graft during this stage, with a nuclear morphology that is predominantly spindle or ovoid in shape, representative of a relatively high cellular meta-

bolic state. The collagen ultrastructure of the native graft remains preserved early in this stage, but a process of replacement with immature collagen secreted by immigrant fibroblasts is soon initiated. Neovascularization of the graft also commences in this stage, with surface and intrasubstance proliferation of vessels likely arising from pseudoligamentum mucosum (synovium) and infrapatellar fat pad (Fig. 8).^{5,22}

Stage II: Rapid Remodeling (2–10 months)

A period of increasing cellularity, increasing immature collagen content and surface hypervascularity of periligamentous tissue follows, during which the graft undergoes significant remodeling.^{22,69,75} Coincident with these morphologic and histologic change that occur within the intraarticular portion of the graft (particularly during the remodeling phase) are significant changes in the structural and material properties of the graft.

Regardless of graft selection, a precipitous drop in biomechanical properties occurs soon after transplantation, followed by a slow return toward (but likely never reaching) baseline values.^{15,19} During this remodeling phase the graft is likely most susceptible to elongation in response to exogenous strain. The precise behavior of the load-elongation curve for grafts during the remodeling phase is unknown, but based on clinically observed graft elongation as measured by KT-1000 arthrometer, the slope of the curve can be assumed to diminish significantly. Periodic monitoring of graft stiffness with KT-1000 arthrometer measurements may be valuable during this stage of graft evolution.

Material properties, however, are not the only consideration when it comes to the risk of graft elongation. The distance separating the fixation points of the graft, ie, the functional length of the graft, also weighs into this risk. Assuming identical biomechanical environments after reconstruction, as well as identical graft material properties, a graft with a greater functional length at time zero (t_0) will experience greater elongation. For example, graft 1 with a t_0 length of L and strain of ϵ will experience one-half the elongation than graft 2 with a t_0 length of $2L$ and the same strain ϵ :

$$\begin{aligned} \epsilon &= \Delta L/L \rightarrow \Delta L = L\epsilon \\ &\text{versus} \\ \epsilon &= \Delta L/2L \rightarrow \Delta L = 2L\epsilon \end{aligned}$$

In practical terms, these concerns may become important when considering a soft tissue graft with fixation points distant to the joint line versus a BPTB construct with aperture femoral-sided fixation and tibial-sided fixation that approaches aperture in nature. The soft tissue graft in this hypothetical situation presents a greater

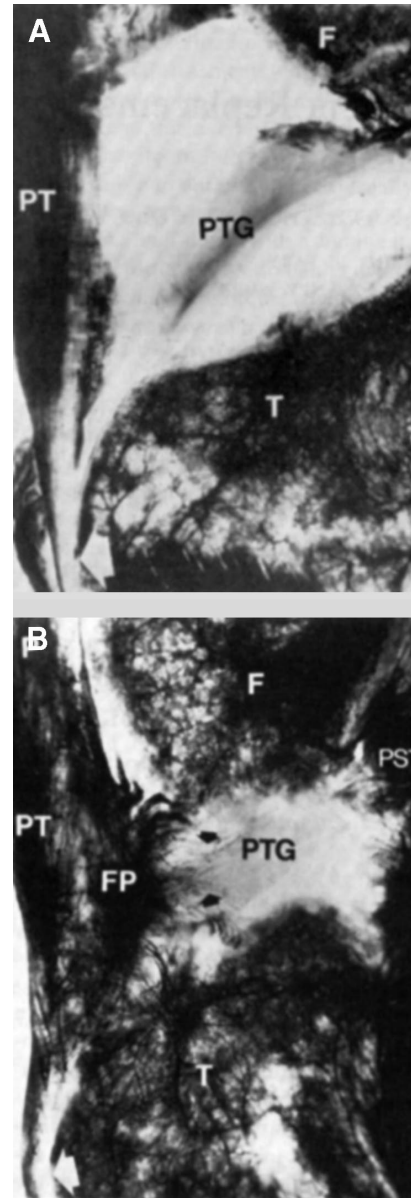


FIG. 8. (A) A 5-mm-thick sagittal section of a canine knee cleared by the Spalteholz technique, 2 weeks after replacement with a patellar tendon graft. The graft (PTG) shows no evidence of perfused vessels. Note the absence of vessels crossing the tibial attachment of the graft (arrow). (The infrapatellar fat pad and posterior cruciate ligament were removed after clearing to permit better visualization.) F = femur, T = tibia, and PT = patellar tendon. (B) A 5-mm-thick sagittal section of a dog's knee 6 weeks after replacement of the anterior cruciate ligament with a patellar tendon graft (PTG). Note the vascular response of the infrapatellar fat pad (FP) and posterior soft tissues (PST). Vessels from the fat pad can be seen extending over the surface of the patellar tendon graft (arrows) and are part of the vascular synovial envelope. Note that the tibial attachments of the graft (white arrows) do not contribute to any vessels to the graft. F = femur, T = tibia, PT = patellar tendon, and P = patella (Reprinted, with permission, from: Arnoczky SP, Tarvin GB, Marshall JL. Anterior cruciate ligament replacement using patellar tendon: an evaluation of graft revascularization in the dog. *J Bone Joint Surg* 64-A:217–224, 1982.).

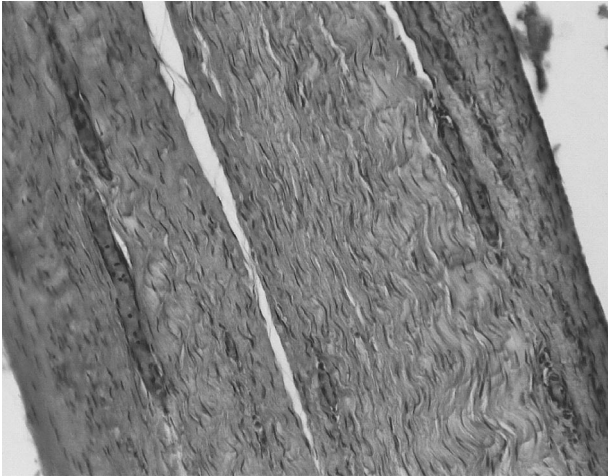


FIG. 9. Photomicrograph of patellar tendon autograft 18 months after anterior cruciate reconstruction. Histology demonstrates mature collagen and fibroblast nuclear morphology. Intrasubstance vascularity is noted (hematoxylin and eosin, $\times 200$). (Reprinted, with permission, from: Delay BS, McGrath BE, Mindell ER. Observations on a retrieved patellar tendon autograft used to reconstruct the anterior cruciate ligament: a case report. *J Bone Joint Surg* 84-A:1436, 2002.)

functional length, possibly making it vulnerable to greater elongation than the BPTB graft.

Stage III: Maturation (10–36 months)

At approximately 12 months postreconstruction, the graft enters a maturation phase, during which the cellularity and metabolic activity of the graft decreases, the collagen structure continues to mature and the vascularity of the graft (at least as measured at the graft surface) drops to values near those typical of normal, control ACLs (Fig. 9).^{22,69,75} Furthermore, improvements in the biomechanical properties of the graft may also occur during this period.

There is evidence that graft maturation occurs at a slower rate in allograft tissue than in autograft tissue, with potential implications for activity progression during postoperative rehabilitation.^{37,40} Additional considerations with potentially deleterious implications for the biomechanical performance of currently available allografts include the age of the donor and use of irradiation for graft sterilization. Even small amounts of irradiation can result in significant weakening of allograft tissue.^{32,67}

Stage IV: Quiescent

Eventually the graft is thought to enter a quiescent phase during which cellularity and collagen structure approach that of baseline ACL levels. The time necessary to reach this stage likely varies somewhat from

patient to patient and from graft type to graft type, but may take up to 3 years.⁶⁹

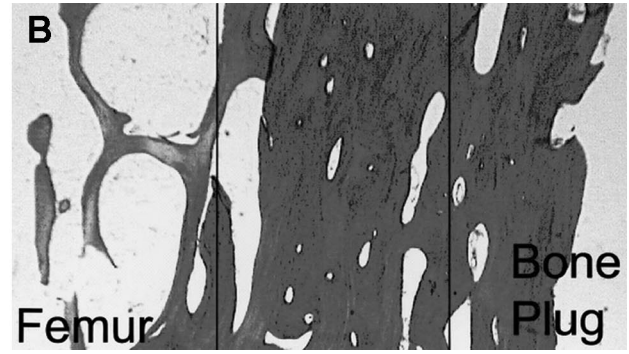
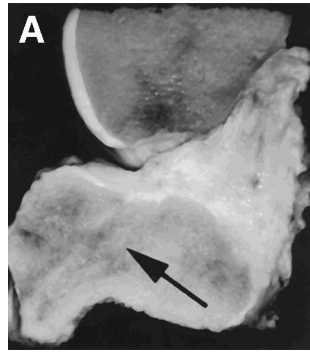
Graft Fixation and Tunnel Incorporation

At time zero after anterior cruciate ligament reconstruction, the proximal and distal fixation points represent the weakest element of the construct. Interference screws are the most commonly used means of obtaining initial rigid fixation of BPTB grafts. Biomechanical studies in human cadaveric specimens have reported initial pull-out strengths of BPTB grafts fixed with metallic interference screws to range from 362 N to 640 N, though the donor age for the specimens tested in these studies was much higher than that of the average patient undergoing ACLR, and these values may therefore underestimate the true fixation strength provided by interference screws.^{13,17,64} Considering the highest of these values, the pull-out strength of the graft at time zero would be only 30% of the load-to-failure of the native ACL, and 27% of the load-to-failure of the tendinous portion of a 10 mm BPTB graft. In addition to bone quality, the geometry of interference screw-bone block contact is another factor affecting initial holding strength. Interference screws should be placed parallel to bone blocks to provide optimal fixation strength. As little as 15 degree divergence can reduce initial fixation strength by as much as 50%.⁶⁵ Additionally, distal interference screw head engagement of the tibial cortex may provide superior fixation strength to cancellous purchase alone.³⁶ With respect to ACL reconstruction using BPTB autograft, interference screw fixation does not vary significantly with screw length, diameter or material (metallic versus bioabsorbable).^{13,44,56,64}

The incorporation of graft bone-plugs into host tunnels occurs through appositional bone formation (Fig. 10).^{39,79} This process has been observed to be complete (with no discernable interface identifiable by light microscopy) as early as 12 weeks postreconstruction in a canine model.⁷⁹ Intrasubstance, traumatic rupture of autogenous hamstring grafts secured with interference screw fixation has been reported as early as 6 weeks postreconstruction, suggesting that significant soft tissue incorporation occurs at a relatively rapid rate.⁶⁶ Though incorporation of bone plugs into tunnels is likely more rapid than incorporation of soft-tissue grafts, perhaps occurring at between 4 and 6 weeks, the precise time-course of tunnel incorporation in humans has not been described.

Incorporation of patellar tendon into surrounding bone tunnel is likely of secondary structural concern. Observational studies comprising specimens retrieved from patients undergoing revision ACLR demonstrate an “in-

FIG. 10. (A) Gross morphology of BPTB autograft bone plug incorporation 18 months after reconstruction. (B) Low power histology of same specimen demonstrating seamless incorporation of graft bone plugs into surrounding bone. (Reprinted, with permission, from: Delay BS, McGrath BE, Mindell ER. Observations on a retrieved patellar tendon autograft used to reconstruct the anterior cruciate ligament: a case report. *J Bone Joint Surg* 84-A: 1435, 1437, 2002.)



direct” type of tendon-to-bone attachment consisting of Sharpey-like collagen fibers perpendicular to the orientation of the graft fibers anchoring to adjacent bone.^{39,79}

Use of Biologics

During the process of ligamentization, manipulation of the load-elongation curve would theoretically facilitate safe, accelerated rehabilitation after reconstruction. Such manipulation may be possible using a variety of growth factors, as demonstrated in recent rabbit and canine models.^{6,78}

Yasuda and colleagues investigated the effects of transforming growth factor- β and epidermal growth factor on the histologic and biomechanical properties of bone-patellar tendon-bone autografts in a canine model.⁷⁸ Animals were killed at 12 weeks postreconstruction and grafts taken from the treatment group demonstrated significantly greater stiffness and load-to-failure than those taken from the sham group. Additionally, the histology of the growth factor-treated grafts—though different from that of the normal ACL—demonstrated less cellularity, more regular crimp pattern and more linear fibril orientation than grafts in the sham group, indicative of an accelerated maturation process.

The use of growth factors to accelerate graft incorporation into bone tunnels is also under investigation.^{3,54,68} Rodeo and colleagues reported trends but no significant difference in the pull-out strength between treatment (bone morphogenic protein-2) and control groups with respect to soft-tissue graft healing to a bone tunnel at 4 and 8 weeks postimplantation.⁶⁸ Anderson and colleagues used a heterogeneous mix of growth factors in a rabbit model and found a significant increase in the load-to-failure of treated semitendinosus ACL reconstructions versus controls at 2, 4, and 8 weeks after reconstruction.³ These authors also observed occasional formation of a direct (4-layer) tendon interface rather than indirect (Sharpey fibers) interface in the treatment group. Martinek and colleagues transfected autogenous

semitendinosus grafts with the gene for bone morphogenic protein-2 and used the construct for ACL reconstruction in a rabbit model.⁵⁴ Both graft stiffness and load-to-failure were significantly increased in the treatment group versus the control group at 8 weeks postreconstruction. Though evidence is increasing to support the use of biologics to accelerate both ligamentization and graft incorporation, further study is needed before introducing their use in clinical practice.

CONCLUSION

There are many graft choices available for reconstruction of the anterior cruciate ligament. The BPTB autograft harvested from the central portion of the patellar tendon is well-suited for ACL reconstruction from anatomic, biologic, and biomechanical perspectives. The timeline and biomechanical implications of graft ligamentization represent the rate-limiting step in advancing activity postreconstruction, but lack of precise knowledge of this timeline in humans makes strict correlation between rehabilitation protocols and graft healing problematic. Nevertheless, the use of biologics holds promise for acceleration of graft healing and more rapid return to unrestricted activity.

REFERENCES

1. Amiel D, Kleiner JB, Roux RD, Harwood FL, Akeson WH. The phenomenon of “ligamentization”: anterior cruciate ligament reconstruction with autogenous patellar tendon. *J Orthop Res* 1986; 4:162–172.
2. Andersen RB, Gormsen J. Fibrin dissolution in synovial fluid. *Acta Rheumatol Scand* 1970;16:319–333.
3. Anderson K, Seneviratne AM, Izawa K, Atkinson BL, Potter HG, Rodeo SA. Augmentation of tendon healing in an intraarticular bone tunnel with use of a bone growth factor. *Am J Sports Med* 2001;29:689–698.
4. Amoczky SP. Anatomy of the anterior cruciate ligament. *Clin Orthop Relat Res* 1983(172):19–25.
5. Amoczky SP, Tarvin GB, Marshall JL. Anterior cruciate ligament

- replacement using patellar tendon. An evaluation of graft revascularization in the dog. *J Bone Joint Surg Am* 1982;64:217–224.
6. Azuma H, Yasuda K, Tohyama H, et al. Timing of administration of transforming growth factor-beta and epidermal growth factor influences the effect on material properties of the in situ frozen-thawed anterior cruciate ligament. *J Biomech* 2003;36:373–381.
 7. Baek GH, Carlin GJ, Vogrin TM, Woo SL, Harner CD. Quantitative analysis of collagen fibrils of human cruciate and meniscofemoral ligaments. *Clin Orthop Relat Res* 1998(357):205–211.
 8. Basso O, Johnson DP, Amis AA. The anatomy of the patellar tendon. *Knee Surg Sports Traumatol Arthrosc* 2001;9:2–5.
 9. Beynnon B, Howe JG, Pope MH, Johnson RJ, Fleming BC. The measurement of anterior cruciate ligament strain in vivo. *Int Orthop* 1992;16:1–12.
 10. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med* 1995;23:24–34.
 11. Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension. A comparison of an open and a closed kinetic chain exercise. *Am J Sports Med* 197;25:823–829.
 12. Blickenstaff KR, Grana WA, Egle D. Analysis of a semitendinosus autograft in a rabbit model. *Am J Sports Med* 1997;25:554–559.
 13. Brown CH, Jr, Hecker AT, Hipp JA, Myers ER, Hayes WC. The biomechanics of interference screw fixation of patellar tendon anterior cruciate ligament grafts. *Am J Sports Med* 1993;21:880–886.
 14. Burks RT, Haut RC, Lancaster RL. Biomechanical and histological observations of the dog patellar tendon after removal of its central one-third. *Am J Sports Med* 1990;18:146–153.
 15. Butler DL, Grood ES, Noyes FR, Olmstead ML, Hohn RB, Arnoczky SP, Siegel MG. Mechanical properties of primate vascularized vs. nonvascularized patellar tendon grafts; changes over time. *J Orthop Res* 1989;7:68–79.
 16. Butler DL, Guan Y, Kay MD, Cummings JF, Feder SM, Levy MS. Location-dependent variations in the material properties of the anterior cruciate ligament. *J Biomech* 1992;25:511–518.
 17. Caborn DN, Urban WP, Jr, Johnson DL, Nyland J, Pienkowski D. Biomechanical comparison between BioScrew and titanium alloy interference screws for bone-patellar tendon-bone graft fixation in anterior cruciate ligament reconstruction. *Arthroscopy* 1997;13:229–232.
 18. Chiroff RT. Experimental replacement of the anterior cruciate ligament. A histological and microradiographic study. *J Bone Joint Surg Am* 1975;57:1124–1127.
 19. Clancy WG, Jr, Narechania RG, Rosenberg TD, Gmeiner JG, Wisnefske DD, Lange TA. Anterior and posterior cruciate ligament reconstruction in rhesus monkeys. *J Bone Joint Surg Am* 1981;63:1270–1284.
 20. Cooper DE. Biomechanical properties of the central third patellar tendon graft: effect of rotation. *Knee Surg Sports Traumatol Arthrosc* 1998(suppl):S16–S19.
 21. Edwards TB, Guanche CA, Petrie SG, Thomas KA. In vitro comparison of elongation of the anterior cruciate ligament and single- and dual-tunnel anterior cruciate ligament reconstructions. *Orthopedics* 1999;22:577–584.
 22. Falconiero RP, DiStefano VJ, Cook TM. Revascularization and ligamentization of autogenous anterior cruciate ligament grafts in humans. *Arthroscopy* 1998;14:197–205.
 23. Fleming BC, Beynnon BD, Renstrom PA, et al. The strain behavior of the anterior cruciate ligament during stair climbing: an in vivo study. *Arthroscopy* 1999;15:185–191.
 24. Fleming BC, Beynnon BD, Renstrom PA, Peura GD, Nichols CE, Johnson RJ. The strain behavior of the anterior cruciate ligament during bicycling An in vivo study. *Am J Sports Med* 1998;26:109–118.
 25. Fleming BC, Ohlen G, Renstrom PA, Peura GD, Beynnon BD, Badger GJ. The effects of compressive load and knee joint torque on peak anterior cruciate ligament strains. *Am J Sports Med* 2003;31:701–707.
 26. Fleming BC, Renstrom PA, Beynnon BD, et al. The effect of weightbearing and external loading on anterior cruciate ligament strain. *J Biomech* 2001;34:163–1670.
 27. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res* 2001;19:1178–1184.
 28. Frank CB, Jackson, DW. The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am* 1997;79:1556–1176.
 29. Furman W, Marshall JL, Girgis FG. The anterior cruciate ligament. A functional analysis based on postmortem studies. *J Bone Joint Surg Am* 1976;58:179–185.
 30. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. *Clin Orthop Relat Res* 1975(106):216–231.
 31. Grana WA, Egle DM, Mahnken R, Goodhart CW. An analysis of autograft fixation after anterior cruciate ligament reconstruction in a rabbit model. *Am J Sports Med* 1994;22:344–351.
 32. Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am* 1981;63:1257–1269.
 33. Hamner DL, Brown CH, Jr, Steiner ME, Hecker AT, Hayes WC. Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. *J Bone Joint Surg Am* 1999;81:549–557.
 34. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL. Quantitative analysis of human cruciate ligament insertions. *Arthroscopy* 1999;15:741–749.
 35. Harrold AJ. The defect of blood coagulation in joints. *J Clin Pathol* 1961;14:305–308.
 36. Harvey AR, Thomas NP, Amis AA. The effect of screw length and position on fixation of four-stranded hamstring grafts for anterior cruciate ligament reconstruction. *Knee* 2003;10:97–102.
 37. Horstman JK, Ahmadu-Suka F, Norrdin RW. Anterior cruciate ligament fascia lata allograft reconstruction: progressive histologic changes toward maturity. *Arthroscopy* 1993;9:509–518.
 38. Howell SM, Knox KE, Farley TE, Taylor MA. Revascularization of a human anterior cruciate ligament graft during the first two years of implantation. *Am J Sports Med* 1995;23:42–49.
 39. Ishibashi Y, Toh S, Okamura Y, Sasaki T, Kusumi T. Graft incorporation within the tibial bone tunnel after anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft. *Am J Sports Med* 2001;29:473–479.
 40. Jackson DW, Grood ES, Goldstein JD, et al. A comparison of patellar tendon autograft and allograft used for anterior cruciate ligament reconstruction in the goat model. *Am J Sports Med* 1993;21:176–185.
 41. Jarvela T, Paakkala T, Kannus P, Jarvinen M. The incidence of patellofemoral osteoarthritis and associated findings 7 years after anterior cruciate ligament reconstruction with a bone-patellar tendon-bone autograft. *Am J Sports Med* 2001;29:18–24.
 42. Jarvela T, Paakkala T, Kannus P, Toivanen J, Jarvinen M. Ultrasonographic and power Doppler evaluation of the patellar tendon ten years after harvesting its central third for reconstruction of the anterior cruciate ligament: comparison of patients without or with anterior knee pain. *Am J Sports Med* 2004;32:39–46.
 43. Johnson LL. The outcome of a free autogenous semitendinosus tendon graft in human anterior cruciate reconstructive surgery: a histological study. *Arthroscopy* 1993;9:131–142.
 44. Johnson LL, vanDyk GE. Metal and biodegradable interference screws: comparison of failure strength. *Arthroscopy* 1996;12:452–456.
 45. Kartus J, Movin T, Papadogiannakis N, Christensen LR, Lindahl S, Karlsson J. A radiographic and histologic evaluation of the patellar

- tendon after harvesting its central third. *Am J Sports Med* 2000; 28:218–226.
46. Kennedy JC, Alexander IJ, Hayes KC. Nerve supply of the human knee and its functional importance. *Am J Sports Med* 1982;10: 329–335.
 47. Kleiner JB, Amiel D, Harwood FL, Akeson WH. Early histologic, metabolic, and vascular assessment of anterior cruciate ligament autografts. *J Orthop Res* 1989;7:235–242.
 48. Kleiner JB, Amiel D, Roux RD, Akeson WH. Origin of replacement cells for the anterior cruciate ligament autograft. *J Orthop Res* 1986;4:466–474.
 49. Kurosaka M, Yoshiya S, Mizuno T, Mizuno K. Spontaneous healing of a tear of the anterior cruciate ligament. A report of two cases. *J Bone Joint Surg Am* 1998;80:1200–1203.
 50. LaPrade RF, Hamilton CD, Montgomery RD, Wentorf F, Hawkins HD. The reharvested central third of the patellar tendon A histologic and biomechanical analysis. *Am J Sports Med* 1997;25:779–785.
 51. Li G, DeFrate LE, Sun H, Gill TJ. In vivo elongation of the anterior cruciate ligament and posterior cruciate ligament during knee flexion. *Am J Sports Med* 2004;32:1415–1420.
 52. Liu SH, al-Shaikh R, Panossian V, et al. Primary immunolocalization of estrogen and progesterone target cells in the human anterior cruciate ligament. *J Orthop Res* 1996;14:526–533.
 53. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slaughterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res* 1995;13:930–935.
 54. Martinek V, Latterman C, Usas A, et al. Enhancement of tendon-bone integration of anterior cruciate ligament grafts with bone morphogenetic protein-2 gene transfer: a histological and biomechanical study. *J Bone Joint Surg Am* 2002;84-A: 1123–1131.
 55. Matava M. Patellar tendon ruptures. *J Am Acad Orthop Surg* 1996;4:287–296.
 56. Matthews LS, Parks BG, Sabbagh RC. Determination of fixation strength of large-diameter interference screws. *Arthroscopy* 1998; 14:70–74.
 57. McFarland EG, Morrey BF, An KN, Wood MB. The relationship of vascularity and water content to tensile strength in a patellar tendon replacement of the anterior cruciate in dogs. *Am J Sports Med* 1986;14:436–448.
 58. Murray MM, Martin SD, Martin TL, Spector M. Histological changes in the human anterior cruciate ligament after rupture. *J Bone Joint Surg Am* 2000;82-A: 1387–1397.
 59. Nordin M, Frankel V. Biomechanics of the knee. In: Nordin M, Frankel V, eds. *Basic Biomechanics of the Musculoskeletal System*. Philadelphia: Lea & Febiger; 1989:115–134.
 60. Noyes, F. R.: Functional properties of knee ligaments and alterations induced by immobilization: a correlative biomechanical and histological study in primates. *Clin Orthop Relat Res* 1977(123): 210–242.
 61. Noyes FR, DeLucas JL, Torvik PJ. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am* 1974; 56:236–253.
 62. Noyes FR, Grood ES. The strength of the anterior cruciate ligament in humans and Rhesus monkeys. *J Bone Joint Surg Am* 1976;58:1074–1082.
 63. Noyes FR, McGinniss GH, Mooar LA. Functional disability in the anterior cruciate insufficient knee syndrome. Review of knee rating systems and projected risk factors in determining treatment. *Sports Med* 1984;1:278–302.
 64. Pena F, Grontvedt T, Brown GA, Aune AK, Engebretsen L. Comparison of failure strength between metallic and absorbable interference screws. Influence of insertion torque, tunnel-bone block gap, bone mineral density, and interference. *Am J Sports Med* 1996;24:329–334.
 65. Pierz K, Baltz M, Fulkerson J. The effect of Kurosaka screw divergence on the holding strength of bone-tendon-bone grafts. *Am J Sports Med* 1995;23:332–335.
 66. Pinczewski LA, Clingeleffer AJ, Otto DD, Bonar SF, Corry IS. Integration of hamstring tendon graft with bone in reconstruction of the anterior cruciate ligament. *Arthroscopy* 1997;13:641–643.
 67. Rasmussen TJ, Feder SM, Butler DL, Noyes FR. The effects of 4 Mrad of gamma irradiation on the initial mechanical properties of bone-patellar tendon-bone grafts. *Arthroscopy* 1994;10:188–197.
 68. Rodeo SA, Suzuki K, Deng XH, Wozney J, Warren RF. Use of recombinant human bone morphogenetic protein-2 to enhance tendon healing in a bone tunnel. *Am J Sports Med* 1999;27:476–488.
 69. Rougraff B, Shelbourne KD, Gerth PK, Warner J. Arthroscopic and histologic analysis of human patellar tendon autografts used for anterior cruciate ligament reconstruction. *Am J Sports Med* 1993;21:277–284.
 70. Rougraff BT, Shelbourne KD. Early histologic appearance of human patellar tendon autografts used for anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 1999; 7:9–14.
 71. Samuelson TS, Drez D, Jr, Maletis GB. Anterior cruciate ligament graft rotation Reproduction of normal graft rotation. *Am J Sports Med* 1996;24:67–71.
 72. Scapinelli R. Studies on the vasculature of the human knee joint. *Acta Anat* 1968;70:305–331.
 73. Schatzmann L, Brunner P, Staubli HU. Effect of cyclic preconditioning on the tensile properties of human quadriceps tendons and patellar ligaments. *Knee Surg Sports Traumatol Arthrosc* 1998(suppl):S56–S61.
 74. Schultz RA, Miller DC, Kerr CS, Micheli L. Mechanoreceptors in human cruciate ligaments. A histological study. *J Bone Joint Surg Am* 1984;66:1072–1076.
 75. Shino K, Kawasaki T, Hirose H, Gotoh I, Inoue M, Ono K. Replacement of the anterior cruciate ligament by an allogeneic tendon graft. An experimental study in the dog. *J Bone Joint Surg Br* 1984;66:672–681.
 76. Svensson M, Kartus J, Ejerhed L, Lindahl S, Karlsson J. Does the patellar tendon normalize after harvesting its central third? A prospective long-term MRI study. *Am J Sports Med* 2004;32:34–38.
 77. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med* 1991;19:217–225.
 78. Yasuda K, Tomita F, Yamazaki S, Minami A, Tohyama H. The effect of growth factors on biomechanical properties of the bone-patellar tendon-bone graft after anterior cruciate ligament reconstruction: a canine model study. *Am J Sports Med* 2004;32:870–880.
 79. Yoshiya S, Nagano M, Kurosaka M, Muratsu H, Mizuno K. Graft healing in the bone tunnel in anterior cruciate ligament reconstruction. *Clin Orthop Relat Res* 2000(376):278–286.