

The Reharvested Central Third of the Patellar Tendon

A Histologic and Biomechanical Analysis*

Robert F. LaPrade,†‡ MD, Christopher D. Hamilton,† MD,
Ronald D. Montgomery,§ DVM, MS, Fred Wentorf,† MS, and Hal D. Hawkins,† MD, PhD

From the †Department of Orthopaedic Surgery, University of Texas Medical Branch, Galveston, Texas, and the §College of Veterinary Medicine, Auburn University, Auburn, Alabama

ABSTRACT

We assessed the histologic, mechanical, and structural properties of the reharvested central-third patellar tendon in greyhounds. Twelve dogs had the central third of the patellar tendon (5 mm) removed with corresponding bone blocks from the patella and tibia; the remaining tendon defect was loosely closed. Six dogs were sacrificed at 6 months and six at 12 months, and the central third of the patellar tendon was harvested from both the operative and the contralateral control knees. Analysis of the structural changes in the tendons revealed a significant increase in thickness for reharvested tendons at both 6 and 12 months when compared with controls. The entire residual tendons were narrower at 6 months and were shorter at 12 months compared with controls. Mechanical testing showed that the average failure load, ultimate tensile strength, strain at failure, and average modulus for the reharvested central third of the patellar tendon were significantly less than that of controls at both 6 and 12 months. Analysis of collagen fiber size by electron microscopy revealed a significant increase in collagen fiber diameter at 6 months (135 ± 41 nm versus 49 ± 4 nm) but no difference between the operative limbs and controls at 12 months. The reharvested bone-patellar tendon-bone complex does not have the same properties as the primary patellar tendon graft up to 1 year after harvest in a canine model, and its use for

revision cruciate ligament reconstruction must be carefully reexamined.

Reconstruction of the ACL for knee instability is one of the most common adult reconstructive procedures performed, with a current estimate of 50,000 cases per year in the United States.¹² Reconstructions are frequently performed on adolescents and young adults who place high functional demands on the reconstructed knee. As the number of ACL reconstructions has risen, so has the number of postreconstruction failures. Current estimates of the number of ACL reconstruction failures range from 0.7% to 8% of all primary ACL reconstructions.^{9,10,27,28} Because of the increasing number of failures, as well as patients' high functional expectations, the number of patients undergoing revision ACL reconstruction has increased.

When a decision is made to perform an ACL reconstruction, much consideration must be given to the type of graft selected to replace the ACL. Graft harvesting techniques, tunnel fixation, graft incorporation, the potential for disease transmission, the structural and biomechanical properties of the graft, and the results of clinical studies using various graft sources must all be assessed in the decision-making process for graft selection.^{7,9-11,13,21,22,24,25,27,28} In light of these myriad graft selection problems in a revision ACL reconstruction, it has been proposed that a reharvest of the ipsilateral central third of the patellar tendon be used as a graft source,^{12,14} and one clinical case has been reported.¹⁴

To our knowledge, no studies have been performed to assess the histologic and biomechanical properties of this tissue to help determine its adequacy as a graft source. We undertook this study to determine whether the reharvested central third of the patellar tendon is a viable graft

* Presented at the Second World Congress on Sports Trauma/22nd annual meeting of the AOSSM, Orlando, Florida, June 1996.

‡ Address correspondence and reprint requests to Robert F. LaPrade, MD, Department of Orthopaedic Surgery, University of Minnesota, Box 492 UMHC, 420 Delaware St. SE., Minneapolis, MN 55455.

No author or related institution has received any financial benefit from research in this study.

source for revision cruciate ligament reconstruction. We used a canine model to assess the histologic, mechanical, and structural properties of the reharvested central third of the patellar tendon.

MATERIALS AND METHODS

Twelve adult greyhounds, aged 2 to 4 years, were used for this study because greyhounds are noted for their size uniformity. The dogs had normal physical examinations and normal orthopaedic examinations of the stifle joint (knee), normal radiographs (AP and lateral views), and no abnormalities on histologic screens, serum chemistry analysis, urinalysis, or serum titers for *Ehrlichia canis* and *Ehrlichia platys*. The dogs were acclimated to the kennel for a minimum of 2 weeks, vaccinated with DA 2 PLP-CPV, and given anthelmintics as indicated by fecal flotation.

The dogs underwent general anesthesia with thiopental sodium and anesthesia was maintained with halothane gas via an endotracheal tube. Prophylactic antibiotics (500 mg cefazolin) were given to all animals. The limb to be operated on was randomly selected, and the contralateral limb served as a control in all animals. The operative limb was aseptically prepared for knee surgery. No tourniquet was used.

An approximately 8-cm incision was made just lateral to the joint midline. Using sharp dissection, the surgeon split the paratenon layer longitudinally over the patellar tendon and carefully elevated the layer medially and laterally (Fig. 1A). Measurements of the length and width of the patellar tendon were taken in situ with a caliper. The central third of the patellar tendon (5 mm width) was then harvested sharply. Care was taken not to lacerate the retropatellar fat pad, and minimal manipulation of the fat pad and tendon was performed. An oscillating saw was used to obtain 5-mm wide by 1-cm long bone blocks from

the patella and tibial tubercle (Fig. 1B). Electrocautery was used for hemostasis to control the bleeding routinely encountered when the superior aspect of the tendon graft is sharply dissected from the fat pad.

Measurements of the length (measured from the inferior pole of the patella to the proximal aspect of the anterior tibial tubercle) and width (medial to lateral distance) of the tendon graft were repeated, and the thickness (measured in the anterior to posterior plane) of the patellar tendon was recorded. Width and thickness measurements were obtained at three consistent sites along the length of the specimen and averaged. The patellar tendon defect was then loosely closed with three interrupted 3-0 nonabsorbable monofilament sutures (Fig. 1C). The paratenon layer was also closed with four interrupted 3-0 nonabsorbable sutures. The skin was approximated with a 2-0 nonabsorbable monofilament running suture.

After surgery, the dogs were monitored daily for pain, infection, anorexia, or other signs of disease or distress. The sutures were removed 10 days after surgery. Beginning 1 month after surgery, the dogs were exercised for 2.5 km on a motorized carousel 3 days a week until the end of the study. They were also allowed unrestricted activity in their pens.

Six dogs were sacrificed 6 months after surgery and the remaining six dogs were sacrificed 12 months after surgery with an overdose of euthanasia solution (Beuthanasia, Schering-Plough, Kenilworth, New Jersey). Anteroposterior and lateral radiographs of the knees were obtained at the time of death. Both the control and operative central-third patellar tendons were harvested by carefully removing the remaining medial and lateral thirds of the patellar tendon from the patella and tibial tuberosity. The only fibers on both the patellar and tibial tubercle attachment sites that were left intact were those in line with the fibers of the central third of the patella tendon. The cross-sectional area, width, and length of the

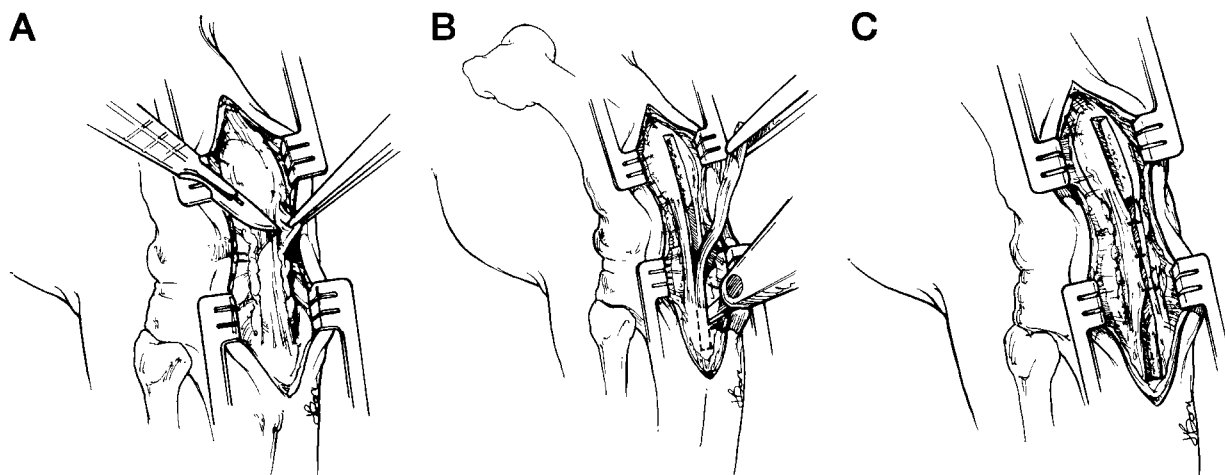


Figure 1. Technique for harvesting the central third patellar tendon. A, careful dissection of the paratenon layer to reveal margins of tendon. B, the central third of the patellar tendon was harvested with a knife and bone blocks were obtained from the patella and tibial tubercle with an oscillating saw. C, loose approximation of the remaining tendon with three 3-0 nylon sutures was performed.

patellar tendon graft were measured and recorded at the time of operation and at the time of death. The collected samples were kept moist in phosphate-buffered saline solution and stored at -40°C until biomechanical testing. Tendon biopsies were also obtained for both hematoxylin and eosin staining and electron microscopic evaluation.

Biomechanical testing was performed on an MTS servo-hydraulic test system (MTS Systems Corp., Eden Prairie, Minnesota). The specimens were potted in methyl methacrylate and loaded on the MTS system. Care was taken to ensure that the methyl methacrylate did not contact the tendon. Calipers and an area digital micrometer were then used to determine the dimensions of the tendon (length, width, thickness). A 10-minute preload was applied with a 44-N longitudinal force to remove any collagen crimping. The patellar tendon was oriented vertically and stretched to failure in pure tension at a strain rate of 100 percent per second. The mode of failure was recorded for each specimen tested.

A statistical analysis was performed using the Student's *t*-test for paired observations for comparisons between the reharvested central third of the patellar tendon and the tendons from the control joints. One-way analysis of variance (ANOVA) was used to measure statistical differences between the reharvested tendon and the controls for each structural and material property.

RESULTS

On gross examination, minimal scarring of the anterior paratenon layer was noted. Careful sharp dissection of the paratenon layer anteriorly allowed for identification of the tendon margins. The retropatellar fat pad appeared to be normal in all knees, and only minimal scarring of the fat pad was noted. In all operative knees, there was an obvious increase in thickness of the patellar tendon that involved the entire width of the tendon (Fig. 2).



Figure 2. Gross appearance of the control (foreground) and operative (background) patellar tendons at 6 months. An obvious difference in thickness was observed.

Dimensions of the Entire Patellar Tendon

When 6-month specimens were compared with controls, there was no difference in length of the tendon, but the operated tendons were significantly narrower and thicker than the control tendons. Patellar tendon length for the 6-month control group averaged 42.8 ± 2.7 mm, and the length of the operative side averaged 42.5 ± 2.1 mm (no significant difference). The average width of the patellar tendons for controls in this group was 15.2 ± 0.9 mm, and the average width for the operative tendons was significantly less at 12.7 ± 0.6 mm ($P < 0.01$). Patellar tendon thickness for the 6-month control group was 2.3 ± 0.2 mm, and the average thickness for the operative tendons was significantly greater at 5.8 ± 1.4 mm ($P < 0.001$).

When 12-month specimens were compared with controls, the reharvested tendons were significantly thicker and shorter than the control tendons, but there were no significant differences in width. Control patellar tendons for the 12-month group averaged 43.3 ± 2.8 mm in length and the operative tendons averaged 39.2 ± 2.6 mm ($P = 0.05$). Patellar tendon width for the 12-month group averaged 14.6 ± 1.4 mm for controls and 14.4 ± 1.4 mm for the tendons of operative animals. The reharvested tendons were significantly thicker than control tendons in this group (4.7 ± 0.7 mm versus 2.2 ± 0.1 mm) ($P < 0.001$).

Histologic Evaluation

Histologic evaluation (hematoxylin and eosin staining) revealed that the reharvested tendons were more cellular than their contralateral controls at both 6 and 12 months. The hypercellularity was found to be greater at 12 months than at 6 months (Fig. 3). Evaluation with polarizing filters revealed that collagen fibers from both the reharvested and control tendons were aligned with the long axis of the tendon at both 6 and 12 months. No disorganization of the collagen background was noted at either time period.

Electron microscopic evaluation revealed a striking visual difference between reharvested and control samples at 6 months. Analysis of collagen fibril size at 6 months revealed a significant increase in average fibril size for the reharvested tendons compared with controls (135 ± 41 nm versus 49 ± 4 nm) ($P < 0.001$) (Fig. 4). There was no difference in collagen fibril size at 12 months for the operative limb compared with the controls. Collagen fibril packing was also analyzed on electron microscopy images. At 6 months, there was a significant decrease in collagen fibril packing for operative (763 fibrils/mm) compared with control tendons (1488 fibrils/mm) ($P < 0.01$). There was no significant difference in collagen fibril packing between operative (1259 fibrils/mm) and control tendons (1218 fibrils/mm) at 12 months.

Tensile Failure Mechanism

All specimens were elongated to complete failure of the patella-patellar tendon-tibial tubercle complex at a strain rate of 100 percent per second (Table 1). For control spec-

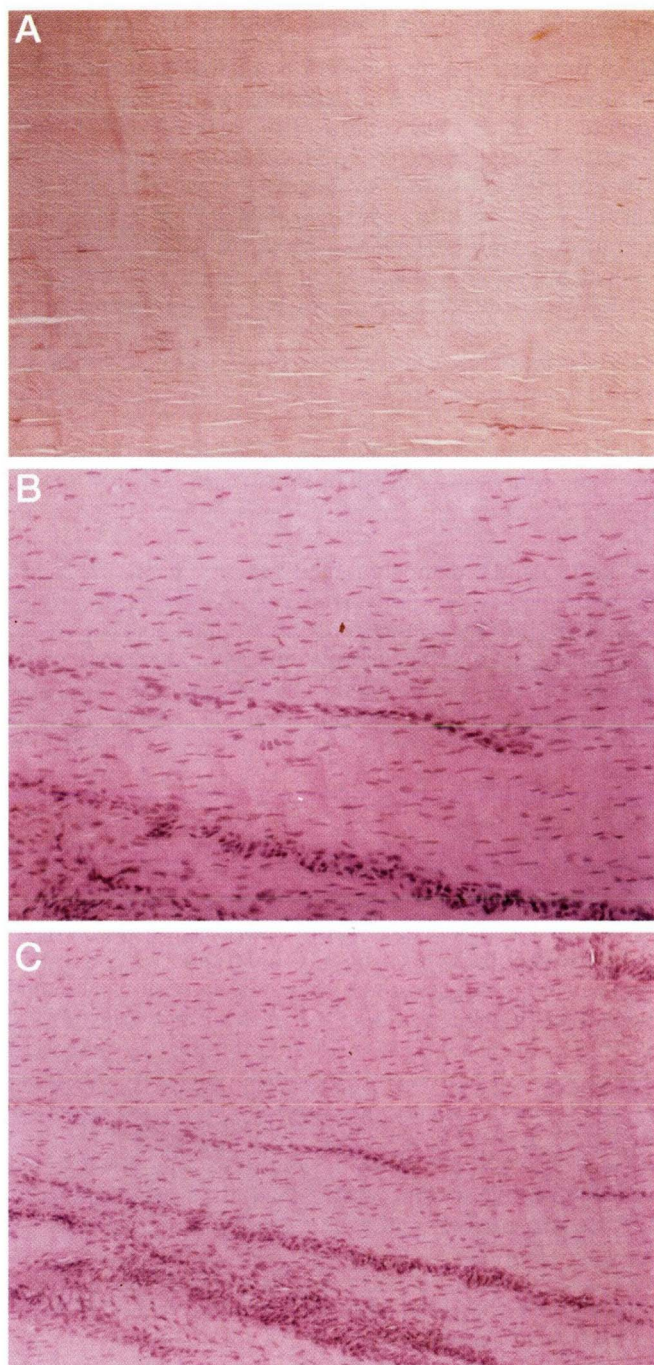


Figure 3. Histologic appearance of the patellar tendon. A, control tendon; B, 6-month operative tendon. C, 12-month operative tendon. An increase in cellularity is seen in the 12-month reharvested tendon compared with control and 6-month reharvested tendons. (Hematoxylin and eosin, original magnification, $\times 16$)

imens (6 and 12 months), the mechanism of failure was avulsion of bone from the distal pole of the patella in four specimens, midsubstance patellar tendon failures in six, and tibial bony avulsions in two, with no difference in failure mechanisms between the 6- and 12-month groups.

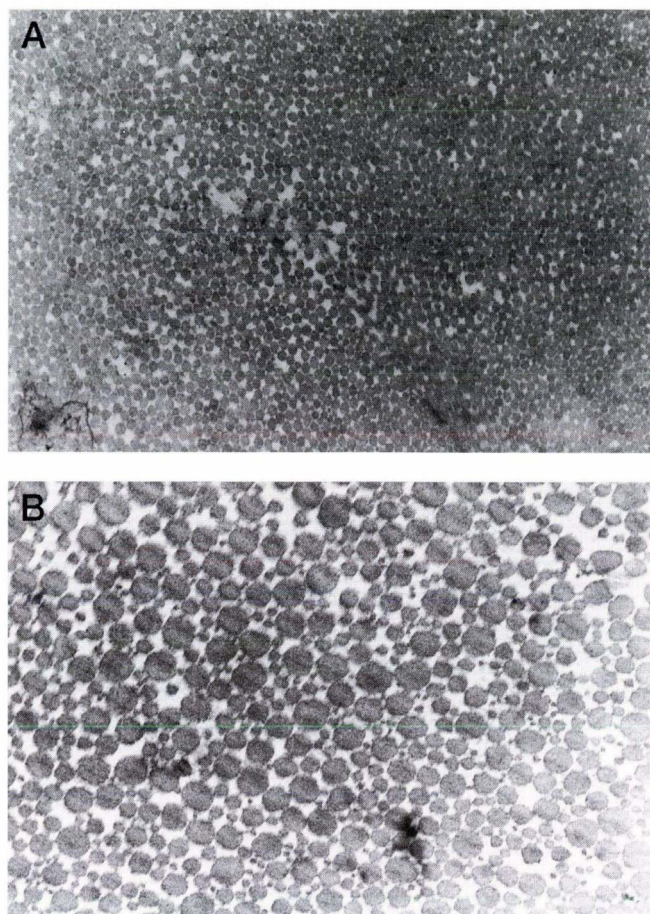


Figure 4. Electron microscopic appearance of the patellar tendons (original magnification, $\times 16,000$). A, control tendons; B, 6-month operative patellar tendon. A significant increase in collagen fibril size is seen in the 6-month reharvested tendon.

The modes of failure for the 6-month reharvested patellar tendons were avulsion from the patella in two knees and midsubstance tendon failures in four. In the 12-month reharvested tendons, there were five midsubstance failures and one avulsion from the patella.

Failure Properties of the Patellar Tendon Complex

The load and energy to failure for the reharvested patellar tendons at both 6 and 12 months were significantly less than that of controls (Table 1). The average load required to cause failure in the control groups was 1430 ± 290 N at 6 months and 1640 ± 470 N at 12 months. There was no significant difference between the two groups of controls. At 6 months after surgery, the reharvested patellar tendons' average load to failure was 53.1% of controls ($P < 0.02$), and at 12 months after surgery the reharvested tendons' average load to failure was 54.3% of controls ($P < 0.01$). The energy to failure for the control preparations was 10.1 ± 4.1 J at 6 months and 12.2 ± 4.1 J at 12 months. The energy required to cause failure for the re-

TABLE 1
Load-Deformation Properties of the Operated Specimens and Contralateral Controls

Time/Procedure	Failure load (kN)	Energy to failure (J)	Failure location
6 month/control	1430 \pm 290	10.0 \pm 4.1	2 midsubstance, 1 tibia, 3 patella
6 month/operated	760 \pm 470	2.7 \pm 1.2	4 midsubstance, 2 patella
12 month/control	1640 \pm 470	12.2 \pm 4.1	4 midsubstance, 1 patella, 1 tibia
12 month/operated	890 \pm 350	4.0 \pm 2.4	5 midsubstance, 1 patella

harvested patellar tendons was significantly decreased to 27.0% ($P < 0.03$) and 32.8% ($P < .0002$) compared with that of the respective control patellar tendons at 6 and 12 months postoperatively. There was no statistical difference in the average load to failure or the total energy required to cause failure between the 6- and 12-month reharvested tendons.

Stress-Strain Behavior of the Patellar Tendon Complex

The average strain to failure for contralateral control tendons at 6 months was $32.0\% \pm 4.0\%$, and the average strain to failure at 6 months for the reharvested patellar tendons was $17.9\% \pm 5.8\%$ ($P = 0.04$). At 12 months, the average percentage strain to failure for contralateral controls was $35.7\% \pm 7.6\%$, and there was a significantly less average strain to failure for the reharvested tendons ($22.2\% \pm 7.2\%$) ($P < 0.01$). The averaged stress-strain relationship for controls and the 6- and 12-month reharvested patellar tendons exhibited a nonlinear response, with an initial nonlinear region, a linear region with a constant modulus, and a short range of nonlinearly just before failure (Fig. 5). The stress-strain response for the control tendons revealed an average modulus of 173 ± 25 MPa at 6 months and 179 ± 61 MPa at 12 months. The average modulus for the reharvested patellar tendons was significantly less at both 6 months (83 ± 24 MPa) ($P < .0001$) and at 12 months (72 ± 31 MPa) ($P < .007$) compared with controls.

DISCUSSION

In this study, we sought to evaluate the suitability of the reharvested central third of the patellar tendon complex as a graft source for cruciate ligament reconstruction.

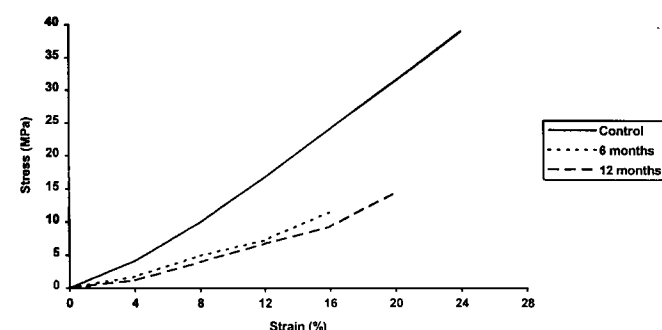


Figure 5. Stress-strain curve for the control and reharvested central-third patellar tendons at 6 and 12 months.

Although there are clinical reports of the use of this graft in patients, scant information is available to help the clinician make a rational decision regarding the ability of the reharvested central third of the patellar tendon to act as a cruciate substitute.^{6,8,17} Karns et al.¹⁴ presented a case report of a professional football player who underwent a repeat harvest of the central-third patellar tendon for a revision ACL reconstruction. No outcome information on the patient was presented as he was noted to be undergoing rehabilitation at the time of the case report. To our knowledge, there has been no previous study analyzing the biomechanical properties of the reharvested central-third bone-tendon-bone complex.

We found that the mechanical testing of 6- and 12-month specimens revealed a striking increase in the stiffness and decrease in the strain and load to failure of the regenerated central third of the patellar tendon. The properties of this regenerate are clearly different from those of the native central third of the patellar tendon, even up to 12 months after harvest in a canine model. This raises serious questions about the suitability of the regenerated central third of the patellar tendon as a cruciate graft source. In our study at 12 months the average failure load was 54% of controls for a tendon that had been minimally devascularized. It is not possible to compare the biomechanical results of our study with those of studies that have looked at the central third of the patellar tendon as a cruciate graft source because these studies have completely devascularized the tendon and transferred it intraarticularly.

In our study, we found the residual central third of the patellar tendon to be thickened for at least 12 months after harvest in a canine model. On gross observation it appeared that the entire residual patellar tendon was hypertrophied and involved in a scar-like process, but we found that, at least for the central third of the tendon, the thickening was initially (6 months) due, in part, to a significant increase of collagen fibril size in the patellar tendon. We theorize that the larger collagen fibrils form in response to the increased stress placed on the residual tendon or represent immature connective tissue. However, by 1 year after surgery, the collagen fibril size and packing of the reharvested patellar tendons resembled that of the contralateral controls.

When comparing the histologic findings with the biomechanical properties of the reharvested central-third bone-patellar tendon-bone complex at 6 and 12 months, we found that, despite an increase in the mass-average diameter of the collagen fibrils (as represented by the increased thickness [mass] and fibril diameter), the average failure

load, failure load per unit area, strain to failure, and modulus were decreased compared with those of controls. This finding is contrary to the reports of Parry et al.,²³ who postulated that the ultimate tensile strength (average failure load) of a tissue is proportional to the mass-average diameter of the collagen fibrils. This may be true for a mature connective tissue, but a reparative tissue likely has more heterogeneity, which may account for variations in mechanical properties. It is presumed that the collagen fibrils of the reharvested central third of the patellar tendon had a decreased average failure load because of a lack of maturation of the covalent crosslinks between fibrils,⁵ microscopic soft tissue "flaws,"²⁹ and other factors (unknown at this time) related to the maturation process.

Two previous studies that examined the strength of the residual patella-patellar tendon-tibial tubercle complex after harvesting of its central or medial third have demonstrated the weakest location in canines occurs at the patellar tendon-patella insertion.^{3,18} In both of these studies almost all patellar tendon complexes failed by bony avulsion. Animals in both studies were allowed cage activities only. Laros et al.¹⁶ reported that restricting the activity of dogs can have deleterious effects on the insertion sites of ligaments, raising a question about the validity of using a canine model that allows activity only in cages. Our study subjects were therefore exercised 2.5 km three times per week on a motorized carousel in addition to being allowed unrestricted cage activity. A review of our sites of failure revealed that 50% of the controls, 67% of the 6-month reharvested complexes, and 83% of the 12-month reharvested central-third patellar tendon complexes had midsubstance failures. It is unclear whether the increase in midsubstance patellar tendon failures seen in our study was due to the exercise regimen or the significant change in strength properties. It is possible that the bone-tendon interface regains strength more rapidly than the tendon itself. Further study is necessary to assess these factors on tendon failure mechanisms in study animals.

We elected to close the patellar tendon defect after harvest because it is our preferred method and the method used by most of our colleagues. There is support in the literature for this method for the purposes of this study. Coupens et al.⁴ found no statistical difference in the width of the donor patellar tendon at any time up to 18 months postoperatively compared with the ipsilateral patellar tendon when the defect was closed. Also, Meisterling et al.²⁰ found no difference in width measured on magnetic resonance imaging scans between the operative and non-operative patellar tendons at an average of 2.5 years postoperatively for a group of 15 patients who had their patellar tendon defects repaired at the time of ACL reconstruction.

Shaffer and Tibone²⁶ used radiographs to compare the patellar tendon length after closure with that in the non-operative limb and noted no difference in the two situations. Burks et al.³ found no differences in mechanical properties when comparing patellar tendon defects closed or left open in a canine model at 3 and 6 months after

surgery. There are advocates for leaving the patellar tendon defect open; some authors have reported that an apparently normal tendon regenerates in this region.¹ Although we did note a significant decrease in width at 6 months in the residual patellar tendon, by 12 months the residual patellar tendon widths were not statistically different from those of controls.

The 12-month results that were obtained in our study also bring into question the effects of a repeat harvest of the central third of the patellar tendon on the residual patellar tendon. The current technique of the initial harvest of the central third of the patellar tendon as a cruciate ligament graft has resulted in minimal apparent morbidity with few reports of rupture of the residual tendon.^{2,15} Matava and Hutton¹⁹ reported that the central third of the human patellar tendon is the thickest portion of the patellar tendon, and that it is biomechanically as strong as the residual two-thirds. Our study and those of others^{3,4,18,20} have shown that the residual patellar tendon hypertrophies to compensate for the loss of its central third. We have shown that at 1 year the structural and mechanical properties of the central third have not returned to normal. Repeat harvest of the central third of the patellar tendon has unknown effects on the residual tendon.

CONCLUSIONS

1. Biomechanical testing of structural and mechanical properties of the reharvested central third of the patellar tendon complex revealed significant alterations in these properties at both 6 and 12 months when compared with controls; the reharvested tendon is incapable of absorbing the same loads as the initial graft as late as 1 year postoperatively.

2. Histologic analysis of the reharvested central third of the patellar tendon revealed that collagen fibrils were hypercellular and oriented with the long axis of the tendon at both 6 and 12 months. Electron microscopy revealed a significant increase in the size of the collagen fibrils and a decrease in collagen fibril packing in reharvested tendons at 6 months compared with controls and no difference in the experimental tendons compared with controls at 12 months. Histologic maturation appears to be an ongoing process at 1 year postoperatively.

3. Significant thickening of the reharvested patellar tendon was seen at both 6 and 12 months when compared with controls.

4. Further long-term studies are necessary to assess the feasibility of reharvesting the central third of the patellar tendon for use as a cruciate ligament graft. We found evidence of an ongoing maturation process of the residual central third of the patellar tendon complex. Although there was evidence of the tendon having no significant ultrastructural changes at 1 year, it is apparent that any possible further improvements in biomechanical properties must take place over a longer time period. Until further studies with longer followup are performed, we recommend that alternative cruciate ligament graft sources be considered.

ACKNOWLEDGMENT

The authors acknowledge the assistance of David J. Simmons, PhD, University of Texas, Galveston, for his work in preparing and helping to analyze the histologic specimens.

REFERENCES

- Berg EE: Intrinsic healing of a patellar tendon donor site defect after anterior cruciate ligament reconstruction. *Clin Orthop* 278: 160–163, 1992
- Bonamo JJ, Krinick RM, Sporn AA: Rupture of the patellar ligament after use of its central third for anterior cruciate reconstruction. A report of two cases. *J Bone Joint Surg* 66A: 1294–1297, 1984
- Burks R, Hout RC, Lancaster RL: Biomechanical and histological observations of the dog patellar tendon after removal of its central one-third. *Am J Sports Med* 18: 146–153, 1990
- Couzens SD, Yates CK, Sheldon C, et al: Magnetic resonance imaging evaluation of the patellar tendon after use of its central one-third for anterior cruciate ligament reconstruction. *Am J Sports Med* 20: 332–335, 1992
- Frank C, McDonald D, Wilson J, et al: Rabbit medial collateral ligament scar weakness is associated with decreased collagen pyridinoline crosslink density. *J Orthop Res* 13: 157–165, 1995
- Fu FH: Editorial summary. *Arthroscopy* 10: 156–157, 1994
- Fulkerson JP, Langeland R: An alternate cruciate reconstruction graft: The central quadriceps tendon. *Arthroscopy* 11: 252–254, 1995
- Goble EM: Review of "Case Report: Revision anterior cruciate ligament reconstruction." *Arthroscopy* 10: 153–155, 1994
- Holmes PF, James SL, Larson RL, et al: Retrospective direct comparison of three intraarticular anterior cruciate ligament reconstructions. *Am J Sports Med* 19: 596–600, 1991
- Howe JG, Johnson RJ, Kaplan MJ, et al: Anterior cruciate ligament reconstruction using quadriceps patellar tendon graft. Part 1. Long-term followup. *Am J Sports Med* 19: 447–457, 1991
- Indelicato PA, Linton RC, Huegel M: The results of fresh-frozen patellar tendon allografts for chronic anterior cruciate ligament deficiency of the knee. *Am J Sports Med* 20: 118–121, 1992
- Johnson DL, Harner CD, Maday MG, et al: Revision anterior cruciate ligament surgery, in Fu FH, Harner CD, Vince KG (eds): *Knee Surgery*. Baltimore, Williams & Wilkins, 1994, pp 877–895
- Jones KG: Reconstruction of the anterior cruciate ligament. A technique using the central one-third of the patellar ligament. *J Bone Joint Surg* 45A: 925–932, 1963
- Karns DJ, Heidt RS Jr, Holladay BR, et al: Case report: Revision anterior cruciate ligament reconstruction. *Arthroscopy* 10: 148–151, 1994
- Langan P, Fontanetta AP: Rupture of the patellar tendon after use of its central third. *Orthop Rev* 16: 317–321, 1987
- Laros GS, Tipton CM, Cooper RR: Influence of physical activity on ligament insertions in the knees of dogs. *J Bone Joint Surg* 53A: 275–286, 1971
- Larson RV: Review of "Case report: Revision anterior cruciate ligament reconstruction." *Arthroscopy* 10: 152, 1984
- Linder LH, Sukin DL, Burks RT, et al: Biomechanical and histologic properties of the canine patellar tendon after removal of its medial third. *Am J Sports Med* 22: 136–142, 1994
- Matava MJ, Hutton WC: A biomechanical comparison between the central one-third patellar tendon and the residual tendon. *Br J Sports Med* 29: 178–184, 1995
- Meisterling RC, Wadsworth T, Ardill R, et al: Morphologic changes in the human patellar tendon after bone-tendon-bone anterior cruciate ligament reconstruction. *Clin Orthop* 289: 208–212, 1993
- Noyes FR, Barber SD: The effect of an extra-articular procedure on allograft reconstructions for chronic ruptures of the anterior cruciate ligament. *J Bone Joint Surg* 73A: 882–892, 1991
- Noyes FR, Butler DL, Grood ES, et al: Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg* 66A: 344–352, 1984
- Parry DA, Barnes GR, Craig AS: A comparison of the size distribution of collagen fibrils in connective tissues as a function of age and a possible relation between fibril size distribution and mechanical properties. *Proc R Soc Lond B Biol Sci* 203: 305–321, 1978
- Paulos LE, Rosenberg TD, Grewe SR, et al: The GORE-TEX anterior cruciate ligament prosthesis. A long-term followup. *Am J Sports Med* 20: 246–252, 1992
- Richmond JC, Manseau CJ, Patz R, et al: Anterior cruciate reconstruction using a Dacron ligament prosthesis. A long-term followup. *Am J Sports Med* 20: 24–28, 1992
- Shaffer BS, Tibone JE: Patellar tendon length change after anterior cruciate ligament reconstruction using the midthird patellar tendon. *Am J Sports Med* 21: 449–454, 1993
- Shelbourne DK, Whitaker HJ, McCarroll JR, et al: Anterior cruciate ligament injury: Evaluation of intraarticular reconstruction of acute tears without repair. Two to seven year followup of 155 athletes. *Am J Sports Med* 18: 484–489, 1990
- Shino L, Inoue M, Horibe S, et al: Reconstruction of the anterior cruciate ligament using allogeneic tendon. Long-term followup. *Am J Sports Med* 18: 457–465, 1990
- Shrive N, Chimich D, Marchuk L, et al: Soft tissue "flaws" are associated with the material properties of the healing rabbit medial collateral ligament. *J Orthop Res* 13: 923–929, 1995