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Effects of Graft Rotation on Initial Biomechanical Failure Characteristics of Bone-Patellar Tendon-Bone Constructs

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Background: Graft-tunnel mismatch is a potential problem during single-incision technique for anterior cruciate ligament reconstruction with the central third of the patellar tendon. Mismatch is present when the graft is too long to fit appropriately in the tunnels that have been created. Graft rotation is one method for addressing this problem.
Purpose: To determine the results of graft rotation up to 540° on initial graft biomechanical properties and graft length.
Study Design: Controlled laboratory study.
Methods: Forty porcine bone-patellar tendon-bone constructs were divided into four groups and constructs were rotated to 0°, 90°, 180°, and 540°, respectively, for each group. Biomechanical testing to failure was performed with the constructs under tension at an elongation rate of 5 cm/sec. Lengths were measured after a 1-kg load was applied to the grafts.
Results: No statistical difference in ultimate failure strength was encountered between any of the groups ($P = 0.915$). The grafts that were twisted to 540° shortened an average of 5.41 mm, which represented an average shortening of 10% of the initial tendon length.
Clinical Relevance: Graft rotation up to 540° does not result in loss of initial graft strength, and may be a solution for graft-tunnel mismatch.

Clinical experience with single-incision ACL reconstruction has shown graft-tunnel mismatch to be a potential problem.[11,23,27] When mismatch occurs, the graft is too long for the tunnels created and protrudes from the tibial tunnel after fixation in the femoral tunnel.

Multiple techniques to resolve this issue have been described, with most of them involving alternative methods of fixation. In 1999, a clinical report of graft rotation as a method of eliminating graft-tunnel mismatch was published.[2] In that report, the authors described a technique whereby external rotation of the graft results in an effective shortening of the ligament portion of the graft, eliminating the excess length. Although a few studies have evaluated the biomechanical properties of the normal ACL and have established the bone-patellar tendon-bone autograft as an effective graft option,[8,9,24] no study has quantified the amount of shortening or determined the effect of extreme rotation on initial graft strength. To our knowledge, the effect of graft rotation has only been evaluated at 90° and 180° of rotation.[8,9]

The objectives of this study were to determine the initial ultimate load to failure in tension of central-third porcine bone-patellar tendon-bone composite grafts in various degrees of rotation and to quantify the associated graft shortening. The hypothesis of this study was that graft rotation would result in decreased load to failure.

MATERIALS AND METHODS

Bone-patellar tendon-bone composite grafts were obtained from nonmatched porcine knee specimens. Specimens were obtained from a local meat packing plant and were from animals processed for food sale at the time of slaughter (Peoria Packing Company, Chicago, Illinois). All specimens were obtained from the hindlimbs after they had already been removed from the carcass, so matching was

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not possible. All of the animals were of approximately the same age at the time of slaughter (11 to 12 months). Previous studies of porcine bone-patellar tendon-bone constructs have demonstrated that the average density of porcine bone closely approximates that of young human bone.[1,17,22] Grafts were harvested by using a standard surgical technique. After harvest, specimens were refrigerated in saline-soaked gauze overnight until ready for testing.

A total of 54 specimens were obtained and included in this study. A pilot study of 11 specimens was performed to standardize the technique of potting and testing. During actual testing, 43 knees were used and 3 specimens that sustained fracture of the bone plugs or failure of the mold were excluded from the data. The data from the remaining 40 specimens that were tested without technical failure were included in this study.

During testing, grafts were fixed with clamps that were modeled after those used by Cooper et al.[9] The tibial tubercle was harvested from the tibia with an oscillating saw. The patella and entire patellar tendon were left intact. Two screws were placed through both the patella and the tibial tubercle in the coronal plane, perpendicular to the tendon (Fig. 1). The patellar tendon was trimmed to the desired 10-mm width by using a fresh scalpel blade. The cross-sectional area of the tendon was determined by using a previously described area micrometer method.[10] Molds were created by using the design described by Cooper et al.[9] (Irmco Tool Works, Barrington, Illinois). The patella and tibial tubercle were potted with acrylic polymer cement (Isocryl, Lang Dental, Chicago, Illinois) (Figs. 2 and 3). The patellar tendon was protected from thermal injury during the potting process, and a phosphate-buffered saline spray was used to keep the tendon moist.

Biomechanical testing was conducted with an Instron materials testing device (Instron Corporation, Canton, Massachusetts) with a 5000-N load cell. The clamps were attached to both the base and load cell with 1-inch threaded steel rods.[9] Appropriate vertical alignment was achieved by sliding the molds within the clamps. Because of the limited width of the molds and the proper alignment of the clamps, no significant differences in horizontal

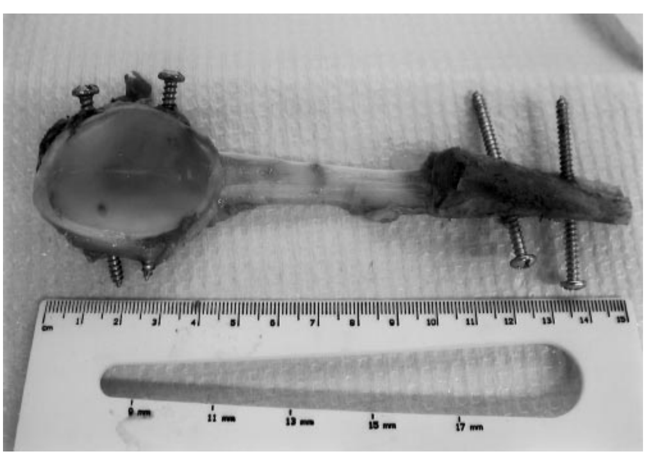

Figure 1. Porcine patella-patellar tendon-tibial tubercle construct after screws have been inserted into bone plugs to prevent pull-out from the acrylic cement during testing.

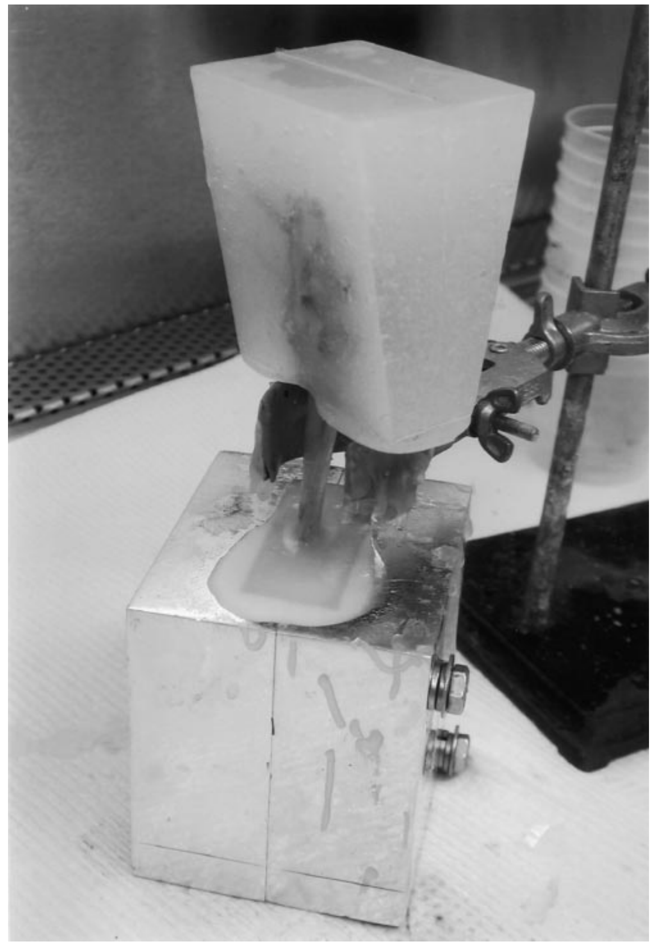

Figure 2. Preparation of mold on the patellar side of the construct after the tibial tubercle has already been molded.

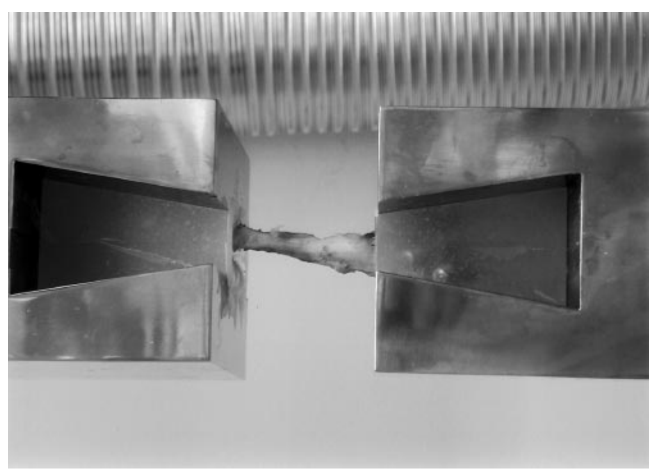

Figure 3. Construct just before testing. The length of the soft tissue varied slightly for each specimen, but averaged near 5 cm.

alignment were encountered. Rotation was achieved by removing the mold from the clamp, rotating the graft to the desired degree, and replacing the mold within the clamp. Because the orientation of the graft could not always be determined after potting was completed, the direction of rotation was not standardized.

Graft length was determined by using the Instron machine. The Instron device was first set in a position-control mode and calibrated with a zero clamp-to-clamp distance. The grips were then separated and the molds inserted as previously described. The Instron device was then set in a load-control mode with a set point of 1.0 kg. After the desired set point was achieved, the graft length could be read directly off the display. This was equal to the length of nonembedded tendon or clamp-to-clamp distance. This clamp-to-clamp measurement was used as an approximation of true tendon length and deformation. Despite the fact that all specimens tested demonstrated midsubstance rupture and although this mechanical testing method is based on past investigations,[8–10,21] nonuniform deformation immediately adjacent to gripped (that is, embedded) tendon decreased the precision of using clamp-to-clamp distance as a determinant of deformation. However, the large strains (typically greater than 4 cm) and sample lengths tended to minimize this confounding effect on clamp-to-clamp measurement, which was used in this study more for comparison purposes between rotated and nonrotated tendons and less as a determinant of true tendon mechanical/structural properties. After each desired rotation (that is, treatment) was performed, this process was repeated and the graft length after rotation was obtained.

An elongation rate of 5 cm/sec was used to approximate the 100% per second rate previously described.[25] This rate was chosen to optimize the chance of obtaining a midsubstance failure (Fig. 4). A load-elongation curve was generated for each specimen tested (Fig. 5).

Four groups of 10 specimens each were included in this study. Group 1 was tested with 0° of rotation, group 2 was tested with 90° of rotation, and groups 3 and 4 were tested with 180° and 540° of rotation, respectively.

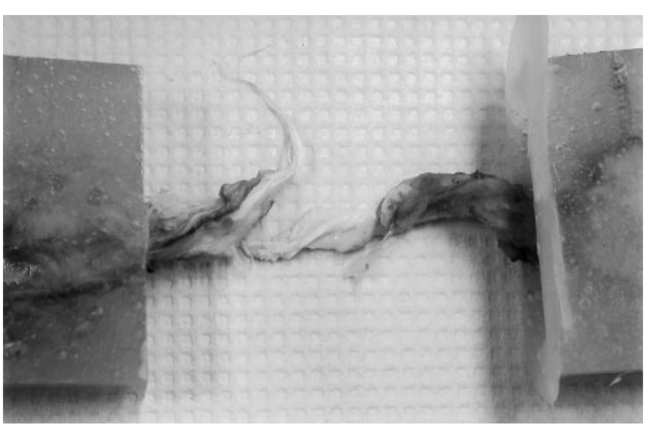

Figure 4. After testing, specimen shows midsubstance failure.

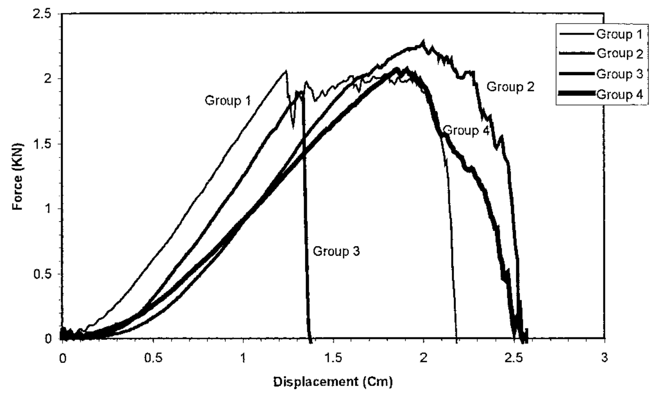

Figure 5. Sample load-elongation curve for each group tested.

A power analysis was performed. The use of 10 specimens per group ensured 87% power for detecting a large effect (F = 0.6) based on a one-way analysis of variance of the square root transformed load-to-failure measurements.[7] A randomization order was used to randomize the testing with regard to rotation. Data were stored on a data acquisition computer system and statistical analysis was then performed. Because the histograms indicated the data were not normally distributed, the nonparametric Kruskal-Wallis test was used. If the P value was less than 0.05 in the Kruskal-Wallis test, we used the Mann-Whitney test to compare individual groups.

RESULTS

Table 1 includes the measurements of ultimate load, shortening, percent shortening of initial tendon length, area, and failure strain for each group. The mean ultimate load to failure for group 1 was 1983 ± 208 N; for group 2, 2017 ± 412 N; and for groups 3 and 4, 1981 ± 285 N and 2065 ± 299 N, respectively. There was no statistically significant difference between any of the groups with respect to ultimate failure ($P = 0.915$).

A similar statistical method was used to analyze data with regard to the other variables. Similarly, no statistically significant difference was present between any of the groups with regard to thickness, cross-sectional area, or initial length. There was a statistically significant increase in strain ($P = 0.013$) and a statistically significant decrease in modulus ($P = 0.06$) between group 4 and the remaining groups.

With regard to change in length with rotation, the amount of shortening achieved increased with increasing degrees of rotation. In group 2, the average shortening was 0.2 mm (range, 0 to 0.5). In group 3, the average shortening was 0.42 mm (range, 0 to 1.5). In group 4, the average shortening was 5.41 mm (range, 5.0 to 8.1). This degree of shortening represented an average of 11% shortening of the initial tendon length. There was a statistically significant difference between groups 1 and 4, groups 2 and 4, and groups 3 and 4 ($P < 0.0005$), but not between groups 1, 2, and 3.

TABLE 1
Results of Mechanical Testing for Each Group Tested

Group	Rotation	Load to failure (N)	Shortening (mm)	Percent shortening of initial tendon length (%)	Area (mm^2)	Failure strain (%)	Modulus
1	0°	1983 ± 208	0	0	39.3 ± 10.4	31.8 ± 8.6	242.2 ± 89.6
2	90°	2017 ± 412	0.21 ± 0.16	0.36 ± 0.28	43.3 ± 12.0	32.2 ± 5.3	226.8 ± 54.0
3	180°	1981 ± 285	0.42 ± 0.45	0.92 ± 0.86	44.9 ± 7.6	32.1 ± 3.8	214.9 ± 46.7
4	540°	2065 ± 299	5.41 ± 1.3[a]	11.0 ± 4.2[a]	41.6 ± 6.5	44.2 ± 9.6	172.3 ± 31.6[a]

[a] Statistically different from the other groups.

DISCUSSION

Graft-tunnel mismatch is a potential problem associated with single-incision ACL reconstruction surgery with patellar tendon autograft or allograft. Graft-tunnel mismatch occurs when incorrect tunnel placement results in the graft protruding from the tibial tunnel after proper placement within the femoral tunnel. Accurate intraarticular measurement techniques as well as a thorough knowledge of ACL anatomy can help prevent occurrence of this problem.[12,16,18–20] Yet, despite the best technique, problems with tunnel placement and graft-tunnel mismatch may still occur. An incidence of up to 26% has been reported.[27,28]

When graft-tunnel mismatch occurs, there are multiple methods to choose from for addressing the problem. Black et al.[5] demonstrated that the length required for adequate interference screw fixation in a porcine hindquarter model could be decreased to 12.5 mm, with no significant difference in torque, divergence, stiffness, displacement, or load to failure. Taylor et al.[29] reported no difference in postoperative KT-1000 arthrometer (Medmetric Corp., San Diego, California) results at 1-year follow-up in a group of 100 patients managed with femoral plug recession. However, potential disadvantages of this technique include graft laceration by the interference screw and an alteration in the femoral isometric point of the graft. Barber[3] reported a technique of flipping one bone plug 180° over its ligamentous insertion, thereby shortening the intraarticular length. At last follow-up, 86% of his 50 patients had good and excellent results and 92% had stable knees by arthrometer testing.

Other strategies for correcting graft-tunnel mismatch problems involve alternate methods of fixation. Initial graft fixation strength was studied by Novak et al.,[23] who compared a screw-and-post model with free bone block interference screw fixation. They found the maximum load to failure of the screw-and-post model to be 374 N, versus 669 N in the free bone block interference screw group in a bovine knee model. A similar method was used by Fowler and DiStefano.[13] Their technique involved using an autograft cancellous core of bone placed in the tibial tunnel, followed by interference screw fixation. Other options used to deal with graft-construct mismatch include screw-and-post and staple fixation of the graft.[15,22]

In 1999, Auge and Yifan[2] described a technique of graft rotation for dealing with graft-tunnel mismatch. They reported that up to a 25% shortening of the collagenous portion of the graft could be achieved with 630° of external graft rotation. In their clinical series, they reported on three patients who underwent this technique during their ACL reconstruction to eliminate graft-tunnel mismatch. At 1-year follow-up, all patients' knees were stable, had KT-1000 arthrometer values less than 3 mm, and no difference in clinical outcome from controls. The obvious advantage of this method over previous methods is that it is quick, technically easy to complete, and maintains osseous graft fixation at the articular surface. Use of this technique alone for minor mismatch differences and combining it with a shorter interference screw for more significant differences would allow one to effectively deal with almost all cases of graft-tunnel mismatch.

To our knowledge, no one has reported on the potential effect that extremes of rotation may have on the initial material properties of the graft. Cooper et al.[8,9] reported a statistically significant increase in ultimate load to failure in graft rotation from 0° to 90° ($P < 0.05$), with no additional increase with further rotation to 180°. In their study of human allograft specimens, the ultimate failure load in the control group with no rotation ($N = 5$) was 2664 N.[9] In the group with 90° of rotation ($N = 5$), the ultimate failure load was 3397 N. In the group with 180° of rotation ($N = 5$), the ultimate failure load was 2684 N. Testing at rotation beyond 180° was not conducted. In another study, however, investigators reported no change in yield strength with 90° of pretwist.[21]

The results of this study indicate that, in a porcine model, no difference in initial graft strength occurs with graft rotation. This would suggest that graft rotation might be used as a method for addressing graft-tunnel mismatch without compromising the initial stability of the construct. An obvious limitation to this recommendation is that it is based on results from an in vitro approximation of ultimate load to failure. The laboratory testing methods did not include cyclic loading or angular or rotation force and do not necessarily reflect the forces that are encountered by the graft in vivo. Second, it is not known how the biologic process of remodeling and revascularization may affect the late biomechanical properties of the graft, nor is it known whether graft rotation may change this process and the ultimate outcome. However, if the initial biomechanics of the graft remain unchanged with rotation, we would expect similar results in vivo and at long-term follow-up. A recent clinical report suggests that the clinical stability of rotated grafts is retained at 1-year follow-up,[2] but larger studies are needed to confirm this result.

An interesting finding of this study is that failure strain (percent elongation) was significantly increased in the 540° rotation group and that modulus was significantly decreased in the 540° group. Although in this study the mean failure strain of the untwisted group reported was higher than that reported by Cooper et al.[9] in a similar study, the results do fall within a range reported by other authors.[4,24,25] No significant difference was noted between the 0°, 90°, and 180° groups (Table 1), which is similar to results reported by others.[8,9,21] A decreased modulus represents a less stiff material, resulting in an increased displacement for any given force. One concern is whether the observed decrease in modulus would result in increased potential for instability at physiologic loads. Further clinical follow-up studies are needed to address this concern.

A porcine model was chosen for this study because of the limited availability of human cadaveric specimens. Because we wanted to control for a very specific variable, in this case rotation, we thought that the large variation in age, sex, and physical condition that would be present in human specimens would be unacceptable. Furthermore, if we had used younger cadaveric specimens, it would have been difficult to obtain the large number of specimens necessary to achieve statistical significance. The porcine model has been used extensively in the past to study the ACL, and the biomechanical properties of porcine soft tissue have been found to closely approximate that of young humans.[14,15,22]

Matched specimens were not available in this study. If we had been able to directly compare two bone-patellar tendon-bone grafts from the same animal at different degrees of rotation, it might have eliminated a potential source of variation in the study. However, given that these animals were all male, all of the same age, and all raised in similar environmental conditions, we believed that the variation among specimens was still minimized.

In the second part of this study we quantified the amount of shortening that could be achieved with rotation. As expected, the amount of shortening increased with the degree of rotation. At 540°, an average shortening of 5.4 mm was observed. This represented an average of 10% of initial tendon length. These results suggest that there may be a relationship between graft shortening and the degree of rotation.

One factor that was not addressed in our study is the direction of graft rotation. It has been determined that natural rotation is evident in collagen stuctures, both macroscopically and microscopically.[6] In the ACL, this rotation has been found to average about 55° in an external direction.[26] In a canine model, the patellar tendon has also shown a natural external rotation of about 5°.[21] Auge and Yifan[2] consistently demonstrated increased shortening with external rotation compared with internal rotation. We were unable to control for external versus internal rotation because of our potting technique. However, the difference in direction may account for our wide range of results in the 540° rotation group (range, 3.4 to 8.1 mm), and consistent external rotation may provide an average shortening greater than the 5.4 mm we observed. On the basis of these data, we recommend an external direction of rotation to most closely replicate native ACL anatomy and to maximize shortening.

In conclusion, graft-tunnel mismatch is a problem that may be encountered during ACL reconstructions in which a single-incision endoscopic technique is used with bone-patellar tendon-bone autograft or allograft material. Various techniques, mostly involving alternative methods of fixation, have been used to deal with this problem. Clinical experience has revealed that graft rotation may be a technically simple approach for correcting this deficiency. Previously, however, the effect of graft rotation on the biomechanical properties of the graft was unknown. This study showed that graft rotation to 540° shortens the soft tissue portion of the graft by an average of 5.4 mm, or 10% of the initial graft length. However, the rotation did appear to decrease the stiffness of the graft and increase the strain to failure. This suggests that graft rotation may be an effective solution for graft-tunnel mismatch, although it is possible that the observed decrease in graft stiffness might result in an increased potential for laxity at physiologic loads. Further clinical studies are needed to evaluate the long-term clinical stability achieved with rotated grafts.

REFERENCES

1. Aerssens J, Boonen S, Lowet G, et al: Interspecies differences in bone composition, density, and quality: Potential implications for in vivo bone research. *Endocrinology 139:* 663–670, 1998
2. Auge WK II, Yifan K: A technique for resolution of graft-tunnel length mismatch in central third bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Arthroscopy 15:* 877–881, 1999
3. Barber FA: Flipped patellar tendon autograft anterior cruciate ligament reconstruction. *Arthroscopy 16:* 483–490, 2000
4. Black J, Hastings G: *Handbook of Biomaterial Properties.* London, Chapman and Hall, 1998
5. Black KP, Saunders MM, Stube KC, et al: Effects of interference fit screw length on tibial tunnel fixation for anterior cruciate ligament reconstruction. *Am J Sports Med 28:* 846–849, 2000
6. Butler DL, Grood ES, Noyes FR, et al: Effects of structure and strain measurement technique on the material properties of young human tendons and fascia. *J Biomech 17:* 579–596, 1984
7. Cohen J: *Statistical Power Analysis for the Behavioral Sciences.* Second edition. Hillsdale, NJ, Lawrence Erlbaum Associates, 1988
8. Cooper DE: Biomechanical properties of the central third patellar tendon graft: Effect of rotation. *Knee Surg Sports Traumatol Arthrosc 6 (Suppl 1):* S16–S19, 1998
9. Cooper DE, Deng XH, Burstein AL, et al: The strength of the central third patellar tendon graft. A biomechanical study. *Am J Sports Med 21:* 818–824, 1993
10. Ellis DG: Cross-sectional area measurements for tendon specimens: A comparison of several methods. *J Biomech 2:* 175–186, 1969
11. Ferrari JD, Bush-Joseph CA, Bach BR Jr: Endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: Surgical technique. *Tech Orthop 13(3):* 262–274, 1998
12. Fineberg MS, Zarins B, Sherman OH: Practical considerations in anterior cruciate ligament replacement surgery. *Arthroscopy 16:* 715–724, 2000
13. Fowler BL, DiStefano VJ: Tibial tunnel bone grafting: A new technique for dealing with graft-tunnel mismatch in endoscopic anterior cruciate ligament reconstruction. *Arthroscopy 14:* 224–228, 1998
14. Fuss FK: Anatomy and function of the cruciate ligaments of the domestic pig (Sus scrofa domestica): A comparison with human cruciates. *J Anat 178:* 11–20, 1991
15. Gerich TG, Cassim A, Lattermann C, et al: Pullout strength of tibial graft fixation in anterior cruciate ligament replacement with a patellar tendon graft: Interference screw versus staple fixation in human knees. *Knee Surg Sports Traumatol Arthrosc 5:* 84–88, 1997

16. Hartman GP, Sisto DJ: Avoiding graft-tunnel mismatch in endoscopic anterior cruciate ligament reconstruction: A new technique. *Arthroscopy 15:* 338–340, 1999
17. Kousa P, Jarvinen TLN, Kannus P, et al: Initial fixation strength of bioabsorbable and titanium interference screws in anterior cruciate ligament reconstruction. Biomechanical evaluation by single cycle and cyclic loading. *Am J Sports Med 29:* 420–425, 2001
18. Kurzweil PR: Formula to calculate the length of the tibial tunnel with endoscopic ACL reconstruction to avoid graft-tunnel mismatch. *Arthroscopy 15:* 115–117, 1999
19. Miller MD, Hinkin DT: The "N + 7 rule" for tibial tunnel placement in endoscopic anterior cruciate ligament reconstruction. *Arthroscopy 12:* 124–126, 1996
20. Morgan CD, Kalman VR, Grawl DM: Definitive landmarks for reproducible tibial tunnel placement in anterior cruciate ligament reconstruction. *Arthroscopy 11:* 275–288, 1995
21. Munns SW, Jayaraman G, Luallin SR: Effects of pretwist on biomechanical properties of canine patellar tendons. *Arthroscopy 10:* 404–411, 1994
22. Nagarkatti DG, McKeon BP, Donahue BS, et al: Mechanical evaluation of a soft tissue interference screw in free tendon anterior cruciate ligament graft fixation. *Am J Sports Med 29:* 67–71, 2001
23. Novak PJ, Wexler GM, Williams JS Jr, et al: Comparison of screw post fixation and free bone block interference screw fixation for anterior cruciate ligament soft tissue grafts: Biomechanical considerations. *Arthroscopy 12:* 470–473, 1996
24. 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
25. 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 56A:* 236–253, 1974
26. Samuelson TS, Drez D Jr, Maletis GB: Anterior cruciate ligament graft rotation. Reproduction of normal graft rotation. *Am J Sports Med 24:* 67–71, 1996
27. Shaffer B, Gow W, Tibone JE: Graft-tunnel mismatch in endoscopic anterior cruciate ligament reconstruction: A new technique of intraarticular measurement and modified graft harvesting. *Arthroscopy 9:* 633–646, 1993
28. Spindler KP, Bergfeld JA, Andrish JT: Intraoperative complications of ACL sugery: Avoidance and management. *Orthopedics 16:* 425–430, 1993
29. Taylor DE, Dervin GF, Keene GC: Femoral bone plug recession in endoscopic anterior cruciate ligament reconstruction. *Arthroscopy 12:* 513–515, 1996