Optimal Graft Length for Anterior Cruciate Ligament Reconstruction: A Biomechanical Study in Beagles

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abstract

The anterior cruciate ligament (ACL) is a major ligament that helps maintain the stability of the knee joint. Injury to the ACL can be treated by replacing the torn ligament. This study determined the optimal flexor tendon length in the bone tunnel in ACL reconstruction.

Autologous ACL reconstruction was performed using a flexor tendon in 54 male beagles, with the graft length in the bone tunnel at 5, 9, 13, 17, 21, and 25 mm (9 dogs per graft length). The maximum tensile strength and stiffness of the reconstructed joint (tibia-ACL-femur triad) were recorded at 45, 90, and 180 days after ACL reconstruction (6 joints per time point). The experiment also included an intact control group (3 dogs) and a control group tested immediately after the reconstruction (3 dogs). For the intact control group, the normal ACL (unreconstructed) and flexor tendon mechanical testing was performed. For the other control group, the normal ACL (unreconstructed) mechanical testing was performed first and then mechanical testing of the specimens was performed immediately after reconstruction.

The maximum tensile strength and stiffness of the reconstructed tibia-ACL-femur triad increased with time after reconstruction, regardless of the graft length in the bone tunnel. Maximum tensile strength and stiffness of the grafts increased with graft length but reached a plateau at 17 mm. Optimal strength and stiffness of the reconstructed ACL are achieved with 17-mm grafts.
The anterior cruciate ligament (ACL) is 1 of 4 major ligaments that maintain the stability of the knee joint. Injury to the ACL destabilizes the knee joint and may cause secondary injury to other intra-articular structures. Severe ACL injury can be treated by replacing the torn ligament with either autograft or allograft. Autograft ACL reconstruction is most often achieved with the patellar or hamstring tendon.

Many factors, including graft strength and graft-to-bone healing, affect the outcomes after ACL reconstruction using autogenous hamstring tendons. The graft strength is mainly determined by the tendon strands when hamstring tendon autografts are used for ACL reconstruction. Trojani et al³ used a transitional double-bundle procedure with multistranded hamstring tendons for ACL reconstruction in 78 patients, and 93% of the patients had satisfactory outcomes. Toritsuka et al³ used a transitional double-bundle ACL reconstruction with 8 strands of hamstring tendons and achieved a success rate of 97.7%. Kondo et al⁷ reported that the postoperative anterior and rotational stability after the anatomic double-bundle ACL reconstruction was significantly better than single-bundle reconstruction in 328 consecutive patients.

Folding the graft tendon increases the strength of the graft itself but could reduce the length of the graft tendon in the bone tunnel. In an intra-articular goat model, Zantop et al⁷ evaluated Achilles tendon split grafts with 15-mm (18 knees) and 25-mm (18 knees) graft lengths in the femoral tunnel. The results indicated that ACL reconstruction with a 15-mm graft length results in significantly less anterior tibial translation after 6 weeks but not after 12 weeks.⁸

Most orthopedic surgeons in China fold the autologous hamstring tendon into 4 strands. The graft length in the bone tunnel using this approach is approximately 17 mm. Whether this is the optimal practice remains to be verified. In the current study, the authors examined the biomechanical properties of the knee joint after autogenous ACL reconstruction with graft lengths ranging from 5 to 25 mm in beagles.

**Materials and Methods**

**Study Design**

A total of 60 healthy adult male beagles (weight range, 13-16 kg) were used. All dogs cleared routine quarantine prior to the study and underwent an anterior drawer test for both knees and a Lachman test. Results of the tests were normal.

The ACL reconstruction was performed in 54 dogs (9 dogs and 18 knees per group), using varying graft lengths (5, 9, 13, 17, 21, or 25 mm) in the bone tunnel. Biomechanical testing was performed at 45, 90, and 180 days after the reconstruction in 3 dogs that were selected randomly from each group at each time point. The strength of normal (unreconstructed) femur-ACL-tibia triad was tested in 3 dogs (control group). The biomechanical property of the reconstructed femur-ACL-tibia triad with graft length filling the entire bone tunnel was tested in 3 dogs immediately after the reconstruction.

**ACL Reconstruction**

ACL reconstruction was performed while the dogs were under anesthesia with ketamine (10 mg/kg administered intra-muscularly) and intravenous sodium pentobarbital (30 mg/kg) in a strictly aseptic environment. The flexor tendon was separated along the deep Achilles tendon and removed. After stripping muscular tissues, the tendon was braided with W4843 Ethibond Excel 2/0 suture at both ends (Figure 1) and stored in physiological saline until use. The medial patellar retinaculum was opened via a medial patellar incision, and the patella was pushed to the lateral side. The ACL was exposed and resected.

**Biomechanical Testing**

Biomechanical testing of the femur-ACL-tibia triad was performed using a universal mechanical testing machine (Zwick Roell Group, Ulm, Germany) (Figure 2), as previously described."
Pre-stretch tension was 2 N, and stretching speed was 10 mm per minute. The measures included the maximum tensile strength and stiffness. The position of the breakpoint was recorded.

**Statistical Analysis**

All statistical analyses were performed using SPSS version 16.0 software (SPSS, Ins, Chicago, Illinois). Data were analyzed with 2-way analysis of variance followed by Dunnett’s t test for pair-wise comparisons. The relationship between the breakpoint and time after the reconstruction, graft length, strength, and stiffness was analyzed with Spearman correlation analysis. Statistical significance was set at a P value less than .05.

**RESULTS**

For the control group, maximum mean tensile strength of a normal ACL was 684.8±48.1 N (n = 12), and mean stiffness was 74.3±7 N/mm (n = 6). For the flexor tendon in the control group, maximum mean tensile strength was 564.2±36.2 N (n = 6), and mean stiffness was 59.9±4.3 N/mm (n = 6). Immediately postoperatively, the maximum mean tensile strength of the reconstructed tibia-ACL-femur triad was 301.9±15 N (n = 6); the mean stiffness was 31.4±2 N/mm (n = 6). All specimens failed at the graft-to-bone junction.

The maximum tensile strength (df=2, F=363.4; P<.05) and stiffness (df=2, F=123.5; P<.05) of the reconstructed tibia-ACL-femur triad increased with time after the reconstruction regardless of the graft length used (Figure 3). Also, the maximum tensile strength (df=5, F=32.7; P<.05) and stiffness (df=5, F=16.9; P<.05) increased with increasing the length of the graft. A significant interaction was noted between time and graft length (df=1, F=1.4; P<.05). A closer inspection of the results indicated that the tensile strength and stiffness reached a plateau at 17-mm graft length. A post hoc analysis revealed that the maximum tensile strength and stiffness at 5, 9, and 13 mm were significantly lower than that at 17, 21 and 25 mm at all 3 time points (Table).

At postoperative day 45, all specimens failed at the graft-bone junction with increasing load. At postoperative day 180, no specimen failed at the graft-bone junction; the break occurred in the middle of the implanted tendon in all cases regardless of the graft length. At postoperative day 90, all specimens in the 5-, 9-, and 13-mm groups failed at the graft-bone junction. Three of 6 specimens in the 17-mm group failed in the graft-bone junction; the remaining 3 specimens failed due to tendon break. Five of 6 specimens in the 21-mm group failed at the graft-bone junction; the remaining 1 specimen failed due to tendon break. Four of 6 specimens in the 25-mm group failed in the graft-bone junction; the remaining 2 specimens failed due to tendon break. The breakpoint position was correlated to the time after the reconstruction (rho=0.82), graft length (rho=0.21), maximum graft strength (rho=0.84), and stiffness (rho=0.72).

**DISCUSSION**

Consistent with the results from Kondo et al and Goradia et al, the current study demonstrated that the tensile strength and stiffness of the reconstructed femur-ACL-tibia triad decreased at 45 days in comparison with immediately postoperatively. From 45 to 180 days, both the strength and stiffness increased over time regardless of the graft length.

Previous studies indicated that the biomechanical property of reconstructed knee is also determined by strength of the graft in addition to the graft-bone junction. In the current study, all ACLs were broken in the middle of the implants when tested on postoperative day 180, demonstrating that the strength of the bone-to-tendon junction exceeded that of implants. This finding also reflects the degenerative changes in the implanted tendon and suggests that improvement of fixation could increase the overall long-term strength of the reconstructed joint. On postoperative day 45, the maximum tensile strength and stiffness were lower than that observed immediately postoperatively. All specimens failed at the graft-bone junction, suggesting that the initial 45 days represents the period for fibrotic changes after graft necrosis and the attachment of the graft to the bone tunnel. The mechanical property was significantly better at graft lengths of 17, 21, and 25 mm than lengths of 5, 9, and 13 mm.
After 90 days postoperatively, the maximum tensile strength and stiffness increased. In the 17-, 21-, and 25-mm groups, 12 specimens failed due to tendon break and 6 specimens failed at the graft-bone junction. All specimens in the 5-, 9-, and 13-mm groups failed at the graft-bone junction. The graft strength and stiffness of the 17-, 21-, and 25-mm groups were better than that in the 5-, 9-, and 13-mm groups. At 180 days postoperatively, the maximum tensile strength and stiffness further increased. All specimens failed due to tendon break within the joint. The results demonstrated that the tendon-bone junction strength has exceeded the intra-articular graft strength at this time point. Also, grafting with 17-, 21-, or 25-mm grafts resulted in superior strength and stiffness than 5-, 9-, or 13-mm grafts.

The current findings have significance for the development of a rehabilitation plan after ACL reconstruction using hamstring tendons. The relatively strong reconstructed ACL immediately postoperatively could allow active functional exercises to be performed. To promote bone-to-tendon healing, the authors recommend starting knee extension and flexion training at 1 week after fixation. On postoperative day 45, the overall strength of the grafts was significantly reduced. As a result, rehabilitation training should be performed conservatively and with caution. On postoperative day 90, the overall strength of the grafts significantly increased, but the bone-to-tendon healing was not complete. Active rehabilitation training could be performed but with caution during this period. On postoperative day 180, the strength of the bone-to-tendon junction exceeded that of the implant.

Considering the difference of knee joint size between beagles and humans, caution must be exercised when attempting to extrapolate the findings to human subjects. Whether a 17-mm graft tunnel is optimal to achieve the optimal strength in humans needs further investigation. The observation period in this study was 180 days. Whether significant changes occur after 180 days needs to be investigated. Also, considering that plaster fixation was not performed in beagles, the results may have been confounded by postoperative activity.

**Conclusion**

Nevertheless, the current study demonstrated that the graft must be sufficiently long to achieve optimal biomechanical performance after the reconstruction. Based on the current findings, 17 mm is sufficient. The performance does not further increase with graft lengths higher than 17 mm.

**References**


