Original Article

Anterior to Posterior Bone Plug Suture Tunnels Provide Optimal Biomechanics for Bone−Patellar Tendon−Bone Anterior Cruciate Ligament Graft

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Purpose: To evaluate different bone−patellar tendon−bone (BPTB) plug suture configurations for pull through strength, stiffness, and elongation at failure in a biomechanical model of suspensory fixation. **Methods:** Forty nonpaired, fresh-frozen human cadaveric BPTB allografts with an average age of 65.6 years were tested. Tensile testing was performed with the use of a custom-designed fixture mounted in a dynamic tensile testing machine. A preload of 90 N was applied to the graft and held for 5 minutes. Following this, a tensile load-to-failure test was performed. The ultimate failure load, elongation at failure, and mode of failure were recorded, and the resulting load−elongation curve was documented. **Results:** The drill tunnel through the cortical surface (anterior to posterior) was found to be significantly stronger than the drill tunnel through the cancellous surface (medial to lateral). There were no significant differences found when comparing the strength of the suture augmentation through the tendon and the drill tunnel alone ($P = .13$ among cancellous groups, $P = .09$ among cortical groups). The cortical drill tunnel with suture augmentation through the tendon showed significantly greater elongation values (13.7 ± 3.2) at failure when compared with either the cancellous or cortical drill tunnel only test groups ($P = .0003$ compared with cancellous alone, $P = .009$ when compared with cortical alone). **Conclusions**: The BPTB suture configuration with an anterior to posterior−directed suture tunnel without a suture through tendon augmentation provides the optimal strength and stiffness while minimizing graft elongation after fixation in a biomechanical model. This configuration is best for preventing suture pull through and failure when passing sutures through the BPTB plug. **Clinical Relevance:** This study biomechanically evaluates the optimal suture configuration in the proximal bone plug for suspensory fixation in the setting of BPTB grafts.

Anterior cruciate ligament (ACL) reconstruction is one of the most common orthopaedic procedures performed in the United States.[1] Athletes, particularly those who participate in contact and high-impact landing sports, pose a high risk for ACL rupture.[2] Many graft choices exist for ACL reconstruction and are dependent on a number of factors. The bone−patellar tendon−bone (BPTB) autograft is one of the most commonly used grafts.[3] It is often employed in the active person or athlete due to faster bony incorporation and reports of greater return to activity level compared to alternative graft choices.[3-5]

There are various methods of femoral fixation for the BPTB autograft.[6] One method of fixation is through an interference fit with a screw, which yields adequate graft fixation strength and stiffness outcomes. The disadvantage of this method, however, is decreased bone surface area healing as well as potential for posterior wall blowout.[7] Cortical suspensory fixation has been introduced as an alternative fixation method that allows increased bone contact surface area for circumferential bony incorporation within the tunnel. Furthermore, cortical suspensory fixation avoids the expansive hoop stress on the tunnel with placement of

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an interference screw, minimizing the risk of posterior wall blowout.[8,9]

Several recent articles have further investigated the viability of suspensory fixation in the BPTB autograft setting. A meta-analysis demonstrated no difference in stability or functional outcomes between patellar tendon and soft-tissue grafts using suspensory fixation.[10] Testing fixation strength and stiffness also rendered equivalent results to screw fixation with minimal graft creep.[11,12]

As cortical suspensory fixation relies primarily on the suture and graft construct for tensioning the reconstructed graft, the biomechanical properties of the construct are important to ensure that this method of fixation is adequate. One method of failure in this construct lies at the suture−graft interface. Typically, the suspensory suture construct is tunneled through the leading end of the bone plug of the graft, and several methods have been described for suture configuration into the plug.[13-15] The direction of the suture bone tunnel varies among surgeons, with sutures passed by drilling either anterior to posterior (AP) through the cortical surface, or medial to lateral (ML) through the cancellous bone. In addition, some techniques reinforce the bone plug drill holes by adding an additional pass with the suture through the tendon at the bone−tendon junction.[16] To date, it is unclear which configuration is best to prevent suture pull-through and failure when passing sutures through the BPTB plug.

The purpose of this study was to evaluate different BPTB plug suture configurations for pull-through strength, stiffness, and elongation at failure in a biomechanical model of suspensory fixation. We hypothesized the drill tunnel through the cortical surface (AP) would be stronger than that in a ML configuration through cancellous bone, and that the suture augmentation through the tendon would provide the greatest strength compared with going through the drill tunnels alone.

Methods

Specimen Preparation

Forty nonpaired, fresh-frozen human cadaveric BPTB allografts were tested in this biomechanical study. These specimens were donated to an allograft organization and then donated to our institution for medical research (JRF Ortho, Centennial, CO). The mean age for these specimens was 65.6 years old and the age range was 28 to 77 years old. There were 11 female specimens and 29 male specimens for this study. Cadaveric biomechanical studies do not require institutional review board approval at our facility. All specimens were stored at −20°C before being thawed at room temperature 6 hours before preparation. The BPTB allograft bone plugs on the patellar side were shaped to a standard uniform size, having a diameter of 10 mm. For all the drill tunnels, a 2.5-mm drill bit was used to create holes 7 mm distal to the proximal point of the patellar bone plug. The suture configurations were made using the Arthrex BPTB Tightrope (Arthrex, Naples, FL). Throughout preparation, specimens were kept hydrated with normal saline.

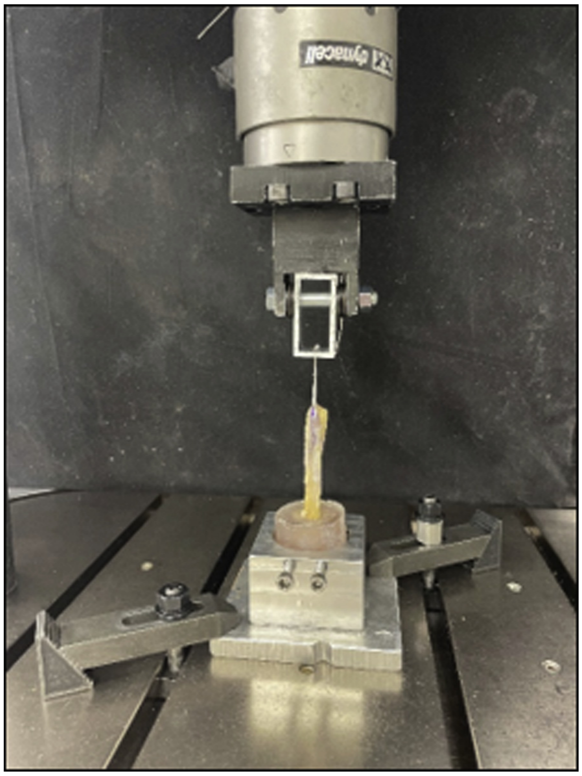

Fig 1. Testing set-up on the dynamic tensile testing machine.

Testing Groups

Once uniformly prepared, the BPTB allograft bone plugs were split into 4 different testing groups. One group included those with a drill tunnel going through the cortical bone (AP). Another testing group included those with a drill tunnel through the cancellous bone (medial to lateral). A third testing group included those with a drill tunnel through the cortical bone and reinforcement with a suture pass going through the bone−patellar tendon interface. Another testing group included those with a drill tunnel through the cancellous bone and reinforcement with a suture pass going through the bone−patellar tendon interface.

Testing

All pullout tests were performed at room temperature. Tensile testing was performed by use of a custom-designed fixture mounted in a dynamic tensile testing machine (Instron ElectroPuls E10000; Instron, Norwood, MA). For each specimen, the potted end of the graft was fixed to the testing bed, and the end of the

Table 1. Mean and Standard Deviations (Mean ± 1 Standard Deviation) of Measurements of Stiffness (N/mm), Failure Load (N), and Elongation at Failure (mm) for All Graft Preparation Groups

	Stiffness, N/mm	Failure Load, N	Elongation at Failure, mm
Cancellous through tendon	36.7 ± 14.4	339.4 ± 126.6	10.3 ± 4.1
Cancellous alone	40.5 ± 23.8	240.7 ± 151.4	6.1 ± 2.2
Cortical through tendon	35.4 ± 14.9	459.9 ± 181.4	13.7 ± 3.2
Cortical alone	70.9 ± 27.1	620.9 ± 217.7	9.2 ± 2.9

graft with the suture configuration was attached to the custom fixture in a way that simulated ideal cortical button fixation (Fig 1). A preload of 90 N was applied parallel to the longitudinal axis of the graft at a rate of 9 N/s and held for 5 minutes. A tensile load-to-failure test was then performed at a rate of 1 mm/s. The ultimate failure load, elongation at failure, and mode of failure were recorded, and the resulting load-elongation curve was documented. Stiffness was calculated as the slope of the linear region of the load-elongation curve.

Statistical Analysis

All statistical analyses were performed using MATLAB (MathWorks, Natick, MA). The results were expressed as the mean ± the standard deviation. A one-way analysis of variance test was performed to determine if there were significant differences in stiffness, ultimate failure load, and elongation to failure between groups. A Student *t* test was performed to evaluate significant pairwise differences ($\alpha = 0.95$) in stiffness, ultimate failure load, and elongation to failure between suture configuration groups.

Results

Stiffness (N/mm)

The test group that was configured with the cortical drill tunnel without a suture augmentation through tendon achieved the highest stiffness (70.9 ± 7.1) (Table 1). This was found to be significantly greater ($\alpha = 0.95$) when compared to the cortical bone drill tunnel with a suture augmentation ($P = .0008$), cancellous bone drill tunnel only ($P = .02$) and cancellous bone drill tunnel with a suture augmentation ($P = .002$). This test group was specifically compared to the test group that was configured with the cortical drill tunnel with a suture augmentation through tendon and was found to have a statistically significant difference ($P = .0008$) (Fig 2). There were no significant differences among other tests group.

Ultimate Failure Load (N)

The test group that was configured with a cortical bone drill tunnel only yielded the greatest ultimate failure load (620.9 ± 217.7) (Table 1) and was significantly stronger ($\alpha = 0.95$) than the drill tunnel through the cancellous surface suture configuration ($P = .0003$). There were no significant differences found when comparing the strength of the cortical bone configuration with a suture augmentation through the tendon and the configurations with the cortical bone drill tunnel alone ($P = .09$) (Fig 2).

Elongation at Failure (mm)

The test group that was configured with a cortical drill tunnel with suture augmentation through the tendon

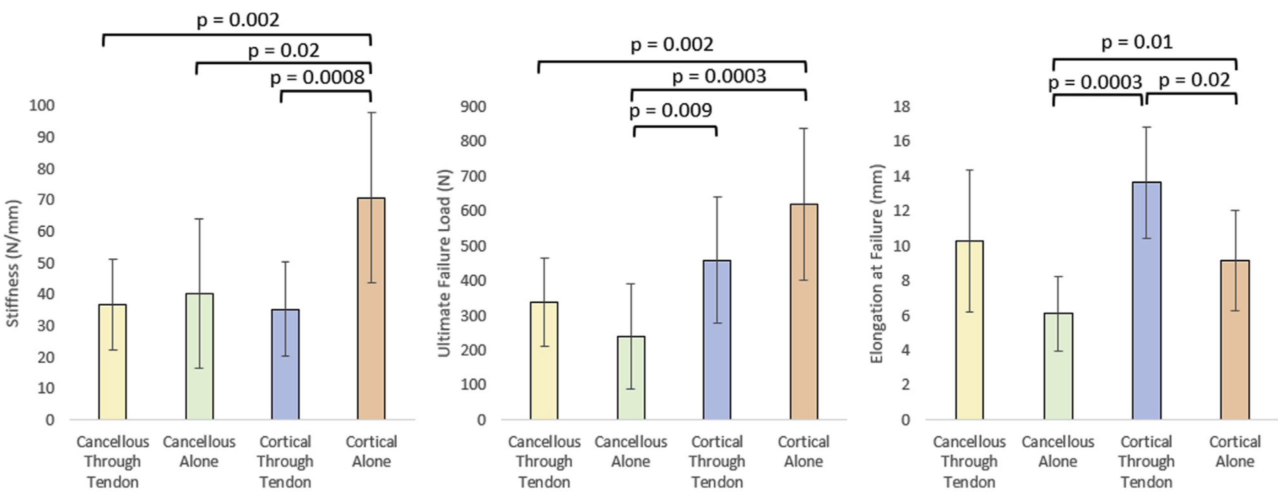

Fig 2. Stiffness (N/mm) of graft preparation groups (left). Failure load (N) of graft preparation groups (center). Elongation at failure (mm) of graft preparation groups (right).

showed significantly greater elongation values (13.7 ± 3.2) at failure when compared to the test group that was configured with a cancellous drill tunnel only ($P =$ .0003) and the test group that was configured with a cortical drill tunnel only ($P =$ .02) (Table 1 and Fig 2). The group that was configured with a cortical drill tunnel only (9.2 ± 2.9) had significantly greater elongation values at failure ($P =$ .01) than the group that was configured with a cancellous drill tunnel only (6.1 ± 2.2). There were no significant differences between all other test groups.

Discussion

Cortical suspensory fixation is a viable method of femoral fixation for BPTB grafts in the setting of both primary and revision ACL reconstruction.[8,10,13] We found that a suture configuration with a simple suture tunnel directed along the AP axis provides the best interface strength and stiffness while minimizing graft elongation after fixation.

A suture configuration oriented through cancellous bone (medial to lateral hole) was biomechanical disadvantageous compared to a suture configuration oriented through cortical bone (AP hole).[9] It is not surprising that a cancellous orientation ultimately failed at a lower load, as fixation is primarily dependent on the quality and characteristics of bone. In fact, the cortical fixation had a nearly 2.5× greater ultimate failure load. The clinical translation of these absolute values is unclear; however, initial graft fixation needs to be as strong as possible to withstand untoward forces in the early postoperative rehabilitation period.[2]

Graft elongation is another important biomechanical property in testing graft fixation. Before complete incorporation, elongation due to sustained tensile forces as well as suture creep remains a factor that contributes to residual laxity.[8,14] Thus, it is critical that the graft maintains high stiffness values without elongating after it is initially fixed. The suture configuration with a simple cortical AP bone tunnel alone demonstrated the best biomechanical properties in this regard.[5] Through tendon augmentation contributed to greater elongation likely due to suture creep, and then reached higher stiffness values once the creep was removed. Finally, the medial to lateral cancellous configuration likely failed before reaching relatively greater elongation values.

When using cortical suspensory fixation for a BPTB graft, we recommend using a simple AP cortical suture configuration because of its superior biomechanical characteristics. Graft fixation is critical in the early postoperative period, as one of the primary sources of failure is the implant−graft interface.[16] There are many interfaces in which a graft may fail, and our study determined that suture configuration may play a large role in early maintenance of graft fixation. Additionally, failure at the suture−bone interface can occur intraoperatively during the graft delivery, where the sutures can pull through the drill hole of the femoral bone plug. In our own experience, this happened on multiple recalled occasions when a medial to lateral construct was prepped and the sutures had pulled through the cancellous bone, damaging the integrity of the femoral bone plug. We feel that this mode of failure is then applicable to both suspensory and interference screw fixation. We do not predict that suture configuration influences graft integrity, thus there is only upside to using a simple AP through-cortical construct in all graft preparations for bone-tendon constructs.

Limitations

There are several limitations to our study. First, this is a biomechanical study and the clinical translation from laboratory to clinical practice may limit the value of this study. Nonetheless, the samples were tested in a standard fashion and tested to failure in a similar force vector that would be realized in clinical practice. Second, although the samples were obtained and prepped in a standard fashion, there may be heterogeneity in testing. However, all samples were obtained from the tissue bank at once, were randomized to each group, and were prepared by a single team. Furthermore, 98% of testing failed at the implant-bone interface, confirming the uniformity in testing the strength of each construct.

Conclusions

The BPTB suture configuration with an AP directed suture tunnel without a suture through tendon augmentation provides the optimal strength and stiffness while minimizing graft elongation after fixation in a biomechanical model. This configuration is best for preventing suture pull-through and failure when passing sutures through the BPTB plug. This study provides biomechanical evidence for surgeons to optimize suspensory fixation in the setting of BPTB autografts.

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