Initial Fixation Strength of Modified Patellar Tendon Grafts for Anatomic Fixation in Anterior Cruciate Ligament Reconstruction

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Summary: Recently it has been shown that anatomic tibial graft fixation in anterior cruciate ligament (ACL) reconstruction is preferable in order to increase isometry and knee stability. To facilitate anatomic patellar tendon graft fixation, customized graft length shortening is necessary. The purpose of this study was to compare the initial fixation strength of four different shortened patellar tendon grafts including three bone plug flip techniques and direct patellar tendon–to–bone interference fit fixation in a model with standardized bone density. Ninety calf tibial plateaus (22 to 24 weeks old) with adjacent patella and extensor ligaments were used. Tendon grafts were shortened by flipping the bone plug over the tendon leaving a tendon-tendon-bone (TTB) construct and, as the first modification in the opposite direction resulting in a tendon-bone-tendon (TBT) construct. The second modification consisted of the TBT construct with interference screw position at the lateral aspect of the bone plug (TBTlat). As the fourth modification the tendon graft was directly fixed (Tdirect) with an interference screw. In addition, a round-threaded titanium (RCI; Smith & Nephew DonJoy, Carlsbad, CA), a round-threaded biodegradable screw (Sysorb; Sulzer Orthopedics, Münisingen, Switzerland), and a conventional titanium interference screw (Arthrex Inc, Naples, FL) were compared. We found that TTB (mean 441 N for biodegradable screw, 357 N for RCI screw, 384 N for conventional screw) and TBT (mean 407 N for biodegradable screw, 204 N for RCI screw, 392 N for conventional screw) construct fixation achieves comparable fixation strength, although failure in the TTB was due to tendon strip off at its ligamentous insertion. The highest failure load was found in TBTlat fixation (mean 610 N for biodegradable screw, 479 N for RCI screw). Therefore, this technique should be recommended when using a tendon flip technique. The failure load for Tdirect fixation (mean 437 N for biodegradable screw, 364 N for RCI screw) was similar to that of TTB and TBT fixation, which may indicate that a patellar-tendon graft harvested without its patellar bone plug and directly fixed with an interference screw is equivalent to a flipped graft. This may additionally reduce harvest site morbidity and eliminates the risk of patellar fracture. The fixation strength of round-threaded biodegradable and conventional titanium interference screws was similar, whereas that of round-threaded titanium screws was significantly lower in the patellar tendon flip-techniques. However, it should be taken into consideration that round-threaded titanium screws are proposed for direct tendon-to-bone fixation. Key Words: Anterior cruciate ligament—Patellar tendon—Anatomic fixation—Interference screw—Fixation strength.
anatomic proximal tibial graft fixation is most isometric. They concluded that anatomic fixation should result in minimal graft elongation during rehabilitation, leading to a more stable long-term result. In addition, in a biomechanical model, Ishibashi et al. reported stability results for a series of ACL reconstructed knees by measuring anterior tibial displacement at different tibial fixation levels. In their study, BPTB grafts were fixed at the anatomic proximal site, the mid-tibial tunnel, and outside the tibial tunnel. They found that anatomic proximal graft fixation achieves the most stable results and should, therefore, be recommended. Anatomic fixation would additionally eliminate tunnel enlargement associated with nonanatomic fixation sites and would possibly reduce wear-related graft damage resulting from the potential windshield wiper effect. These findings suggest that an anatomic fixation at the original ACL insertion sites is preferable.

To facilitate anatomic fixation, a technique that allows customized shortening of the BPTB graft by rotating one bone plug 180° proximally onto the tendon has recently been described. Flipping the bone plug over its ligamentous insertion, however, may substantially change the graft’s initial fixation strength. Therefore, the first purpose of the present study was to compare the initial fixation strength of the patellar tendon flip technique and two modifications in a simulation of young human femoral graft fixation in a calf tibial bone model.

To allow anatomic hamstring or quadriceps tendon graft fixation, there is an increased interest in direct tendon-to-bone fixation using biodegradable and soft-threaded metal interference screws. The direct patellar tendon-to-bone fixation may be advantageous because tendon harvest without its patellar bone plug results in most cases in an appropriate graft length for anatomic fixation. Furthermore, graft harvest morbidity may be reduced and the risk of patellar fracture could be eliminated. Therefore, the second purpose of the present study was to compare the initial fixation strength of direct patellar tendon interference fit fixation with that of the patellar tendon flip techniques.

Because of the unknown fixation properties of round-threaded titanium and biodegradable interference screws and conventional titanium screws in patellar tendon flip and direct patellar tendon-to-bone fixation, the third purpose of the present study was to compare the fixation strength of these three screws.

MATERIALS AND METHODS

Graft Modification and Study Groups

Four different modifications of patellar-tendon graft fixation were compared using three different interference screws. The first patellar-tendon graft was shortened by flipping the bone plug over the tendon leaving a tendon-tendon-bone (TTB) construct as originally described by Morgan et al. (Fig 1A). For the first modification of this graft the bone plug was flipped in the opposite direction resulting in a tendon-bone-tendon (TBT) construct (Fig 1B). The second modification consisted of the flipped TBT construct with interference screw fixation at the lateral aspect of the bone plug (TBT lat) (Fig 1C). As the third modification the tendon graft was directly fixed (T direct) with an interference screw after it has been previously compressed using a modified baseball-stitch (Fig 1D).

A round-threaded titanium interference screw (RCI; Smith & Nephew DonJoy, Carlsbad, CA), a round-threaded biodegradable interference screw (Sysorb; Sulzer Orthopaedics, Münningen, Switzerland), and a conventional titanium interference screw (Arthrex Inc, Naples, FL) were compared (Fig 2). Nine specimens were tested in each group. After specimen preparation and graft insertion, interference screws were randomly chosen to reduce observer dependent variability. Ten groups were assigned:

I, TTB fixation with round-threaded biodegradable interference screw

II, TTB fixation with round-threaded titanium interference screw

III, TTB fixation with conventional titanium interference screw

IV, TBT fixation with round-threaded biodegradable interference screw

V, TBT fixation with round-threaded titanium interference screw

VI, TBT lat fixation with round-threaded biodegradable interference screw

VII, TBT lat fixation with round-threaded titanium interference screw

VIII, T direct fixation with round-threaded biodegradable interference screw

IX, T direct fixation with round-threaded titanium interference screw

Interference Screws

The biodegradable interference screw (Sysorb is made of pure poly-(D,L-lactide). The screw is 23 mm in length (thread diameter, 8 mm; core diameter, 6.2 mm) and its thread pitch is 3 mm. The screw and the driver are characterized by a specially designed turbine-like shape with six curved blades which increases the implant resistance against breakage.
Figure 1. (A) Patellar tendon flip technique (TTB) fixation as described by Morgan et al. using the round-threaded biodegradable interference screw. (B) Modified patellar tendon flip technique (TBT) fixation with the round-threaded titanium interference screw. (C) Modified patellar tendon flip technique with lateral screw fixation (TBTlat) using the biodegradable interference screw. (D) Direct tendon-to-bone fixation with the round-threaded titanium interference screw.
The round-threaded titanium interference screw (RCI) is 25 mm in length (thread diameter, 7 mm; core diameter, 4 mm; head diameter, 8 mm) and its thread pitch is 2.25 mm. Its surface is polished.

The conventional titanium interference screw (Arthrex) is 25 mm in length (thread diameter, 8 mm; core diameter, 5.56 mm) and its thread pitch is 2.86 mm.

Biomechanical Model

In this study, 90 fresh bovine proximal tibiae (aged 22 to 24 weeks) were used to simulate young human femoral bone density, partially due to findings described by Brown et al. We further refined the model by isolating a reproducible location for the graft and screw insertion as described elsewhere. The fixation site represents a trabecular bone density of 0.8 g/cm³ similar to what is expected in young humans.

Proximal calf tibiae were harvested from a local butcher. Specimen were stored at \(-20°C\) and were thawed 12 hours prior to testing. Proximal tibiae were cut 5.5 cm distally to the intercondylar spine and bone tunnels were prepared using the serial dilation technique described by Johnson and van Dyk in 1-mm increments. Dilators (Instrument Makar Inc, Okemos, MI, and Sulzer Orthopedics, Münsingen, Switzerland) were inserted into the cancellous bone from the proximal direction. Bone tunnels for groups I to VIII were dilated until a diameter of 10 mm and a length of 20 mm was reached, because the expected mean graft-tunnel mismatch was calculated to be approximately 20 mm. Tunnels in groups IX and X were dilated until the smallest possible graft diameter (7 to 9 mm) previously measured in the sizing holes of a working station (Sulzer Orthopaedics, Münsingen, Switzerland) and a length of 25 mm as recommended for the direct hamstring tendon interference fit fixation.

Grafts in groups I to VIII were manually inserted into the tunnels, while grafts in groups IX and X were pulled in with a strong suture that had been previously secured to the free tendon end. To minimize possible graft laceration in groups IX and X, a tunnel notcher was used (Linvatec, Largo, FL) to create a small notch as a guide for screw insertion, thus preventing clockwise rotation of the screw around the tendon. Screws were inserted using a digitally controlled torque screw driver (Wera Werk; Hermann Werner, Wuppertal, Germany) while recording peak insertion torque. The torque screw driver was scaled from 0.035 Nm to 3.5 Nm in increments of 0.001 Nm. The screws were always inserted in the same position with respect to bone tunnel and graft.

We found that the bovine patellar bone plug consists almost entirely of cortical bone as already described by Butler et al. and over two thirds of the tibial bone plug consists of the ligamentous insertion of the...
patellar tendon. Therefore, the lateral retinaculum, whose tibial insertion is more proximal than that of the patellar tendon and which is attached to the patella over a strong ligamentous strand, was used. Standardized rectangular 20 × 10 mm bone plugs were harvested from the tibial insertion using an oscillating saw. The harvested graft and its bone-ligament junction is grossly comparable to the human BPTB graft. To control for specimen uniformity width of proximal tibiae, free tendon length, bone plug length, and bone plug width were recorded.

Biomechanical Testing and Data Analysis

Specimens were kept moist with saline spray during all preparation and testing. Holes were drilled through the intercondylar spine and the patella perpendicular to the long axis of the bone tunnel. To mount the patella-retinaculum-tibia construct to the material testing machine (Zwick 1455; Zwick, Ulm, Germany) 8-mm steel bolts were passed through the drill holes, allowing rotational adjustment in the axis of the bolts. A preload of 10 N was applied and the construct was then loaded until failure under displacement control of 1 mm per second. Load was applied parallel to the long axis of the bone tunnel. Failure mode was recorded (graft pullout, midsubstance tendon rupture, tendon rupture inside the tunnel, tendon strip off from its bony insertion, bone plug fracture) and maximum failure load and ultimate stiffness were determined from the load-displacement curve.

The ten groups were compared using the Mann-Whitney U Wilcoxon rank sum test. Linear regression analysis was performed between maximum pullout force and screw insertion torque within each group and between the groups. To determine the influence of additional variables, correlation analyses were performed between maximum pullout force or insertion torque and the following variables: bone plug width, bone plug length, and width of proximal tibia. Another correlation analysis was performed between stiffness and tendon length.

RESULTS

Results are shown in Table 1. The highest failure load was found for TBTLat (mean, 610 N in group VII and 479 N in group VIII) fixation (VII > I: P = .0003, VII > IV: P = .0005, VIII > II: P = .0054, VIII > V: P = .0005). Between TTB (mean, 441 N in group I, 357 N in group II, and 384 N in group III) and TBT fixation (mean, 407 N in group IV, 204 N in group V, and 392 N in group VI) there was only a significant difference between groups II and V (P = .0031) with the RCI screw. Failure load of Tdirect (mean, 437 N in group IX and 364 N in group X) and TTB or TBT

| Table 1. Results for Pullout Tests and Specimen Uniformity |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | I (Biodeg)      | II (RCI)        | III (Conv)      | IV (Biodeg)     |
| Failure load (N)| 441 ± 32        | 357 ± 84        | 384 ± 50        | 407 ± 88        |
| Range (N)       | 388 - 481       | 264 - 353       | 286 - 493       | 308 - 543       |
| Stiffness (N/mm)| 31.7 ± 7        | 27.6 ± 7.2      | 31.6 ± 6.2      | 32.4 ± 3.5      |
| Insertion torque (Nm)| 2.41 ± 0.52 | 2.45 ± 0.38 | 3.02 ± 0.21 | 2.71 ± 0.35 |
| Failure mode (range in N)| | | | |
| Pulloff | 2 (304-454) | 3 (324-353) | — — | 8 (308-485) |
| Midsubstance rupture | — — | — — | — — | — — |
| Rupture inside tunnel | — — | — — | 1 (543) | 2 (514-516) |
| Tendon strip off | 7 (388-481) | 6 (264-551) | 9 (286-493) | 8 (308-485) |
| Bone pig fracture | — — | — — | — — | — — |
| Mean tunnel diameter (mm) | 10 | 10 | 10 | 10 |
| Width of proximal tibia (cm) | 8.57 ± 0.58 | 8.54 ± 0.9 | 8.57 ± 0.62 | 8.7 ± 0.59 |
| Tendon length (mm) | 82 ± 4.04 | 85.7 ± 7.53 | 77.5 ± 7.70 | 85.7 ± 7.53 |
| Bone plug width (mm) | 9.77 ± 0.36 | 9.9 ± 0.21 | 9.93 ± 0.08 | 9.91 ± 0.14 |
| Bone plug length (mm) | 20.3 ± 0.37 | 20.2 ± 0.37 | 20.3 ± 0.35 | 20.3 ± 0.38 |
fixation was comparable, except between groups X and V ($P = .0243$) with the RCI screw. Main failure mode in TTB fixation was tendon stripping off from its ligamentous insertion site along the bone plug, whereas in all other groups fixation failed mainly because of graft pullout from the bone tunnel.

The biodegradable screw showed superior failure load compared with the round-threaded titanium screw for TTB, TBT, and TBT$_{lat}$ fixation ($I > II: P = .0092$, $IV > V: P = .0118$, VII > VIII: $P = .0017$). There was no significant difference for failure load between the biodegradable screw and the conventional titanium screw in TTB and TBT fixation, whereas the round-threaded titanium screw failed at a significantly lower load compared with the conventional screw in TBT fixation ($VI > V: P = .0013$).

Stiffness of fixation was found highest for T$_{direct}$ fixation using the biodegradable screw, and it was found lowest for TBT fixation using the round-threaded titanium screw. For direct tendon fixation, we found significant positive linear correlations between failure load and screw insertion torque in groups IX ($r^2 = 0.66, P = .0078$) and X ($r^2 = 0.79, P = .0013$). Correlation analyses revealed no significant influence of bone plug width, bone plug length, or width of the proximal tibia on either pullout force or screw insertion torque. There was also no significant influence of tendon length on construct stiffness.

DISCUSSION

The first purpose of the present study was to compare the initial fixation strength of three patellar tendon flip-techniques with interference screw fixation. TTB and TBT fixation exhibit similar fixation strength, although the failure in TTB fixation occurred mainly because of the tendon stripping off from its ligamentous insertion. In TBT fixation, the interference screw is inserted at the cortical side of the bone plug and its threading may not perforate the hard cortical bone. Conventionally, interference screws are inserted along the cancellous part of the bone plug, which might increase fixation strength due to the threading cutting deeply into the cancellous bone. In general, it is reasonable to assume that, beside the bone stock quality of the graft site, two major variables may influence bone plug fixation in ACL reconstruction. The first variable is the influence of screw diameter on fixation strength, which may mainly determine fixation strength by a press-fit mechanism. The second major variable is the threading contact area, which is, beside the thread pitch, mainly presented by the thread contact pitch.

The second purpose of this study was to compare the fixation strength of direct patellar tendon to bone fixation with that of the patellar tendon flip-techniques. We could demonstrate that TTB, TBB, and T$_{direct}$ fixation reach comparable initial strength values. Harvesting the patellar tendon graft without its attached patellar bone plug may have distinct advantages for the patient. First, patellofemoral problems, especially kneeling pain associated with the graft harvest, may be reduced. Secondly, the risk of patellar fracture could be eliminated. In groups IX and X, we found significant positive linear correlations between screw insertion torque and failure load, suggesting that screw insertion torque may be useful as a positive predictor for failure load when using direct patellar tendon to bone fixation in the clinical situation.

The third purpose of this study was to compare three different interference screws. The biodegradable interference screw tested provides a comparable initial fixation strength as conventional titanium screws in TTB and TBT fixation. The use of biodegradable interference screws has distinct advantages over their metal analogs, which have led to an increased use of these implants in BPTB graft fixation. These advantages include undistorted magnetic resonance imaging, easier revision surgery, and a decreased potential of graft laceration. In this study, we have not tested these screws for conventional bone-tendon-bone graft fixation because these data exist already and have been recently published elsewhere. In that study, various biodegradable interference screws were compared in the same model as presented here. The conventional titanium screw and the biodegradable poly-(D,L-
lactide) interference screw had failure load values of 822 ± 130 N and 713 ± 210 N, respectively,22 which differ substantially from the data presented here. However, it should be taken in consideration that circular bone plugs were harvested in that previous study in contrast to rectangular bone plugs as in the present study and originally described for the patellar tendon flip technique.3 Shapiro et al.32 found that circular bone plugs provide approximately 20% greater fixation strength than rectangular bone plugs, which makes it reasonable to assume that TBT lat fixation may be at least comparable to conventional BTB graft fixation.

To decrease the potential of graft laceration, the round-threaded interference screw (RCI) was originally developed for direct hamstring tendon graft fixation.18,19,53 Therefore, we have chosen to test this implant for TTB and T direct fixation because, in this situation, it is essential to have an implant that will not lacerate the tendinous part of the graft. In fact we found comparable fixation strength for biodegradable and round-threaded titanium screws in T direct fixation. However, in TTB fixation the RCI screw showed lower strength values compared with the biodegradable implant as already described for hamstring tendon fixation.17 In TTB fixation, the RCI showed a markedly lower fixation strength because of its blunt threads. We should take in consideration that this implant was not developed for bone plug fixation.

We have studied the initial fixation strength of patellar tendon flip-techniques and direct patellar tendon-to-bone fixation. Some questions still remain to be addressed in future studies such as the viability of tendon-to-bone healing under this fixation, fixation slippage, and the decrease of fixation strength resulting from the construct’s viscoplastic properties.

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